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ORIGINAL ARTICLE

Modelling of the temporal indoor radon variation in Bulgaria

Kremena Ivanova[1] · **Zdenka Stojanovska**[2]

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Abstract

In this study, temporal variations of indoor radon concentrations in Bulgaria were investigated. The radon concentrations were measured by nuclear track detectors as part of the Bulgarian National Survey, performed in the dwellings of 28 regional districts. The detectors were exposed through a year in two consecutive time periods of different lengths. For 2433 dwellings, measurements could be completed for both time periods, while for 345 dwellings they could only be completed for one of the periods. To estimate any missing radon concentrations, a temporal correction procedure was developed. This procedure, which included development of a linear correlation between the ln-transformed radon concentrations from the 9-month period [CRn(L)] and from the 3-month period [CRn(S)]. A normal distribution of the data, which is a condition for linear regression, was achieved when the ln-transformed radon concentrations were grouped by climate zone, then by regional districts, and finally by the presence/absence of a basement in the investigated building. The linear models obtained for each group showed reasonable coefficients of determination ($R^2 \approx 0.50$) and root mean square errors (RMSEs) of about 0.50. When these correlations were used to reconstruct radon concentrations in missing measurement periods, it turned out that the reconstructed data (for 345 dwellings) were within the 95% confidence interval of the measured data (for 2433 dwellings). The geometric means of CRn(L) and CRn(S) were 76 Bq/m^3 and 100 Bq/m^3, respectively, for 2433 dwellings, which are almost equal to those of 75 Bq/m^3 and 98 Bq/m^3, which represent the measured and reconstructed data together (for 2778 dwellings).

Keywords Indoor radon · Dwellings · Temporal variation · Linear models climate zone · District

Introduction

Radon (^{222}Rn) is a radioactive, natural gas with a physical half-life of 3.82 days. It is a member of the ^{238}U decay chain and a direct decay product of ^{226}Ra, which is present in any type of soil. Consequently, the radon activity in any soil depends on the ^{226}Ra concentration in that soil. The pathway from radon concentration in soil to indoor radon concentration is controlled by many factors. In general, the accumulated indoor radon concentration (CRn) is subject to spatial and temporal variability. It depends on the soil underneath buildings (UNSCEAR 2000, Annex B), the building characteristics, and the living habits of the residents (Keskikurua et al. 2001). Furthermore, CRn exhibits diurnal, monthly and seasonal variations as a consequence of changes in meteorological conditions (Groves-Kirkby et al. 2015). Any outdoor/indoor temperature difference or wind generates pressure differences which can affect the penetration of radon into a building and its transport within the building. Moreover, humidity in the underlying soil has an impact on radon transport in the soil as well as on radon exhalation from its surface.

Generally, for an assessment of public exposure to indoor radon the annual mean indoor radon concentration CRn(A) is required. CRn(A) includes temporal variations and, thus, reflects the real radon level in an individual building. Typically, CRn(A) is measured by nuclear track detectors exposed for a period of 1 year or for a number of consecutive periods (such as 3 or 6 months) of the year (among others: Tsapalov and Kovler, 2018; Al-Khateeb et al. 2017; Stojanovska et al. 2011, 2016; Gulan et al. 2013). If annual measurements cannot be performed, CRn(A) could be

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✉ Kremena Ivanova
kivanova1968@gmail.com; k.ivanova@ncrrp.org

[1] National Centre of Radiobiology and Radiation Protection, 3 Sv. Georgi Sofiyski St., 1606 Sofia, Bulgaria

[2] Faculty of Medical Sciences, Goce Delcev University of Stip, 10-A Krste Misirkov st, 2000 Stip, Republic of Macedonia

estimated based on short-term measurements and proper temporal correction.

For such a correction, linear regression models are commonly used because they are simple to apply and provide reasonable temporal corrections of CRn(A) (Stojanovska et al. 2011, 2013, 2017; Ramola et al. 2016). To establish a linear dependence between two variables (e.g., radon concentration CRn measured during the long and the short period) requires the existence of a normal distribution for both variables. Usually, however, in many studies the CRn values are characterized by a log-normal distribution that is mathematically normalized by logarithmic transformations. Also, some exceptions are reported in the literature, especially when surveys cover a geologically diverse territory (Vukotic et al. 2019; Ivanova et al. 2017).

To analyze temporal and spatial variations of CRn across the Bulgarian territory, a national survey was performed from April 2015 until March 2016. The CRn was measured in two consecutive long and short periods with a duration of 9 and 3 months, respectively. The measured CRn is presented and discussed in detail in this paper with focus on the applied temporal corrections.

Materials and methods

Area under study

Bulgaria is located on the North–East part of the Balkan Peninsula in South–East Europe. The territory is characterized by geological, geographical and climate diversity. The tectonic settle of the country shows four zones with different stratigraphic complexes ranging from early Paleozoic, Mesozoic, Cenozoic and Quaternary. The topography includes lowlands, plains, hills, low and high mountains, many valleys and deep gorges characterized by alternating bands of high and low terrain that extend from east to west across the country. As a consequence of the varied landscape, the contrasts in the climate are distinct among regions. According to geography and the influence of climatic factors, Bulgaria has five climatic zones (Fig. 1, left) (Donchev and Karakashev, 2004). The territory of the country is organized into 28 districts (Fig. 1, right) with 264 municipalities.

Design of survey

The National survey was organized in the same way as a previous pilot study (Ivanova et al. 2013). Hundred sampling locations were identified for each district, following a two-stage stratified sampling scheme. The first stage included stratification of districts into 264 municipalities which were then subdivided into towns and villages. The number of detectors in each stratum was determined proportionally to the population density. In each settlement, the dwellings where the indoor radon measurements should be performed were randomly selected by Regional health inspectors using a door-to-door approach. All participants received detectors together with handling instructions. Questionnaires about dwelling characteristics were filled out by interviewing the residents.

The survey was carried out in 2800 dwellings for 1 year from April 2015 to March 2016, subdivided into two consecutive measurement periods of different duration. Due to loss of detectors at the end of the two periods, the number of measurements actually made was lower than the number of distributed detectors. In the end, 2613 results were available for the longer measurement period (April 2015–December 2015) and 2597 results for the shorter measurement period

Fig. 1 Maps of Bulgaria. Left: climate zones; right: administrative organization with name and code of districts

(January 2016–March 2016). In 2433 dwellings, the measurements were completed for both periods, while in 345 dwellings the CRn was measured only in one of the periods.

Radon measurements

In each dwelling, the CRn measurement was carried out in an occupied room on the ground floor by a Radosys RSVF nuclear track detector. This type of detector consists of two CR-39 chips located in a double chamber. After exposure, processing of the detectors was done in a laboratory of the National Centre of Radiobiology and Radiation Protection in Sofia following the ISO 11,665–4 (2012) procedure. Two batches of detectors were used, each calibrated in the Radon Calibration Service Laboratory of the Federal Office for Radiation Protection (BfS), Germany. The detector background was analyzed twice, before and at the end of the sampling period to quantify any ageing and fading of detector characteristics. The total uncertainty reported for each result includes contributions from track density, background, calibration factor, and exposure time. The methodology of uncertainty estimation is explained in more detail in (Stojanovska et al. 2017). The minimum detectable radon concentration was estimated to be 10 Bq/m^3, taking into account the calibration coefficient, the background tracks and the exposure time for the used detectors batch.

Results and discussion

Measured data characterization

Descriptive statistics of the indoor radon concentrations in the 2433 dwellings where the measurements were completed for both periods are present in Table 1.

As a result of the unequal contribution of warm and cold months, a difference between the measured CRn was observed. The CRn(S) concentrations measured during the period of one cold (winter) season are higher than the CRn(L) concentrations measured during the longer period which included the warmer spring, summer and autumn seasons. This is expected, because during the colder months the dwellings are heated which creates a higher pressure gradient between the underneath soil and the building thus supporting radon in soil to enter the building. Furthermore, the radon accumulation is also supported during the cold months, when the inhabitants keep windows closed to save energy. Such seasonal differences have been observed by many other authors (e.g. Zunic et al. 2006; Stojanovska et al. 2011; Miles et al. 2012; Sogukpinar et al. 2013; Muntean et al. 2014; Szabó et al. 2014).

Table 1 Descriptive statistics of radon concentrations CRn (L) and CRn(S), measured in 2433 dwellings; L: long period from April 2015 to December 2015; S: short period from January 2016 to March 2016

Statistic	CRn(L) Bq/m^3	CRn(S) Bq/m^3
Minimum	11	11
Maximum	995	1983
1st Quartile	44	55
Median	76	92
3rd Quartile	132	181
Arithmetic mean (AM)	99	144
Geometric mean (GM)	76	100
Geometric standard deviation (GSD)	2.08	2.31

In addition to the differences in the measured indoor radon concentrations observed for the both measurement periods [CRn(L) < CRn(S)], the difference in the geometric means is also evident.

The distribution of both datasets has approximately a log-normal shape (Fig. 2, right). The null hypothesis that CRn(L) and CRn(S) follow a log-normal distribution was not accepted by a Kolmogorov–Smirnov test at a 95% significance level. Consequently, both datasets were not normalized after their ln-transformation.

Regional variability and normal distribution of measured data

Since the purpose of this study was to determine a temporal correction as a linear relationship between CRn(L) and CRn(S), a normalization of the datasets was needed. As mentioned previously, the normal distribution of CRn(L) and CRn(S) values through ln-transformation was not achieved. Information about the measurement location, characteristics of tectonic unit, climate and building, from the completed questionnaires were used. Those characteristic is named factors, further in the paper. Initially, each available factor was tested if it significantly affected the CRn(L) and CRn(S) variations. Moreover, only statistically significant factors were used to group the lnCRn(L) and lnCRn(S). After many attempts it turned out that the best possible way for lnCRn(L) and lnCRn(S) normalization was based on their regional grouping. This was done, starting from larger to smaller territories, according to climate zones and then administrative regions. After each regional grouping, the normal distribution of the data in the subgroups was tested, and the corresponding Kolmogorov–Smirnov test error probabilities obtained for lnCRn(L) and lnCRn(S) grouped by climate zone are given in Table 2. It is noted that only the lnCRn(L) and lnCRn(S) data from the moderately continental climate zone did not pass the test (KS, $p < 0.05$). Since the moderately continental zone is larger in comparison with the remaining climatic zones, it was assumed that the fact that the data do not follow a normal distribution could be

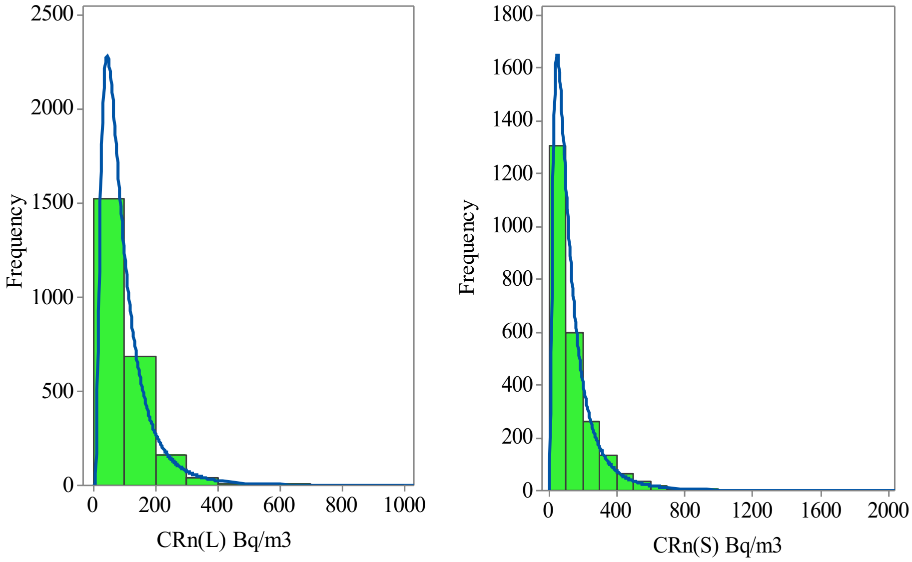

Fig. 2 Histograms of CRn(L) and CRn(S) (fitted with log–normal function); *L* long period from April 2015 to December 2015; *S* short period from January 2016 to March 2016

Table 2 Terror probability (*p*) of the Kolmogorov–Smirnov test applied for normality testing of the lnCRn(L) and lnCRn(S) data grouped by climate zone and district; district code see Fig. 1; L: long period from April 2015 to December 2015; S: short period from January 2016 to March 2016

Clime zone	District code situated in the zone	Variable	KS test (*p*)
Marine (M)	2, 3, 8	lnCRn(L)	0.16
		lnCRn(S)	0.21
Continental Mediterranean (CM)	1, 9, 21, 26	lnCRn(L)	0.96
		lnCRn(S)	0.26
Transitional continental (TC)	13, 16, 20, 24	lnCRn(L)	0.39
		lnCRn(S)	0.63
Moderately continental	4, 5, 6, 7, 10, 11, 12, 14, 15, 17, 18, 19, 22, 23, 25, 27	lnCRn(L)	0.004
		lnCRn(S)	0.01
Moderately continental	4, 5, 6, 7, 10, 11, 12, 14, 15, 17, 18, 19, 22	lnCRn(L)	0.06
		lnCRn(S)	0.24
Moderately continental	23 (Buildings with basement)	lnCRn(L)	0.38
		lnCRn(S)	0.20
Moderately continental	23 (Buildings without basement)	lnCRn(L)	0.62
		lnCRn(S)	0.99
Moderately continental	25 (Buildings with basement)	lnCRn(L)	0.09
		lnCRn(S)	0.01
Moderately continental	25 (Buildings without basement)	lnCRn(L)	0.62
		lnCRn(S)	0.93
Moderately continental	27 (Buildings with basement)	lnCRn(L)	0.27
		lnCRn(S)	0.23
Moderately continental	27 (Buildings without basement)	lnCRn(L)	0.49
		lnCRn(S)	0.61

related with the size of the territory. The explanation of this could be that a larger territory is more diverse than a smaller territory, which might imply that factors influencing the CRn show more pronounced variations in a larger as compared to a smaller territory.

The difference between CRN(L) and CRN(S) [CRn(L) < CRn(S)] is significant for all climate zones (Fig. 3). The geometric means of CRn(L) and CRn(S) in the continental Mediterranean zone are higher than those in all other zones. This is a consequence of the geology, that is, the

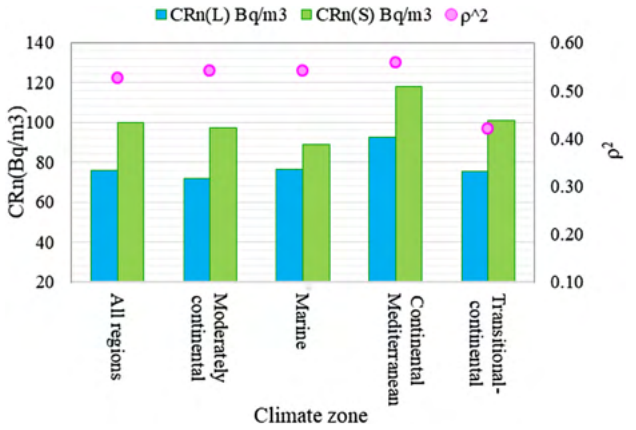

Fig. 3 Geometric means of CRn (L) and CRn (S) with Spearman coefficient of determination (ρ^2) for different climate zone; *L* long period from April 2015 to December 2015; *S* short period from January 2016 to March 2016

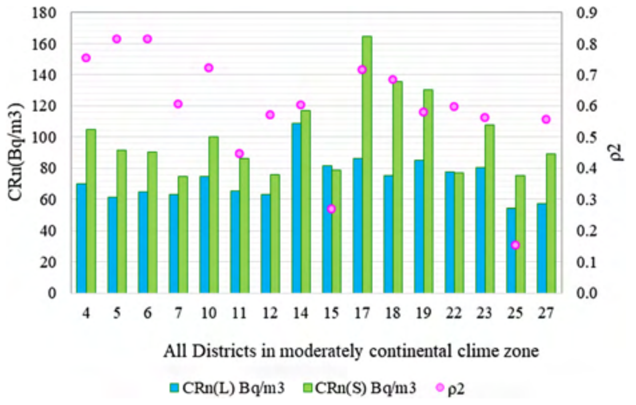

Fig. 4 GM's of CRn (L) and CRn (S) with Spearman coefficient of determination (ρ^2) in districts of moderately continental climate zone; *L* long period from April 2015 to December 2015; *S* short period from January 2016 to March 2016; codes of district see Fig. 1

existence of regions with high radon potential in that zone. Nevertheless, the difference between CRn(L) and CRn(S) in the continental Mediterranean zone is similar to that in zones with moderately continental and transitional continental climate. The difference between CRn(L) and CRn(S) is smallest in the marine zone. This situation is due to the small annual temperature variations in this zone caused by the influence of the Black Sea. On the other hand, the strength of correlation between CRn(L) and CRn(S) in the transitional continental zone is a little bit lower in comparison to that in the other zones. More specifically, the Spearman coefficient of determination varied from 0.420 for the transitional continental region to 0.559 for the continental Mediterranean region.

The next step was to achieve a normal distribution of the data from the moderately continental climate zone. For that purpose, the data were grouped by district and a normal distribution was tested in each subgroup. In the 13 districts, a normal distribution was accepted while in three of them (district codes: 23; 25; 27) a further normalization was required. The error probabilities of the Kolmogorov–Smirnov test of the grouping are also given in Table 2.

The CRn(L), CRn(S) and Spearman coefficient for each district in moderately continental climate zones are presented in Fig. 4. It was found that the CRn(L) and CRn(S) values do neither show a normal distribution nor a pronounced correlation with each other. Namely, in regions with a normal distribution, there is a large variability of CRn (L) and CRn (S) among the districts, but also a large variability of CRn (L) and CRn (S) differences and corresponding correlation coefficients. For example, the highest CRn(L) concentration was obtained for district 14, while the highest CRn(S)′ concentration was obtained for district 17 in which the difference between CRn(L) and CRn(S) is also highest (Fig. 4). An excellent correlation between CRn(L) and CRn(S) was found for districts 5 and 6 (see also high ρ^2 in Fig. 4), while the lowest correlation with a normal distribution was observed in district 15, where the difference between CRn(L) and CRn(S) is smallest in comparison to the other districts in the moderately continental zone. In districts with codes 23 and 27, the distributions of CRn(L) and CRn(S) are not normal, but there is a good correlation between them (as indicated by the Spearman coefficient of determination). In contrast, for district number 25 a correlation between CRn(L) and CRn(S) does not exist.

To accomplish a normal distribution of lnCRn(L) and lnCRn(S) for districts with codes 23, 25, 27, the radon concentrations were grouped in rural and urban municipalities. The analysis showed, however, that this classification was significant only for CRn(L) and, thus, CRn(S) variability and normal distribution could not be achieved. According to results in these three districts, a more detailed grouping of the territorial division, such as by municipalities, was not possible due to the insufficient number of CRn measurements in them.

It was found that a reasonable normal distribution could be achieved if the results in each of these districts were grouped into buildings with and without a basement. The results of lnCRn(L) and lnCRn(S) normality testing for each group are given in the last six rows of Table 2. A normal distribution of lnCRn(L) and lnCRn(S) was also obtained for districts number 23; 27 and for district number 25 for buildings without a basement, while lnCRn(S) in buildings with basement for district 25 did not follow a normal distribution. Finally, a regression analysis of lnCRn(L) and lnCRn(S) was applied for each group, when a normal distribution was achieved. The parameters of the developed linear models are presented in Table 3. The quality of each model is expressed by the Pearson coefficient of determination (R^2)

Table 3 Generated regression models: lnCRn(L) = a × lnCRn(S) + b

Clime zone	District code situated in the zone	a	b	R^2	RMSE
Marine	2, 3, 8	0.67	1.35	0.58	0.43
Continental Mediterranean	1, 9, 21, 26	0.57	1.81	0.49	0.48
Transitional continental	13, 16, 20, 24	0.58	1.67	0.43	0.61
Moderately continental	4, 5, 6, 7, 10, 11, 12, 14, 15, 17, 18, 19, 22	0.63	1.44	0.54	0.48
	23 Buildings with basement	0.72	1.02	0.57	0.57
	23 Buildings without basement	0.47	2.28	0.39	0.50
	25 Buildings without basement	0.38	2.61	0.15	0.73
	27 Buildings with basement	0.87	0.10	0.67	0.45
	27 Buildings without basement	0.58	1.63	0.38	0.66

and root mean square error (RMSE). High R^2 values and the low RMSE values indicate a reasonable model. Both R^2 (Pearson) and ρ^2 (Spearman) coefficients used in the present study indicate the strength of correlation between two variables. The Pearson coefficient (R^2) was used when data follow a normal distribution.

From the R^2 and RMSE values in Table 3, it can be concluded that the quality of the generated models is similar. The exception is the model for district 25 with the lowest $R^2 = 0.15$ and the highest RMSE = 0.73. The reasons for this result are not yet clear but will be investigated during the next survey.

The generated models were used to reconstruct the missing data for CRn in 345 buildings. In the case of missing CRn(L), the models from Table 3 were applied, while for missing CRn(S) the functions lnCRn(S) = a × lnCRn(L) + b were generated the same way.

The scatter diagram of lnCRn(L) versus lnCRn(S) for the measured and reconstructed results is shown in Fig. 5. From the figure it is clearly seen that all reconstructed results are in the 95% confidence interval.

When the results for these additional 345 buildings were added, the previous mean values and their dispersion (Table 1) did not change much (Table 4). The annual CRn concentration for each of the 2778 buildings was estimated as weighted means of the measurements in both periods, weighed by the length of the periods (Ivanova et al. 2019).

The GM of CRn(S) in this survey is practically the same as the GM of 99 Bq/m^3 (GSD: 2.25) obtained in the previous pilot national survey performed in four districts (with codes 3; 16; 22 and 23) during 6 months, from October 2011 to May 2012 (Ivanova et al. 2013).

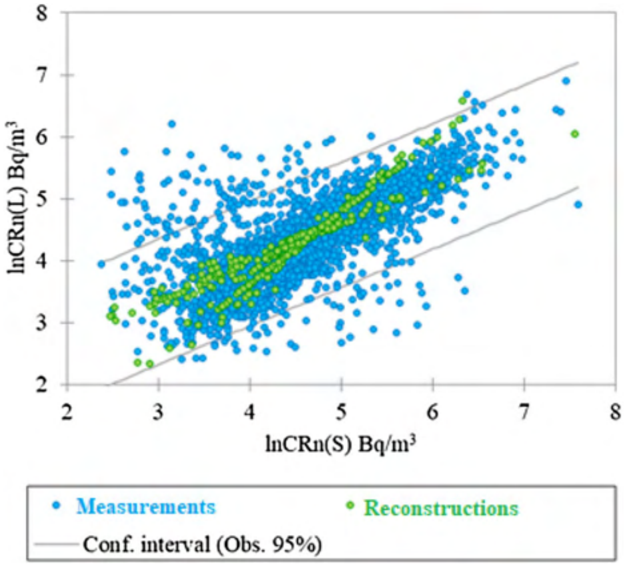

Fig. 5 Scatter diagram of lnCRn (L) versus lnCRn (S) for the measured and reconstructed results

Table 4 Basic descriptive statistics of CRn(L) and CRn(S) in 2778 dwellings

Sample	CRn(L) Bq/m^3	CRn(S) Bq/m^3
No. of dwellings	2778	2778
Minimum	10	11
Maximum	995	1983
Arithmetic mean (AM)	98	141
Geometric mean (GM)	75	98
Geometric standard deviation (GSD)	2.07	2.30

Conclusion

This paper presents the analyses of indoor radon concentration variations measured in two successive periods of 9 and 3 months, marked as CRn(L) and CRn(S), respectively. The measurements were done in ground floor rooms of 2778 dwellings in 28 districts, based on the Bulgarian National survey performed from April 2015 to March 2016. Due to the different contribution to mean radon concentrations of hot and cold months during the measuring periods, the radon concentrations during winter time [CRn(S)] were higher compared to the radon concentrations in the others months of the year [CRn(L)]. The present analysis also showed differences in CRn(L) and CRn(S) concentrations between climatic zones.

Modelling of the temporal variation was done by linear regression, using lnCRn(L) and lnCRn(S) when available for both periods.

It turned out that a normal distribution of the lnCRn(L) and lnCRn(S) variables which is a condition for generating a linear function was not achieved after ln-transformation of the data. Therefore, the distribution of the lnCRn(L) and lnCRn(S) values grouped by factors that significantly affect CRn variation were investigated. The analysis showed that a normal distribution could be achieved by grouping the data according to their affiliation to a spatially distributed territory such as climate zones, or districts. Therefore, the normal distribution for 25 (of 28) districts was proved. For two districts a normal distribution could only be achieved when the data were grouped according to the presence of a basement in the building. A normal distribution of the data from the third district was realized only for buildings without the "basement" category, while for buildings with basement it could not be achieved.

For groups with normal distribution, linear models provided good coefficients of determination. The developed models were used to reconstruct the missing data for CRn in 345 buildings. The reconstructed data were within the 95% confidence interval of the measured data.

The temporal correction developed in the present study can be implemented both for CRn(L) and annual CRn estimation, if only measurements during the three winter months [CRn(S)] are available. This could shorten the time of measurements and number of detectors required for any follow-up surveys. The results can also be used as a basis for the study and determination of seasonal factors for the regions in Bulgaria, and for implementing the national action plan to address long-term health risks from radon exposures to the general population.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Al-Khateeb H, Nuseirat M, Aljarrah K, Al-Akhras M, Bani-Salameh H (2017) Seasonal variation of indoor radon concentration in a desert climate. Appl Radiat Isot 130:49–53

Donchev D, Karakashev H (2004) Physical and socio-economical geography of Bulgaria. Slovo, Veliko Tarnovo

Groves-Kirkby CJ, Crockett RG, Denman AR, Phillips PS (2015) A critical analysis of climatic influences on indoor radon concentrations: implications for seasonal correction. J Environ Radioact 148:16–26

Gulan L, Bochicchio F, Carpentieri C, Milic G, Stajic J, Krstic D, Zunic ZS (2013) High annual radon concentration in dwellings and natural radioactivity content in nearby soil in some rural areas of Kosovo and Metohija (Balkan region). Nucl Tech Radiat Prot 28(1):60–67

Ivanova K, Stojanovska Z, Tsenova M, Badulin V, Kunovska B (2013) Pilot survey of indoor radon in the dwellings of Bulgaria. Radiat Prot Dosim 157(4):594–599

Ivanova K, Stojanovska Z, Tsenova M, Kunovska B (2017) Building-specific factors affecting indoor radon concentration variations in different regions in Bulgaria. Air Qual Atmos Health 10(9):1151–1161

Ivanova K, Stojanovska Z, Kunovska B, Chobanova N, Badulin V, Benderev A (2019) Analysis of the spatial variation of indoor radon concentrations (national survey in Bulgaria). Environ Sci Pollut Res Int 26(7):6971–6979

Keskikurua T, Kokottia H, Lammib S, Kalliokoskia P (2001) Effect of various factors on the rate of radon entry into two different types of houses. Build Environ 36:1091–1098

Miles JCH, Howarth CB, Hunter N (2012) Seasonal variation of radon concentrations in UK homes. J Radiol Prot 32:275–287

Muntean L, Cosma C, Dinu AL, Dicu T, Moldovan D (2014) Assessment of annual and seasonal variation of indoor radon levels in dwelling houses from Alba County. Rom J Phys 59(1–2):163–171

Ramola R, Prasad M, Kandari T, Pant P, Bossew P, Mishra R, Tokonami S (2016) Dose estimation derived from the exposure to radon, thoron and their progeny in the indoor environment. Sci Rep 6(1):31061

Sogukpinar H, Algin E, Asici C, Altinsoz M, Cetinkaya H (2013) Seasonal indoor radon concentration in Eskisehir Turkey. Radiat Prot Dosim 162(3):410–415

Stojanovska Z, Januseski J, Bossew P, Zunic Z, Tollefsen T, Ristova M (2011) Seasonal indoor radon concentration in FYR of Macedonia. Radiat Meas 46(6–7):602–610

Stojanovska Z, Bossew P, Tokonami S, Zunic Z, Bochicchio F, Boev B, Ristova M, Januseski J (2013) National survey of indoor thoron concentration in FYR of Macedonia (continental Europe—Balkan region). Radiat Meas 49:57–66

Stojanovska Z, Boev B, Zunic ZS, Ivanova K, Ristova M, Tsenova M, AjkaS Taleski V, Bossew P (2016) Variation of indoor radon concentration and gamma dose rate in different outdoor and indoor environments. Radiat Environ Biophys 55(2):171–183

Stojanovska Z, Ivanova K, Bossew P, Boev B, Zunic Z, Tsenova M, Curguz Z, Kolarz P, Zdravkovska M, Ristova M (2017) Prediction of Long-Term Indoor Radon Concentrations based on short-term measurements. Nucl Tech Radiat Prot 32(1):77–84

Szabó Z, Jordan G, Szabó C, Horváth Á, Holm Ó, Kocsy G, Csige I, Szabó P, Homoki Z (2014) Radon and thoron levels, their spatial and seasonal variations in adobe dwellings—a case study at the great Hungarian plain. Isotopes Environ Health Stud 50(2):211–225

Tsapalov A, Kovler K (2018) Indoor radon regulation using tabulated values of temporal radon variation. J Environ Radioact 183:59–72

UNSCEAR (2000). Sources and Effects of Ionising Radiation. Volume 1: Report to the General Assembly with Scientific Annexes. Annex B. Exposures from natural radiation sources UNSCEAR 2000 Report (New York: United Nations)

Vukotic P, Antovic N, Djurovic A, Zekic R, Svrkota N, Andjelic T, Svrkota R, Mrdak R, Bjelica N, Djurovic T, Dlabac A, Bogicevic M (2019) Radon survey in Montenegro—a base to set national radon reference and "urgent action" level. J Environ Radioact 196:232–239

Zunic ZS, Kobal I, Vaupotic J, Kozak K, Mazur J, Birovljev A, Janik M, Celikovicr I, Ujic P, Demajo A, Krsticr G, Jakupi B, Quarto M, Bochicchio F (2006) High natural radiation exposure in radon spa areas: a detailed field investigation in Niska Banja (Balkan region). J Environ Radioact 89(3):249–260