Radon potential mapping of the Tralee-Castleisland and Cavan areas (Ireland) based on airborne gamma-ray spectrometry and geology.

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Abstract

The probability of homes in Ireland having high indoor radon concentrations is estimated on the basis of known in-house radon measurements averaged over 10 x 10 km grid squares. The scope for using airborne gamma-ray spectrometer data of the Tralee-Castleisland area of county Kerry and county Cavan to predict radon potential (RP) in two distinct areas of Ireland was evaluated in this study. Airborne data are compared statistically with in-house radon measurements in conjunction with geological and ground permeability data to establish linear regression models and produce radon potential maps. The best agreement between the percentage of dwellings exceeding the Reference Level (RL) for radon concentrations in Ireland (%>RL), estimated from indoor radon data, and modelled RP in the Tralee-Castleisland area is produced using models based on airborne gamma-ray spectrometry equivalent uranium (eU) and ground permeability data. Good agreement was obtained between the %>RL from indoor radon data and RP estimated from eU data in the Cavan area using terrain specific models. In both areas, RP maps derived from eU data are spatially more detailed than the published 10-km grid map. The results show the potential for using airborne radiometric data for producing RP maps.

1. Introduction

To prevent the public being exposed to high radon levels, it is necessary to carry out indoor radon measurements in homes and workplaces and remedial work where high levels are found. To ensure resources are targeted a first step is to identify those areas most at risk. The probability of having high indoor radon concentrations above the Reference Level (RL, 200 becquerels per cubic metre of air, Bq m^{-3}) in Ireland is currently estimated on the basis of known in-house radon measurements, grouped into and averaged over 10 x 10 km grid squares (Fennell et al, 2002a,b; Murphy and Organo, 2008).

The potential for high indoor radon concentrations depends on multiple factors including the amount of ^{226}Ra in the ground underneath buildings, the permeability of the ground, building characteristics, and ventilation. In this study only the correlation between indoor radon levels and the ground characteristics were investigated. Correlations between indoor radon levels and local geology are well documented (Appleton and Miles, 2010; Barnet et al., 2010; Friedmann and Gröller, 2010; Kemski et al., 2009; Scheib et al., 2009). Uranium and radium concentrations in surface rocks and soils are an indicator of the potential for radon emissions from the ground. The correlation between airborne surveys of gamma rays from ^{214}Bi, converted to eU (equivalent uranium), and indoor radon concentrations has been demonstrated in England, Canada, Czech Republic, Northern Ireland, Norway, Sweden and the USA (Åkerblom, 1987, Appleton et al., 2008, 2011; Ford et al., 2001; IAEA, 2003; Mikšová and Barnet, 2002; Smethurst et al., 2008).

A trial airborne geophysical survey to support mineral exploration, inform land-use planning and provide environmental baseline data was conducted in June 2006 in three selected areas in the Republic of Ireland. The Joint Airborne Geoscience Capability (JAC) established between the Geological Survey of Finland (GTK) and British Geological Survey (BGS), carried out the survey under contract to the Geological Survey of Ireland (GSI). The survey was conducted across the three selected survey areas: (1) Cavan-Monaghan-Leitrim, (2) Tralee-Castleisland in County Kerry and (3) Silvermines in County Tipperary. Parts of the Cavan, Tralee-Castleisland and Silvermines areas are known to be characterised by high radon concentrations in dwellings (Fennell, 2002 a, b; Organo et al, 2004; Organo and Murphy, 2007).

In the study reported here, a radon potential mapping system was developed using (1) radiometric data from the airborne surveys, (2) subsoil parent material and bedrock geology data, and (3) indoor radon data and applied in the Tralee-Castleisland and Cavan areas (Figure 1). The Silvermines area was not included in the study because the area is small and insufficient indoor radon data are available to validate radon potential maps derived from the airborne radiometric data. A range of terrain specific linear regression models are statistically validated against the indoor radon data in order to assess whether radon potential maps can be derived by predictive modelling of ground permeability and airborne gamma-ray spectrometry data.

2. Radon and geology in Ireland

High radon concentrations in buildings are associated with Carboniferous limestone and uranium-rich Namurian shales in both County Kerry and County Clare (O'Connor et al., 1994; GSI, 1995; Organo and Murphy, 2007). In the Castleisland area it is reported that the limestones have undergone extensive karstification and are characterised by a complex network of underground caves and passages which provide potential pathways for the migration of radon-bearing groundwater. Radon is soluble in water and may thus be transported for distances of up to 5 km in streams flowing underground in limestone and then released when a gas phase is introduced (e.g. by turbulence or by pressure release). Elevated radon emissions are probably derived from radium deposited on the surfaces of fractures and cavities in limestones; the high specific surface area of the radium permits efficient release of radon and high migration rates are promoted by the high permeability of the limestone. Relatively high radium concentrations may be found in residual soils over limestones (Cliff and Miles, 1997; UNSCEAR, 2000).

Limestones are overlain by Namurian shales known to be enriched in uranium in some places (O'Connor et al., 1994). Uranium and/or radium from the shales could be transported into cavities in the adjacent limestones and emit radon gas. The GSI detected high radiation levels in carborne surveys of areas underlain by Namurian shales around Tralee and in a broad band between Killorglin and Killarney in 1981 but no high indoor radon concentrations have been identified to date. A similar geology exists in County Clare to the north of Tralee-Castleisland where O'Connor et al (1992, 1993) concluded that the ultimate source of radon remains conjectural.

3. Materials and Methods

3.1 Indoor radon data

Although the relationship between geology and radon in Ireland has been evaluated in previous studies in some areas, no systematic geological evaluation of the indoor radon measurements in Ireland has yet been undertaken. The Radiological Protection Institute of Ireland (RPII) maintains a database of some 41,000 measurements in homes and nearly 4,000 measurements in schools which is the largest dataset of indoor radon measurements in Ireland. The production of modern radon hazard maps requires accurate location data for each indoor radon measurement. Unfortunately, this information is difficult to obtain in Ireland because accurate postal coordinates are not currently available. This lack of accurate location information makes it difficult to use this data in radon hazard mapping such as currently used in the UK (Miles and Appleton, 2005).

Summary statistics for those indoor radon measurements in the Tralee-Castleisland area with postal addresses that indicate they are located within the urban areas (townlands) of Abbeydorney (n=31), Ardfert (47), Castleisland (477), Castlemaine (28), Killorglin (39), and Tralee (789) were provided by the RPII. Approximate geographical coordinates were obtained for about 300 measurement addresses in the Castleisland area by linking the addresses with a commercially available database of geographical coordinates. Measurements were used only when an address was unique and when an adequately large number of measurements (>15) were available to calculate summary statistics for a bedrock\superficial geological combination (average number of measurements for the six combinations used in this study is 44; range 17 – 85). The relationship between eU and the percentage of dwellings above the RL is broadly the same for (a) the summary indoor radon data for the six urban centres and (b) summary indoor radon data for houses with approximate geographical coordinates that were grouped by bedrock\superficial geology combination. Summary statistics for the two subsets were therefore amalgamated and used to model the relationship between indoor radon, radiometric data and the permeability of bedrock and subsoil parent material in the Tralee-Castleisland area.

In the Cavan area, the RPII provided indoor radon summary statistics for seven of the main townlands located within or at the border of the area surveyed. The number of measurements in each townland area ranged from 6 to 51 (average 18) so the probabilities of exceeding the RL calculated by log-normal modelling from some of these data will have a relatively high uncertainty.

3. 2 Geology

The Tralee-Castleisland survey area is underlain by Devonian sandstones with subsidiary siltstones and conglomerates, lower Carboniferous limestones, and middle Carboniferous (Namurian) shales and sandstones folded in E-W trending anticlinal-synclinal structures (Figure 2; Pracht, 1996). The Cavan survey area is underlain principally by Ordovician, Silurian, Devonian and Carboniferous strata (Figure 3; Gerachty, 1997).

Geological radon potential mapping generally requires indoor radon and radiometric data to be grouped by bedrock and superficial geology (Miles and Appleton, 2005). Digital superficial geology data is not currently readily available from the GSI so the TEAGASC (Agriculture and Food Development Authority of Ireland) subsoil parent material (SPM) digital data for Ireland (Fealy et al., 2004) was used instead. Bedrock in the Castleisland area is mainly overlain by glacial till derived from Carboniferous Limestone, Namurian shales and sandstones and Devonian sandstones (Figure 4). Blanket peat covers much of the higher ground and alluvium, river and glaciofluvial gravel deposits are located in the valleys. In the Cavan survey area, bedrock is mainly overlain by glacial till derived from Ordovician and Silurian sandstones, shales and turbidites, Carboniferous (Namurian) shales and sandstones, cherts and sandstones, alluvium and peat. Made ground covers a very small part of the survey area, Cavan being the largest urban area.

3.3 Permeability

After uranium and radium concentration, the permeability and moisture content of rocks and soils are probably the next most significant factors influencing the concentration of radon in soil gas (Duval and Otton, 1990; Grasty, 1997). Appleton et al. (2008, 2011) demonstrated that the permeability of the ground can in some cases be a significant variable when using linear regression to model indoor radon.

Bedrock and subsoil parent materials (SPM) in the Castleisland area were assigned to numeric permeability classes broadly following the classification described in Scheib et al. (2006). Soil parent material data is not available for the made ground areas so SPM information from areas immediately adjacent to the urban areas was used when attaching SPM codes to airborne data points intersecting the areas of made ground. This numeric permeability class is used in multivariate regression analysis of the relationship between the RPII indoor radon and the airborne radiometric data using data grouped by bedrock geology and subsoil parent material (equivalent to superficial geology). Permeability was used in the linear regression modelling in the Castleisland area but not included in radon potential (RP) modelling of the Cavan area because linear regression models for the adjacent Ordovician and Silurian terrains of the SE sector of Northern Ireland indicate that permeability is not a significant variable (Appleton et al., 2011).

3.4 Airborne radiometric data

The airborne 256-channel gamma spectrometry data covers 0.3-3 MeV at 200-metre or 100-m line spacing, 56-metre height, except over towns where a height of about 250 metres was used. The spectrometric data is averaged over flying distances of about 70 metres. A range of corrections is applied to the data including removing aircraft, cosmic and radon background; application of stripping corrections derived from calibration data and application of height attenuation corrections. Gamma rays from ^{40}K, ^{214}Bi, and ^{208}Tl were measured. Following guidelines for radioelement mapping using gamma ray spectrometry data (IAEA, 2003), the last two were converted to equivalent uranium (eU) and equivalent thorium (eTh). The ^{214}Bi gamma peak effectively reports short-lived radon decay product concentrations in the top 30 cm or so of the ground, from which some degree of loss of radon may occur. All the quality control (QC) and application of stripping corrections are based on calibration data derived from concrete pads with known K, Th and U concentrations so using the original ^{214}Bi spectral data was not a practical option.

In QC procedures applied to the survey data, no evidence was detected that temporal variations in ground moisture levels (IAEA, 2003) had a significant impact on the spatial distribution of eU in the Tralee-Castleisland and Cavan areas. Two other possible sources of uncertainty in the radiometric data are (1) in limestone regions where soil radon concentrations can be strongly affected by temperature/pressure driven convective air flows in the ground (O'Connor et al., 1992) and (2) over urban areas where a significant proportion of the ground area is covered in buildings and/or paving, and tarmac. When data are acquired across populated areas, high fly conditions may result in zones of reduced or loss of geophysical signal. Appleton et al. (2008) found that there is greater uncertainty attached to average eU data for urban areas but concluded that airborne eU data from 250m flight heights can be used for estimating radon potential in urban areas as long as uncertainty is reduced by using data in the statistical analysis only when there are 4 or more airborne measurements over a particular 1-km grid square\bedrock\SPM polygon.

In contrast to the Northern Ireland data where low or negative eU concentrations are associated with urban areas (Appleton et al., 2008), most of the negative eU values in the Tralee-Castleisland and Cavan areas are associated with peat deposits, where the gamma-ray signal is attenuated due to high soil moisture, and very few negative eU values are associated with urban areas and made ground.

3.5 Data analysis

The study reported here is based on the development of linear regression models of the relationship between airborne radiometric data and results of indoor radon measurements in dwellings following methods described by Appleton et al. (2008, 2011). In each of the survey areas, the GSI 1:100,000 scale bedrock geology, 1:50,000 scale TEAGASC subsoil parent material (SPM) and a 1-km grid were intersected in ESRI® ArcGIS to produce the shapefiles which store nontopological geometry and attribute information for the spatial features that form the basis for data analysis and the production of geological radon potential hazard maps. For data grouped by 1km grid square\bedrock\SPM, we used stepwise linear regression or, more commonly, repeated the linear regression analysis after removing independent variables from the model if (a) the b-coefficients were not significant and/or (b) the ANOVA p-value for an independent variable was >0.05, in order to produce modelled estimates of radon potential (RP). The goodness of fit between %>RL estimated from indoor radon data and RP predicted using linear regression models was evaluated by calculation of the mean squared deviation (MSD) in the Tralee-Castleisland area.

4. Results and discussion

4.1 Tralee-Castleisland

In the Tralee-Castleisland area, combined bedrock\SPM explains 36% of the variation in eU and 52% for K and eTh although there is substantial spatial variation within bedrock\SPM combinations. High eU (average >1.4 ppm) characterises (a) most of the Carboniferous limestone\SPM combinations apart from where limestone is overlain with till derived from Namurian sandstones and shales, (b) the Namurian Clare Shale Formation, and (c) Namurian (undifferentiated) where this is overlain by gravels, till derived from Devonian sandstones and till derived from Carboniferous limestones. The Devonian geological units have generally low eU. Very low radiometric signals are associated with all types of peat (compare Figures 4 and 5).

Linear regression models were derived from the indoor radon (%>RL), radiometric (K, eTh, eU) and permeability (P) data. Stepwise regression indicated that K and eTh are not significant parameters. Four models based on eU and permeability (P) for the Tralee-Castleisland area (TC) and for the Northern Ireland multi-disciplinary, multi-detector Tellus survey data (Beamish and Young, 2009) for the Carboniferous of the SW sector of Northern Ireland (NI) were evaluated. In these models, the maximum percentage above 200 Bq m^{-3} for the Northern Ireland Carboniferous data set is approximately 7%, compared with 29% for Tralee-Castleisland. The percentage of the variance explained by eU in all four models is high (73-86%; Table 1). Permeability accounts for 10% of the total variance in model TC-eU-P (i.e. model based on the relationship between indoor radon (%>RL), eU and P in the Tralee-Castleisland area) and only 2% in model NI-TC-eU-P (i.e. model based on the relationship between indoor radon (%>RL), eU and P in both Tralee-Castleisland and the SW sector of Northern Ireland).

The best agreement between the estimated percentage exceeding the RL and modelled RP estimates for the six townlands in the Tralee-Castleisland area is produced by the TC-eU-P and NI-TC-eU-P models. Mean squared deviation (MSD) statistics indicate that the TC-eU-P model gives the most accurate estimates (Table 1). RP estimated using the four models is slightly low at high RP and slightly high at low RP. The RP map derived using the TC-eU-P model (Figure 7) shows a much higher level of spatial detail compared with the published 10-km grid radon map (Figure 8) in the RP map.

4.2 Cavan

In the Cavan area, combined bedrock\SPM explains 15% of the variation in eU, 76% for K and 64% for eTh. There is substantial spatial variation within bedrock\SPM combinations. High eU (average >1.4 ppm) is not associated, on average, with any of the bedrock\SPM combinations, although there are some discrete sectors where Lower Carboniferous limestone, Silurian sandstone and conglomerate, and Silurian turbidite has eU >1.27 mg kg^{-1} (Figure 9). The relatively high eU that characterises the Ordovician and Silurian strata in the southeast sector of Northern Ireland (Appleton et al., 2008) continues west into the Cavan area and the radiometric signatures for the Carboniferous terrains of Cavan and the southwest sector of Northern Ireland are also closely comparable.

Linear regression modelling of the estimated percentage of dwellings above RL in 1-km\bedrock\SPM polygons was carried out using the NI-TC-eU model developed for radon mapping in the Tralee-Castleisland area. The NI-TC-eU model produces estimated RP values over the Ordovician and Silurian strata that are much higher than indicated on the RPII 10-km grid map and also significantly higher than the RP values mapped for similar strata in the southeast sector of Northern Ireland (Appleton et al., 2008). Recent research using the Tellus data for Northern Ireland indicate that terrain specific linear regression models give the best fit between the percentages of dwellings exceeding the RL estimated from indoor radon data and RP estimated from airborne gamma spectrometry data (Appleton et al., 2011). Permeability was not included in models for the Ordovician and Silurian terrains of the SE sector of Northern Ireland because stepwise regression modelling indicates that permeability is not a significant variable in this geological setting. The RP map for the Cavan area (Figure 10) produced using four terrain specific models derived from the Northern Ireland Tellus data (Table 2) is spatially more detailed than the published 10-km grid map (Figure 11). Using these terrain specific models reduces the RP estimates for the Ordovician-Silurian terrain to a level that is comparable to those observed in the southeast sector of Northern Ireland. Considering the uncertainties associated with the locations of the indoor radon measurements together with uncertainties in using linear regression models based on Northern Ireland data, there is reasonable agreement between the percentage of dwellings exceeding the RL calculated from indoor radon data for seven townland areas and radon potential (RP) estimated from eU data using the terrain specific models (Table3). In some cases (e.g. Ballyconnell and Cavan) a wide variation of geological units and corresponding RPs exist within a townland so the average RP values (Table 3) may not be directly related to the %>RL in dwellings because the distribution of dwellings with measured indoor radon is not known accurately.

5. Conclusions

Geological and airborne radiometric data, sometimes in conjunction with ground permeability data, can be used to produce radon potential maps. The best agreement between the percentage exceeding the RL (%>RL), estimated from indoor radon data, and modelled radon potential (RP) for the six townlands in the Tralee-Castleisland area (County Kerry) is produced by models based on airborne eU and ground permeability (P) data. Mean squared deviation (MSD) statistics indicate that the TC (Tralee-Castleisland) eU-P model gives the most accurate RP estimates. Comparison of the RP map derived using the TC-eU-P model with the published 10-km grid radon map shows a much higher level of spatial detail in the RP map.

A radon potential map for the Cavan area derived using four terrain specific models derived from the Northern Ireland Tellus data is spatially more detailed than the published 10-km grid map. Reasonably close agreement was obtained between (1) the percentage of dwellings exceeding the RL, estimated from indoor radon data for seven townland areas and (2) modelled radon potential (RP) estimated from eU data using the terrain specific models.

Uncertainties in the modelling would be better described if accurate geographic coordinates could be obtained for the indoor radon measurements. Without this information it is difficult to update the radon map for Ireland or to fully validate radon mapping based on airborne radiometric, geological and soil data.

Whereas the radiometric data can be used in conjunction with geological and subsoil parent material data to produce provisional radon hazard maps, it is recommended that the maps produced in this study should be used with caution and that they should be validated using accurately located indoor radon measurements as soon as practicable.

Radon mapping based on targeted in-house measurements would be more cost-effective than using an airborne survey carried out only for the purpose of producing radon maps. It is recommended therefore that airborne radiometric survey data should be used for radon mapping only if the data is collected as part of a multi-disciplinary, multi-detector survey such as the Tellus project in Northern Ireland (Beamish and Young, 2009). Radon maps based on the airborne radiometric data from such surveys would be a valuable by-product that could be used to help target future in-house radon measurement campaigns.

Airborne geophysical (magnetic field, electrical conductivity and terrestrial gamma-ray spectrometry) and soil geochemical surveys are intended to be carried out in the five border counties of the Republic of Ireland (Donegal, Leitrim, Cavan, Monaghan and Louth) and Sligo between 2011 and the end of 2013 by the GSI and the GSNI funded by the European Union supported Structural Funds INTERREG IVA Programme which seeks to address the economic and social problems which result from the existence of borders. A radon risk map of the newly surveyed areas will be produced using the methods described here and in Appleton et al. (2011).

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Table 1. Summary of linear regression model parameters, model percentage variances and mean squared deviation (MSD) between estimated %>RL and modelled RP for urban areas.

	Linear regression model name			
	TC-eU-P	**NI-TC-eU-P**	**TC-eU***	**NI-TC-eU**
Variance percentages				
eU	73%	86%	73%	86%
Permeability	10%	2%	Ni	Ni
Residual	17%	12%	27%	14%
Model statistics				
Residual standard error	3.1	2.4	3.7	2.6
R^2	0.83	0.88	0.73	0.86
F	22.5	113.6	27.7	191.1
No. data	12	33	12	33
Coefficients				
eU	20.08	16.67	18.72	17.50
Permeability	3.28	1.35	ni	ni
Intercept	-25.59	-15.74	-15.07	-13.55
MSD	8	10	12	12

ni = not included in regression; * = see Figure 5.

Table 2. Summary of linear regression model parameters applied to the Cavan area based on data from Northern Ireland (Appleton et al., 2008, 2011).

Cavan Bedrock	Acid intrusives and Ordovician acid volcanics	Carboniferous Sdst, and shale	Carboniferous limestones	Ordovician and Silurian sedimentary/ Metasedimentary units
Source of model data	SE sector of Northern Ireland: Palaeozoic intrusives	SW sector of Northern Ireland: Carboniferous not including limestones	SW sector of Northern Ireland: Carboniferous limestones	SE sector of Northern Ireland: Ordovician Gilnahirk Gp., Moffatt Shale and Silurian Gala Gp.
eU coefficient (β)	10.1	0.62	21.7	5.5
Intercept (α)	-8.1	-0.13	-17.5	-6.1

Table 3. Percentage exceeding the Reference Level (%>RL) estimated from indoor radon data compared with radon potential (RP) modelled from eU data in the Cavan area.

	Indoor radon data				Estimate from eU		
Townland	No.	GM	GSD	%>RL	Min RP	Max RP	Avg RP
Ballybay*	14	37	2.3	2.0	0.0	1.3	0.5
Ballyconnell	17	72	2.8	13.8	2.6	9.4	4.9
Castleblayney*	51	54	2.2	5.7	1.6	4.5	2.6
Cavan	12	67	1.7	5.8	0.7	17.5	6.4
Cootehill	20	42	1.6	0.8	0.0	1.3	0.6
Shercock	9	34	1.6	1.6	0.5	2.7	1.6
Stradone	6	55	2.3	6.0	0.0	6.0	2.7

*Estimate from eU based on adjacent 1km\bedrock polygons as no airborne data available directly over townland

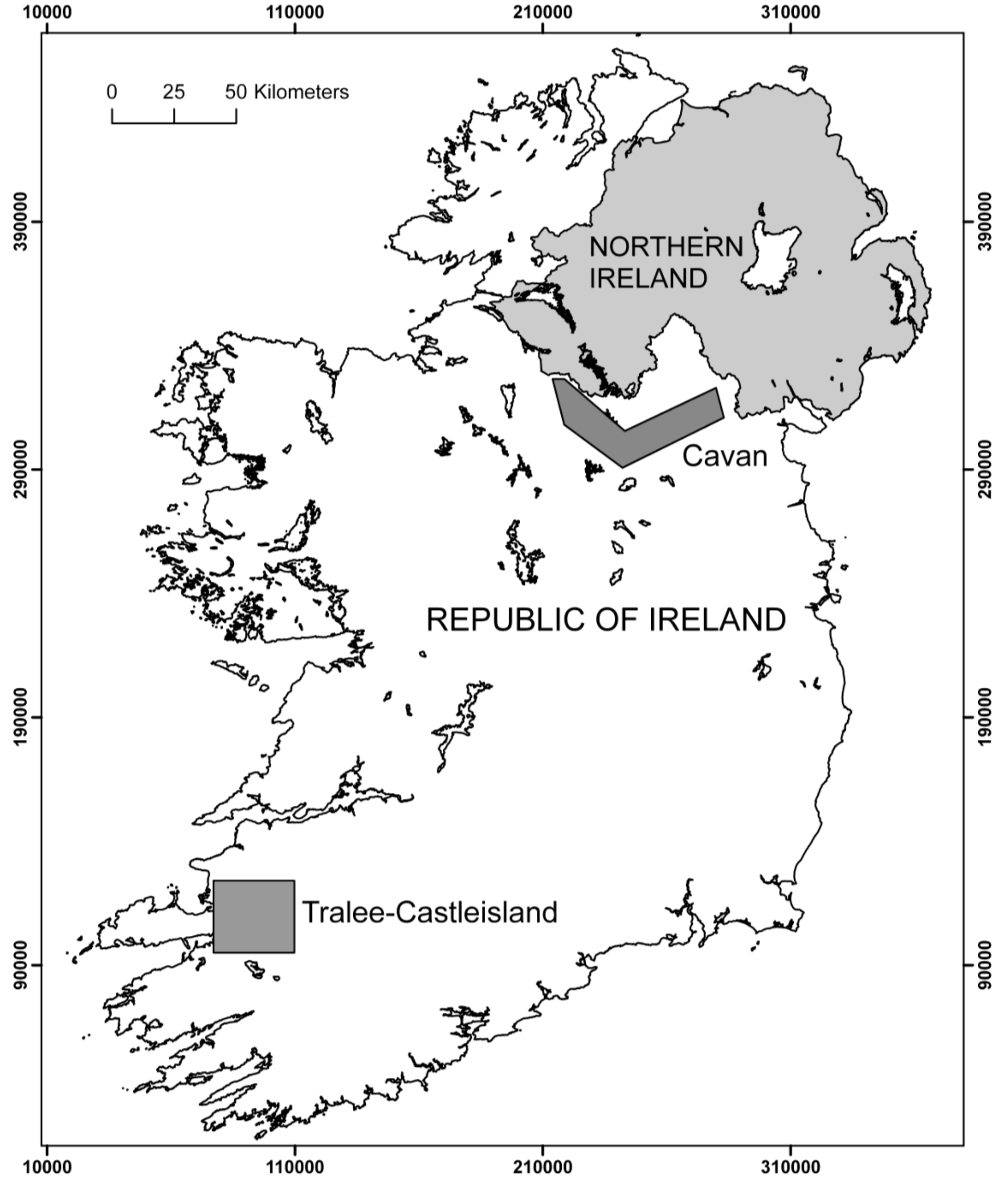

Figure 1. Location of the Tralee-Castleisland and Cavan airborne radiometric survey areas (Tellus survey covered all of Northern Ireland (Beamish and Young, 2009))

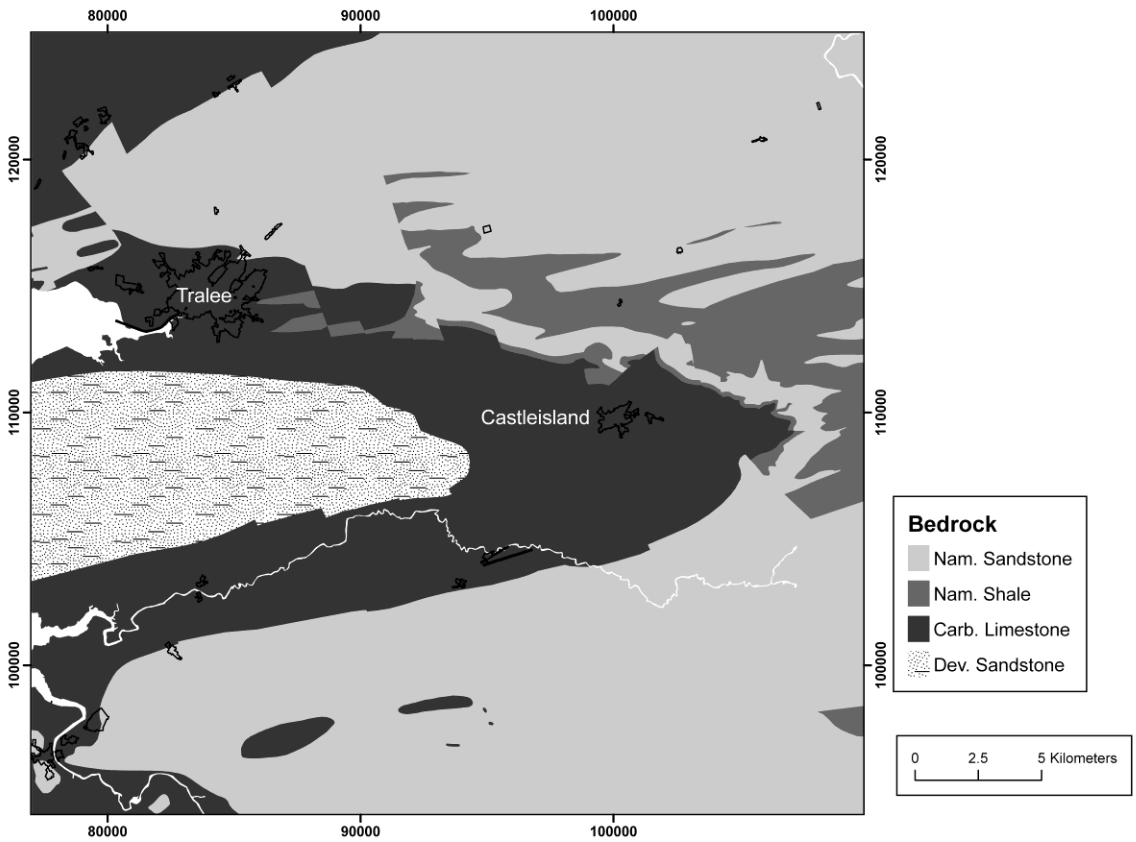

Figure 2: Simplified bedrock geology of the Tralee-Castleisland area (urban areas outlined in black)

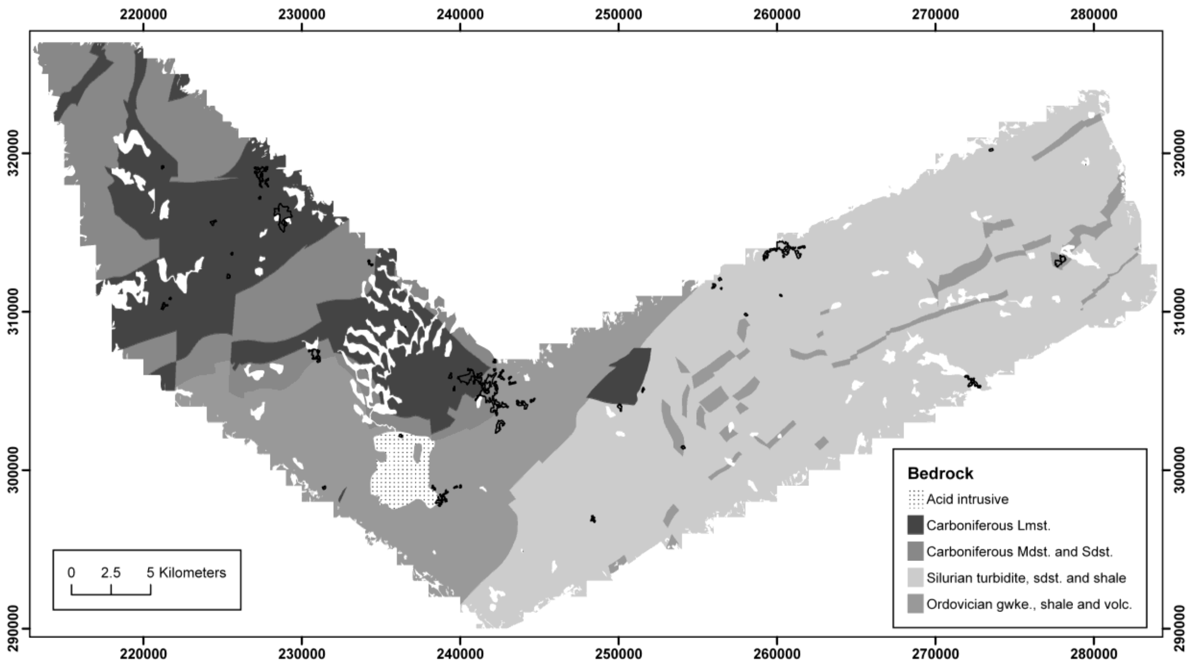

Figure 3. Simplified bedrock geology of the Cavan area (white areas = Loughs (lakes))

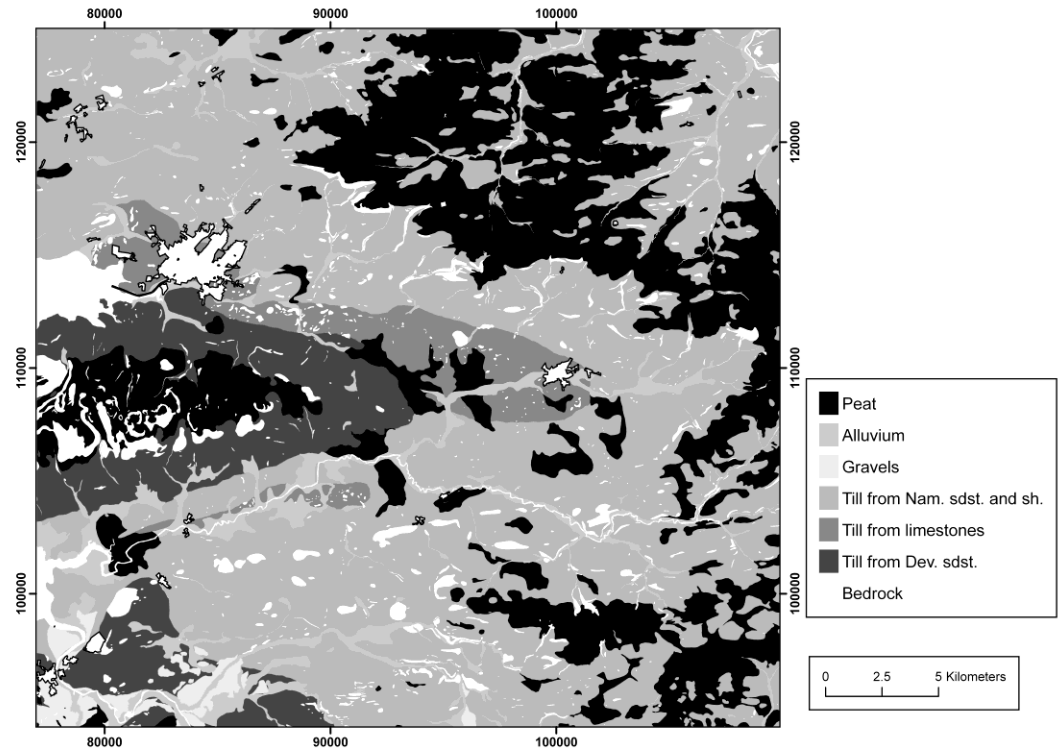

Figure 4. Soil parent material map of the Castleisland area (areas classified as Made Ground, including the urban areas of Tralee, and Castleisland, are outlined in black; derived from Fealy et al., 2004; data prepared by the Spatial Analysis Group, TEAGASC, Kinsealy Research Centre. Funded by NDP.)

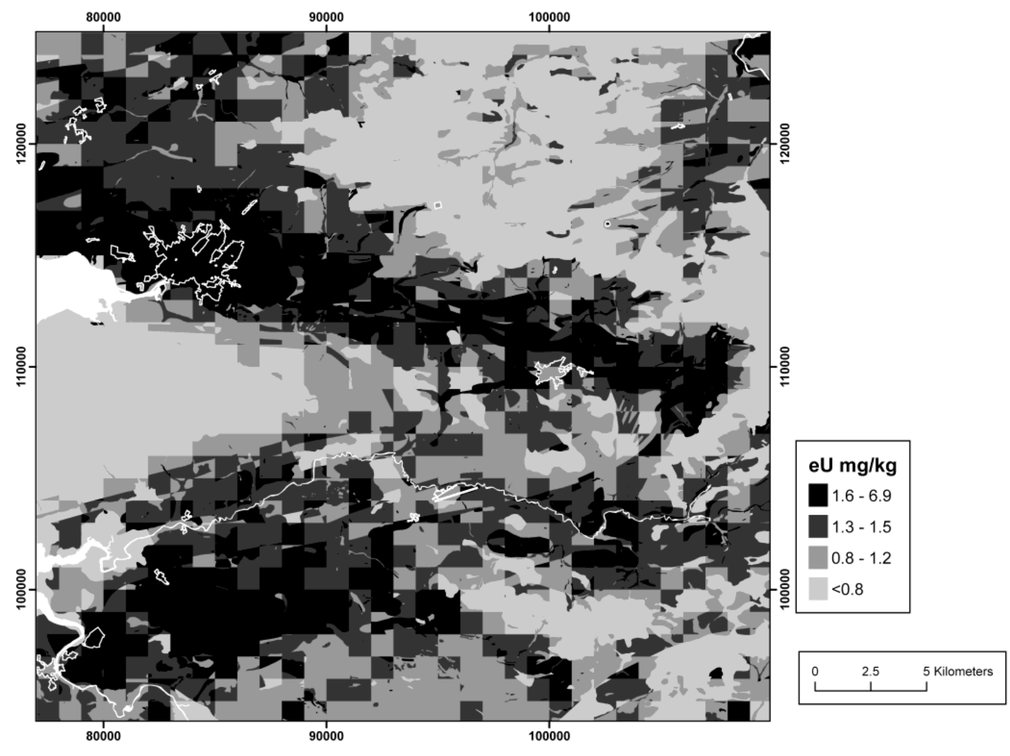

Figure 5. Average eU (mg kg^{-1}) for airborne data grouped by 1-km\bedrock\SPM polygons in the Tralee-Castleisland area (main urban areas outlined in white)

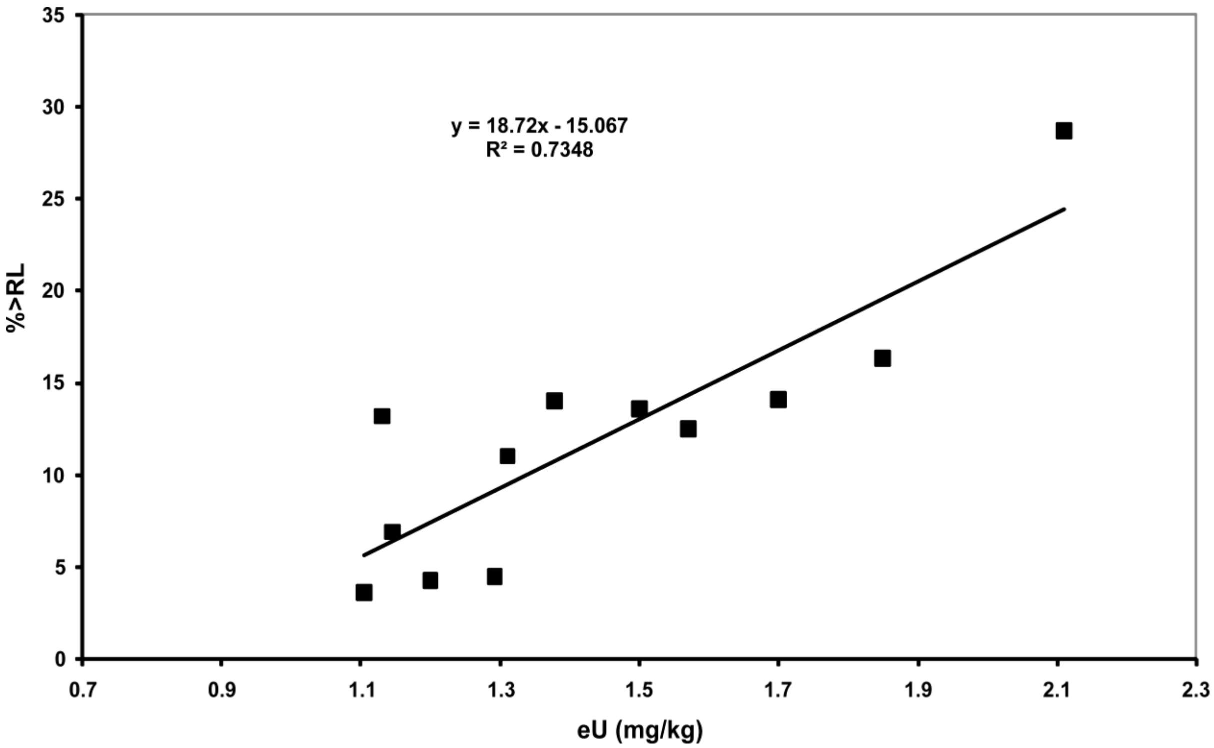

Figure 6. Relationship between eU and %>RL for linear regression model TC-eU (Tralee-Castleisland area)

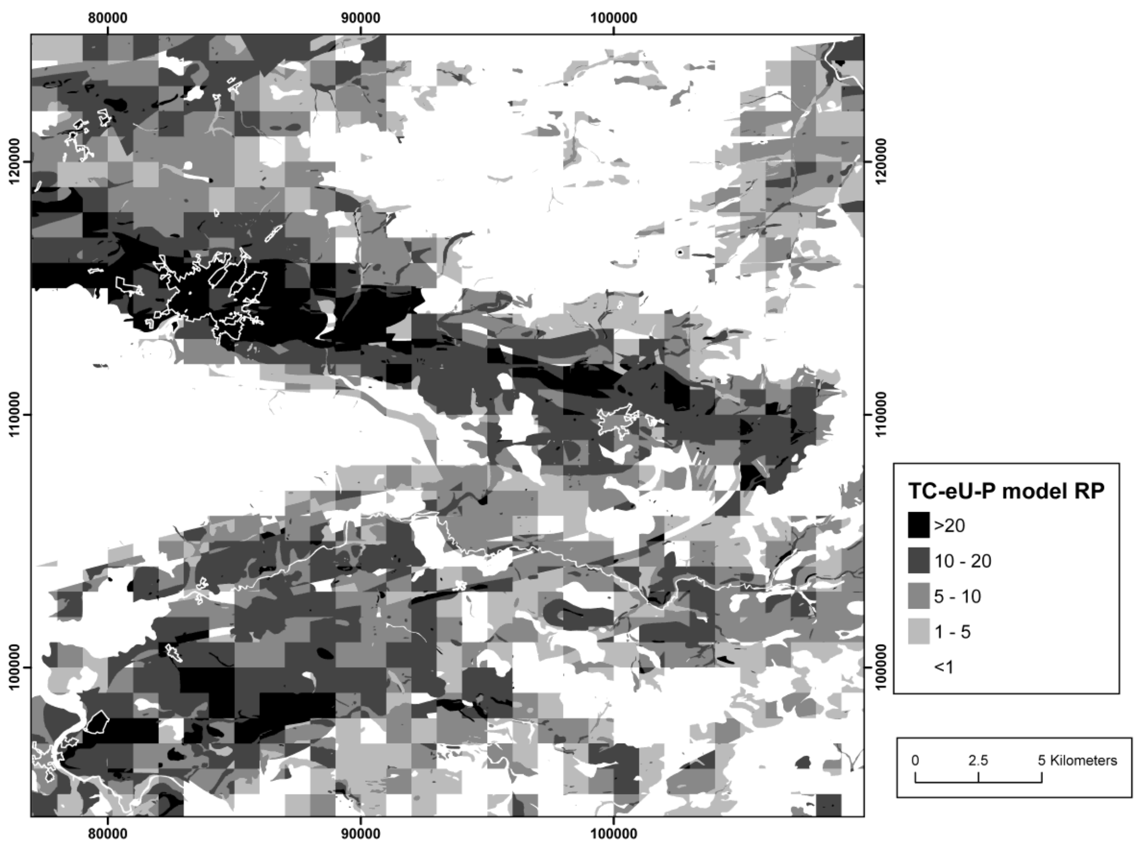

Figure 7. Radon potential (RP; modelled %>RL) map of the Tralee-Castleisland area produced using the TC-eU-P linear regression model (urban areas outlined in white)

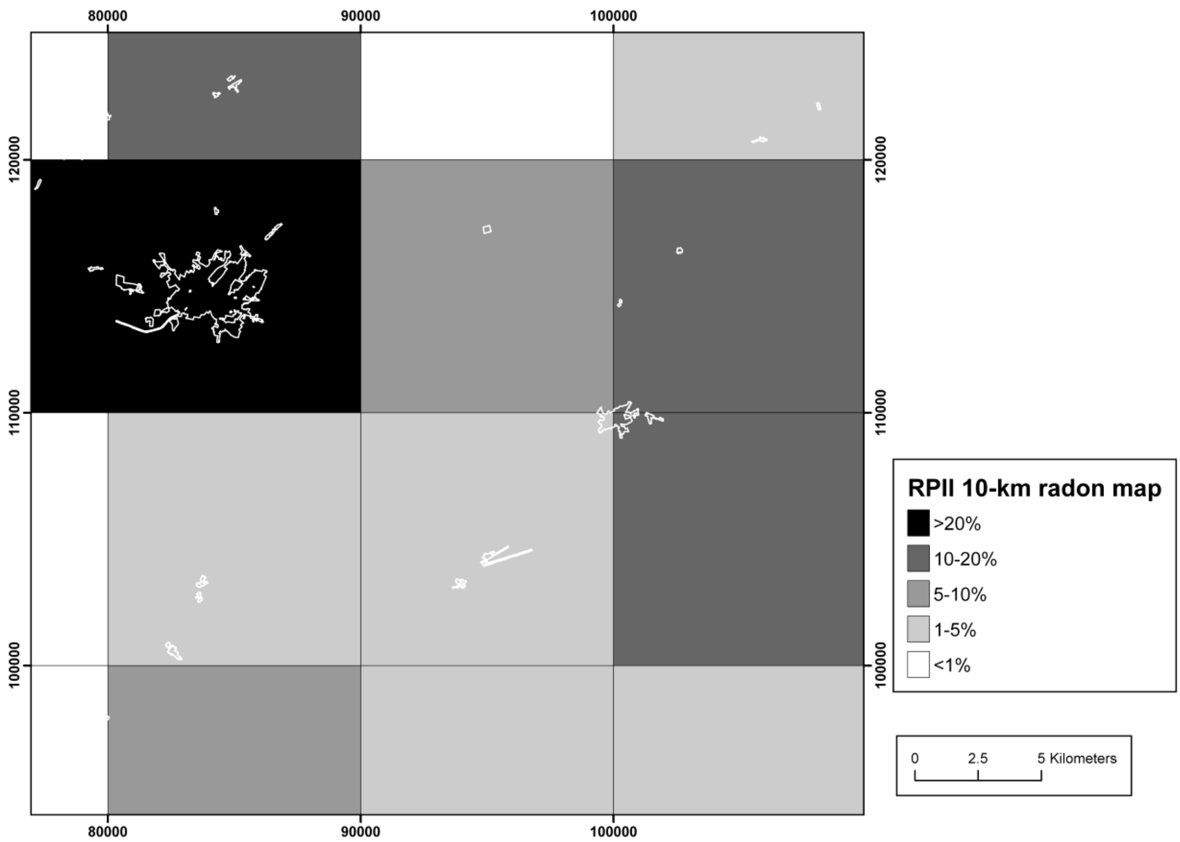

Figure 8. RPII 10-km grid radon map of the Tralee-Castleisland area (main urban areas outlined in white; map redrawn from the data in Fennell et al.(2002a))

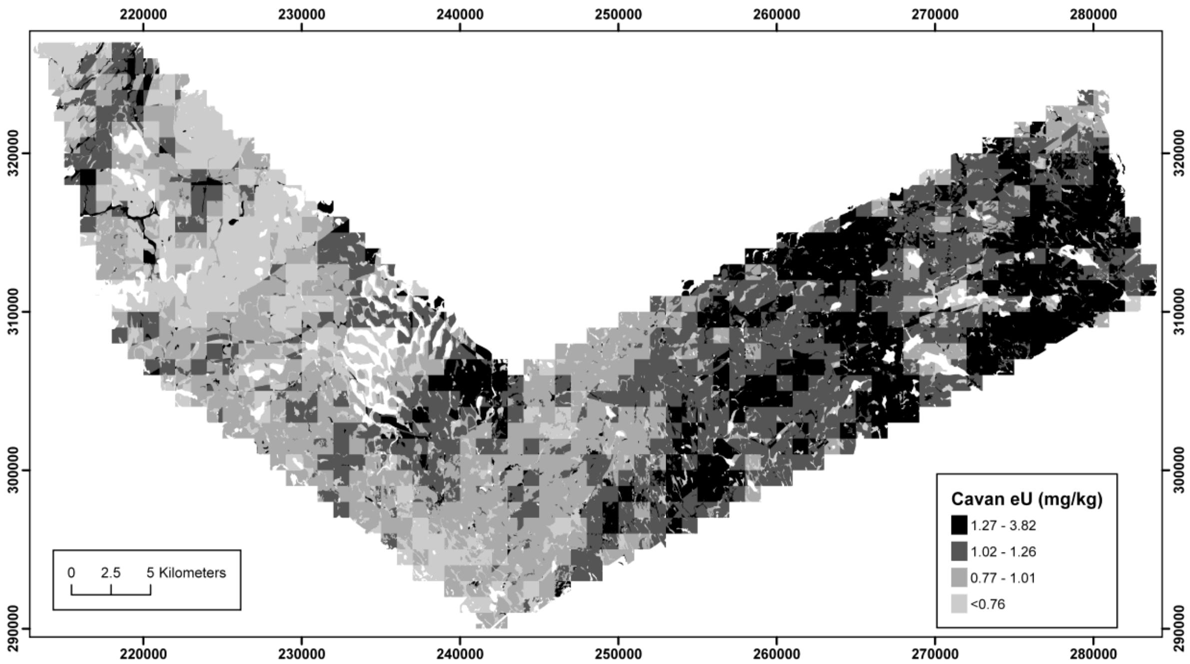

Figure 9. Average eU (mg kg^{-1}) for airborne data grouped by 1-km\bedrock\SPM polygons in the Cavan area

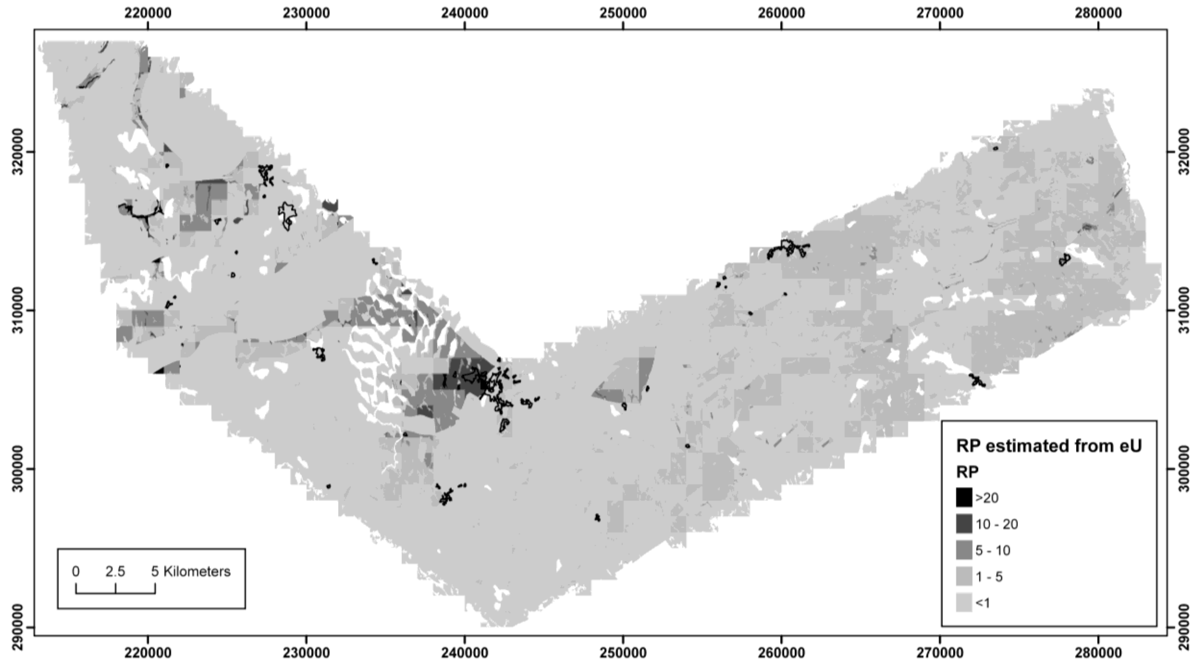

Figure 10. Radon potential (RP; modelled %>RL) map of the Cavan area produced using the terrain specific linear regression models (Table 2) (urban areas outlined in black).

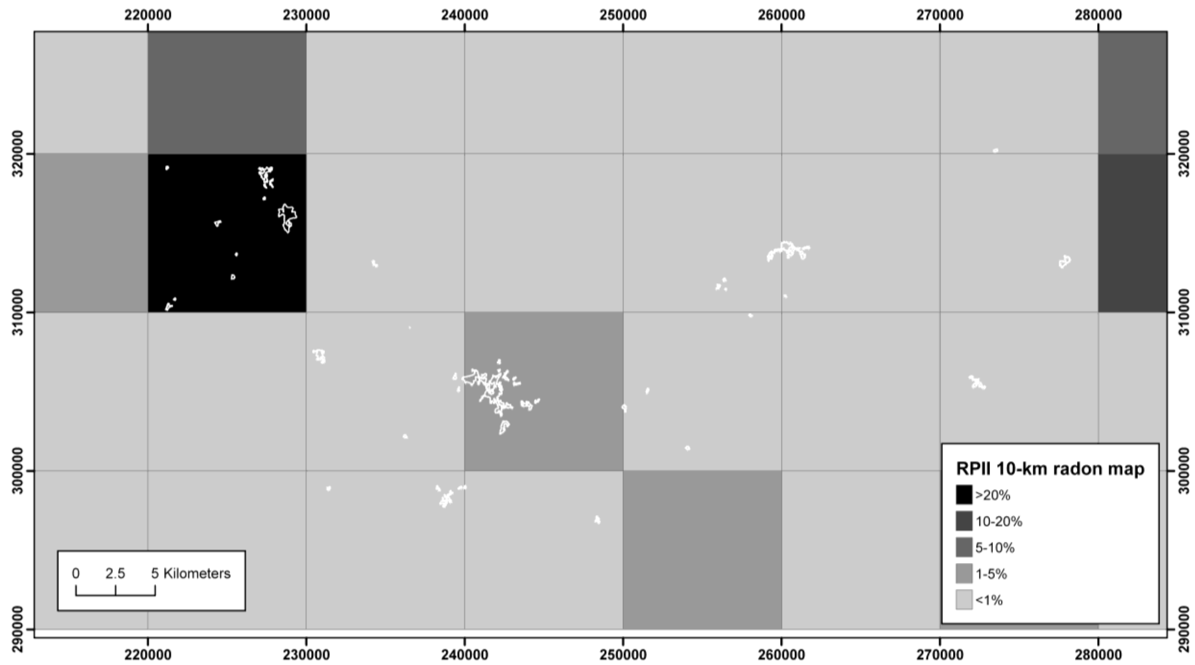

Figure 11. RPII 10-km grid radon map of the Cavan area (urban areas outlined in white; map redrawn from the data in Fennell et al. (2002a).