Radon Flux Characteristics

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Radon is a noble radioactive gas, and almost half of the effective doses from all ionising radiation comes from exposure to radon and its short-lived decay products. Radon flux measurements provide information about how much radon rises from the ground toward the atmosphere, thus, they could serve as good predictors of indoor radon concentrations. Although there are many different mapping methods with many different input data, radon flux data are generally missing and are not included for the delineation of radon priority areas (RPA).

Keywords: radon flux ; radon priority area ; variations ; meteoroloical factors

1. Introduction

Radon is a noble radioactive gas, and almost half of the effective doses from all ionising radiation comes from exposure to radon and its short-lived decay products [1]. Radon was first recognised as a health problem among miners in the United States of America [2] and Czechoslovakia [3]; thus, it was identified as a human carcinogenic [4]. Afterwards, radon in indoor environments started to be monitored more systematically through national radon programmes [5][6][7]. Finally, radon is identified as one of the major causes of lung cancer, accounting for between 3% to 14% of all lung cancers [8]; consequently, it was included in the Basic Safety Standards (BSS) for protection against ionizing radiation [9]. BSS requires that EU member states define radon reference levels, establish a radon action plan, delineate Radon Priority Areas (RPA, i.e., areas where the annual average radon concentration is expected to be higher than the reference level in a significant number of dwellings), and inform the public about their radon levels [9].

Being chemically inert, radon has been used in many environmental studies as well. It is used as a tracer gas for the individuation of hidden active and dormant faults [10][11][12][13][14][15], monitoring of volcanic activity and groundwater movement, and earthquake prediction [16][17][18][19][20]; to improve Atmospheric Transport Models (ATM); to investigate atmospheric mixing processes; and to estimate fluxes of greenhouse gases (GHG) using the Radon Tracer Method [21][22][23][24][25][26][27][28][29][30][31][32][33][34].

To increase the accuracy of both radiation protection measurements and those used for GHG modelling, traceability to SI units is needed for radon release rates from soil, radon concentration in the atmosphere, and valid models for radon dispersal. Both radiation protection and climate research need to improve the accuracy of low-level radon concentration measurements and to ensure traceability to SI units. In this regard, the metrological project EMPIR 19ENV01 “Radon metrology for use in climate change observation and radiation protection at the environmental level” (traceRadon) [35] aims to develop traceable methods for the measurement of outdoor low-level radon activity concentrations in the range of 1 to 100 Bqm^{-3} with uncertainties of 10% (k = 1), and to improve the accuracy of radon flux measurements. Both the climate and radiation protection communities will benefit from these data [35][36]. Improving accuracy and providing measurements capable of resolving diurnal variations will help climate change research by providing necessary inputs for the Radon Tracer Method, which is used to better estimate greenhouse gases emission [22][34].

2. Radon Priority Area—RPA

Maps of environmental radioactivity are important on a local, regional, national and even worldwide scale as they assist in the planning and decision making of both authorities and citizens.

The identification of RPAs is a sensitive task as it raises some obligations for the region under consideration [9]. In such areas, radon measurements in workplaces are required, and awareness programs and a strategy for reducing radon exposure in dwellings should be established. In some countries, radon measurements in workplaces are required outside of the RPA also [37]. A definition of RPA was not given precisely in BSS; instead, it was left to member states to provide their own definition of the RPA, which as a consequence led to different RPA maps. Therefore, many efforts have been made to discuss a concept of the RPA [38][39][40][41][42].

According to the questionnaire on indoor radon surveys issued in European countries, 11 out of 19 countries have reported 300 Bqm^{-3} as the Reference Level (RL), while some have chosen 100 or 200 Bqm^{-3} as a RL [43]. Most of the countries participating in the questionnaire have defined RPA on the basis of the percentage of dwellings having indoor radon concentration above RL, i.e., an area is defined as an RPA if the probability of the indoor radon concentration is above certain RL. This probability (threshold) ranges from 1% in the case of Malta and the United Kingdom up to 30% in the case of the Czech Republic [43]. Norway defined all of its territory as RPA. Two other definitions of RPA were also used: an area is defined as RPA (i) if the mean indoor radon concentration of the area is above RL, or (ii) if certain conditions are fulfilled (e.g., the gamma dose rate is above a certain level) [41].

As reported in the BSS, the identification of RPA needs a relatively simple statistical procedure that involves a few types of input data. The most common approach uses data that are expressed in the same method of measure, e.g., indoor radon concentration and the Reference Level. In that case, in order to get a reliable estimation of the RPA, it is important to carry out representative indoor radon surveys [6][7][44][45].

Other approaches involve the use of qualitative (non-measured) input data, such as the type of geology and/or lito-stratigraphic data, and quantitative data with different unit measures (e.g., geological, geochemical, morphological, and meteorological data) that in general represent proxy variables related to the geogenic radon potentially delivered by the Earth's surface (e.g., Geogenic Radon Potential or Geogenic Radon Hazard Index), while indoor radon concentration is used for the determination of the RPA [46][47][48][49][50]. The GRHI could be conceptualized in terms of a measure of the "Rn proneness" of an area due to geogenic factors, i.e., a tool to decide whether an area is as RPA as the one used for the definition of the RPA. GRHI incorporates available geological data [49]. On the other hand, GRP is mainly defined through the "Czech method" [46], combining the radon in soil and permeability measurements, which depends on soil properties, hydrology and geology and, therefore, is limited by the availability of the required data [49].

The use of different available input data related to radon production and migration from the Earth's subsurface to the shallow environment, and the ability to enter buildings (e.g., measured quantities, geological data, meteorological data, and anthropogenic factors) led to the development of different mapping methods by using spatial regression techniques (Geographical Weighted Regression, Empirical Bayesian Regression Kriging, Machine Learning, Forest Regression) [48][51][52][53][54][55][56].

In Germany, Petermann et al. (2022) have shown that reducing high radon concentrations only in RPA will affect only a small proportion of residents as less than 1% of lung cancer fatalities are attributable to radon located in the RPA [40]. Therefore, when the aim is to reduce collective risk rather than individual, a map of lung cancer incidences would be more suitable [40]. A decision matrix on the choice of the appropriate radon map that would best serve its purpose is proposed in Hughes et al. in [57].

One of the tasks within the metrological research project 16ENV10 "Metrology for radon monitoring" (MetroRADON—http://metroradon.eu, accessed on 25 November 2020) was to evaluate different mapping methods for the delineation of the RPAs and to develop a strategy to harmonise possible inconsistences of radon levels across the border [58]. In the framework of the MetroRADON project, an intercomparison exercise of different mapping methods was performed to construct geogenic radon potential maps, and it was concluded that different methods predict similar classifications of RPAs, while problems emerge only when the thresholds for the classification of RPAs are close to mean indoor radon concentrations [59].

Since there are different criteria for the definition and identification of RPAs, it is difficult to compare maps created by different national authorities. Bossew et al. demonstrated that the identification of RPAs across country borders is affected by the type of data aggregation (e.g., the geometry of the data support) and the scale of the used support [41]. This problem is defined as the Modifiable Areal Unit Problem (MAUP): the higher the support used to aggregate data, the more difficult the harmonisation of the results at the boundaries [41][60][61][62].

Although in the abovementioned mapping methods, many different input data were used, it could be noticed that data on radon flux were generally missing and were not included for delineation of the RPA. Radon flux measurements take a long time and, therefore, are not cheap, while soil gas measurement is simpler and faster, even when not a dynamic measurement. Radon flux gives an idea of how much radon comes out of the ground towards the atmosphere and, therefore, represents a good predictor of the radon that could enter buildings. Radon in the soil gas only gives information on the level of radon concentration in the ground, but this radon may never escape into the atmosphere. Therefore, Rn flux measurements should be very useful to identify the RPA. Consequently, the aim here is to investigate to what extent radon flux was used, or could be used, for delineation of RPA.

3. Radon Flux Applications

Radon concentrations in soil gas, ground water, outdoor and indoor air, and radon flux are used to study many different phenomena and problems, from radiation protection to identification of hydrocarbon contamination in the soil. Although all these quantities describe parts of the same process—radon transport from ^{226}Ra decaying to different surrounding media—different quantities are more suitable for various phenomena, and in some cases, several of these quantities can be used together.

In the reviewed literature, the amount of radon activity that exhales each second per square meter is called "radon flux" or "radon exhalation rate". Herein, the term "radon flux" is used. Radon flux is most commonly expressed in $mBqm^{-2}s^{-1}$ or $Bqm^{-2}h^{-1}$. However, when radon flux was expressed in atoms $cm^{-2}s^{-1}$, conversion to $mBqm^{-2}s^{-1}$ was used (1 atom $cm^{-2}s^{-1}$ = 21.0 $mBqm^{-2}s^{-1}$).

Several examples regarding the use of radon flux are listed with a short explanation.

- Radon flux is used in the radon tracer method to monitor emissions of different gases, and it is most often used for greenhouse gases. In this method, radon flux is often considered constant over time and uniform, especially when performing large-scale studies [22][28][32][63][64][65][66][67]. More recent radon flux models revealed large spatial and temporal variability [68][69][70]. Grossi et al. (2014) improved the radon tracer method by using the model developed at the University of Huelva to calculate time-dependent values of radon flux [23]. In this model, it is considered that the only sink for radon is radioactive decay, and that dilution by atmospheric mixing is the same for radon and for other trace gases. Therefore, the surface emissions for any trace gas can be determined if the mixing ratios for these gases and radon are known, provided that radon flux is also known [64][65]. The TraceRadon project aims to build a metrological chain to ensure high-quality flux measurements that could provide increase data input for the radon flux method [36]. Some of the gases investigated in different studies include CO_2 [32][63][71], CH_4 and N_2O [27][64][72], CO_2, CH_4, N_2O, and CFCs [28], CH_4 [22][23][65], CO_2 and CH_4 [66], N_2O [67] and H_2 [73].

- As there is large enrichment of ^{222}Rn concentration in groundwaters compared to surface waters, ^{222}Rn is used as a tracer to identify areas with groundwater discharge [74][75]. From continuous measurements of ^{222}Rn in water, radon fluxes can be calculated for further used to estimate water fluxes that are otherwise difficult to measure [74][75].

- Radon flux is also used to plan, monitor, and evaluate the remediation of uranium mine and mill sites [76]. Ota et al., have investigated the effectiveness of clay-covered soil surfaces in radon flux suppression. From 80 days of continuous radon flux measurements of clay-covered soil surface and bare soil surface, it was found that suppression of the mean radon flux was 80% [77] In the USA, regulations require that radon flux from active uranium mill tailing should not exceed 740 $mBqm^{-2}s^{-1}$ [78]; however, although remediation is designed to fulfil requirements for radon flux, monitoring is not mandatory [79][80]. In Argentina, radon flux measurements are performed periodically in mining and processing sites [81]. Radon flux is also measured in India [82]. Radon flux was measured to evaluate the effectiveness of earthen cover after 20 years of service [80], as well as the effects of vegetation, clay cap, and environmental variables [83]. Due to high radium content, radon flux measurement is also of interest for phosphogypsum piles and their remediation [84].

- Very high values of radon flux can be found over active faults, so radon flux measurements can be used to identify faults [85][86]. Various researchers have also performed measurements along and perpendicular to the fault [87][88]. A study by Richon et al. found that superficial soil can mask faults, causing radon fluxes to be indistinguishable from background levels [89]. On the other hand, radon flux measurements, especially over faults, can be used to predict earthquakes [90]. Steinitz et al. found a statistically significant relation between radon flux and weak earthquakes during a multiyear study [91]. A study by Yakovleva and Karataev showed that using radon flux in combination with radon concentration in soil gas may improve the sensitivity of predictions, compared to using only one of these parameters [92].

- Radon concentrations in caves can be calculated based on radon flux [93].

- Radon flux can be used for radiation protection purposes. For example, Lucchetti et al. integrated gamma dose rate measurements with radon and thoron flux measurements to assess people's exposure to natural radiation and potential indoor radon [94]. However, radon exhalation was measured from soil samples, not in situ. Ramola et al. (2011) used radon flux to estimate indoor radon concentrations [95]. However, radon flux was also calculated based on the radon concentration in soil gas and not measured. Stavitskaya et al. considered radon flux to carry out assessments of the radon risks of building plots [96]. Baeza et al. measured radon flux together with other parameters and indoor radon concentrations, and showed that radon flux alone is sometimes a good predictor of indoor radon concentrations, but in other cases, the correlation is much weaker [97]. Even negative correlations have been found in some cases [98]. Leshukov et al. investigated correlations between coal mine locations and radon flux, as well as indoor radon concentrations, to identify areas where radon preventative measures need to be taken during construction [99].

- Another important topic related to radiation protection purposes concerns building materials (commonly referred to as exhalation rate), which are the second most important source of indoor radon after soil. Building materials rich in ^{226}Ra, such as granites or tuffs, represent a significant source of indoor radon [100][101]. The contribution to the indoor radon concentration from building materials is even more pronounced in energy-efficient buildings because an increase in the airtightness of homes increases the accumulation of radon indoors [102].

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4. Factors Influencing Radon Flux

Radon is formed in rocks and soil from the alpha decay of ^{226}Ra, contained in mineral grains, with the recoil energy of 86 keV. If placed close to the surface of the grain, radon atoms could leave the grain and reach interstitial space (pore), and if they have enough energy left, they could enter surrounding soil grains and become trapped. Although radon atoms can diffuse through the grains into the pores, the diffusion coefficient of radon in solids is very small; hence, a diffusion length is very small too (10^{-32}–10^{-13} m). This process could be neglected compared to the recoil [103][104][105]. The amount of radon that escapes the rock/soil grain into the pore space with respect to the number of radon atoms that are produced in the grain is defined as the emanation factor ε. There are numerous physical factors affecting radon emanation, such as the radium distribution in grains; the size, shape, and crystal structure of the grain; moisture content; grain (soil) temperature; atmospheric pressure; and radiation damage [106].

4.1. Soil Moisture

Soil moisture will reduce the speed of emanated atoms due to the much greater stopping power of water, which reduces the probability that emanating radon will embed in surrounding grain. This effect increases with the water content, up to the saturation level. The saturation is achieved faster for materials with smaller grain size [105][107][108][109]. However, it was also shown that with an increase of moisture content, the radon emanation factor decreases after reaching a peak. For different types of soil, the emanation coefficient reaches maximum at different water content: for general types of soil, emanation reaches maximum for water content of 5%; for gravel at 1–2%; and for clay at 10–15% [110].

4.2. Emanation Coefficient

Radium distribution in solid grains also influences radon emanation. In many primary minerals, radium is distributed uniformly in the grain. In this case, the emanation coefficient is inversely proportional to the grain size until it reaches a saturated value [111]. In the case of secondary minerals, radium is often distributed mostly on the grain surface, causing an almost constant emanation coefficient with grain size [112]. It has been observed that radionuclides with a larger radius tend to accumulate on the grain surface, unlike smaller particles, such as potassium, which tends to be in crystal lattice [113]. The emanation coefficient increases monotonously in the range of temperatures from −20 °C to 45 °C [114].

In addition to “objective” physical factors, there are also experimental factors that could influence the results of emanation factors, such as the sample preparation, sample instrument, environment, and methods. Emanation factors reach values up to 0.25 for minerals, 0.40 for rocks, and 0.83 for soil, with an average of 0.03, 0.13, and 0.20, respectively [106][115].

4.3. Diffusion-Advection

Once the radon atom emanates from the grain, it can move from the soil pores toward the shallow environment and escape into the atmosphere. The dominant radon transport mechanisms are diffusion, advection and exhalation [103][116]. In general, diffusion can be described by the Ficks law: the diffusion coefficient in porous materials depends on the pore structure (tortuosity), pore fluids (water), adsorption properties of the solid matrix, temperature, etc. Radon diffusion will decrease with both a decrease in grain size and an increase in water content [105][117]. Mainly radon produced in shallow soil layers contributes to surface radioactivity due to a short diffusion length that for most soil ranges between 0.5 m and 1.5 m [117][118].

Radon in the soil can also be transported to the surface by advection processes due to pressure differences. The influence of meteorological conditions occurs near to the surface, while at greater depths, advection is only due to pressure changes (i.e., faults and fractures) and the presence of gas carriers, such as CO_2, CH_4, and N_2 [7][18][119][120][121][122][123].

Radon transfer from the parent material to the atmosphere is influenced by several physical factors, such as porosity, temperature, pressure gradients, and moisture [124]. A good correlation between radon flux and the porosity of the material was found [125][126].

Bedrocks, superficial deposits, and faults (fracturing) also affect radon flux. Faults increase radon flux, and the influence of superficial deposits depends on the physico-chemical characteristics of the deposits [87][127][128]. The condition of the soil surface also significantly influences radon flux. For example, if the soil surface is frozen or covered by water, the exhalation rate will be drastically reduced. Yamazawa et al. investigated the effect of snow and frozen soil on radon diffusion from the soil to the atmosphere. They found that frozen soil reduces diffusion by a factor of 2, while a 1.2 m thick layer of snow reduces radon flux by a few dozen [129]. Upper horizons formed by weathering crust can have similar effects [46].

When the radium rich layer is covered by a material with low radium content, exhalation is reduced. The thickness of the soil cover and other soil properties—such as compactness, water retention, and geochemistry—will affect radon flux as well [117][130]. It is very important to consider the perturbed ground, which can completely change all of the parameters related to radon exhalation, especially in urban areas [131]. More importantly, radon flux can differ drastically even among adjacent building plots, therefore causing high local spatial variations. Seismic activity [90][132][133], and also traffic and other urban vibrations [131], can cause large temporal variations in radon flux also.

4.4. Moisture and Temperature

The influence of water content is opposite for emanation and exhalation. The combined effect on radon exhalation is such that exhalation increases with the water content until “saturation” is achieved. At this point, radon emanation does not increase with water content, but the diffusion through the water is much slower than diffusion through the air, causing the exhalation to decrease with increased water content. Therefore, radon exhalation shows maximum value at some level of water content, which depends on the soil properties. For many materials, maximum exhalation is achieved for water content of several percent to 10%, and a significant drop in exhalation is observed for water content above 25% [76][117][134][135][136][137].

The temperature also affects different processes occurring in the soil. Increasing soil temperature reduces adsorption and increases the emanation coefficient, thereby increasing the concentration of radon in soil gas [116]. The diffusion coefficient also increases with the temperature; consequently, overall, radon exhalation increases with the temperature. Ambient temperature weakly affects exhalation when it is lower than the soil temperature. However, if the ambient temperature is higher than the soil temperature, it will further increase radon exhalation [105][116]. The variability of radon flux from the same experiment in one period mirrored the changes in the air temperature, while in another period no regular changes of radon flux in tandem with air temperature were observed [138].

Radon exhalation is also affected by other metrological parameters. Light rainfall does not affect exhalation a lot, but heavy rainfall can saturate the soil, greatly reducing the exhalation process. Average yearly radon flux can be significantly different for rainy and dry years [79][105][116][139]. Measured radon exhalation from soil constantly decreased with the precipitation, starting from 19.6 ± 0.7 $mBqm^{-2}s^{-1}$ for dry soil, over 12.7 ± 0.3 $mBqm^{-2}s^{-1}$ after 10 mm of rain per day, 10.3 ± 0.2 $mBqm^{-2}s^{-1}$ (additional 14.6 mm of precipitation) to 8.7 ± 0.2 $mBqm^{-2}s^{-1}$ (for another 25.9 mm 3 days after) [140].

4.5. Pressure

In general, radon flux is expected to decrease with increasing ambient pressure [116]. The correlation is difficult to demonstrate because usually many different parameters are changing at the same time [79]. Furthermore, the changes in pressure are cyclic; thus, long-term average fluxes are not greatly dependent on the pressure [117]. Additionally, it was found that an increase in wind speed increases radon flux [79][116] and the correlation between air humidity and radon flux is weak [141].

4.6. Other

Relief and vegetation can also have influence on radon flux. Vegetation has direct influence because radon transports through plants. Plants can take up radon from the soil and release it into the atmosphere, effectively serving as radon pumps. Indirect influence is the influence on the soil water content, microclimate, and gas permeability. The influence of relief is indirect because soil development and water content depend on the topography [131].

A survey of literature shows that although most authors find similar trends in the influence of different parameters on radon flux, there is no consensus. For example, Yang et al. found a negative correlation between soil temperature and radon exhalation [141]. Kropat et al. found almost no correlation between secondary permeability, as well as faults and fractures, and radon exhalation. Furthermore, Zmazek et al. found a negative correlation between air pressure and radon flux at some measurement sites before earthquakes [133][142]. In recent research, no strong correlation between porosity and radon flux has been observed [137]. All of these studies show that radon flux is a very complex process; moreover, it is not possible to construct models that are universally applicable, even in rough approximation.

Yang et al. have performed 2 years of continuous measurements of radon flux using numerous environmental parameters: soil water content, soil and air temperature, air humidity, precipitation, wind speed, and directions [143]. A multiple regression analysis was performed by using air pressure, air temperature, soil temperature at 20 cm depth, and the soil water content. Obtained coefficients indicate that air pressure is not an important parameter, which is confirmed with similar long-term continuous measurements by Mazur and Kozak in [138]. Positive and negative effects of air and soil temperature on radon flux were obtained, respectively. The negative effect contradicts other experimental studies and should be further investigated [114]. As radon flux showed strong autocorrelations, including them in forecasting should increase performance significantly. This model can explain about 61% of the variation when autocorrelations are included, compared to only 28% when correlations are excluded [143].

4.7. Diurnal and Seasonal Variations of Radon Flux

Daily outdoor radon variations show typical behaviour, namely, high concentration in the early morning due to an inverse atmosphere mixing. The increase of temperature during sunrise increases atmosphere mixing, causing an increase of radon in the upper atmosphere [26][144][145]. As the major source of outdoor radon is the radon flux from soil, it could be expected that daily variations of radon flux follow a similar pattern as outdoor radon. However, radon flux exhibits the opposite behaviour of outdoor radon concentration. The key factor leading to diurnal variation of radon flux is soil temperature, as variation of soil temperature causes variation of absolute humidity. Thus, radon flux is highest in the afternoon when the temperature is highest and, consequently, the humidity in the soil is lowest, while during the night, radon flux is lowest due to the lowest temperature of the soil (i.e., highest soil humidity). Daily variation of radon flux measured at the campus of Munich-Neuherberg ranged from 2.5 to 50.7 Bqm^{-2} h^{-1} with an average of 25.3 Bq$m^{-2}h^{-1}$. Regarding seasonal variations, the highest radon fluxes were in March and the lowest in October [141].

Seasonal variations of radon flux were investigated by many researchers [68][69][141][145][146][147][148][149][150]. In summary, all these papers agree and found high exhalation rates in seasons characterised by lower precipitation, while lower exhalation rates occurred in months with higher precipitation, higher moisture content, or for frozen soils and/or snow coverage. The summer-to-winter ratio of measured radon flux ranged from almost 1 up to 2.54.

References

1. UNSCEAR (United Nation Scientific Committee on the Effects of Atomic Radiation Report). Report of the United Nation Scientific Committee on the Effects of Atomic Radiation Sixty-Sixth Session; United Nations: New York, NY, USA, 2019; pp. 110–114.
2. Lundin, F.E.; Wagoner, J.K.; Archer, V.E. Radon daughter exposure and respiratory cancer: Quantitive and temporal as pects. In Joint Monograph No.1. NIOSH and NIESH; U.S. Department of Health, Education and Welfare, Public Health Service: Washington DC, USA, 1971.
3. Sevc, J.; Kunz, E.; Placek, V. Lung cancer in uranium miners and long-term exposure to radon daughter products. Heal th Phys. 1976, 30, 433–437.
4. IARC (International Agency for Research on Cancer). Monographs on the Evaluation of Carcinogenic Risks to Humans: Manmade mineral Fibres and Radon; WHO: Geneva, Switzerland, 1988.
5. UNSCEAR (United Nation Scientific Committee on the Effects of Atomic Radiation Report). Sources and Effects of Ioni zing Radiation; United Nations: New York, NY, USA, 2000; pp. 98–99.

6. Pantelić, G.; Čeliković, I.; Živanović, M.; Vukanac, I.; Nikolić, J.K.; Cinelli, G.; Gruber, V. Qualitative Overview of Indoor Radon Surveys in Europe. J. Environ. Radioact. 2019, 204, 163–174.
7. IAEA National and Regional Surveys of Radon Concentration in Dwellings. Review of Methodology and Measurement Techniques. In Analytical Quality in Nuclear Application; IAEA: Vienna, Austria, 2013.
8. WHO (World Health Organization). Handbook on Indoor Radon; WHO: Geneva, Switzerland, 2009.
9. Council Directive 2013/59/Euratom of 5 December 2013 Laying Down Basic Safety Standards for Protection against th e Dangers Arising from Exposure to Ionising Radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/ 29/Euratom, 97/43/Euratom and 2003/122/Euratom. Available online: https://eur-lex.europa.eu/eli/dir/2013/59/oj (acces sed on 25 November 2020).
10. Benà, E.; Ciotoli, G.; Ruggiero, L.; Coletti, C.; Bossew, P.; Massironi, M.; Mazzoli, C.; Mair, V.; Morelli, C.; Galgaro, A.; e t al. Evaluation of tectonically enhanced radon in fault zones by quantification of the radon activity index. Scientific Rep orts 2022, 12, 21586, https://doi.org/10.1038/s41598-022-26124-y.
11. Ciotoli, G.; Bigi, S.; Tartarello, C.; Sacco, P.; Lombardi, S.; Ascione, A.; Mazzoli, S; Soil gas distribution in the main cose ismic surface rupture zone of the 1980, Ms = 6.9, Irpinia earthquake (southern Italy). J. Geophys. Res. Solid Earth 201 4, 119, 2440–2461, https://doi.org/10.1002/2013JB010508.
12. Ascione, A.; Ciotoli, G.; Bigi, S.; Buscher, J.; Mazzoli, S.; Ruggiero, L.; Sciarra, A.; Tartarello, M.C.; Valente, E.; Assessi ng mantle versus crustal sources for non-volcanic degassing along fault zones in the actively extending southern Apen nines mountain belt (Italy). Geol. Soc. Am. Bull. 2018, 130, 1697–1722, https://doi.org/10.1130/B31869.1.
13. Seminsky, KZh.; Bobrov, A. A.; Demberel, S.; Variations in radon activity in the crustal fault zones: Spatial characteristic s. Phys. Solid Earth 2014, 50(6), 795–881, https://doi.org/10.1134/S1069351314060081.
14. Chen, Z.; Li, Y.; Liu, Z. Wang, J.; Zhou, X.; Du, J.; Radon emission from soil gases in the active fault zones in the Capit al of China and its environmental effects. Sci. Rep. 2018, 8, 16772, https://doi.org/10.1038/s41598-018-35262-1
15. Koike, K.; Yoshinaga, T.; Yoshinaga, T.; Ueyama, T.; Asaue, H.; Increase radon-222 in soil gas because of cumulative s eismicity at active faults. Earth Planets Space 66(57), 1–9. 2014, 66(57), 1-9, https://doi.org/10.1186/1880-5981-66-57 10.1186/1880-5981-66-57.
16. Igarashi, G.; Saeki, S.; Takahata, N.; Sumikawa, K.; Tasaka, S.; Sasaki, Y.; Takahashi, M.; Sano, Y. Ground-Water Rad on Anomaly before the Kobe Earthquake in Japan. Science 1995, 269, 60–61.
17. Kawada, Y.; Nagahama, H.; Omori, Y.; Yasuoka, Y.; Ishikawa, T.; Tokonami, S.; Shinogi, M. Time-Scale Invariant Chang es in Atmospheric Radon Concentration and Crustal Strain Prior to a Large Earthquake. Nonlinear Process. Geophys. 2007, 14, 123–130.
18. Ciotoli, G.; Lombardi, S.; Annunziatellis, A. Geostatistical Analysis of Soil Gas Data in a High Seismic Intermontane Bas in: Fucino Plain, Central Italy. J. Geophys. Res. Solid Earth 2007, 112, 1–23.
19. Sainz, C.; Rábago, D.; Fuente, I.; Celaya, S.; Quindós, L.S. Description of the Behavior of an Aquifer by Using Continu ous Radon Monitoring in a Thermal Spa. Sci. Total Environ. 2016, 543, 460–466.
20. Mollo, S.; Tuccimei, P.; Galli, G.; Iezzi, G.; Scarlato, P. The Imprint of Thermally Induced Devolatilization Phenomena on Radon Signal: Implications for the Geochemical Survey in Volcanic Areas. Geophys. J. Int. 2017, 211, 558–571.
21. Locatelli, R.; Bousquet, P.; Hourdin, F.; Saunois, M.; Cozic, A.; Couvreux, F.; Grandpeix, J.Y.; Lefebvre, M.P.; Rio, C.; B ergamaschi, P.; et al. Atmospheric Transport and Chemistry of Trace Gases in LMDz5B: Evaluation and Implications for Inverse Modelling. Geosci. Model Dev. 2015, 8, 129–150.
22. Grossi, C.; Vogel, F.R.; Curcoll, R.; Àgueda, A.; Vargas, A.; Rodó, X.; Morguí, J.A. Study of the Daily and Seasonal Atm ospheric CH4 Mixing Ratio Variability in a Rural Spanish Region Using 222Rn Tracer. Atmos. Chem. Phys. 2018, 18, 5 847–5860.
23. Grossi, C.; Vogel, F.R.; Morgui, J.A.; Curcoll, R.; Àgueda, A.; Batet, O.; Nofuentes, M.; Occhipinti, P.; Vargas, A.; Rodó, X. First Estimation of CH4 Fluxes Using the 222Rn Tracer Method over the Central Iberian Peninsula. WIT Trans. Ecol. Environ. 2014, 183, 233–244.
24. Chambers, S.D.; Galeriu, D.; Williams, A.G.; Melintescu, A.; Griffiths, A.D.; Crawford, J.; Dyer, L.; Duma, M.; Zorila, B. A tmospheric Stability Effects on Potential Radiological Releases at a Nuclear Research Facility in Romania: Characterisi ng the Atmospheric Mixing State. J. Environ. Radioact. 2016, 154, 68–82.
25. Chambers, S.D.; Wang, F.; Williams, A.G.; Xiaodong, D.; Zhang, H.; Lonati, G.; Crawford, J.; Griffiths, A.D.; Ianniello, A.; Allegrini, I. Quantifying the Influences of Atmospheric Stability on Air Pollution in Lanzhou, China, Using a Radon-Ba sed Stability Monitor. Atmos. Environ. 2015, 107, 233–243.

26. Chambers, S.D.; Williams, A.G.; Crawford, J.; Griffiths, A.D. On the Use of Radon for Quantifying the Effects of Atmospheric Stability on Urban Emissions. Atmos. Chem. Phys. 2015, 15, 1175–1190.

27. Vinod Kumar, A.; Sitaraman, V.; Oza, R.B.; Krishnamoorthy, T.M. Application of a Numerical Model for the Planetary Boundary Layer to the Vertical Distribution of Radon and Its Daughter Products. Atmos. Environ. 1999, 33, 4717–4726.

28. Biraud, S.; Ciais, P.; Ramonet, M.; Simmonds, P.; Kazan, V.; Monfray, P.; O'Doherty, S.; Spain, T.; Jennings, S. European Greenhouse Gas Emissions Estimated from Continuous Atmospheric Measurements and Radon 222 at Mace Head, Ireland. J. Geophys. Res. 2000, 105, 1351–1366.

29. Vogel, F.R.; Ishizawa, M.; Chan, E.; Chan, D.; Hammer, S.; Levin, I.; Worthy, D.E.J. Regional non-CO2 greenhouse gas fluxes inferred from atmospheric measurements in Ontario, Canada. J. Integr. Environ. Sci. 2012, 9, 41–55.

30. Kikaj, D.; Chambers, S.D.; Kobal, M.; Crawford, J.; Vaupotič, J. Characterizing Atmospheric Controls on Winter Urban Pollution in a Topographic Basin Setting Using Radon-222. Atmos. Res. 2020, 237, 104838.

31. Vargas, A.; Arnold, D.; Adame, J.A.; Grossi, C.; Hernández-Ceballos, M.A.; Bolivar, J.P. Analysis of the Vertical Radon Structure at the Spanish "El Arenosillo" Tower Station. J. Environ. Radioact. 2015, 139, 1–17.

32. Van Der Laan, S.; Karstens, U.; Neubert, R.E.M.; Van Der Laan-Luijkx, I.; Meijer, H.A.J. Observation-based estimates of fossil fuel-derived CO2 emissions in the Netherlands using 14C, CO and 222Radon. Tellus B 2010, 62, 389–402.

33. Levin, I.; Hammer, S.; Eichelmann, E.; Vogel, F.R. Verification of greenhouse gas emission reductions: The prospect of atmospheric monitoring in the polluted areas. Philos. T. R. Soc. A 2011, 369, 1906–1924.

34. Levin, I.; Karstens, U.; Hammer, S.; DellaColetta, J.; Maier, F.; Gachkivskyi, M. Limitations of the radon tracer method (RTM) to estimate regional greenhouse gas (GHG) emissions—A case study for methane in Heidelberg. Atmos. Chem. Phys. 2021, 21, 17907–17926.

35. Röttger, A.; Röttger, S.; Grossi, C.; Vargas, A.; Curcoll, R.; Otáhal, P.; Hernández-Ceballos, M.Á.; Cinelli, G.; Chambers, S.; Barbosa, S.A.; et al. New metrology for radon at the environmental level. Meas Sci. Technol. 2021, 32, 124008.

36. Röttger, S.; Röttger, A.; Grossi, C.; Vargas, A.; Karstens, U.; Cinelli, G.; Chung, E.; Kikaj, D.; Rennick, C.; Mertes, F.; et al. Radon metrology for use in climate change observation and radiation protection at the environmental level. Adv. Geosci. 2022, 57, 37–47.

37. NSC Nuclear Safety Council Instrucción. IS-33, de 21 de Diciembre de 2011, del Consejo de Seguridad Nuclear, Sobre Criterios Radiológicos Para la Protección Frente a la Exposición a la Radiación Natural. 2012. Available online: https://www.boe.es/buscar/doc.php?id=BOE-A-2012-1238 (accessed on 19 October 2022).

38. Bochicchio, F.; Venoso, G.; Antignani, S.; Carpentieri, C. Radon Reference Levels and Priority Areas Considering Optimisation and Avertable Lung Cancers. Radiat. Prot. Dosim. 2017, 177, 87–90.

39. Bossew, P. Radon Priority Areas—Definition, Estimation and Uncertainty. Nucl. Technol. Radiat. Prot. 2018, 33, 286–292.

40. Petermann, E.; Bossew, P.; Hoffmann, B. Radon hazard vs. radon risk—On the effectiveness of radon priority areas. J. Environ. Radioact. 2022, 244–245, 106833.

41. Bossew, P.; Čeliković, I.; Cinelli, G.; Ciotoli, G.; Domingos, F.; Gruber, V.; Leonardi, F.; Nikolov, J.; Pantelić, G.; Pereira, A.; et al. On harmonization of radon maps. J. Eur. Radon Assoc. 2022, 3, 1–10.

42. Giustini, F.; Ruggiero, L.; Sciarra, A.; Beaubien, S.E.; Graziani, S.; Galli, G.; Pizzino, L.; Tartarello, M.C.; Lucchetti, C.; Sirianni, P.; et al. Radon Hazard in Central Italy: Comparison among Areas with Different Geogenic Radon Potential. Int. J. Environ. Res. Public Health 2022, 19, 666.

43. Cinelli, G.; Bochicchio, F.; Bossew, P.; Carpentieri, C.; De Cort, M.; Gruber, V.; Leonardi, F.; Tollefsen, T.; Trevisi, R. Similarities and differences between radon surveys across Europe: Results from MetroRADON questionnaire. J. Eur. Radon Assoc. 2022, 3, 1–9.

44. Bochicchio, F.; Campos-Venuti, G.; Piermattei, S.; Nuccetelli, C.; Risica, S.; Tommasino, L.; Torri, G.; Magnoni, M.; Agnesod, G.; Sgorbati, G.; et al. Annual average and seasonal variations of residential radon concentration for all the Italian Regions. Radiat. Meas. 2005, 40, 686–694.

45. Antignani, S.; Carelli, V.; Cordedda, C.; Zonno, F.; Ampollini, M.; Carpentieri, C.; Venoso, G.; Bochicchio, F. An affordable proxy of representative national survey on radon concentration in dwellings: Design, organisation and preliminary evaluation of representativeness. Radiat. Meas. 2013, 50, 136–140.

46. Neznal, M.; Neznal, M.; Matolín, M.; Barnet, I.; Miksova, J. The New Method for Assessing the Radon Risk of Building Sites. 2004. Available online: https://www.radon-vos.cz/pdf/metodika.pdf (accessed on 2 March 2022).

47. Kemski, J.; Siehl, A.; Stegemann, R.; Valdivia-Manchego, M. Mapping the geogenic radon potential in Germany. Sci. Total Environ. 2001, 272, 217–230.

48. Bossew, P. Mapping the geogenic radon potential and estimation of radon prone areas in Germany. Radiat. Emerg. Me d. 2015, 4, 13–20.

49. Bossew, P.; Cinelli, G.; Ciotoli, G.; Crowley, Q.G.; De Cort, M.; Elío Medina, J.; Gruber, V.; Petermann, E.; Tollefsen, T. Development of a Geogenic Radon Hazard Index—Concept, History, Experiences. Int. J. Environ. Res. Public Health 2 020, 17, 4134.

50. Quindos, L.S.; Fernández, P.L.; Ródenas, C.; Gómez-Arozamena, J.; Arteche, J. Conversion factors for external gamm a dose derived from natural radionuclides in soils. J. Environ. Radioact. 2004, 71, 139–145.

51. Cinelli, G.; Tondeur, F.; Dehandschutter, B. Development of an indoor radon risk map of the Walloon region of Belgium, integrating geological information. Environ. Earth Sci. 2011, 62, 809–819.

52. Ciotoli, G.; Voltaggio, M.; Tuccimei, P.; Soligo, M.; Pasculli, A.; Beaubien, S.E. Geographically weighted regression and geostatistical techniques to construct the geogenic radon potential map of the Lazio region: A methodological proposal for the European Atlas of Natural Radiation. J. Environ. Radioact. 2017, 166, 355–375.

53. Elío, J.; Cinelli, G.; Bossew, P.; Gutiérrez-Villanueva, J.L.; Tollefsen, T.; De Cort, M.; Nogarotto, A.; Braga, R. The first v ersion of the Pan-European Indoor Radon Map. Nat. Hazards Earth Syst. Sci. 2019, 19, 2451–2464.

54. Giustini, F.; Ciotoli, G.; Rinaldini, A.; Ruggiero, L.; Voltaggio, M. Mapping the geogenic radon potential and radon risk b y using Empirical Bayesian Kriging regression: A case study from a volcanic area of central Italy. Sci. Total Environ. 201 9, 661, 449–464.

55. Petermann, E.; Meyer, H.; Nussbaum, M.; Bossew, P. Mapping the geogenic radon potential in Germany using machin e learning. Sci. Total Environ. 2021, 754, 142291.

56. Fernández, A.; Sainz, C.; Celaya, S.; Quindós, L.; Rábago, D.; Fuente, I. A new methodology for defining radon priority areas in Spain. Int. J. Environ. Res. Public Health 2021, 18, 1352.

57. Hughes, M.B.; Elío, J.; Crowley, Q.G. A user's guide to radon priority areas, examples from Ireland. J. Eur. Radon Asso c. 2022, 3, 1–12.

58. Maringer, F.J.; Wiedner, H.; Stietka, M. EMPIR 16ENV10 Project MetroRADON Final Publishable Report. 2021. Availab le online: http://metroradon.eu/index.php/documents/ (accessed on 21 October 2022).

59. Gruber, V.; Baumann, S.; Alber, O.; Laubbichler, C.; Bossew, P.; Petermann, E.; Ciotoli, G.; Pereira, A.; Domingos, F.; T ondeur, F.; et al. Comparison of radon mapping methods for the delineation of radon priority areas—An exercise. J. Eu r. Radon Assoc. 2021, 2, 1–14.

60. Jelinski, D.E.; Wu, J. The modifiable areal unit problem and implications for landscape ecology. Landscape Ecol. 1996, 11, 129–140.

61. Mathews, A.J.; Ellis, E.A. An evaluation of tornado siren coverage in Stillwater, Oklahoma: Optimal GIS methods for a s patially explicit interpretation. Appl. Geogr. 2016, 68, 28–36.

62. Swift, A.; Liu, L.; Uber, J. Reducing MAUP bias of correlation statistics between water quality and GI illness. Comput. E nviron. Urban Syst. 2008, 32, 134–148.

63. Hirsch, A.L. On using 222Rn and CO2 to calculate regional-scale CO2 fluxes. Atmos. Chem. Phys. 2007, 7, 3737–374 7.

64. Van der Laan, S.; Neubert, R.E.M.; Meijer, H.A.J. Methane and nitrous oxide, emissions in the Netherlands: Ambient m easurements support the national inventories. Atmos. Chem. Phys. 2009, 9, 9369–9379.

65. Thom, M.; Bösinger, R.; Schmidt, M.; Levin, I. The Regional Budget of Atmospheric Methane of a Highly Populated Are a. Chemosphere 1993, 26, 143–160.

66. Schmidt, M.; Graul, R.; Sartorius, H.; Levin, I. Carbon dioxide and methane in continental Europe: A climatology, and 22 2Radonbased emission estimates. Tellus B 1996, 48, 457–473.

67. Schmidt, M.; Glatzel-Mattheier, H.; Sartorius, H.; Worthy, D.E.; Levin, I. Western European N2O emissions: A top-down approach based on atmospheric observations. J. Geophys. Res. 2001, 106, 5507–5516.

68. Szegvary, T.; Conen, F.; Ciais, P. European 222Rn inventory for applied atmospheric studies. Atmos. Environ. 2009, 43, 1536–1539.

69. López-Coto, J.; Mas, J.L.; Bolivar, J.P. A 40-year retrospective European radon flux inventory including climatological v ariability. Atmos. Environ. 2013, 73, 22–33.

70. Karstens, U.; Schwingshackl, C.; Schmithüsen, D.; Levin, I. A process-based 222radon flux map for Europe and its com parison to long-term observations. Atmos. Chem. Phys. 2015, 15, 12845–12865.

71. Gaudry, A.; Polian, G.; Ardouin, B.; Lambert, G. Radon calibrated emissions of CO2 from South Africa. Tellus B 1990, 42B, 9–19.

72. Wilson, S.R.; Dick, A.L.; Fraser, P.J.; Whittlestone, S. Nitrous oxide flux estimates for south-eastern Australia. J. Atmos. Chem. 1997, 26, 169–188.

73. Hammer, S.; Levin, I. Seasonal variation of the molecular hydrogen uptake by soils inferred from continuous atmospheric observations in Heidelberg, southwest Germany. Tellus B 2009, 61, 556–565.

74. Burnett, W.C.; Dulaiova, H. Estimating the dynamics of groundwater input into the coastal zone via continuous radon-222 measurements. J. Environ. Radioact. 2003, 69, 21–35.

75. Su, X.; Lu, C.; Li, M.; Wang, Y.; Wang, N. Using 222Rn temporal and spatial distributions to estimate the groundwater discharge rate and associated nutrient fluxes into high salinity lakes in Badain Jaran Desert, Northwest China. Sci. Total Environ. 2023, 857, 159359.

76. Lawrence, C.E.; Akber, R.A.; Bollhöfer, A.; Martin, P. Radon-222 exhalation from open ground on and around a uranium mine in the wet-dry tropics. J. Environ. Radioact. 2009, 100, 1–8.

77. Ota, M.; Iida, T.; Yamazawa, H.; Nagara, S.; Ishimori, Y.; Sato, K.; Tokizawa, T. Suppression of Radon Exhalation from Soil by Covering with Clay-mixed Soil. J. Nucl. Sci. Technol. 2007, 44, 791–800.

78. EPA (Environmental Protection Agency). Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings. 1954. Available online: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-F/part-192 (accessed on 25 November 2022).

79. Altic, N. Final-Technical Bases and Guidance for Radon Flux Monitoring at Uranium Mill Tailing Sites, Report: (RFTA 11-010) DCN-TR-01-0. 2011. Available online: https://www.nrc.gov/docs/ML1118/ML11186A899.pdf (accessed on 25 November 2022).

80. Fuhrmann, M.; Benson, C.; Likos, W.; Stefani, N.; Michaud, A.; Waugh, J.; Williams, M. Radon fluxes at four uranium mill tailings disposal sites after about 20 years of service. J. Environ. Radioact. 2021, 237, 106719.

81. Gnoni, G.; Palacios, M. Measurements of Radon Exhalation Flux and Atmospheric Radon in Uranium Minning and Progressing Sites. In Sources and Measurements of Radon and Radon Progeny Applied to Climate and Air Quality Studies, Proceedings of the Technical Meeting Held in Vienna/Organized by the International Atomic Energy and Co-Sponsored by the World Meteorological Organization, Vienna, Austria, 14–18 November 2011; IAEA: Vienna, Austria, 2011; pp. 29–38.

82. Sahoo, B.K.; Mayya, Y.S.; Sapra, B.K.; Gaware, J.J.; Banerjee, K.S.; Kushwaha, H.S. Radon exhalation studies in an Indian uranium tailings pile. Radiat. Meas. 2010, 45, 237–241.

83. Morris, R.C.; Fraley, L. Effects of vegetation, A clay cap, and environmental variables on Rn-222 fluence rate from reclaimed U mill tailings. Health Phys. 1989, 56, 431–440.

84. Dueñas, C.; Liger, E.; Cañete, S.; Pérez, M.; Bolívar, J.P. Exhalation of 222Rn from phosphogypsum piles located at the Southwest of Spain. J. Environ. Radioact. 2007, 95, 63–74.

85. Miklyaev, P.S.; Petrova, T.B.; Marennyy, A.M.; Shchitov, D.V.; Sidyakin, P.A.; Murzabekov, M.A.; Lopatin, M.N. High seasonal variations of the radon exhalation from soil surface in the fault zones (Baikal and North Caucasus regions). J. Environ. Radioact. 2020, 219, 106271.

86. Miklyaev, P.S.; Petrova, T.B.; Shchitov, D.V.; Sidyakin, P.A.; Murzabekov, M.A.; Marennyy, A.M.; Nefedov, N.A.; Sapozhnikov, Y.A. The results of long-term simultaneous measurements of radon exhalation rate, radon concentrations in soil gas and groundwater in the fault zone. Appl. Radiat. Isot. 2021, 167, 109460.

87. Vaupotič, J.; Gregorič, A.; Kobal, I.; Žvab, P.; Kozak, K.; Mazur, J.; Kochowska, E.; Grządziel, D. Radon concentration in soil gas and radon exhalation rate at the Ravne Fault in NW Slovenia. Nat. Hazards Earth Syst. Sci. 2010, 10, 895–899.

88. He, H.; Chen, Z.; Liu, Z.; Gao, Z.; Hu, L.; Lu, C.; Shao, J.; Li, Y. Fluid geochemistry in Xiaojiang fault zone, southeastern Tibetan plateau: Implications for fault activity. Appl. Geochem. 2022, 105507.

89. Richon, P.; Klinger, Y.; Tapponnier, P.; Li, C.X.; Van Der Woerd, J.; Perrier, F. Measuring radon flux across active faults: Relevance of excavating and possibility of satellite discharges. Radiat. Meas. 2010, 45, 211–218.

90. Papastefanou, C. Variation of radon flux along active fault zones in association with earthquake occurrence. Radiat. Meas. 2010, 45, 943–951.

91. Steinitz, G.; Begin, Z.B.; Gazit-Yaari, N.A. Statistically Significant Relation between Rn Flux and Weak Earthquakes in the Dead Sea Rift Valley. Geology 2003, 31, 505–508.

92. Yakovleva, V.S.; Karataev, V.D. Radon Flux Density at the Earth’s Surface as a Possible Indicator of the Stress and Strain State of the Geological Environment. J. Seismol. 2007, 1, 67–70.
93. Rowberry, M.D.; Martí, X.; Frontera, C.; Van De Wiel, M.J.; Briestenský, M. Calculating flux to predict future cave radon concentrations. J. Environ. Radioact. 2016, 157, 16–26.
94. Lucchetti, C.; Briganti, A.; Castelluccio, M.; Galli, G.; Santilli, S.; Soligo, M.; Tuccimei, P. Integrating radon and thoron flux data with gamma radiation mapping in radon-prone areas. The case of volcanic outcrops in a highly-urbanized city (Roma, Italy). J. Environ. Radioact. 2019, 202, 41–50.
95. Ramola, R.C.; Prasad, G.; Gusain, G.S. Estimation of indoor radon concentration based on radon flux from soil and groundwater. Appl. Radiat. Isot. 2011, 69, 1318–1321.
96. Stavitskaya, K.; Ryzhakova, N.; Udalov, A.; Almyakov, P. Comparative analysis of the measuring results of the radon flux density and Ra-226 specific activity for different soils types. AIP Conf. Proc. 2019, 2101, 020013.
97. Baeza, A.; García-Paniagua, J.; Guillén, J.; Montalbán, B. Influence of architectural style on indoor radon concentration in a radon prone area: A case study. Sci. Total Environ. 2018, 610–611, 258–266.
98. Abodunrin, O.P.; Akinloye, M.K. Determination of radon exhalation rates from soil around buildings in Lagos environments using passive measurement technique. J. Environ. Health Sci. 2020, 18, 129–135.
99. Leshukov, T.; Larionov, A.; Legoshchin, K.; Lesin, Y.; Yakovleva, S. The Assessment of Radon Emissions as Results of the Soil Technogenic Disturbance. Int. J. Environ. Res. Public Health 2020, 17, 9268.
100. Tuccimei, P.; Moroni, M.; Norcia, D. Simultaneous determination of 222Rn and 220Rn exhalation rates from building materials used in Central Italy with accumulation chambers and a continuous solid-state alpha detector: Influence of particle size, humidity and precursors concentration. Appl. Radiat. Isot. 2006, 64, 254–263.
101. Kuzmanović, P.; Todorović, N.; Nikolov, J.; Hansman, J.; Vraničar, A.; Knežević, J. Assessment of radiation risk and radon exhalation rate for granite used in the construction industry. J. Radioanal. Nucl. Chem. 2019, 321, 565–577.
102. Yarmoshenko, I.V.; Vasilyev, A.V.; Onishchenko, A.D.; Kiselev, S.M.; Zhukovsky, M.V. Indoor radon problem in energy efficient multi-storey buildings. Radiat. Prot. Dosim. 2014, 160, 53–56.
103. Nazaroff, W. Radon transport from soil to air. Rev. Geophys. 1992, 30, 137–160.
104. Nazaroff, W.W.; Moed, B.A.; Sextro, R.G. Soil as a source of indoor radon: Generation, migration, and entry. In Radon and Its Decay Products in Indoor Air; Nazaroff, W.W., Nero, A.V., Eds.; JohnWiley & Sons: New York, NY, USA, 1988; pp. 57–112.
105. Hassan, N.M.; Hosoda, M.; Ishikawa, T.; Sorimachi, A.; Sahoo, S.K.; Tokonami, S.; Fukushi, M. Radon Migration Process and Its Influence Factors; Review. JPN J. Health Phys 2009, 44, 218–231.
106. Sakoda, A.; Ishimori, Y.; Yamaoka, K. A comprehensive review of radon emanation measurements for mineral, rock, soil, mill tailing and fly ash. Appl. Radiat. Isot. 2011, 69, 1422–1435.
107. Bossew, P. The radon emanation power of building materials, soils and rocks. Appl. Radiat. Isot. 2003, 59, 389–392.
108. Zhuo, W.; Iida, T.; Furukawa, M. Modelling Radon Flux Density from the Earth’s Surface. J. Nucl. Sci. Technol. 2006, 43, 479–482.
109. Sakoda, A.; Ishimori, Y.; Hanamoto, K.; Kataoka, T.; Kawabe, A.; Yamaoka, K. Experimental and modelling studies of grain size and moisture content effects on radon emanation. Radiat. Meas. 2010, 45, 204–210.
110. Markkanen, M.; Arvela, H. Radon emanation from soils. Health Phys. 1992, 45, 269–272.
111. Barillon, R.; Özgümüs, A.; Chambaudet, A. Direct recoil radon emanation from crystalline phase. Influence of moisture content. Geochim. Cosmochim. Acta 2005, 69, 2735–2744.
112. Morawska, L.; Phillips, C.R. Dependence of the radon emanation coefficient on radium distribution and internal structure of the material. Geochim. Cosmochim. Acta 1993, 57, 1783–1797.
113. Baeza, A.; Del Rio, M.; Jimenez, A.; Miro, C.; Paniagua, J. Influence of geology and soil particle size on the surface area/volume activity ratio for natural radionuclides. J. Radioanal. Nucl. Chem. 1995, 189, 289–299.
114. Iskandar, D.; Yamazawa, H.; Iida, T. Quantification of the dependency of radon emanation power on soil temperature. Appl. Radiat. Isot. 2004, 60, 971–973.
115. Quindos, L.S.; Fernandez, P.L.; Soto, J. A method for the measurement of the emanation factor for 222Rn. in small samples of porous materials. Radiat. Prot. Dosim. 1994, 56, 171–173.
116. Porstendörfer, J. Properties and Behaviour of Radon and Thoron and Their Decay Products in the Air. J. Aerosol. Sci. 1994, 25, 219–263.

117. IAEA (International Atomic Energy Agency). Measurement and Calculation of Radon Releases from NORM Residues: Technical Reports Series No. 474. Available online: https://www-pub.iaea.org/MTCD/Publications/PDF/trs474_webfile.pdf (accessed on 25 November 2020).

118. Keller, G.; Hoffmann, B. The Radon Diffusion Length as a Criterion for the Radon Tightness, IRPA-10: 10. In Proceedings of the International Congress of the International Radiation Protection Association, Hiroshima, Japan, 14–19 May 2000.

119. Etiope, G.; Lombardi, S. Evidence for radon transport by carrier gas through faulted clays in Italy. J. Radioanal. Nucl. Chem. 1995, 193, 291–300.

120. Ielsch, G.; Cushing, M.E.; Combes, P.; Cuney, M. Mapping of the geogenic radon potential in France to improve radon risk management: Methodology and first application to region Bourgogne. J. Environ. Radioact. 2010, 101, 813–820.

121. Ciotoli, G.; Ascione, A.; Bigi, S.; Lombardi, S.; Mazzoli, S. Soil gas distribution in the main coseismic surface rupture zone of the 1980, Ms=6.9, irpinia earthquake (Southern Italy). J. Geophys. Res. Solid Earth 2014, 119, 2440–2461.

122. Ciotoli, G.; Etiope, G.; Guerra, M.; Lombardi, S.; Duddridge, G.A.; Grainger, P. Migration of gas injected into a fault in low-permeability ground. Q. J. Eng. Geol. Hydrogeol. 2005, 38, 305–320.

123. Maffucci, R.; Ciotoli, G.; Pietrosante, A.; Cavinato, G.P.; Millia, S.; Ruggiero, L.; Sciarra, A.; Bigi, S. Geological hazard assessment of the coastal area of Rome (Central Italy) from multi-source data integration. Eng. Geol. 2022, 297, 106527.

124. Cinelli, G.; Tositti, L.; Capaccioni, B.; Brattich, E.; Mostacci, D. Soil gas radon assessment and development of a radon risk map in Bolsena, Central Italy. Environ. Geochem. Health 2015, 37, 305–319.

125. Lee, S.C.; Kim, C.K.; Lee, C.K.; Kang, H.D. Natural radionuclides contents and radon exhalation rates in building materials used in South Korea. Radiat. Prot. Dosim. 2001, 94, 269–274.

126. Lucchetti, C.; Castelluccio, M.; Altamore, M.; Briganti, A.; Galli, G.; Soligo, M.; Tuccimei, P.; Voltaggio, M. Using a scale model room to assess the contribution of building material of volcanic origin to indoor radon. Nukleonik 2020, 65, 71–76.

127. Yarmoshenko, I.; Malinovsky, G.; Vasilyev, A.; Onischenko, A.; Seleznev, A. Geogenic and anthropogenic impacts on indoor radon in the Techa River region. Sci. Tot. Environ. 2016, 571, 1298–1303.

128. Yakut, H.; Tabar, E.; Yıldırım, E.; Zenginerler, Z.; Ertugral, F.; Demirci, N. Soil Gas Radon Measurement Around Fault Lines on The Western Section of the North Anatolian Fault Zone in Turkey. Radiat. Prot. Dosim. 2017, 173, 405–413.

129. Yamazawa, H.; Miyazaki, T.; Moriizumi, J.; Iida, T.; Takeda, S.; Nagara, S.; Sato, K.; Tokizawa, T. Radon exhalation from a ground surface during a cold snow season. Int. Congr. Ser. 2005, 1276, 221–222.

130. Ferreira, A.; Daraktchieva, Z.; Beamish, D.; Kirkwood, C.; Lister, T.R.; Cave, M.; Wragg, J.; Lee, K. Indoor radon measurements in south west England explained by topsoil and stream sediment geochemistry, airborne gamma-ray spectroscopy and geology. J. Environ. Radioact. 2018, 181, 152–171.

131. Wiegand, J. A guideline for the evaluation of the soil radon potential based on geogenic and anthropogenic parameters. Environ. Geol. 2001, 40, 949–963.

132. Zmazek, B.; Živčić, M.; Vaupotič, J.; Bidovec, M.; Poljak, M.; Kobal, I. Soil radon monitoring in the Krško Basin, Slovenia. Appl. Radiat. Isot. 2002, 56, 649–657.

133. D'Incecco, S.; Petraki, E.; Priniotakis, G.; Papoutsidakis, M.; Yannakopoulos, P.; Nikolopoulos, D. CO2 and Radon Emissions as Precursors of Seismic Activity. Earth Syst. Environ. 2021, 5, 655–666.

134. Hosoda, M.; Shimo, M.; Sugino, M.; Furukawa, M.; Fukushi, M. Effect of soil moisture content on radon and thoron exhalation. J. Nucl. Sci. Technol. 2007, 44, 664–672.

135. Avramović, D.; Čeliković, I.; Ujić, P.; Vukanac, I.; Kandić, A.; Jevremović, A.; Antonijević, D.; Lončar, B. Radon exhalation rate of some building materials common in Serbia. RAD Conf. Proc. 2019, 3, 119–122.

136. Pyngrope, A.; Saxena, A.; Khardewsaw, A.; Sharma, Y.; Sahoo, B.K. Effect of soil's porosity and moisture content on radon and thoron exhalation rates. J. Radioanal. Nucl. Chem. 2022, 331, 1975–1984.

137. Janik, M.; Omori, Y.; Yonehara, H. Influence of humidity on radon and thoron exhalation rates from building materials. Appl. Radiat. Isot. 2015, 95, 102–107.

138. Mazur, J.; Kozak, K. Complementary system for long term measurements of radon exhalation rate from soil. Rev. Sci. Instrum. 2014, 85, 022104.

139. Ferry, C.; Beneito, A.; Richon, P.; Robe, M.-C. An Automatic Device for Measuring the Effect of Meteorological Factors on Radon-222 Flux from Soils on the Long Term. Radiat. Prot. Dosim. 2021, 93, 271–274.

140. Müllerová, M.; Holý, K.; Blahušiak, P.; Bulko, M. Study of radon exhalation from the soil. J. Radioanal. Nucl. Chem. 2018, 315, 237–241.
141. Yang, J.; Buchsteiner, M.; Salvamoser, J.; Irlinger, J.; Guo, Q.; Tschiersch, J. Radon Exhalation from Soil and Its Dependence From Environmental Parameters. Radiat. Prot. Dosim. 2017, 177, 21–25.
142. Kropat, G.; Bochud, F.; Murith, C.; Palacios, M.; Baechler, S. Modeling of geogenic radon in Switzerland based on ordered logistic regression. J. Environ. Radioact. 2017, 166, 376–381.
143. Yang, J.; Busen, H.; Scherb, H.; Hürkamp, K.; Guo, Q.; Tschiersch, J. Modeling of radon exhalation from soil influenced by environmental parameters. Sci. Total Environ. 2019, 656, 1304–1311.
144. Porstendörfer, J.; Butterweck, G.; Reineking, A. Diurnal Variation of the Concentrations of Radon and Its Short-Lived Daughters in the Atmosphere near the Ground. Atmos. Environ. 1991, 25A, 709–713.
145. Sesana, L.; Caprioli, E.; Marcazzan, G.M. Long Period Study of Outdoor Radon Concentration in Milan and Correlation between Its Temporal Variations and Dispersion Properties of Atmosphere. J. Environ. Radioact. 2003, 65, 147–160.
146. Griffiths, A.D.; Zahorowski, W.; Element, A.; Werczynski, S. A map of radon flux at the Australian land surface. Atmos. Chem. Phys. 2010, 10, 8969–8982.
147. Zhuo, W.; Chen, B.; Li, D.; Liu, H. Reconstruction of Database on Natural Radionuclide Contents in Soil in China. J. Nucl. Sci. Technol. 2008, 45, 180–184.
148. Hirao, S.; Yamazawa, H.; Moriizumi, J. Estimation of the Global 222Rn Flux Density from the Earth's Surface. Japanese. J. Health Phys. 2010, 45, 161–171.
149. Kitto, M. Interrelationship of indoor radon concentrations, soil-gas flux, and meteorological parameters. J. Radioanal. Nucl. Chem. 2005, 264, 381–385.
150. Prasad, G.; Ishikawa, T.; Hosoda, M.; Sorimachi, A.; Sahoo, S.K.; Kavasi, N.; Tokonami, S.; Sugino, M.; Uchida, S. Seasonal and diurnal variations of radon/thoron exhalation rate in Kanto-loam area in Japan. J. Radioanal. Nucl. Chem. 2012, 292, 1385–1390.