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Radon in Dwellings The Irish National Radon Survey

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ABSTRACT

This report presents the results of a survey of radon in domestic dwellings in Ireland carried out by the Radiological Protection Institute of Ireland (RPII) between 1992 and 1999. The survey was carried out to identify areas of the country most at risk from high indoor radon levels.

The survey was geographically based using the 10 km grid squares of the Irish National Grid as the unit area. Indoor radon measurements were carried out for 12 months using passive alpha track detectors in houses selected at random in each grid square throughout the country. The results were used to predict the percentage of houses in each grid square with radon levels in excess of 200 Bq/m^3 (the Reference Level for houses). Grid squares across the country in which this prediction exceeds 10% are designated High Radon Areas. Radon prediction maps, detailing the distribution of High Radon Areas, were produced for each county.

Radon measurements were carried out in 11,319 houses throughout the country. Radon levels varied from 10 to 1,924 Bq/m^3 with an average indoor radon concentration of 89 Bq/m^3. Using the GeoDirectory database, which provides the number of residential units in each grid square, it has been estimated that 91,019 houses throughout the country, or 7% of the total, have indoor levels in excess of 200 Bq/m^3 and that the population-weighted average indoor radon concentration is 91 Bq/m^3.

1. INTRODUCTION

The link between long-term exposure to high levels of radon gas and increased risk of developing lung cancer has long been widely accepted [1]. In 1990, the Irish Government adopted an annual average radon gas concentration of 200 Bq/m^3 as the national Reference Level above which remedial action to reduce the indoor radon level in a dwelling should be considered. During the late 1980s and the early 1990s a number of surveys were carried out to identify areas of the country most affected.

Between 1985 and 1989, a population-weighted radon survey was carried out by the Department of Experimental Physics, University College Dublin (UCD), in which measurements over 3 months were made in 1,300 houses throughout the country. From this survey, it was estimated that 4% of the national housing stock has indoor radon concentrations above 200 Bq/m^3 [2]. The survey also indicated that the probability of finding a house with elevated indoor radon levels was highest in the western counties, with 11% of houses in the Mayo-Galway-Clare region predicted to have elevated indoor radon concentrations.

Between 1989 and 1992, the RPII carried out further detailed surveys in the West of Ireland in areas previously identified by the UCD study as being radon prone. More intensive surveys were also carried out in Moycullen and Salthill in County Galway, and south Cork city. The main finding of these surveys was the identification of areas in parts of Galway and Mayo, where it was estimated that more than 10% of houses have radon levels greater than 200 Bq/m^3 [3]. The highest radon concentration found during the surveys was a level of 2,399 Bq/m^3 in the Salthill area of Galway city.

Based upon the results of these surveys it was apparent that radon levels varied considerably from county to county. To assist in identifying areas at greatest risk of high indoor radon levels, the RPII initiated a national survey in 1992. Unlike the population-weighted UCD survey, this survey was geographically-based.

Five reports detailing the results of successive phases of the survey have been published [4-8]. This report describes the methodology of the survey and the results obtained in greater depth, and presents the radon prediction maps for the country.

2. SURVEY METHODOLOGY

The primary objective of the survey was to determine, in detail, the geographical distribution of radon levels in dwellings throughout Ireland. The mapping technique used in this survey was developed by the UK National Radiological Protection Board (NRPB) in the early 1990's, and uses the results of indoor radon measurements, in houses selected at random, to predict the percentage of houses with radon levels above the reference level for an area [9]. Mapping may be carried out using administrative unit areas such as townlands, local authority boundaries, District Electoral Divisions etc. However, as these administrative areas are irregularly shaped and sized, data sampling can be difficult. For geographically-based surveys it is preferable to use unit areas of identical shape and size, which ensures that the same number of householders are invited to participate in the survey for each unit area. Unit areas based upon the Ordnance Survey's National grid are consistent in shape and size and were selected for this survey.

The 10 km grid square was chosen as a compromise between the requirement for detailed mapping and the need for sufficient results within each area to allow a meaningful statistical analysis to be carried out. Statistical advice indicated that a minimum sample size of five dwellings per grid square was appropriate for this survey [10]. In order to ensure that this sample size was achieved a minimum of 50 householders per grid square were initially invited to participate. In 1995 this figure was increased to 70 to improve the number of responses from each grid square. The householders' names and addresses were randomly selected from the Register of Electors and invited by letter to participate in the survey. When agreeing to participate householders were asked to indicate, as accurately as possible, the locations of their homes on a county map provided. This information was then used to assist in assigning the measurement result for each dwelling to the correct grid square. The location marked by the householder on the county map was checked against an Ordnance Survey map to confirm that it generally agreed with where it should be, based upon the postal address of the participant's house. If there was not general agreement then the result for that house was not included in the final data analysis. The participants were asked to complete a questionnaire that included questions about various physical features of the house and the living habits of the occupants.

The radon detectors used in this survey were passive alpha track detectors. The detector consists of a two part polypropylene holder and a CR-39 (poly allyl diglycol carbonate) detection plastic. The CR-39 records the tracks created when the alpha particles, emitted during the decay of radon, strike the plastic. The holder acts as a simple radon diffusion chamber, allowing the entry of radon gas, but excluding radon decay products, dust and moisture. Radon and its decay products are electrically charged when formed, so any electrostatic charges inside the detector will affect where they plate out, leading to a non-uniform deposition of tracks across the plastic. During the manufacturing of the polypropylene holders graphite is added as a conductor so that the holders will be electrically neutral. To reduce the effects of electrostatic charges on the plastics, they are dipped in a 5% solution of detergent and allowed to dry, prior to being assembled with the holders. The detergent absorbs moisture from the air allowing the electrostatic charges on the plastic to leak away. Upon completion of a measurement the plastics are removed from their holders and chemically etched for 8 hours in a 6.25 M NaOH solution at 75 ºC. The chemical etching enlarges the tracks created by the alpha particles. The tracks are viewed using a Leitz Ergolux AMC microscope and analysed using a Leica Quantimet Q520 image analysis system. Tracks are accepted as genuine if their size and shape fall within acceptable limits. A track density is determined for each plastic.

The CR-39 plastics are subjected to regular quality checks. Each sheet of plastics comprises typically 110 elements. To determine whether a sheet of plastics is suitable for use, five plastics are removed and analysed to determine a background value for the sheet. Sheets with large backgrounds are rejected as unsuitable for use. An additional five plastics are also removed and exposed in the RPII's radon chamber to a known radon source, to determine a sensitivity factor for the sheet.

Each participant was issued with two radon detectors and instructed to place one in the main living area and the second in an occupied bedroom. A twelve month measurement period was selected which avoided the necessity of having to correct the results for seasonal variations in radon concentrations. On return to the RPII, the detectors were processed and the annual average radon concentration for each dwelling was calculated by averaging the results of the two measurements, assuming equal occupancy between the bedroom and living area. All householders were individually notified in writing of their measurement results and, where appropriate, recommendations were made regarding the necessity for remedial action.

The country was surveyed on a phased basis, by county, between 1992 and 1999. During the course of the survey invitations to participate in free radon measurements were sent to approximately 53,000 householders. At the launch of each new phase of the survey, a press release was issued and radio interviews and articles in local newspapers were undertaken to encourage those householders receiving survey invitations to participate. Typical participation responses ranged from 17 - 36% for each county.

3. RESULTS

Radon measurements were completed in a total of 12,649 houses. Before inclusion in the final analysis, the result for each house was validated, i.e. it was confirmed that both detectors from the house were returned and the grid square location of the house was known. The final number of valid measurements was 11,319 which represents a sampling rate of 1 in 116 houses throughout the country, based upon the housing statistics for 2000 [11]. There were 837 grid squares surveyed with ten or more valid measurements obtained in 529 squares.

A summary of the results of these measurements for each county is presented in Table 1. A total of 993 of the dwellings surveyed had radon concentrations in excess of the Reference Level of 200 Bq/m^3. The county with the largest proportion of high radon houses measured was County Sligo where 20% of the houses exceeded the Reference Level.

The summarised results for all the measurements are detailed in Table 2. The mean annual indoor radon concentration for the dwellings measured was 89 Bq/m^3. The maximum value of 1,924 Bq/m^3 was measured in a house in County Kerry. While the overall Geometric Standard Deviation (GSD) for the measurements was 2.40, it should be noted that the GSDs for individual grid squares ranged from 1.23 to 5.86. The value of 2.40 for the national GSD is consistent with results from previous surveys carried out by the RPII between March 1989 and December 1992, where a mean value of 2.40 was obtained from measurements carried out in 1755 houses [3].

Completed questionnaires were received from 10,122 (89%) of the participants. Information regarding the house type was given in 9961 questionnaires. Assuming that these questionnaires are representative of all houses surveyed, the most common type of house surveyed was a bungalow (52%) followed by a two storey detached house (27%). The remaining house types included single and two storey terraced and semi-detached houses. In Dublin, the predominant house type surveyed was a two storey semi-detached house (46%) followed by a two storey terraced house (18%). As the survey is geographically, rather than population based, the large number of bungalows surveyed reflects the fact that most of the houses surveyed were in rural areas. A summary of the questionnaire responses is included in Appendix I.

County	No. of Dwellings Measured	No. >200 Bq/m^3 (% of dwellings measured)	Mean (Bq/m^3)	Max (Bq/m^3)
Carlow	194	30 (15%)	123	1562
Cavan	180	5 (3%)	67	780
Clare	742	66 (9%)	88	1489
Cork	1211	71 (6%)	76	1502
Donegal	487	18 (4%)	69	512
Dublin	155	6 (4%)	73	260
Galway	1213	181 (15%)	112	1881
Kerry	932	52 (6%)	70	1924
Kildare	480	29 (6%)	90	1114
Kilkenny	181	16 (9%)	100	717
Laois	334	17 (5%)	83	565
Leitrim	145	6 (5%)	60	433
Limerick	524	41 (8%)	77	1102
Longford	132	8 (6%)	75	450
Louth	124	14 (11%)	112	751
Mayo	1184	152 (13%)	100	1214
Meath	233	18 (8%)	102	671
Monaghan	120	4 (3%)	68	365
Offaly	286	7 (2%)	68	495
Roscommon	235	17 (7%)	91	1387
Sligo	270	54 (20%)	145	969
Tipperary	852	63 (7%)	79	1318
Waterford	162	20 (12%)	119	1359
Westmeath	289	20 (7%)	91	699
Wexford	469	54 (12%)	99	1124
Wicklow	185	24 (13%)	131	1032

Table 1. Summary of Survey Results for each County

Number of Dwellings Measured	No. Measured >200 Bq/m^3	Min (Bq/m^3)	Max (Bq/m^3)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD
11,319	993	10	1924	89	57	2.40

Table 2. National Survey Results

4. DATA ANALYSIS

It has been shown that the distribution of radon levels in dwellings approximates a log-normal distribution [12] and that such a log-normal approximation appears to hold whether a whole country, or a smaller area such as a 10 km grid square, is considered [9].

To test the data set for log-normality, 20 grid squares were selected with between 32 and 67 houses measured per square. Figures 1a and b show the normal quantile plots for the measured and standardised radon concentration data respectively. The quantile plot in figure 1a is based upon the raw residuals combined from the 20 grid squares; figure 1b presents the same data in terms of standard deviations (standardised residuals). If the overall distribution was perfectly log-normal then the plotted data would appear as a straight line. It can be seen from the plots there is a deviation from linearity in the data in the upper tail of the distribution, indicating a slight departure from log normality; however, overall the agreement is quite good.

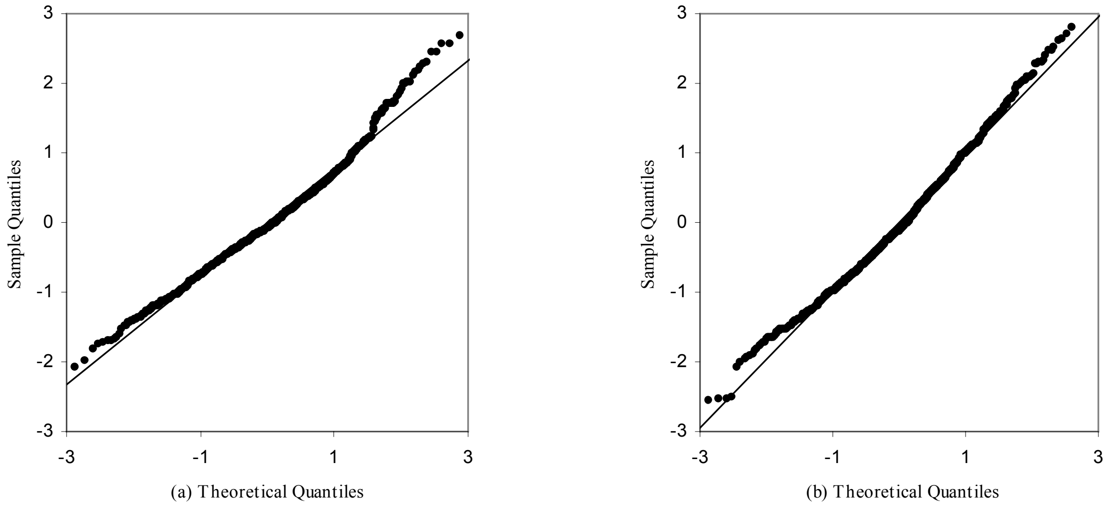

Figure 1: Q-Q Plots to test for log-normal distribution (a) Raw residuals and (b) Standardised residuals

Gunby *et al.* [13] describe the UK data set as being composed of a base radon level due to the outdoor air radon concentration and an additional log-normal distribution of radon in domestic dwellings. The Irish data set was examined for evidence of a similar contribution from outdoor air. Following subtraction of different constants from the data set, the resulting distributions were examined to see if the log-normality of the distribution was improved. It can be seen from Figure 2 that the log-normality of the data set can be improved by subtracting a value of 6 Bq/m^3 from the data. Although the value of the mean radon concentration in outdoor air in Ireland has not been measured, a value of 6 Bq/m^3 appears to be consistent with measurements obtained in other European countries.

The proportion of houses exceeding the Reference Level of 200 Bq/m^3 in any grid square can be read from statistical tables of the area under the standardised normal curve once the $\hat{k}$ is known. $\hat{k}$ is a transformed threshold for use with the standard normal distribution and is calculated for each grid square using the formula

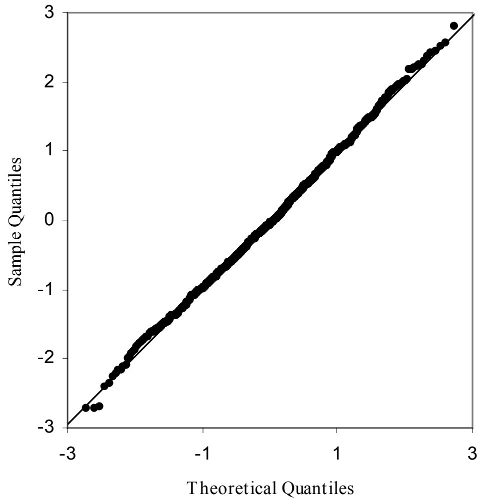

Figure 2: Log-normally transformed Q-Q Plot

$$\hat{k} = \frac{\ln(200) - \ln(GM)}{\ln(GSD)}$$

where GM and GSD are the geometric mean and geometric standard deviation of the measurement results. Grid squares where the predicted percentage of dwellings with radon concentrations above 200 Bq/m^3 is 10% or greater, are designated High Radon Areas. A table is included in Appendix II which lists the results for each grid square.

For grid squares with five or more valid measurements, the GM and GSD were calculated from the data within the square. Figure 3 shows the number of valid measurements in each grid square included in the survey analysis. In 86 grid squares, out of a total of 837 squares surveyed, less than five valid measurements were available upon completion of the survey. For these grid squares it was not possible to accurately determine the GM or GSD from the data available. In order to obtain representative values for the GM and GSD, a smoothing procedure using the available data within the square and data in surrounding squares was carried out.

A weighting matrix was generated for each square which was then applied to the radon measurements in the surrounding grid squares. The weighting matrix, unique for each square, took into account the amount of data within the square in question and also data in the surrounding squares and the variance in that data. For grid squares along the sea coast the weighting matrix was adjusted to take account of data not being available for neighbouring squares which cover the sea. A full description of this model is given by Pawitan and Fennell [14] and is based on the approach of Breslow and Clayton [15]. An example of the smoothing algorithm, which illustrates how the GM and GSD are calculated, is given in Appendix III.

Figure 3: Map showing the number of valid measurements per 10 km grid square

Radon prediction maps, based upon the results obtained, were produced for each county and are presented in Figures 5 to 8 (an index map is provided in Figure 4). The predictions are represented by 5 percentage bands i.e., <1%, 1-5%, >5-10%, >10-20% and >20%. The two percentage bands 10-20% and >20% delimit the High Radon Areas. For a small number of the grid squares, as many as 50% of dwellings are predicted to have radon levels greater than 200 Bq/m^3.

While the survey was conducted on a 10 km grid square basis, until now population distribution data, based on the 1996 census, has only been available on a District Electoral Division (DED) basis, of which there are 3,440 covering the country. In most cases the DEDs correspond to irregularly shaped areas that can be associated with towns and villages; they do not coincide with the 10 km squares.

In July 2000 a new database (GeoDirectory) was made available by the Ordnance Survey of Ireland and An Post, the Irish Postal Service [11]. This database contains a validated record for every postal delivery point throughout the country. As every building has a postal address, the database contains a record for every building throughout the country. The location of each building has been determined using a GPS system and its National Grid co-ordinates stored on the database. Each data point was subsequently visited to determine whether the purpose of the building was either residential or commercial. The predominant residential building type in Ireland is a private house; there are relatively few residential buildings with multiple delivery points, such as apartment blocks. Thus the number of residential delivery points within each 10 km grid square will approximate the number of houses within each square.

For each 10 km grid square the housing density data from GeoDirectory were combined with the individual grid square predictions from the National Survey to estimate the number of high radon houses within each square. It has been estimated that 91,019 houses, throughout the country, have indoor radon levels which exceed 200 Bq/m^3.

This combined GeoDirectory – Radon dataset was also used to calculate the population-weighted average indoor radon level. When the distribution of houses, and thus the population, throughout the country is taken into account the population-weighted average indoor radon concentration was calculated to be 91 Bq/m^3.

5. DISCUSSION

It is evident from Figures 5 to 8 that there is considerable geographical variation in indoor radon concentrations across the country. There are 837 grid squares covering the Republic of Ireland; of these, 234 (28%) have been classified as High Radon Areas. In particular, counties in the south-east of the country, namely Carlow, Kilkenny, Waterford, Wexford and Wicklow, and in the west, namely, Clare, Galway, Mayo and Sligo, have a higher proportion of affected areas.

This survey is a geographically based survey. However, in estimating the scale of the radon problem, the housing density, as well as the distribution of High Radon Areas across the country, must be taken into account. Using the GeoDirectory dataset the number of houses predicted to have levels in excess of 200 Bq/m^3 is 91,019 or 7% of the housing stock in 2000. To allow comparison with radiation doses arising from other sources, the radiation dose due to radon exposure can be calculated using an exposure-dose conversion factor of 1 millisievert (mSv) radiation dose per 40 Bq/m^3 radon concentration in a dwelling, assuming an occupancy of 7000 hours per annum [16]. Using this conversion factor, an occupant of a house with an indoor radon level of 200 Bq/m^3, the national Reference Level, receives a radiation dose from radon of 5 mSv per annum. Using occupancy levels derived from the 1996 Census data, it is estimated that between 280,000 and 322,000 people (based on 95% confidence intervals) are receiving doses greater than 5 mSv per annum from radon within their homes.

It is interesting to investigate the distribution of high radon houses, i.e. houses with indoor radon levels > 200 Bq/m^3, throughout the country based upon the 10% High Radon Area criterion. Table 3 examines the relationship between the predicted number of high radon houses across the country and their occurrence in High Radon Areas. In this table sensitivity is defined as the number of high radon houses correctly identified in the High Radon Areas as a percentage of the total number of high radon houses predicted throughout the whole country. Specificity is likewise defined as the number of low radon houses correctly identified in areas where the prediction is less than 10%, as a percentage of the total number of low radon houses found in the whole survey area.

Using the survey predictions and the GeoDirectory database, 59,336 of the 91,019 predicted high radon houses in the country are located in High Radon Areas. This constitutes 65% of the total number of high radon houses in the country and 21% of all houses within the High Radon Areas. The High Radon Areas cover 28% of the country. Grid squares not classified as High Radon Areas contain 78% of all houses throughout the country and encompass 72% of the area of the country. Three

		Specificity (81%)	Sensitivity (65%)	
Radon Areas	Area	Houses < 200 Bq/m^3	Houses >200 Bq/m^3	
< 10%	72%	989,110 (97%)	31,683 (3%)	1,020,793
> 10% (High)	28%	227,827 (79%)	59,336 (21%)	287,163
		1,216,937	91,019	1,307,956

Table 3. Distribution of High Radon Houses

percent of houses within this area have concentrations in excess of 200 Bq/m^3. The relative risk factor of 7 indicates that a house in a High Radon Area has a risk 7 times greater than a house located elsewhere of having an indoor radon concentration in excess of 200 Bq/m^3.

To date radon measurements have been made in approximately 20,000 houses which represents only 1.5% of the national housing stock in 2000 (GeoDirectory). Of the estimated 91,000 high radon houses, approximately 2,300 (2.5%) have been identified. By targeting future surveys in the High Radon Areas, and carrying out measurements in approximately 300,000 houses, approximately 60,000 high radon houses could be identified – this represents a detection rate of 1 in 5 houses measured. In contrast, to identify the 31,683 high radon houses located outside these High Radon Areas measurements would have to be carried in over 1,020,000 houses – a detection rate of 1 in 30. It is obvious that surveys targeted at the High Radon Areas will provide a higher rate of detection and a better return of resources invested.

Ongoing survey work can only identify high radon levels in existing houses. The radon prediction maps are also used to identify areas of the country where new houses are more likely to have elevated indoor levels. In order to prevent future radon problems in new housing the Irish Building Regulations require that some degree of radon preventive measures are incorporated in every new house at the time of construction. The Technical Guidance Documents [17], which provide guidance on compliance with the requirements of the Building Regulations, now require that the foundations in all new dwellings incorporate a potential means of extracting radon from the sub-structure. In addition, new dwellings in High Radon Areas must be fitted with a sealed membrane of low permeability. To determine the degree of radon preventative measures required for a new house the architect must now consult the RPII's radon prediction maps to determine the radon designation of the area in which the house is being built.

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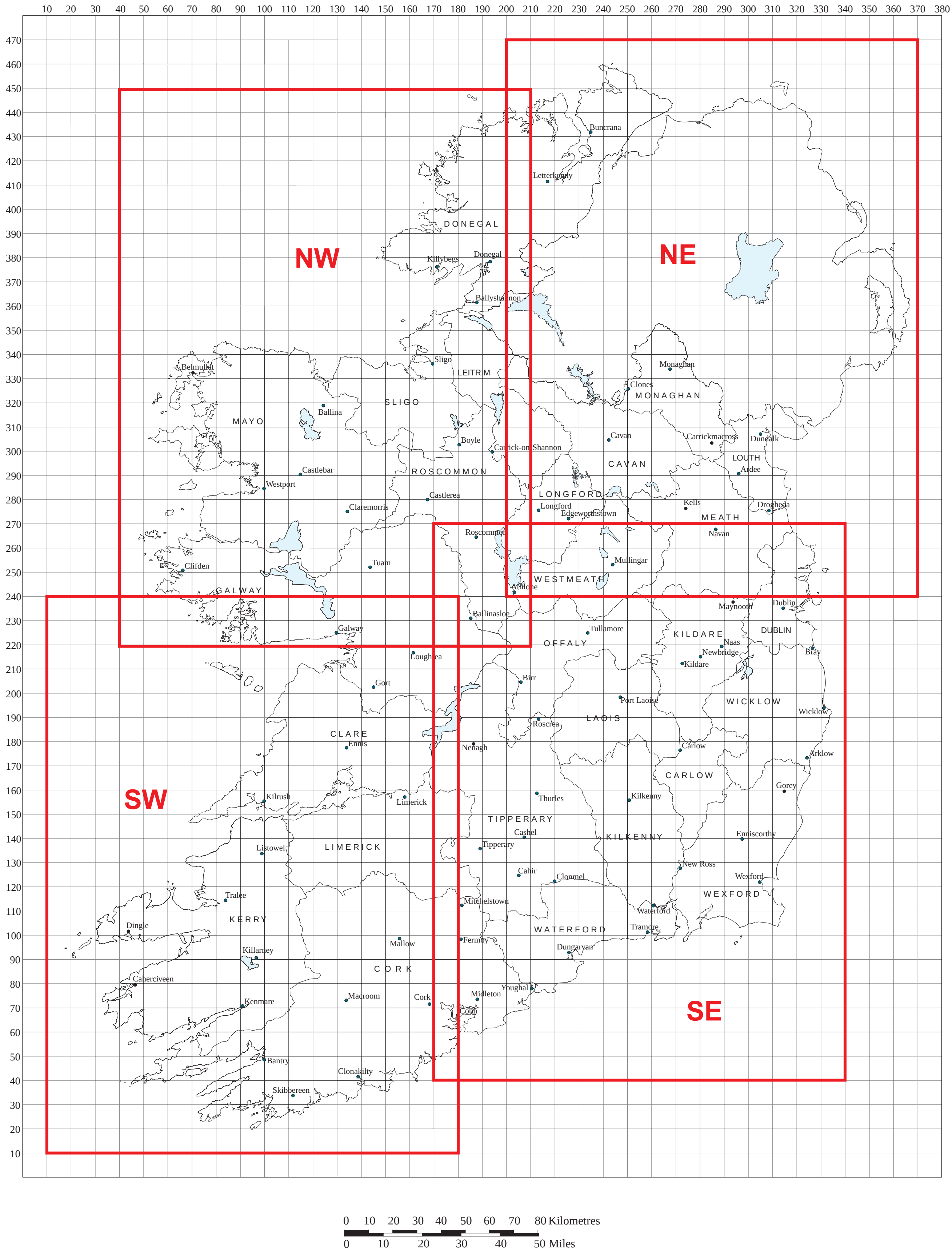


Figure 4: Index Map of Ireland

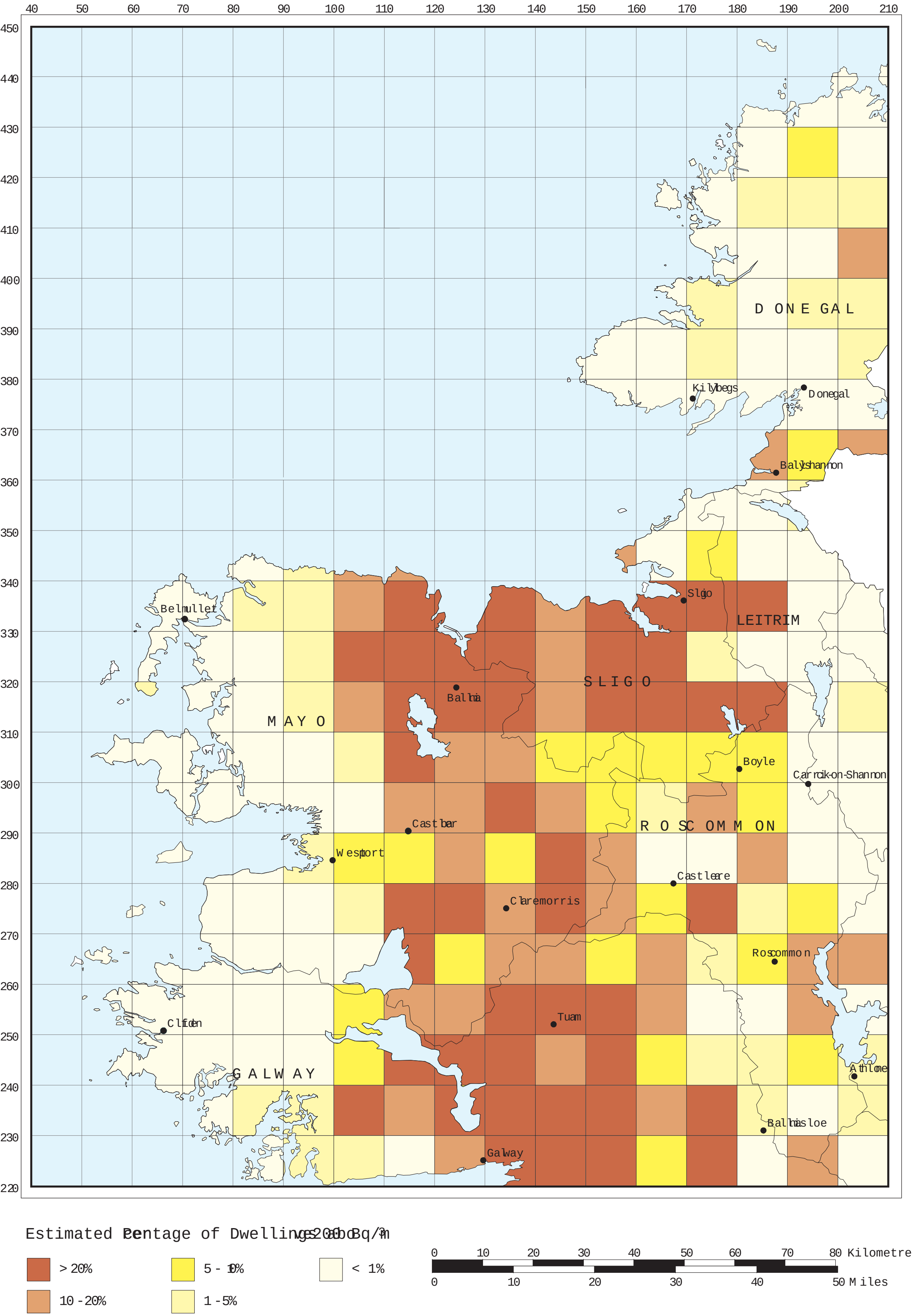


Figure 5: Radon Prediction Map for the North West of Ireland

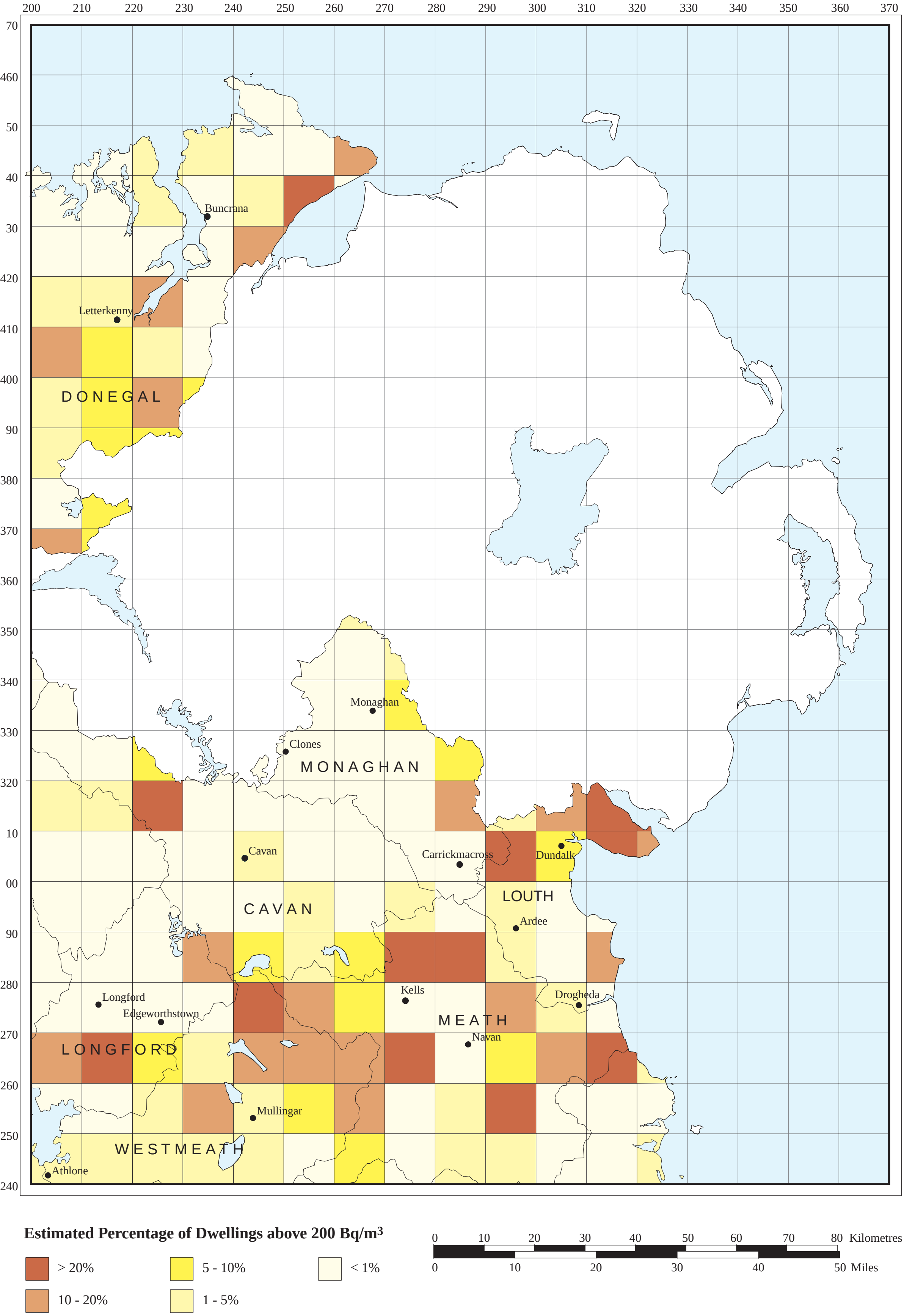


Figure 6: Radon Prediction Map for the North East of Ireland

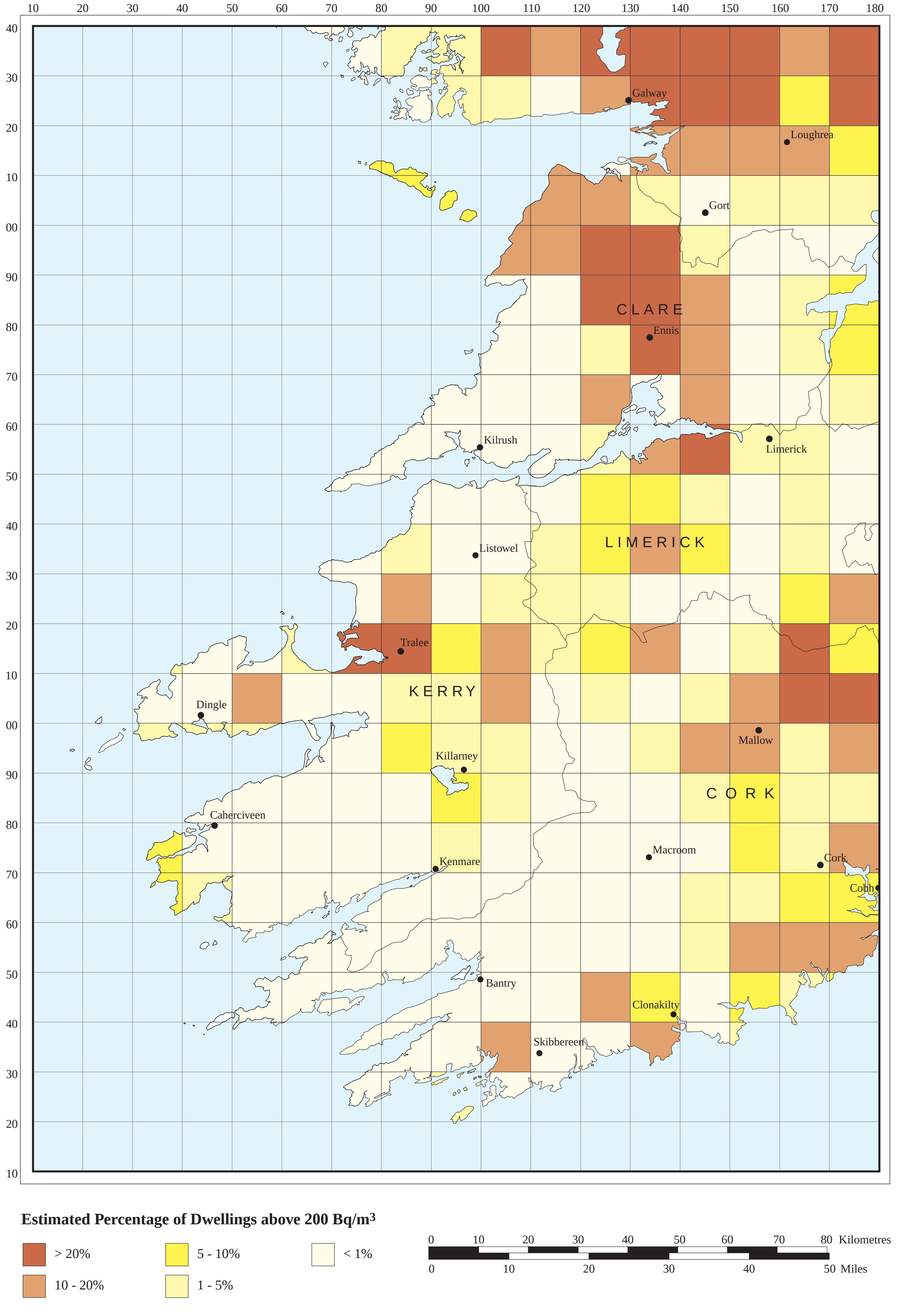


Figure 7: Radon Prediction Map for the South West of Ireland

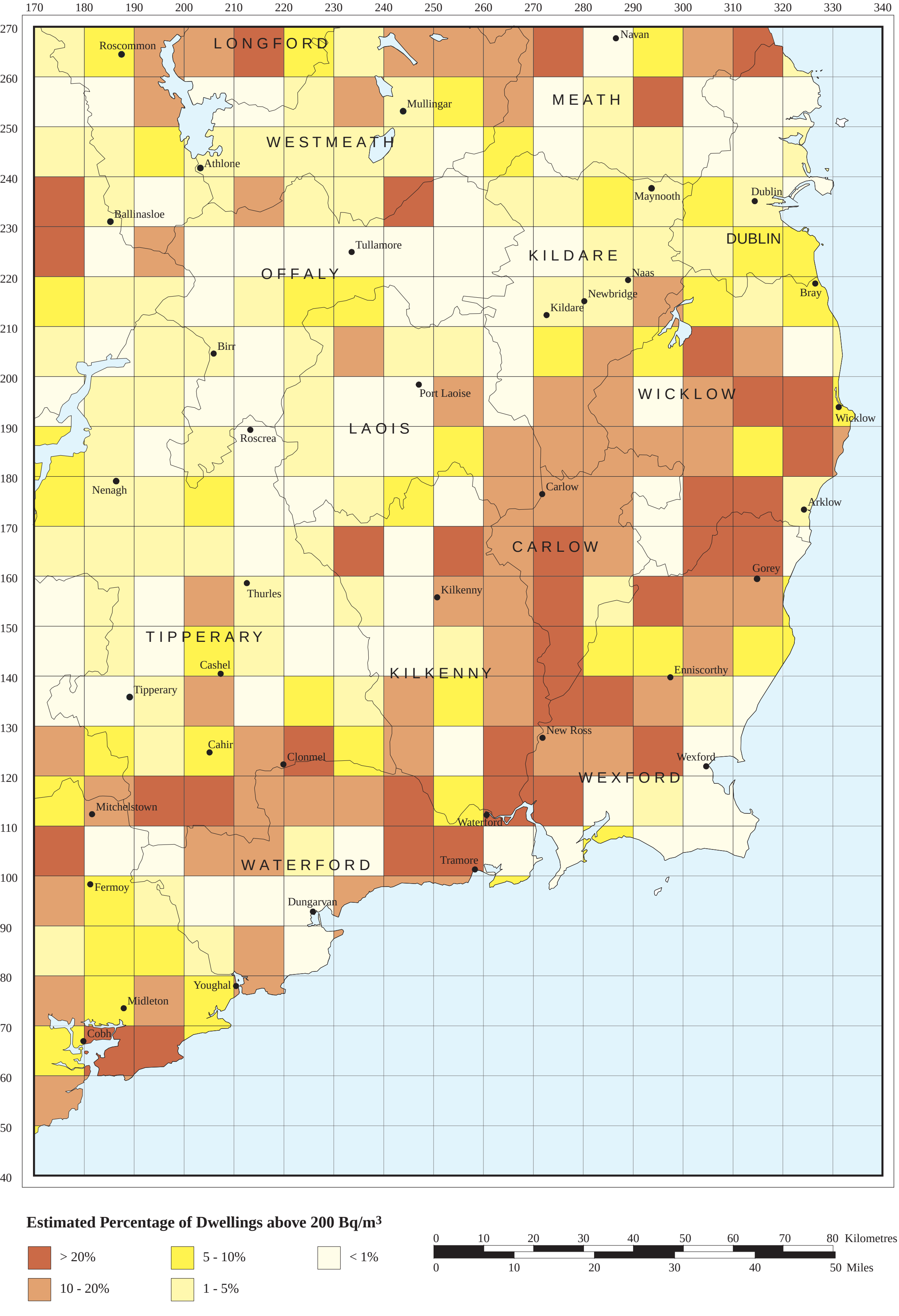


Figure 8: Radon Prediction Map for the South East of Ireland

APPENDIX I

QUESTIONNAIRE DATA

House Type	No. Houses	% of Total
Detached (2 storey)	2729	27
Semi-detached (single storey)	323	3
Semi-detached (2 storey)	660	7
Terraced (single storey)	95	1
Terraced (2 storey)	367	4
Bungalow	5198	52
Other	589	6
Total	9961	

Table 4: Distribution of House Types

House Age	No. Houses	% of Total
< 1900	1527	15
1900 – 1919	569	6
1920 – 1944	999	10
1945 – 1964	1092	11
1965 – 1985	4023	41
> 1985	1673	17
Total	9883	

Table 5: Distribution of House Age

Water Supply	No. Houses	% of Total
Public	4556	46
Private	651	7
Spring (Public)	485	5
Spring (Private)	1849	19
Lake (Group)	1124	11
Lake (Public)	368	4
Bore Hole	789	8
Other	170	2
Total	9992	

Table 6: Distribution of Water Supply

APPENDIX II

VALIDATED MEASUREMENT RESULTS FOR EACH GRID SQUARE

Table 7 details the number of validated measurement results, the descriptive statistics and the percentage of houses predicted to have indoor radon levels greater than 200 Bq/m^3 for each grid square. Values for the Geometric Mean (GM), Geometric Standard Deviation (GSD) or $\hat{k}$ (the transformed threshold for use with the standard normal distribution) have not been calculated for squares in which fewer than five results were obtained. A smoothing algorithm is used to derive a prediction for these squares based upon the data available in that square and data in surrounding squares.

Note: Grid squares are referred to in terms of their Easting and Northing coordinates. To obtain the 10 km grid reference for any point, locate the first vertical grid line to the left of the point and read the figure labelling the line on the top or bottom margin. Next locate the first horizontal grid line below the point and read its label on the left or right margin.

Sample references: Tralee is located in grid square 0811.
Tullamore located in grid square 2322.

Table 7: Summary of Validated Measurement Results for each 10 km Square

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
306	12	9.32	116	43	3.26	1.30
307	12	5.77	71	38	2.99	1.52
309	7	1.74	71	54	2.07	1.80
310	18	0.41	43	33	2.10	2.43
311	0	1.11	-	-	-	-
406	24	1.04	52	31	2.32	2.22
407	34	0.23	43	33	1.97	2.66
408	11	0.00	36	30	1.86	3.06
409	3	2.04	96	-	-	
410	13	0.00	43	37	1.67	3.29
411	4	0.81	30	-	-	-
503	3	0.99	22	-	-	-
504	7	0.00	30	27	1.62	4.15
505	9	0.00	26	24	1.39	6.44
506	22	0.00	27	22	1.72	4.07
507	13	0.99	52	32	2.38	2.11
508	20	0.06	39	30	1.95	2.84
509	2	2.24	124	-	-	-
510	10	16.23	107	59	3.44	0.99
511	15	0.05	33	25	2.12	2.77
524	8	0.00	21	19	1.65	4.70
525	12	0.57	42	25	2.55	2.22
526	11	0.00	22	19	1.65	4.70
527	0	0.80	-	-	-	-
530	3	0.01	25	-	-	-
604	13	0.01	36	27	2.02	2.85
605	4	0.02	22	-	-	-
606	13	0.00	23	20	1.67	4.49
607	11	0.00	22	19	1.70	4.44
608	2	0.30	21	-	-	-
609	6	0.00	33	29	1.87	3.09
610	23	0.15	43	35	1.90	2.72
611	12	1.46	54	37	2.33	1.99
612	0	0.80	-	-	-	-
613	0	0.80	-	-	-	-
623	4	0.32	22	-	-	-
624	15	0.04	32	20	2.27	2.81
625	24	0.92	44	31	2.29	2.25
626	12	0.00	22	20	1.50	5.68
627	2	0.05	21	-	-	-
628	1	0.03	18	-	-	-
629	6	0.00	21	20	1.41	6.70
630	13	0.00	25	23	1.50	5.33
631	7	3.69	64	42	2.63	1.61
632	11	0.00	35	29	1.76	3.42
633	9	0.00	26	24	1.52	5.06
634	0	0.05	-	-	-	-

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
702	7	0.00	35	33	1.45	4.85
703	10	0.00	41	37	1.54	3.91
704	6	0.00	45	32	2.16	2.38
705	11	0.00	28	23	1.82	3.61
706	13	0.00	36	32	1.65	3.66
707	6	0.00	25	25	1.24	9.67
708	7	0.00	21	19	1.60	5.01
709	35	0.94	50	36	2.14	2.25
710	11	0.00	34	28	1.89	3.09
711	29	39.45	373	130	5.04	0.27
712	10	0.00	27	25	1.55	4.74
713	5	0.00	35	27	2.18	2.57
714	7	0.00	19	18	1.40	7.16
715	0	0.16	-	-	-	-
721	0	8.67	-	-	-	-
722	2	0.88	26	-	-	-
723	12	0.00	35	27	1.93	3.05
724	23	0.01	30	22	2.00	3.18
725	13	0.35	44	22	2.55	2.36
726	14	0.18	37	26	2.26	2.50
727	19	0.00	26	22	1.70	4.16
728	9	0.00	27	24	1.74	3.83
729	26	0.00	27	24	1.63	4.34
730	21	0.00	38	33	1.70	3.40
731	21	0.00	27	24	1.67	4.13
732	23	0.00	28	26	1.43	5.70
733	29	0.00	40	35	1.63	3.57
734	2	0.13	21	-	-	-
802	7	0.00	37	33	1.63	3.69
803	7	0.32	62	51	1.95	2.05
804	10	0.00	29	26	1.64	4.12
805	1	0.11	23	-	-	-
806	16	0.00	31	28	1.60	4.18
807	18	0.03	36	28	1.95	2.94
808	10	0.61	48	38	2.16	2.16
809	22	8.14	92	56	2.52	1.38
810	17	4.89	77	44	2.55	1.62
811	32	25.57	180	94	3.14	0.66
812	6	16.20	133	62	3.23	1.00
813	20	2.68	60	43	2.30	1.85
814	7	0.00	42	36	1.81	2.89
815	23	0.02	32	24	1.98	3.10
816	4	0.06	23	-	-	-
820	6	8.67	96	72	2.70	1.03
821	2	8.67	31	-	-	-
822	6	0.30	68	57	1.93	1.91
823	4	1.05	44	-	-	-
824	8	0.00	33	27	1.82	3.34
825	5	0.00	58	56	1.42	3.63

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
826	2	0.76	114	-	-	-
827	21	0.00	34	29	1.80	3.29
828	20	0.04	34	23	2.09	2.93
829	17	0.00	36	30	1.80	3.23
830	14	0.31	42	31	2.18	2.39
831	15	0.04	38	30	1.97	2.80
832	10	0.00	33	31	1.40	5.54
833	13	1.60	61	41	2.23	1.98
834	10	0.39	48	39	2.09	2.22
902	9	4.90	77	55	2.27	1.57
903	16	0.41	47	35	2.07	2.40
904	14	0.54	50	40	2.01	2.31
905	3	0.13	23	-	-	-
906	12	0.00	29	23	1.94	3.26
907	16	2.76	60	45	2.27	1.82
908	17	6.27	91	73	1.95	1.51
909	27	2.60	69	53	2.02	1.89
910	26	4.96	84	57	2.16	1.63
911	15	5.67	85	45	2.65	1.53
912	15	0.09	48	39	1.84	2.68
913	31	0.76	49	35	2.13	2.31
914	17	0.00	33	30	1.62	3.93
915	13	0.01	33	22	2.15	2.88
916	22	0.00	27	24	1.70	4.00
920	11	5.16	71	42	2.71	1.57
922	17	1.82	58	38	2.33	1.96
923	18	1.24	54	44	2.05	2.11
924	2	0.99	14	-	-	-
925	13	0.00	20	18	1.51	5.84
926	9	0.00	32	29	1.51	4.69
927	8	0.00	51	45	1.74	2.69
928	31	4.49	75	44	2.47	1.67
929	27	0.90	52	32	2.25	2.26
930	5	0.00	23	21	1.63	4.61
931	3	2.26	55	-	-	-
932	3	1.84	34	-	-	-
933	4	2.29	32	-	-	-
934	2	4.17	64	-	-	-
1002	23	0.56	49	36	2.05	2.39
1003	11	10.24	115	46	3.23	1.25
1004	13	0.27	51	39	1.98	2.39
1005	21	0.00	31	28	1.56	4.42
1006	4	0.28	32	-	-	-
1007	12	0.05	37	27	2.13	2.65
1008	24	2.77	77	31	2.71	1.87
1009	16	2.39	62	45	2.21	1.88
1010	26	14.67	121	62	3.04	1.05
1011	13	10.11	94	53	2.86	1.26
1012	14	1.67	60	47	2.07	1.99

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
1013	16	0.02	50	44	1.67	2.95
1014	13	0.67	53	43	2.01	2.20
1015	20	0.00	30	27	1.62	4.15
1016	23	0.03	36	28	1.93	2.99
1017	26	0.00	26	22	1.68	4.25
1018	22	0.00	35	30	1.78	3.29
1019	14	19.96	176	58	4.27	0.85
1020	0	11.48	-	-	-	-
1022	8	3.67	63	46	2.43	1.66
1023	5	27.06	157	114	2.34	0.66
1024	3	7.50	120	-	-	-
1025	18	5.51	71	45	2.59	1.57
1026	9	0.00	39	32	1.97	2.70
1027	14	4.09	73	38	2.71	1.67
1028	33	8.07	89	54	2.55	1.40
1029	16	0.00	32	28	1.64	3.97
1030	6	1.27	56	40	2.49	1.76
1031	13	18.86	123	92	2.38	0.90
1032	11	23.97	159	93	2.90	0.72
1033	13	11.52	111	59	2.79	1.19
1034	2	12.23	259	-	-	-
1102	15	0.00	43	39	1.62	3.39
1103	15	0.00	45	40	1.62	3.34
1104	10	0.02	48	41	1.85	2.58
1105	5	0.00	35	35	1.19	10.02
1106	17	0.30	51	42	1.88	2.47
1107	11	0.00	39	33	1.91	2.78
1108	11	0.01	37	30	2.00	2.74
1109	37	0.66	50	40	1.97	2.37
1110	16	0.13	53	45	1.77	2.61
1111	19	4.19	70	48	2.34	1.68
1112	25	1.44	57	42	2.10	2.10
1113	13	4.82	76	49	2.41	1.60
1114	20	0.12	48	41	1.80	2.70
1115	17	0.01	34	28	1.91	3.04
1116	18	0.00	36	30	1.77	3.32
1117	3	0.96	23	-	-	-
1118	16	0.01	38	31	1.86	3.00
1119	39	11.84	112	48	3.31	1.19
1120	12	14.45	108	72	2.61	1.06
1121	1	10.50	151	-	-	-
1122	20	0.00	33	31	1.42	5.32
1123	10	11.24	102	79	2.17	1.20
1124	21	31.75	213	117	3.04	0.48
1125	18	11.37	102	75	2.27	1.20
1126	22	20.73	135	90	2.67	0.81
1127	25	35.34	244	121	3.74	0.38
1128	35	7.47	82	55	2.45	1.44
1129	16	10.55	98	62	2.58	1.24

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
1130	17	22.87	157	90	2.91	0.75
1131	39	28.19	175	122	2.35	0.58
1132	22	34.63	232	138	2.50	0.40
1133	17	20.20	141	89	2.65	0.83
1134	0	15.00	-	-	-	-
1203	13	0.27	59	52	1.76	2.38
1204	8	15.25	113	72	2.70	1.03
1205	14	0.00	38	32	1.74	3.31
1206	8	0.00	42	36	1.77	3.00
1207	15	0.00	46	41	1.63	3.24
1208	8	0.59	61	48	2.02	2.03
1209	14	0.00	30	29	1.40	5.74
1210	20	1.03	65	55	1.82	2.16
1211	10	6.17	78	47	2.65	1.49
1212	11	3.54	67	48	2.33	1.69
1213	13	6.99	92	74	1.98	1.46
1214	20	8.12	92	60	2.41	1.37
1215	27	4.97	89	44	2.53	1.63
1216	21	11.59	139	51	3.13	1.20
1217	22	3.26	66	43	2.36	1.79
1218	15	27.72	177	94	3.51	0.60
1219	19	41.81	259	161	2.80	0.21
1220	18	19.34	142	90	2.51	0.87
1221	6	0.00	73	65	1.66	2.22
1222	48	17.38	129	72	2.99	0.93
1223	21	24.37	154	107	2.43	0.70
1224	24	26.27	158	111	2.52	0.64
1225	20	13.07	113	79	2.28	1.13
1226	15	7.53	95	69	2.12	1.42
1227	13	40.37	270	149	3.23	0.25
1228	21	12.85	116	99	1.87	1.12
1229	39	19.26	130	98	2.27	0.87
1230	21	11.59	96	62	2.67	1.19
1231	23	24.04	157	125	1.95	0.70
1232	28	20.99	148	95	2.51	0.81
1233	3	21.30	150	-	-	-
1303	10	13.73	111	73	2.53	1.09
1304	23	5.99	87	65	2.09	1.52
1305	11	0.60	60	51	1.87	2.18
1306	11	0.00	37	34	1.48	4.52
1307	18	0.19	55	47	1.75	2.59
1308	5	0.00	55	47	1.91	2.24
1309	12	1.57	62	49	2.04	1.97
1310	28	0.41	51	42	1.87	2.49
1311	18	13.97	131	59	3.10	1.08
1312	14	0.01	45	38	1.77	2.91
1313	12	11.08	99	76	2.23	1.21
1314	16	5.84	91	71	1.96	1.54
1315	10	13.97	105	74	2.50	1.09

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
1316	6	0.00	39	29	2.19	2.46
1317	67	27.81	192	104	3.02	0.59
1318	14	23.24	147	99	2.62	0.73
1319	13	26.45	184	114	2.39	0.65
1320	14	4.88	79	65	2.01	1.61
1321	17	15.16	129	50	3.81	1.04
1322	29	29.94	207	107	3.23	0.53
1323	22	48.03	276	192	2.47	0.05
1324	21	39.88	231	150	2.95	0.27
1325	19	53.53	303	217	2.59	-0.09
1326	44	13.76	117	82	2.26	1.09
1327	26	13.53	110	83	2.22	1.10
1328	23	9.86	93	69	2.30	1.28
1329	23	21.90	147	104	2.33	0.77
1330	31	14.44	116	79	2.39	1.07
1331	13	38.11	241	141	3.15	0.30
1332	5	48.93	293	194	2.49	0.03
1333	6	20.88	135	112	2.00	0.84
1403	6	0.00	65	61	1.45	3.20
1404	8	0.00	45	40	1.65	3.21
1405	15	4.15	88	77	1.78	1.66
1406	17	2.17	64	50	2.05	1.93
1407	11	0.03	56	48	1.72	2.63
1408	8	1.96	74	63	1.90	1.80
1409	19	16.65	148	71	2.91	0.97
1410	9	2.65	71	43	2.39	1.76
1411	13	0.05	58	51	1.67	2.66
1412	20	0.07	44	36	1.84	2.81
1413	11	5.03	85	62	2.12	1.56
1414	15	3.46	61	45	2.35	1.75
1415	19	20.75	134	85	2.84	0.82
1416	33	10.10	91	56	2.73	1.27
1417	24	16.13	129	66	3.09	0.98
1418	20	13.29	117	67	2.68	1.11
1419	21	4.99	77	53	2.27	1.62
1420	14	0.72	65	55	1.79	2.22
1421	11	12.81	109	82	2.19	1.14
1422	15	41.09	268	155	3.02	0.23
1423	20	39.89	227	156	2.56	0.26
1424	29	19.56	129	90	2.55	0.85
1425	39	22.74	154	99	2.53	0.76
1426	28	16.13	120	75	2.71	0.98
1427	29	23.38	164	89	3.06	0.72
1428	25	25.29	162	120	2.15	0.67
1429	16	13.06	106	74	2.42	1.13
1430	19	8.26	86	56	2.53	1.37
1431	8	18.23	126	97	2.20	0.92
1432	4	19.57	108	-	-	-
1433	22	10.23	102	78	2.12	1.25

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
1438	2	0.10	16	-	-	-
1503	0	4.55	-	-	-	-
1504	10	7.27	89	63	2.27	1.41
1505	12	11.93	107	77	2.26	1.17
1506	17	1.76	72	61	1.82	1.98
1507	23	8.31	92	71	2.13	1.37
1508	15	7.07	91	55	2.44	1.45
1509	18	10.38	97	63	2.52	1.25
1510	15	14.92	117	74	2.59	1.04
1511	9	1.63	65	51	2.07	1.88
1512	26	0.01	38	32	1.75	3.27
1513	18	0.91	50	38	2.13	2.20
1514	27	0.01	50	45	1.58	3.26
1515	49	1.62	58	43	2.09	2.09
1516	14	0.11	44	36	1.94	2.59
1517	15	0.00	37	32	1.73	3.34
1518	27	0.38	46	37	1.97	2.49
1519	19	0.05	41	34	1.86	2.86
1520	12	4.63	74	33	3.07	1.61
1521	25	15.15	116	86	2.26	1.04
1522	35	22.44	145	95	2.67	0.76
1523	17	24.74	154	100	2.71	0.70
1524	14	43.4	233	172	2.43	0.17
1525	25	24.97	164	92	3.08	0.69
1526	18	8.75	92	68	2.25	1.33
1527	25	13.30	108	60	2.96	1.11
1528	12	16.19	136	119	1.69	0.99
1529	13	8.98	88	61	2.47	1.31
1530	19	9.83	94	55	2.74	1.28
1531	16	33.62	207	128	2.84	0.43
1532	17	22.87	145	110	2.23	0.75
1533	17	26.68	167	125	2.10	0.63
1534	8	17.12	111	69	3.01	0.97
1537	8	0.00	56	50	1.63	2.84
1538	7	0.00	27	24	1.74	3.83
1539	1	0.34	10	-	-	-
1604	8	1.96	73	61	1.93	1.81
1605	18	12.84	106	82	2.21	1.12
1606	38	6.25	83	60	2.21	1.52
1607	34	4.03	74	57	2.08	1.71
1608	12	4.06	75	55	2.17	1.67
1609	14	4.88	74	53	2.28	1.61
1610	17	24.74	190	94	3.01	0.69
1611	14	32.59	237	106	4.00	0.46
1612	28	9.54	95	60	2.53	1.30
1613	8	3.10	74	53	2.21	1.67
1614	9	3.56	78	65	1.96	1.67
1615	21	1.02	67	58	1.75	2.21
1616	21	0.99	48	30	2.38	2.19

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
1617	15	1.37	68	55	1.89	2.03
1618	30	1.88	55	42	2.17	2.01
1619	8	0.00	26	24	1.53	4.99
1620	8	2.99	59	43	2.49	1.68
1621	22	13.52	115	88	2.11	1.10
1622	11	6.71	84	66	2.16	1.44
1623	15	11.96	112	84	2.09	1.18
1624	28	7.73	96	58	2.41	1.41
1625	17	12.19	104	49	3.37	1.16
1626	19	19.61	135	76	3.07	0.86
1627	22	7.98	133	45	2.93	1.39
1628	10	0.06	53	45	1.84	2.45
1629	9	1.38	63	52	2.00	1.94
1630	18	9.81	106	63	2.48	1.27
1631	21	28.29	197	111	2.79	0.57
1632	13	26.45	161	118	2.29	0.64
1633	14	23.24	142	101	2.51	0.74
1634	10	0.90	47	37	2.29	2.04
1635	8	0.00	30	27	1.58	4.38
1637	17	0.54	61	52	1.77	2.36
1638	2	0.86	33	-	-	-
1639	10	0.86	47	30	2.48	2.09
1641	5	0.00	45	41	1.69	3.02
1704	0	9.67	-	-	-	-
1705	11	15.44	108	83	2.36	1.02
1706	27	5.79	83	65	2.07	1.54
1707	24	16.13	120	85	2.35	1.00
1708	11	1.21	83	76	1.61	2.03
1709	14	12.83	105	63	2.80	1.12
1710	13	20.27	132	93	2.49	0.84
1711	18	7.92	85	52	2.64	1.39
1712	21	14.21	110	76	2.45	1.08
1713	28	0.86	50	39	2.06	2.26
1714	11	0.00	41	35	1.67	3.40
1715	23	0.77	53	36	2.12	2.28
1716	18	4.48	66	38	2.71	1.67
1717	25	9.34	110	55	2.70	1.30
1718	21	5.34	74	47	2.49	1.59
1719	11	0.00	33	27	1.95	3.00
1720	13	2.73	69	56	2.03	1.80
1721	12	7.90	82	59	2.41	1.39
1722	8	20.24	137	75	3.19	0.85
1723	22	28.62	184	110	2.84	0.57
1724	23	3.12	60	36	2.57	1.82
1725	7	0.00	42	39	1.50	4.03
1726	23	1.93	63	50	2.00	2.00
1727	11	29.57	236	106	3.17	0.55
1728	6	0.22	63	48	2.09	1.94
1729	7	13.24	101	56	3.14	1.11

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
1730	9	5.74	83	56	2.32	1.51
1731	14	35.12	221	130	3.07	0.38
1732	8	3.21	62	42	2.52	1.69
1733	16	34.34	235	123	3.30	0.41
1734	9	5.45	87	70	2.01	1.50
1735	7	0.00	29	25	1.87	3.32
1737	8	0.55	60	44	2.10	2.04
1738	8	1.12	56	43	2.22	1.93
1739	13	1.89	71	55	1.95	1.93
1740	9	0.69	67	55	1.87	2.06
1741	8	0.14	56	45	1.97	2.20
1742	1	0.80	50	-	-	-
1805	0	13.98	-	-	-	-
1806	14	20.83	145	91	2.60	0.82
1807	21	8.79	94	70	2.18	1.35
1808	12	8.07	86	65	2.28	1.36
1809	15	9.40	96	70	2.25	1.29
1810	20	0.34	58	50	1.75	2.48
1811	24	10.43	96	60	2.63	1.25
1812	15	6.20	74	38	3.05	1.49
1813	20	0.19	40	30	2.06	2.63
1814	20	1.30	57	37	2.24	2.09
1815	19	2.18	58	41	2.29	1.91
1816	3	4.68	100	-	-	-
1817	28	1.44	54	42	2.09	2.12
1818	26	1.93	65	51	1.99	1.99
1819	23	2.10	55	41	2.24	1.97
1820	24	0.15	45	37	1.86	2.72
1821	18	3.50	67	50	2.21	1.75
1822	16	0.84	57	48	1.92	2.19
1823	22	2.65	62	49	2.12	1.87
1824	14	4.99	76	62	2.09	1.59
1825	11	0.46	61	50	1.86	2.23
1826	9	9.95	95	79	2.09	1.26
1827	10	2.66	75	62	1.93	1.78
1828	7	12.75	102	49	3.50	1.12
1829	14	5.89	74	54	2.36	1.52
1830	11	9.46	104	48	3.06	1.28
1831	16	37.67	250	138	3.20	0.32
1832	7	0.00	30	25	1.84	3.41
1833	6	24.00	147	85	3.20	0.74
1834	10	0.22	43	27	2.39	2.30
1835	9	0.00	39	37	1.40	5.01
1836	6	11.23	101	66	2.55	1.18
1837	6	0.00	50	43	1.82	2.57
1838	4	0.77	25	-	-	-
1839	7	0.00	43	40	1.52	3.84
1840	7	0.06	61	49	1.92	2.16
1841	4	1.41	62	-	-	-

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
1842	7	0.00	39	36	1.65	3.42
1843	9	0.00	45	41	1.69	3.02
1844	2	1.56	75	-	-	-
1906	12	29.52	175	116	2.70	0.55
1907	14	14.44	106	71	2.63	1.07
1908	13	5.57	76	44	2.68	1.54
1909	13	2.08	71	57	1.94	1.89
1910	15	0.18	60	52	1.71	2.51
1911	12	36.29	254	126	3.53	0.37
1912	10	2.66	57	39	2.50	1.78
1913	31	1.89	59	46	2.07	2.02
1914	11	0.32	41	29	2.33	2.28
1915	15	0.63	56	47	1.91	2.24
1916	14	4.31	71	50	2.33	1.64
1917	13	3.34	65	47	2.30	1.74
1918	15	0.01	43	38	1.76	2.94
1919	25	1.97	61	43	2.17	1.98
1920	20	1.07	55	40	2.09	2.18
1921	28	3.04	71	60	1.94	1.82
1922	15	13.28	109	70	2.59	1.10
1923	8	0.00	53	51	1.41	3.98
1924	8	6.51	109	97	1.65	1.44
1925	8	19.95	126	95	2.38	0.86
1926	9	18.44	127	94	2.29	0.91
1927	9	7.51	92	58	2.44	1.39
1928	8	0.45	62	52	1.91	2.08
1929	6	0.00	69	62	1.66	2.31
1930	5	0.19	75	63	1.94	1.74
1931	8	0.14	64	55	1.79	2.22
1932	7	0.00	51	46	1.68	2.83
1933	11	0.02	48	40	1.82	2.69
1934	8	0.00	51	50	1.30	5.28
1935	3	4.60	164	-	-	-
1936	9	5.74	74	41	2.87	1.50
1937	9	0.00	58	52	1.64	2.72
1938	12	0.01	43	35	1.87	2.78
1939	2	2.53	95	-	-	-
1940	9	0.00	35	31	1.78	3.23
1941	1	1.99	30	-	-	-
1942	6	7.02	78	59	2.43	1.37
1943	11	0.06	54	47	1.77	2.54
2006	6	9.81	93	55	2.78	1.26
2007	14	5.89	76	57	2.29	1.52
2008	13	3.93	77	62	2.01	1.68
2009	10	0.02	73	67	1.53	2.57
2010	7	18.61	127	86	2.52	0.91
2011	16	36.18	260	124	3.73	0.36
2012	23	6.25	83	62	2.18	1.50
2013	24	11.01	103	68	2.43	1.22

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
2014	18	9.45	90	58	2.59	1.30
2015	13	11.31	103	66	2.51	1.20
2016	11	4.18	80	66	1.96	1.65
2017	12	5.24	76	56	2.27	1.55
2018	9	2.30	69	50	2.17	1.79
2019	13	0.11	63	57	1.64	2.54
2020	36	2.50	70	55	1.95	1.93
2021	21	0.17	64	58	1.59	2.67
2022	8	0.00	48	43	1.69	2.93
2023	9	1.15	66	55	1.92	1.98
2024	29	1.29	68	58	1.77	2.17
2025	10	0.90	78	71	1.65	2.07
2026	12	11.93	112	77	2.25	1.18
2027	5	0.36	80	68	1.86	1.74
2028	16	0.01	54	49	1.58	3.07
2029	8	0.02	61	51	1.79	2.35
2030	9	0.01	59	50	1.74	2.50
2031	11	1.63	60	38	2.36	1.93
2032	9	0.00	33	32	1.26	7.93
2033	11	0.32	57	46	1.90	2.29
2034	0	0.80	-	-	-	-
2036	8	11.61	104	60	2.79	1.17
2037	5	0.00	48	37	2.21	2.13
2038	0	3.69	-	-	-	-
2039	6	4.81	95	84	1.79	1.49
2040	6	17.61	133	81	2.61	0.94
2041	11	2.09	85	76	1.68	1.87
2042	5	0.00	74	67	1.67	2.13
2043	5	0.00	46	42	1.63	3.19
2044	2	0.73	26	-	-	-
2107	18	12.63	111	77	2.30	1.15
2108	6	11.47	108	72	2.38	1.18
2109	5	0.00	95	89	1.53	1.90
2110	17	15.16	114	83	2.35	1.03
2111	13	16.18	126	96	2.10	0.99
2112	31	17.40	121	84	2.52	0.94
2113	10	0.00	35	29	1.87	3.09
2114	14	2.22	65	46	2.18	1.89
2115	30	1.73	56	42	2.14	2.05
2116	10	0.34	47	34	2.19	2.26
2117	27	0.37	44	35	2.00	2.51
2118	16	0.25	43	35	2.01	2.50
2119	8	0.00	44	43	1.27	6.43
2120	14	0.00	64	61	1.38	3.69
2121	16	1.20	78	69	1.66	2.10
2122	14	0.00	62	59	1.43	3.41
2123	22	13.30	110	82	2.24	1.11
2124	13	1.21	70	61	1.78	2.06
2125	20	0.39	64	56	1.68	2.45

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
2126	6	21.49	138	115	1.97	0.82
2127	17	0.79	66	54	1.79	2.25
2128	11	0.00	56	52	1.45	3.63
2129	7	0.00	57	49	1.68	2.71
2130	9	0.00	59	56	1.43	3.56
2131	6	3.25	82	64	2.03	1.61
2132	8	0.00	36	34	1.43	4.95
2136	1	7.48	112	-	-	-
2137	7	6.80	82	59	2.40	1.39
2138	1	5.72	28	-	-	-
2139	26	9.35	97	71	2.20	1.31
2140	4	7.85	109	-	-	-
2141	15	4.69	73	56	2.20	1.61
2142	8	0.00	64	60	1.47	3.13
2143	14	0.20	59	51	1.73	2.49
2144	6	0.64	48	34	2.61	1.85
2208	8	0.00	60	52	1.74	2.43
2209	9	0.00	77	74	1.37	3.16
2210	8	3.21	79	65	1.96	1.67
2211	3	13.01	102	-	-	-
2212	40	20.10	154	87	2.70	0.84
2213	20	6.07	81	51	2.47	1.51
2214	18	0.69	66	57	1.74	2.27
2215	17	0.00	33	29	1.68	3.72
2216	11	2.46	78	66	1.84	1.82
2217	14	0.00	55	51	1.47	3.55
2218	16	2.84	69	56	2.02	1.81
2219	15	1.37	70	58	1.83	2.05
2220	18	1.24	71	61	1.76	2.10
2221	17	7.90	87	68	2.18	1.38
2222	17	0.13	63	54	1.64	2.65
2223	25	4.02	85	64	1.94	1.72
2224	17	2.88	80	68	1.81	1.82
2225	10	1.88	75	62	1.87	1.87
2226	5	7.02	92	71	2.16	1.34
2227	8	0.00	70	65	1.53	2.64
2228	7	0.65	63	48	2.08	1.95
2229	24	0.00	40	38	1.39	5.04
2230	8	0.00	47	42	1.70	2.94
2231	6	28.93	196	104	3.00	0.60
2232	8	5.26	74	55	2.33	1.53
2238	0	7.51	-	-	-	-
2239	8	14.74	114	82	2.33	1.05
2240	13	4.70	100	88	1.66	1.62
2241	5	14.33	121	101	1.89	1.07
2242	6	0.00	48	43	1.76	2.72
2243	7	2.84	79	65	1.95	1.68
2244	4	1.31	28	-	-	-
2308	3	11.78	182	-	-	-

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
2309	9	10.15	100	75	2.20	1.24
2310	8	0.00	65	61	1.45	3.20
2311	14	11.32	100	69	2.44	1.19
2312	19	8.43	93	75	2.06	1.36
2313	23	2.41	61	43	2.24	1.91
2314	14	0.03	44	38	1.82	2.77
2315	8	2.89	69	58	2.07	1.70
2316	5	21.24	139	105	2.15	0.84
2317	20	4.64	86	65	1.99	1.63
2318	5	0.00	52	50	1.30	5.28
2319	14	0.00	54	49	1.56	3.16
2320	11	11.06	104	69	2.41	1.21
2321	18	6.29	90	66	2.10	1.49
2322	32	0.74	68	61	1.67	2.32
2323	16	1.67	70	58	1.86	1.99
2324	18	1.32	68	57	1.82	2.10
2325	13	10.90	109	80	2.11	1.23
2326	14	4.64	93	80	1.76	1.62
2327	16	0.07	71	65	1.51	2.73
2328	6	18.19	123	94	2.25	0.93
2329	11	0.00	46	42	1.51	3.79
2330	13	0.01	53	47	1.67	2.82
2331	14	0.24	64	57	1.67	2.45
2332	1	0.98	39	-	-	-
2339	1	9.72	158	-	-	-
2340	5	0.00	77	68	1.78	1.87
2341	5	0.00	62	59	1.43	3.41
2342	8	0.55	83	75	1.61	2.06
2343	12	0.05	57	50	1.70	2.61
2344	12	1.17	59	48	2.01	2.04
2409	1	12.79	70	-	-	-
2410	9	45.80	291	179	2.85	0.11
2411	7	20.37	129	88	2.64	0.85
2412	20	12.85	116	94	1.95	1.13
2413	9	13.26	114	87	2.13	1.10
2414	9	0.07	51	44	1.89	2.38
2415	12	0.20	80	72	1.52	2.44
2416	9	0.15	101	96	1.38	2.28
2417	18	7.92	86	64	2.25	1.41
2418	17	0.00	58	53	1.50	3.28
2419	33	0.01	53	49	1.51	3.41
2420	21	2.43	74	56	1.96	1.89
2421	17	0.66	68	59	1.71	2.28
2422	12	0.01	52	45	1.71	2.78
2423	14	20.83	139	94	2.52	0.82
2424	16	3.16	95	85	1.62	1.77
2425	22	2.45	88	78	1.64	1.90
2426	13	18.30	119	86	2.53	0.91
2427	10	27.61	172	110	2.66	0.61

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
2428	11	8.72	112	94	1.76	1.34
2429	6	0.00	37	34	1.52	4.23
2430	10	1.12	72	62	1.79	2.01
2431	7	0.00	32	31	1.25	8.35
2432	1	0.30	40	-	-	-
2442	6	12.47	109	66	2.63	1.15
2443	4	2.24	45	-	-	-
2444	12	0.01	55	51	1.64	2.76
2445	7	0.60	66	56	1.92	1.95
2509	0	10.50	-	-	-	-
2510	6	21.49	155	82	2.98	0.82
2511	12	6.05	99	83	1.79	1.51
2512	5	0.00	53	47	1.70	2.73
2513	9	5.45	94	83	1.78	1.53
2514	18	1.60	66	54	1.90	2.04
2515	10	11.03	100	76	2.21	1.22
2516	7	41.44	236	162	2.48	0.23
2517	8	0.19	47	34	2.25	2.19
2518	16	6.38	84	52	2.48	1.48
2519	25	11.40	110	81	2.12	1.20
2520	19	1.53	75	66	1.72	2.04
2521	23	0.07	55	49	1.63	2.88
2522	5	0.00	48	44	1.61	3.18
2523	9	0.77	47	32	2.45	2.05
2524	7	0.00	54	48	1.64	2.88
2525	19	8.94	94	73	2.13	1.33
2526	14	13.51	105	79	2.31	1.11
2527	6	10.04	106	79	2.12	1.24
2528	12	4.17	94	84	1.68	1.67
2529	10	1.56	68	51	2.03	1.93
2530	5	0.77	80	68	1.89	1.69
2531	7	0.00	46	40	1.82	2.69
2532	11	0.00	50	46	1.50	3.62
2533	2	0.35	33	-	-	-
2534	3	0.39	24	-	-	-
2542	0	10.50	-	-	-	-
2543	5	22.83	151	89	2.81	0.78
2544	6	0.00	54	49	1.62	2.92
2545	5	0.00	68	60	1.71	2.24
2609	1	5.13	14	-	-	-
2610	6	0.00	54	47	1.71	2.70
2611	8	39.85	321	131	4.75	0.27
2612	9	22.56	140	103	2.37	0.77
2613	10	18.95	140	111	1.93	0.90
2614	8	14.49	103	70	2.71	1.05
2615	15	13.05	109	72	2.48	1.12
2616	10	18.39	119	81	2.70	0.91
2617	23	17.68	132	87	2.44	0.93
2618	23	11.00	113	87	1.99	1.21

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
2619	30	0.48	69	61	1.62	2.46
2620	14	0.03	61	55	1.60	2.75
2621	21	0.37	71	63	1.59	2.49
2622	13	0.89	54	38	2.17	2.14
2623	20	2.68	78	63	1.87	1.85
2624	10	7.60	101	82	1.90	1.39
2625	6	10.28	102	60	2.64	1.24
2626	13	12.16	114	89	2.00	1.17
2627	10	6.94	109	95	1.68	1.43
2628	10	7.60	90	68	2.17	1.39
2629	6	0.12	78	68	1.73	1.97
2630	8	0.00	54	47	1.74	2.61
2631	7	0.00	51	47	1.59	3.12
2632	9	0.00	38	34	1.65	3.54
2633	20	0.46	61	51	1.76	2.42
2634	6	0.00	62	56	1.59	2.75
2635	3	1.65	62	-	-	-
2643	8	0.00	31	26	1.79	3.50
2644	6	15.37	118	96	2.04	1.03
2709	1	0.80	35	-	-	-
2710	15	0.30	50	42	1.90	2.43
2711	13	22.05	147	94	2.64	0.78
2712	19	10.58	110	94	1.84	1.24
2713	14	22.32	145	116	2.02	0.77
2714	15	32.92	228	133	2.50	0.45
2715	12	44.97	211	186	1.74	0.13
2716	19	26.65	166	117	2.32	0.64
2717	35	12.46	112	83	2.13	1.16
2718	32	10.65	117	85	1.99	1.24
2719	17	14.92	125	98	1.99	1.04
2720	22	9.86	107	83	2.00	1.27
2721	26	1.33	74	64	1.71	2.12
2722	15	0.00	43	38	1.62	3.44
2723	19	3.44	83	67	1.85	1.78
2724	11	0.08	68	61	1.60	2.53
2725	13	0.92	66	55	1.82	2.16
2726	10	27.61	177	111	2.60	0.62
2727	17	0.63	66	57	1.72	2.31
2728	12	23.61	155	100	2.61	0.72
2729	8	4.03	88	75	1.84	1.61
2730	11	0.79	67	57	1.80	2.14
2731	9	0.17	65	55	1.76	2.28
2732	6	0.00	45	41	1.67	3.09
2733	7	7.17	82	44	2.99	1.38
2734	1	3.24	128	-	-	-
2810	13	9.16	96	67	2.32	1.30
2811	8	0.00	39	35	1.63	3.57
2812	17	11.77	117	101	1.79	1.17
2813	21	23.74	162	96	2.76	0.72

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
2814	15	5.04	101	90	1.65	1.59
2815	10	4.79	85	71	1.93	1.58
2816	15	10.93	106	83	2.05	1.23
2817	22	11.19	114	93	1.88	1.21
2818	25	17.41	142	94	2.24	0.94
2819	14	13.97	124	94	2.02	1.07
2820	20	12.85	120	78	2.31	1.12
2821	49	1.57	79	70	1.65	2.10
2822	34	2.02	82	73	1.65	2.01
2823	16	6.38	102	88	1.73	1.50
2824	6	3.40	91	74	1.88	1.57
2825	9	1.44	90	83	1.58	1.92
2826	11	0.00	55	52	1.39	4.09
2827	7	0.00	78	75	1.35	3.27
2828	8	30.87	199	117	2.84	0.51
2829	14	0.67	71	62	1.70	2.21
2830	6	0.85	102	96	1.50	1.81
2831	9	14.97	113	83	2.32	1.05
2832	7	8.93	93	68	2.29	1.30
2910	20	0.00	47	42	1.61	3.28
2911	17	4.44	81	64	1.99	1.66
2912	14	27.41	184	99	3.15	0.61
2913	15	11.75	111	85	2.06	1.18
2914	16	6.10	90	64	2.13	1.51
2915	18	28.67	179	124	2.33	0.57
2916	7	0.00	77	71	1.57	2.30
2917	14	0.27	71	64	1.60	2.42
2918	20	12.85	119	83	2.17	1.14
2919	10	0.19	82	77	1.51	2.32
2920	27	7.72	111	99	1.64	1.42
2921	25	11.40	124	80	2.15	1.20
2922	15	1.16	76	64	1.72	2.10
2923	50	1.90	84	75	1.61	2.06
2924	14	2.02	87	77	1.64	1.93
2925	6	28.59	163	113	2.59	0.60
2926	7	6.80	103	89	1.77	1.42
2927	9	15.48	122	92	2.13	1.03
2928	9	1.20	98	91	1.49	1.97
2929	13	1.71	80	71	1.70	1.95
2930	8	23.91	156	140	1.63	0.73
2931	4	4.82	40	-	-	-
3010	13	0.00	35	33	1.46	4.76
3011	18	0.85	59	44	1.98	2.22
3012	22	0.00	37	35	1.47	4.52
3013	9	2.56	71	49	2.23	1.75
3014	15	18.54	154	80	2.76	0.90
3015	19	12.63	119	101	1.81	1.15
3016	16	36.55	194	152	2.22	0.34
3017	9	32.15	182	133	2.33	0.48

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
3018	7	12.27	106	89	2.03	1.14
3019	2	16.58	141	-	-	-
3020	7	39.60	230	149	2.87	0.28
3021	6	6.63	115	103	1.61	1.39
3022	20	1.71	74	63	1.78	2.00
3023	33	7.46	102	72	2.05	1.42
3024	8	0.00	84	79	1.42	2.65
3025	5	0.00	110	103	1.44	1.82
3026	9	10.36	104	80	2.10	1.23
3027	18	1.28	81	71	1.63	2.12
3028	9	0.00	53	49	1.49	3.53
3029	8	0.00	73	70	1.42	2.99
3030	24	9.34	102	73	2.14	1.32
3031	4	10.80	80	-	-	-
3110	17	0.00	37	34	1.48	4.52
3111	15	0.00	35	30	1.77	3.32
3112	3	0.08	27	-	-	-
3113	14	0.00	44	42	1.34	5.33
3114	15	8.35	97	59	2.47	1.35
3115	18	13.07	119	62	2.84	1.12
3116	18	22.25	140	107	2.25	0.77
3117	11	24.93	148	101	2.67	0.70
3118	12	5.50	108	97	1.60	1.54
3119	9	28.36	164	145	1.71	0.60
3120	9	14.22	132	121	1.60	1.07
3121	8	1.18	74	65	1.79	1.93
3122	24	5.51	100	89	1.68	1.56
3123	8	3.79	83	70	1.91	1.62
3124	7	0.00	64	56	1.73	2.32
3125	6	0.00	56	53	1.39	4.03
3126	8	32.27	209	115	3.18	0.48
3127	6	0.40	81	71	1.73	1.89
3128	7	18.33	126	81	2.66	0.92
3129	7	0.00	42	39	1.54	3.79
3130	10	29.29	179	101	3.37	0.56
3131	8	31.57	220	112	3.22	0.50
3214	1	6.46	54	-	-	-
3215	0	6.44	-	-	-	-
3216	11	0.00	43	37	1.71	3.15
3217	7	1.12	77	62	1.87	1.87
3218	7	23.75	153	109	2.27	0.74
3219	12	27.82	189	108	2.80	0.60
3220	5	0.00	68	61	1.70	2.24
3221	24	6.81	92	77	1.91	1.48
3222	19	5.06	88	72	1.90	1.59
3223	15	0.00	40	36	1.66	3.38
3224	17	1.56	60	44	2.10	2.04
3225	11	0.02	53	47	1.73	2.64
3226	9	3.04	65	42	2.48	1.72

Grid Square	No. of Houses	Prediction (%)	Mean (Bq/m^3)	GM (Bq/m^3)	GSD	$\hat{k}$
3230	8	18.79	121	83	2.66	0.90
3231	4	24.55	237	-	-	-
3318	2	13.03	105	-	-	-
3319	10	8.12	105	90	1.80	1.36
3320	4	3.87	51	-	-	-
3321	0	5.26	-	-	-	-

APPENDIX III

AN EXAMPLE OF THE SMOOTHING ALGORITHM

For squares in which there were fewer than five valid measurement results the GM and GSD were estimated from data in the surrounding squares. A smoothing algorithm, optimised on the Irish data set using the cp-criterion, was used. The procedure is best illustrated by an example.

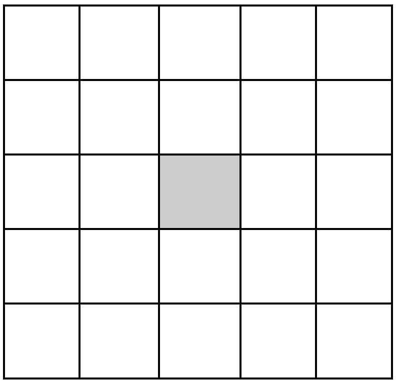
There are 837 squares in the Irish National 10 km grid covering the 26 counties of the Republic of Ireland. Figure 9 represents a five by five section of the Irish National 10 km grid. The grey shaded square in Figure 9a represents a grid square with valid results for only three houses (29 Bq/m^3, 32 Bq/m^3 and 239 Bq/m^3). As there are not enough data within this square, to determine the GM and GSD with any degree of certainty, the data in the surrounding grid squares will be used. To improve the log-normal distribution of the data within these squares a log-normal transformation was carried out whereby 6 Bq/m^3 was subtracted from the raw data.

The number of valid measurement results in each of the surrounding 24 squares is shown in Figure 9b. A weighting matrix, with *i* rows and *j* columns, was generated (Figure 9c) which takes into account the number of houses in each square and the variability of the data within that square. In this example only the central five by five portion of the matrix is shown - the weighting factors quickly fall off to zero as you move further away from the central square. The weighting matrix was then applied to the data, which in this example is the log of geometric means for each square (Figure 9d), and the resultant matrix summed to give the interpolated GM for the square in question.

$$Smoothed\,GM = \exp\left[\sum_{i=1}^{n}\left(\sum_{j=1}^{n}\left(c_{ij} \times d_{ij}\right)\right)\right]$$

In this example the smoothed log of the GM is 3.6. The GM and GSD were determined separately in this manner for all squares with fewer than 5 valid measurements.

The proportion of houses exceeding the Reference Level for each square is determined in the usual way. It should be noted that for all smoothed squares a log transformation, identical to that performed on the raw data, must be carried out for the Reference Level.



(a) 10 km National Grid

9	21	21	15	30
11	23	18	25	21
20	19	3	28	26
11	15	14	13	15
18	13	11	12	9

(b) No. of houses per grid square

0.00	0.01	0.02	0.01	0.00
0.01	0.04	0.13	0.04	0.01
0.02	0.14	0.15	0.16	0.02
0.01	0.04	0.12	0.03	0.01
0.00	0.01	0.02	0.01	0.00

(c) Weighting Factors

4.05	3.93	3.06	3.86	3.50
3.36	3.34	3.38	3.82	3.64
3.35	3.47	3.95	3.52	3.76
2.99	3.66	3.72	3.65	3.41
3.89	4.05	4.07	3.85	3.74

(d) ln(GM)

Figure 9: An Example of the Smoothing Algorithm