Regional Workshop on Development of Radon Maps and the Definition of Radon-Prone Areas

Introduction to radon mapping

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Factors affecting indoor radon

Indoor radon concentration is affected by multiple factors

GAS

\[ \begin{align*}
^{226}\text{Ra} & \rightarrow \beta \rightarrow ^{222}\text{Rn} \\
^{230}\text{Th} & \rightarrow \beta \rightarrow ^{226}\text{Ra} \\
^{234}\text{Th} & \rightarrow \beta \rightarrow ^{228}\text{Th} \rightarrow \beta \rightarrow ^{230}\text{Th} \rightarrow \beta \rightarrow ^{234}\text{Th} \\
^{238}\text{U} & \rightarrow \alpha \rightarrow ^{234}\text{U} \\
\end{align*} \]
Factors affecting indoor radon

1. **Geogenic factors**: source of indoor radon, and factors controlling radon transport into dwellings
   - Geology (bedrock, surface and near-surface deposits, topsoil geochemistry, ...)
   - Soil texture, permeability, etc.

2. **Meteorological factors**: enhance radon transport into dwellings, and influence life styles and building characteristics
   - Barometric pressure (difference indoors - outdoors)
   - Precipitation, height of the building (heating), etc.

3. **Anthropogenic factors**: enhance radon transport and accumulation into dwellings
   - Height of the building (stack effect)
   - Type of foundation, ventilation, etc.
Factors affecting indoor radon

Sketch presented at the
3rd International Conference Radon in the Environment
Krakow, 27-31 May 2019
Bossew et al. Development of a geogenic radon hazard index GRHI

Radon maps are not useful for evaluating the radon risk in a particular house
Radon Action Plans

- The long term aim is to **reduce** the number of **radon induced lung cancer cases**

- RAPs are **multidisciplinary**, all stakeholder groups should be involved (definition, implementation, follow-ups, ...)

- **Radon maps** are the basic tools for planning the RAPs

- Stakeholder should be involved in the development of radon maps (**correct interpretation**)

- **Different types of radon maps** exist depending on their application (not mutually exclusive)

- Maps are **not fixed**, they should be upgraded periodically (e.g. new data / models / knowledge)

Fuente: Ringer W., ERA Radon Training Course, Ciudad Rodrigo, Spain 2016
Radon maps

Radon maps should be adapted to the objectives of the Radon Plan. Two targets:

a) **Protection of individuals**: reducing extremes, even if only one person is affected

b) **Protection of the collective**: reduce collective dose

This requires a multidisciplinary approach, with different criteria (no mutually exclusive) depending on the aims of the programme:

a) **Protection of individuals**: detect dwellings with high radon concentration (so remediation activities can start), and/or prevent the radon accumulation indoors (building regulations). In this cases, probability maps play an important role in the radon action plan

b) **Protection of collective**: reduce radon exposure to inhabitants. Reduction policy should be spatially focused where the majority of the collective dose occurs. Such areas are where the highest radon-related lung cancer incidence is expected, even if indoor radon concentrations are relatively low. Maps which link radon and population density are essential
Radon mapping

- **Delineate radon priority (prone) areas**: areas where the radon risk may be higher than others

- **Radon activities** (e.g. public awareness, building regulations, etc.) should be “prioritized” in these areas. However, since there is not a safe radon concentration (“Linear No-Threshold” model), protection activities should continue to be implemented in areas with lower risk.

- **RPAs do not have an unambiguous natural physical definition**, it is a political decision (partly a pragmatic one – availability of data) and different criteria may be used depending on national strategies and data available.

- **Different strategies (criteria, models) may lead to contradictory information** and it can be expected that RPAs do not match across borders, with a consequent negative impact on the fidelity of information, a loss of credibility, and diminished public trust and interest.
Radon mapping

- Accurate mapping is important:
  - To increase public awareness of radioactive environment
  - To target homeowners so remediation work can be carried out
  - As it may affect building regulations; e.g. all new homes in “Radon Priority Areas” must be build with a radon barrier

- Possible misinterpretation (false sense of security!!)
  - Maps **DO NOT** delineate safe and unsafe areas
  - Indoor radon maps are not useful for assessing the radon risk at a particular dwelling

- Two types of maps depending on the datasets used:
  - **Indoor Radon Maps**: based on indoor radon measurements
  - **Geogenic Radon Maps**: based on geological information

Some examples of operable RPA definitions, based on different Rn measures (all of them are valid)

- An area (B = grid cell, municipality, district, ...), in which the average indoor radon concentration (C) exceed a Reference Level (RL = 50, 100, 200, 300 Bq m⁻³; some countries have several limits at the same time). \( \text{AM}_B(C) > \text{RL} \); measure = \( \text{AM}_B \)

- Same, but indoor concentration in dwellings on ground floor; or in a standardize house (statistically adjust the radon concentration for representing the “typical” dwelling of the area)

- An area (B) where the probability of having an indoor radon concentration higher than the RL is greater than p (p = 1%, 10%, ...). \( \text{Prob}_B(C>\text{RL}) > p \); measure = \( \text{Prob}_B \)

- The areas B which represent the upper percentage (e.g. 5%, 10%) of the radon measurements. Measure = percentile

- An area, in which the collective exposure is among an upper percentage (e.g. 5%, 10%). Measure = \( \text{AM}_B(C) \times \text{Population} \)

- An area, in which the expected radon induced lung cancer cases (assuming LNT model) may exceed a certain amount in a time frame (e.g. 35 – 70 years). Measure = \( f(Dose_B - \text{Population} - \text{Risk conversion factors}) \)
Radon priority areas

Problems and difficulties:

• Radon priority (prone) areas definition has profound political and socio-economic implications (e.g. measure and remediate workplaces, install radon barriers, possible economic depreciation of dwellings, etc.). All possible stakeholder groups should collaborate in the definition of RPA (Difficult)

• It is a decision that has to be taken with the available information, not always complete (e.g. there is not radon data in a specific area) and with a high degree of uncertainty (e.g. are radon samples representative of the long-term radon exposure in a house and/or area?) (Difficult)

• Radon maps may have also profound implications on workplaces and schools. However, radon maps are normally developed based on radon measurements at dwellings ---> radon behaviour at workplaces ≠ dwellings

• High spatial (and temporal) variation of indoor radon concentration (two neighbour houses may have very different radon concentrations). We can only know if a house has a radon problem by testing it!!!

• Communication risk: people and policymakers (and even some “radon experts”) may consider that an area classified as no-RPA is safe, then it is not necessary to test my house for radon or carry out public awareness in those areas. Maps DO NOT delineate safe and unsafe areas (neither are useful for assessing the risk in a particular house)
Some examples
(based on my experience, mainly Ireland and EU; but there are many more)
Indoor radon map of Europe

Indoor radon measurements

**Data:** annual average indoor radon concentration measured on ground floor of residential dwellings

**Participating countries** provide summary statistics estimated over 10 km x 10 km grid cells without communicating the original data to guarantee confidentiality (Original data remain with suppliers!)

**In each cell,** statistics are calculated:

- Number of measurements
- Arithmetic mean (AM)
- Standard deviation (SD)
- AM(ln data) → GM = exp(AM ln)
- SD(ln data) → GSD = exp(SD ln)
- Median
- Minimum
- Maximum

**JRC:** plausibility checks, statistics over cells, map

**Source:** European Commission, Joint Research Centre (JRC), Ispra, Italy [https://remon.jrc.ec.europa.eu/About/Atlas-of-Natural-Radiation](https://remon.jrc.ec.europa.eu/About/Atlas-of-Natural-Radiation)
Indoor radon dose map of Europe

- Evaluate radon exposure to European inhabitants (radiation dose from indoor radon)
- The European Indoor Rn Map (EIRM) currently shown in the European Atlas of Natural Radiation (EANR) is regionally incomplete. Data generation is slow: coordination of national, regional, and local authorities (difficult!!)
- Only ground floor measurements, although most people live in higher floors. When started in 2006, it was concluded (Prague conference) that if at all, only for ground floor rooms representative data would be available. It seems that this argument is still valid.
- Exposure requires input of demographic and sociological knowledge:
  - Time spent indoors (home and workplace)
  - How much time spent at either?
  - They are usually located in some distance
- Physics inputs:
  - Equilibrium factors, unattached fraction. Reasonable to use default values? What values?
  - Rn characteristic of workplaces! Data only for homes; workplaces probably different.
Indoor Radon Dose map of Europe

- Existing indoor Rn database
- Coregionalization model
- Geogenic factors: Bedrock, U and K$_2$O in ground

- Completed (by model) indoor Rn database (ground floor)
- Completed (by model) indoor Rn database (all floors)

- Sociological databases
- Representative Rn surveys
- Literature
- Rn surveys

- Exposure
- models of usage patterns

- EF

- Dose

- Dose Calculation Factor (DCF)
All-European indoor radon map

**Objective:** produce an All-European Indoor Radon Map by minimising data processing, and therefore we prefer to estimate the radon average directly by indoor radon measurements carried out at each grid (i.e. AM).

**Mean value and the confidence interval:**

\[
\bar{x} = \frac{1}{n} \sum_{i} x_i \pm t_{\left(1-\frac{\alpha}{2}, n-1\right)} \frac{s}{\sqrt{n}}
\]

- The **confidence interval** decreases when the sample size increases. In our cases, the Cl$_{95\%}$ ($\alpha = 0.05$) for sample size of about 30-40 data is around ±5%, and generally lower than 15 - 30%.
- **30 measurements seems reasonable for obtaining a good estimation of the radon exposure in a specific grid** although the assumption of data independence is not valid (i.e. there is spatial correlation between indoor radon measurements which can be modelled by the variogram).
- For the final All-European Indoor radon map we use therefore the AM of the grids with 30 or more measurements, and the value predicted by RK in the grids with less than 30 measurements.
Regression kriging: predictions in two-steps

1. **Regression estimation** of the dependent variable (e.g. AM) based on secondary variables (e.g. geogenic factors: Geology, U, K₂O).

2. **Spatial distribution of the residual** (Ordinary Kriging)

Final estimates are the sums of the regression estimates and the ordinary kriging estimates.

\[
E[X] = e^{\mu + \frac{\sigma^2}{2}} \quad \text{var}[X] = e^{(2\mu + \sigma^2)} \cdot (e^{\sigma^2} - 1)
\]

Source: Elio et al. 2019. *First steps towards an All-European Indoor Radon Map*  
[https://doi.org/10.5194/nhess-2019-102](https://doi.org/10.5194/nhess-2019-102) (open discussion)
The all-European indoor radon map represents the average value of indoor radon concentration in ground floor.

It is not representative of the radon exposure to European citizens since most people do not leave on ground floor.

It may overestimate the radon exposure since for most residential buildings Rn decreases with floor level.

A floor correction model must be developed – to be further investigated.

Maybe regional trend? (due to regionally different building styles? climate?) – to be further investigated.

At a location (grid cell), which is the fraction of rooms in basement, ground, 1, 2, and >2 floors? Link with population density? – to be further investigated.

Bossew et al 2018
**Dose conversion**

Annual dose: \( D \ [\text{mSv} \ y^{-1}] = C_{Rn} \cdot F_E \cdot T \cdot F_O \cdot F_D \)

**Challenges (to be further investigated):**

1. **Annual indoor radon concentration \((C_{Rn})\):**
   a) **Predictions** over grid cells of 10 x 10 km. Can we improve predictions? New statistical models (e.g. ML)? Other secondary variables (e.g. soil permeability)?
   b) **Floor correction** model

2. **Equilibrium factor \((F_E)\):** convert \(C_{Rn}\) to the Equivalent Equilibrium Concentration (EEC) of radon daughters. Take default values (e.g. 0.4 UNSCEAR)? Regional trends? Dependence of usage?

3. **Time expend indoors?** (Occupancy factor - \(F_O\)). UNSCEAR recommend a value of 0.8. Can we use it for all Europe? Differences between rural vs. urban areas?

4. **Time spend at home vs. workplaces?** Rn characteristic of workplaces in general different from dwellings. Can we model this?

5. **Commuting patters.** Workplace in most cases not at same location as home. Sometimes quite far away... people commute 100 km. How to model such effect?

6. **Dose conversion factor \((F_D)\):** dose coefficient applied to the EEC. International recommendation 9\( \cdot 10^{-6} \) mSv per Bq m\(^{-3}\) h (under discussion).
FIRST TRY:

- Indoor radon concentration at ground floor level and standard dose conversion factors.
- Uncertainty analysis by Monte Carlo simulation:

\[
\begin{align*}
N_{\text{sim}} &= 100 \\
C_{\text{Rn}} &\sim N(\text{AM}_z, \text{SD}_z) \quad [\text{truncated ln}\text{Rn} > 0] \\
F_D &\sim N(9\cdot10^{-6}; 1.5\cdot10^{-6}) \\
F_O &\sim N(0.8, 0.03) \\
F_E &\sim LN(0.4, 1.15)
\end{align*}
\]

- Map the AM and SD of the simulated values

Note: It is a sensitive issue. Whether and how it can be published must be decided by the JRC (and national authorities)
Indoor radon map of Ireland
**Objective:** estimate the probability of having an indoor radon concentration above the reference level of 200 Bq m$^{-3}$ by grid cells of 10 km x 10 km ($\text{Prob}[\text{InRn}] > RL$)

**Method:**

- Select radon measurements in each grid cell
- Calculate the geometry mean (GM) and the geometric standard deviation (GSD) in each grid cell
- Assuming a lognormal distribution estimate the probability of exceeding an indoor radon concentration of 200 Bq m$^{-3}$
- When the number on indoor radon measurements in a grid cell were 5, or lower, the probability was estimated base on the neighbour cells

\[
\hat{k} = \frac{\ln 200 - \ln GM}{\ln \text{GSD}}
\]

![Indoor radon map of Ireland](image.png)
1. Based on indoor measurements.

2. Indoor radon was sampled using passive alpha track detectors (CR-39), which were located in homes for a minimum of 3 months and seasonally adjusted to give an annual value.

3. Estimate the probability of having an indoor concentration > 200 Bq m⁻³ in grids of 10x10 km (i.e. <1%, 1-5%, >5-10%, >10-20% and >20%).

4. “High Risk Area” was defined as the area in which >10% of homes are above the reference level.

5. Estimated that > 7% of the national building stock has high radon concentration (> 200 Bq m⁻³).

6. Over 320,000 people may be living in homes with high radon concentrations.

7. 35% of the houses with high radon concentration are in areas classified as “Low Risk Area”.

Source: EPA (www.radon.ie)
A new radon map of Ireland

Logistic regression model for detecting radon prone areas in Ireland

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HIGHLIGHTS

- A new high spatial resolution radon risk map of Ireland has been developed.
- Logistic regression models were evaluated for radon mapping.
- Indoor radon measurements and relevant geological information were used.
- Probabilities of having an indoor radon concentration above 200 Bq m⁻² were predicted.
- About 10% of the total Irish population may be affected by high indoor radon levels.

GRAPHICAL ABSTRACT

- Dependent variable: Indoor Radon
- Logistic regression
- Predicted probability (≥90% over 200 Bq m⁻²)
- Exploratory variables: Geoclimatic factors
Geogenic indoor radon map

- Geological data
- TELLUS/Radon soil-gas
- Other factors
  - Geographical (e.g. altitude)
  - Environmental (e.g. temperature)

EPA Radon Risk Map of Ireland (Grids 10 x 10 km)
Geogenic indoor radon map

Logistic Regression Model

| Dependent variable (Y): | Explanatory variables (X = X₁, X₂, ..., Xₙ): | Predicted probability (P[Y=1|X]): |
|---|---|---|
| Indoor Radon | e.g. Bedrock geology; Quaternary geology; Subsoil permeability; Aquifer type; U-Ra concentrations, Rn in soil-gas, etc. | Estimate the probability of having a indoor radon concentration above a Reference Level (e.g. 200 Bq m⁻³) |

1. Estimate regression coefficients (β):

\[
\log \left( \frac{P[Y = 1|X]}{1 - P[Y = 1|X]} \right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n
\]

2. Predict the probability of occurrence:

\[
P[Y = 1|X] = \frac{1}{1 + e^{-(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n)}}
\]

3. Radon Map:

Five probability bands: P < 1%; 1% ≤ P < 5%; 5% ≤ P < 10%; 10% ≤ P < 20%; and P ≥ 20%
Estimate the occurrence probability of binary variables (i.e. Indoor Radon > 200 Bq m$^{-3}$)

**Dependent variable (Y):**
Indoor Radon
- High ($\text{lnRn} \geq 200$ Bq m$^{-3}$) = 1
- Low ($\text{lnRn} > 200$ Bq m$^{-3}$) = 0

**Explanatory variables ($X = X_1, X_2, ..., X_n$):**
- First test: $n = 4$
  - Bedrock geology; Quaternary geology; Subsoil permeability; Aquifer type

**Predicted probability ($P[Y=1|X]$):**
Estimate the probability of having a indoor radon concentration above the reference level of 200 Bq m$^{-3}$
Geogenic indoor radon map

Model

- **Subsoil Permeability - SP (β₃)**
  - Permeability (↑) → Probability (↑)

- **Aquifer Type - AT (β₄)**
  - Highest probability: Karstified aquifers
  - Lowest probability: Unproductive aquifers

- **Bedrock Geology - BG (β₁)**
  - Highest probabilities: Group 9 (Triassic sandstone, mudstone, evaporite) and Group 7 (granite and intrusive rocks).
  - Lowest probability: Group 1 (Cambrian greywacke, slate, quartzite)

- **Quaternary Geology - QG (β₂)**
  - Highest probabilities: Shale tills and Granite tills
  - Lowest probability: Marine deposits

\[
\log\left(\frac{P(Y = 1|X)}{1 - P(Y = 1|X)}\right) = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4
\]

\[
P(Y = 1|X) = \frac{1}{1 + e^{-(\beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4)}}
\]

| Coefficients: | Estimate | Std. Error | z value | Pr(>|z|) |
|---------------|----------|------------|---------|----------|
| β₀ (Intercept) | -4.699   | 0.338      | -13.910 | < 2e-16 *** |
| β₁ BG: Group 9 | 3.593    | 0.874      | 4.073   | 0.000 *** |
| β₁ BG: Group 7 | 1.547    | 0.291      | 5.006   | 0.000 *** |
| β₁ BG: Group 12| 1.421    | 0.348      | 4.082   | 0.000 *** |
| β₁ BG: Group 10| 1.352    | 0.395      | 3.428   | 0.000 *** |
| β₁ BG: Group 2 | 1.123    | 0.297      | 3.783   | 0.000 *** |
| β₁ BG: Group 11| 0.981    | 0.303      | 3.238   | 0.000 *** |
| β₁ BG: Group 6 | 0.971    | 0.304      | 3.195   | 0.000 *** |
| β₁ BG: Group 8 | 0.738    | 0.304      | 2.427   | 0.015 *** |
| β₁ BG: Group 5 | 0.730    | 0.310      | 2.352   | 0.019 *** |
| β₁ BG: Group 4 | 0.450    | 0.319      | 1.408   | 0.159 *** |
| β₁ BG: Group 3 | 0.350    | 0.316      | 1.107   | 0.268 *** |
| β₁ BG: Group 1 | 0.000    |            |         |           |
| β₂ QG: Shale till | 1.858    | 0.172      | 10.810  | < 2e-16 *** |
| β₂ QG: Granite till | 1.789    | 0.141      | 12.730  | < 2e-16 *** |
| β₂ QG: Bedrock | 1.419    | 0.132      | 10.735  | < 2e-16 *** |
| β₂ QG: Sandstone till | 1.314    | 0.134      | 9.811   | < 2e-16 *** |
| β₂ QG: Metamorphic till | 1.054    | 0.153      | 6.898   | 0.000 *** |
| β₂ QG: Sandstone and shale till | 0.813    | 0.129      | 6.325   | 0.000 *** |
| β₂ QG: Limestone till | 0.772    | 0.126      | 6.151   | 0.000 *** |
| β₂ QG: Peat | 0.531    | 0.174      | 3.053   | 0.002 *** |
| β₂ QG: Glacio-fluvial | 0.000    |            |         |           |
| β₂ QG: Marine deposits | -0.075   | 0.255      | -0.293  | 0.770 *** |
| β₃ SP: High | 1.057    | 0.095      | 11.170  | < 2e-16 *** |
| β₃ SP: Moderate | 0.713    | 0.054      | 13.130  | < 2e-16 *** |
| β₃ SP: Low | 0.000    |            |         |           |
| β₄ AT: Karstified | 0.743    | 0.150      | 4.946   | 0.000 *** |
| AT: Interglacial | 0.000    |            |         |           |
| AT: Poor-moderate productive | -0.034   | 0.154      | -0.224  | 0.823 *** |
| AT: Productive fissured | -0.385   | 0.169      | -2.836  | 0.002 *** |
| AT: Unproductive | -0.387   | 0.168      | -2.296  | 0.022 *** |

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
\[
\log \left( \frac{P(Y = 1|X)}{1 - P(Y = 1|X)} \right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4
\]

\[
P(Y = 1|X) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4)}}
\]

**Predictions**

| Geogenic indoor radon map | Predictions: 960 polygons (intersect Bedrock Geology, Quaternary Geology, Subsoil Permeability, and Aquifer Type) | Indoor Radon Risk Map |

![Image of indoor radon risk map]
Geogenic indoor radon map

New map vs. EPA map

Indoor Radon Risk Map
Prob [ln(Rn) > 200 Bq/m³]
- < 1%
- 1% - 5%
- 5% - 10%
- 10% - 20%
- > 20%

Resolution 1 km x 1 km

EPA Indoor Radon Risk Map
Prob [ln(Rn) > 200 Bq/m³]
- < 1%
- 1% - 5%
- 5% - 10%
- 10% - 20%
- > 20%

Resolution 10 km x 10 km
Estimation of residential radon exposure and definition of Radon Priority Areas based on expected lung cancer incidence

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ABSTRACT

Radon is a naturally occurring gas, classified as a Class 1 human carcinogen, being the second most significant cause of lung cancer after tobacco smoking. A robust spatial definition of radon distribution in the built environment is therefore essential for understanding the relationship between radon exposure and its adverse health effects on the general population. Using Ireland as a case study, we present a methodology to estimate an average indoor radon concentration and calculate the expected radon-related lung cancer incidence. We use this approach to define Radon Priority Areas at the administrative level of Electoral Divisions (EDs).

Geospatial methods were applied to a data set of almost 32,000 indoor radon measurements, sampled in Ireland between 1992 and 2013. Average indoor radon concentrations by ED range from 21 to 338 Bq m⁻³, corresponding to an effective dose ranging from 0.8 to 13.3 mSv y⁻¹ respectively. Radon-related lung cancer incidence by ED was calculated using a dose-effect model giving between 15 and 239 cases per million people per year, depending on the ED. Based on these calculations, together with the population density, we estimate that of the approximately 2,300 lung cancer cases currently diagnosed in Ireland annually, about 280 may be directly linked to radon exposure. This figure does not account for the synergistic effect of radon exposure with other factors (e.g., tobacco smoking), so likely represents a minimum estimate. Our approach spatially defines areas with the expected highest incidence of radon-related lung cancer, even though indoor radon concentrations for these areas may be moderate or low. We therefore recommend that both indoor radon concentration and population density by small area are considered when establishing national radon action plans.
Radon exposure

- Same dataset: 31,910 dwellings
- Predict an average indoor radon concentration (e.g. EDs)
- Geostatistic analysis (Kriging)
Radon exposure (health effects)

- **Average indoor radon concentration (EDs)**
- **Expected lung cancer cases**
- **Population density**
- **Expected number of lung cancer cases (2016)**

### a) Annual effective dose (mSv y\(^{-1}\)):
\[ D = C_{Rn} \cdot F_E \cdot T \cdot F_D \]

### b) Number of lung cancer cases per year per million people:
\[ ELCC = 18 \text{ [mSv y}^{-1}] \cdot D \text{ [mSv y}^{-1}] \]

### c) Population density by EDs (3409):
- Year 2016
  - Average: 1,400 inhabitants
  - Range: 66 - 38,900
  - Areas: 0.04 km\(^2\) - 162 km\(^2\)

### d) Annual lung cancer cases:
- 286 [CI\(_{95\%}\): 150 - 474] for 2016
- 276 [CI\(_{95\%}\): 144 - 457] for 2011
Radon exposure (health effects)

Most people are exposed to a radon concentration below 200 Bq m$^{-3}$, is it efficient to define a radon-priority area only based on the reference level?

Should be included the possible health effects (i.e. expected lung cancer incidences) in the definition of RPA?

Include housing/population data (e.g. total number of dwellings with an indoor radon concentration higher than the reference level / People who may be exposed to high radon concentrations)?

![Indoor Radon ≈ Lognormal distribution](image)

**GM = 57; GSD = 2.4**

![Radon Exposure by Electoral Divisions](image)

**Average (Bq m$^{-3}$) | EDs | Population | LCC***
--- | --- | --- | ---
20 - 25 | 4 | 1,791 | 1,683 | 0 | 0
25 - 50 | 324 | 3,946 | 30 | 405 | 230 | 12 | 12
50 - 75 | 1,229 | 1,966,203 | 2,048,778 | 87 | 91
75 - 100 | 850 | 1,121,589 | 1,167,142 | 68 | 71
100 - 125 | 451 | 517,534 | 533,289 | 41 | 42
125 - 150 | 267 | 251,055 | 258,696 | 24 | 25
150 - 175 | 132 | 174,096 | 182,087 | 20 | 21
175 - 200 | 68 | 89,221 | 91,546 | 12 | 12
200 - 225 | 46 | 34,158 | 34,906 | 5 | 5
225 - 250 | 17 | 16,055 | 16,298 | 3 | 3
250 - 275 | 11 | 11,247 | 11,544 | 2 | 2
275 - 338 | 10 | 10,673 | 10,666 | 2 | 2

**Total** | 3,409 | 4,588,252 | 4,761,865 | 276 | 286

*LCC: Estimated lung cancer cases*
Rapid radon potential classification using soil-gas radon measurements in the Cooley Peninsula, County Louth, Ireland

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Abstract
A rapid method for local-scale radon risk assessment using in situ radon soil-gas measurements and a national-scale soil permeability data set have been evaluated. We test and validate our approach in a case study on the Cooley Peninsula, County Louth, Ireland. In total, 60 radon soil-gas measurements from 48 points were carried out in an area of approximately 160 km² over a 5 days period. Results of radon potential classification are compared with the legislative indoor radon map of Ireland, with more than 400 indoor radon measurements in the study area. Soil-gas radon concentrations on the Cooley Peninsula ranged from very low values (< 10 kBq m⁻³) to extremely high (up to 112 kBq m⁻³), whereas indoor radon concentrations ranged from 3 to 863 Bq m⁻³. The Cooley Peninsula is therefore mostly classified as a moderate–high and high radon potential area. The percentage of indoor radon variance explained by soil-gas radon concentration, soil permeability and geology is approximately 30% (12, 9.3, and 8.6%; respectively). Our findings show that radon potential classification can detect radon priority areas with a reasonable degree of accuracy, even with a relatively low number of point measurements in relation to the size of the area studied. We demonstrate that active radon measurements and geostatistical modelling can significantly reduce the time and cost required to evaluate an area in relation to expected indoor radon concentrations. This approach is viable to produce a radon potential map in rural areas, or where land-use has been re-designated for new housing, where few or no indoor radon measurements are available.
Geogenic radon maps

Radon potential

➢ Test if soil-gas radon surveys are useful to detect radon priority areas at large scale
  • Can the methodology be applied in areas where no indoor radon measurements are available?
  • Case study: the Cooley Peninsula (High Radon Risk Area).
  • More than 400 indoor radon measurements are available in the study area.

Cooley Peninsula

Source: EPA (www.epa.ie/radiation/radonmap)
1. In-situ radon measurements are useful for detection of radon prone areas at local scale
2. In-situ soil permeability measurements may improve the Radon Potential classification (local scale)
3. For regional scale maps a method to estimate the radon activity in soil-gas and soil-permeability should be implemented
Geogenic radon maps

Radon potential: Cooley Peninsula

1. In-situ radon measurements are useful for detection of radon prone areas at local scale
2. In-situ soil permeability measurements may improve the Radon Potential classification (local scale)
3. For regional scale maps a method to estimate the radon activity in soil-gas and soil-permeability should be implemented
Soil-gas radon predictions (Airborne data)

Radon estimation in soil gas

a) $^{238}\text{U} \text{[Bq kg}^{-1}] = 12.35 \text{ eU [ppm]}$

b) Secular equilibrium:

$$^{226}\text{Ra} \text{[Bq kg}^{-1}] = ^{238}\text{U} \text{[Bq kg}^{-1}]$$

c) Soil properties:

$$C_{\text{Rn}} \text{[Bq m}^{-3}] = \frac{C_{\text{Ra}} \cdot \epsilon \cdot \rho}{n} \cdot \frac{1}{1 - S_F + S_F K_{\text{w/Air}}}$$

d) Monte Carlo simulations:

Percentile 75%
Radon potential

Radiometric data ($^{238}\text{U}$) $\rightarrow$ Radium ($^{226}\text{Ra}$) $\rightarrow$ Radon ($^{222}\text{Rn}$)

Radon Potential (RP)

$$RP = \frac{C_{\text{Rn}}}{(-\log_{10}(k) - 10)}$$

- Radon ($C_{\text{Rn}}$)
- Subsoil permeability ($-\log(k)$)

Radon Potential (RP)
Radon potential

Radiometric data \(^{238}\text{U}\) → Radium \(^{226}\text{Ra}\) → Radon \(^{222}\text{Rn}\)

\[ RP = \frac{C_{\text{Rn}}}{-\log_{10}(k) - 10} \]

Radon potential (RP)

<table>
<thead>
<tr>
<th>Radon Potential</th>
<th>No. ≤ RL</th>
<th>No. &gt; RL</th>
<th>InRn</th>
<th>Prob (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>1,053</td>
<td>68</td>
<td>35</td>
<td>6</td>
</tr>
<tr>
<td>M-L</td>
<td>3,964</td>
<td>312</td>
<td>44</td>
<td>7</td>
</tr>
<tr>
<td>M-H</td>
<td>7,779</td>
<td>1,276</td>
<td>61</td>
<td>14</td>
</tr>
<tr>
<td>H</td>
<td>1,721</td>
<td>451</td>
<td>74</td>
<td>21</td>
</tr>
</tbody>
</table>
Summary

1. Prob $[\ln R_n > 200 \text{ Bq m}^{-3}]$
2. Divided a country in radon risk categories
3. N. of dwellings/population that may be affected by high radon concentrations (e.g.):
   - Approx. 185,000 dwellings in Ireland
   - Up to 460,000 people

1. Independent of anthropogenic factors (e.g. house type)
2. Risk classification only based on radon source (i.e. soil-gas radon concentration) and its availability to move into a house (i.e. soil permeability)
3. Possibility to characterize areas for radon risk where indoor radon measurements are not available
1. Average concentration in an area
2. Calculate the effective dose (ranges from 0.8 to 13.3 mSv y⁻¹)
3. Epidemiological studies:
   - Lung cancer
   - Others: skin, stomach or brain cancer, Non-Hodgkin’s Lymphoma, etc.

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1. Expected radon-induced lung cancer incidence
2. Knowing the population density, the expected radon-related lung cancer cases may be estimated:
   - In 2016 = 286 (CI₉₅%: 150 – 474)
   - In 2011 = 276 (CI₉₅%: 144 – 457)
<table>
<thead>
<tr>
<th>Country</th>
<th>Reference Level</th>
<th>Objectives</th>
<th>Methods</th>
<th>Resolution</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>200 and 400 Bq m⁻³</td>
<td>Divide the country in three classes: i.e. average annual concentration &lt;200, 200 - 400, and &gt; 400 Bq m⁻³</td>
<td>Annual mean radon concentration in a standard situation</td>
<td>Administrative Level (i.e. municipality)</td>
<td>Friedmann 2005</td>
</tr>
<tr>
<td>Azerbaijan</td>
<td>200 Bq m⁻³</td>
<td>Display the indoor radon concentration values</td>
<td>Arithmetic mean of indoor radon gas concentration values</td>
<td>10km x 10km and district</td>
<td>Hoffmann et al. 2017</td>
</tr>
<tr>
<td>Belgium (Walloon region)</td>
<td>400 Bq m⁻³</td>
<td>Percentage of dwellings above the RL taking into account geological information</td>
<td>Moving average between geological units</td>
<td>1 km x 1 km</td>
<td>Cinelli et al. 2011</td>
</tr>
<tr>
<td>Hungary</td>
<td>200 Bq m⁻³</td>
<td>Percentage of standard houses (i.e. one-storied, no basement houses) above the RL. Reports also the arithmetic mean, and the maximum value</td>
<td>Lognormal model</td>
<td>Various: Administrative level (i.e. counties), and Grids 10x10 km</td>
<td>Minda et al. 2009</td>
</tr>
<tr>
<td>Italy (Abruzzo)</td>
<td>100, 200 and 300 Bq m⁻³</td>
<td>Risk that a standard houses exceeds the RL. Divide the country in seven categories.</td>
<td>Bayesian spatial quantile regression, and Bayesian model for spatial cluster detection</td>
<td>Administrative level (i.e. counties)</td>
<td>Sarra et al. 2016</td>
</tr>
<tr>
<td>Italy (Lombardy)</td>
<td>200 and 400 Bq m⁻³</td>
<td>Percentage of houses above the RLs. RPA when the RL (200 or 400 Bq m⁻³) is below the lower confidence limit at 95% of the quantile 0.9 (P[InRn &gt; R.L] ≥ 10%).</td>
<td>Geostatistical simulation (i.e. multi-Gaussian sequential simulation).</td>
<td>Administrative Level (i.e. municipality)</td>
<td>Borgoni et al. 2010</td>
</tr>
</tbody>
</table>
## Some other methods for radon mapping (cont.)

<table>
<thead>
<tr>
<th>Country</th>
<th>Reference Level</th>
<th>Objectives</th>
<th>Methods</th>
<th>Resolution</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macedonia</td>
<td>100 and 200 Bq m⁻³</td>
<td>Display the probabilities of having an indoor radon concentration higher than 100 and 200 Bq m⁻³, and the expectation.</td>
<td>Estimations are derived from $^{226}$Ra concentration in soil</td>
<td>Grids 5x5 km</td>
<td>Bossew et al. 2013</td>
</tr>
<tr>
<td>Malta</td>
<td>100 Bq m⁻³</td>
<td>Display the indoor radon concentration values</td>
<td>Average of geometric mean annual indoor radon gas concentration values for each sampling point</td>
<td>Grids 5x5 km</td>
<td>Baluci et al. 2013</td>
</tr>
<tr>
<td>Norway</td>
<td>200 Bq m⁻³</td>
<td>Percentage of houses above the R.L. based on indoor radon and geological information (Bedrock geology, and Quaternary geology). RPA when $P[\text{InRn} &gt; \text{R.L}] \geq 20 %$.</td>
<td>Classify geological polygons according to local (polygon) statistics or national (class) statistics</td>
<td>Geological polygons</td>
<td>Watson et al. 2017</td>
</tr>
<tr>
<td>Spain</td>
<td>300 Bq m⁻³</td>
<td>Identify 3 radon classes</td>
<td>Model that use as input data: national indoor radon databases; natural $\gamma$-radiation map (MARNA); Geological maps</td>
<td>Geological unit</td>
<td>García-Talavera et al. 2013</td>
</tr>
<tr>
<td>Switzerland</td>
<td>100 and 300 Bq m⁻³</td>
<td>Percentage of homes having an indoor radon concentration $&lt; 100$, 100 - 300, and $&gt; 300$ Bq m⁻³</td>
<td>Ordered logistic regression model</td>
<td>Grids 10x10 km</td>
<td>Kropat et al. 2017</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>200 Bq m⁻³</td>
<td>Percentage of houses above the R.L. taking into account geological information. RPA when $P[\text{InRn} &gt; \text{R.L}] \geq 1 %$</td>
<td>Lognormal model, corrections to account year-to-year variation and random variations (i.e. Bayesian statistics)</td>
<td>Grids 1x1 km</td>
<td>Miles et al. 2007; Miles et al. 2011; Daraktchieva et al. 2015</td>
</tr>
</tbody>
</table>