INDOOR RADON ACTIVITY CONCENTRATION AND EFFECTIVE DOSE RATES AT SCHOOLS AND THERMAL SPAS OF ILGIN

by

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Indoor radon activity concentrations and radon doses on the ground floor and basement floor of 19 schools (kindergardens, primary schools, secondary schools, and high schools) and thermal spas of Ilgin district in Konya, have been measured using the AlphaGUARD PQ 2000PRO radon detector, for three days in the first half of 2016. According to the results, while the indoor radon concentration for only one location, in total, is above the Turkish action level of 400 Bqm^{-3}, the values for 10 locations are above the reference level of 100 Bqm^{-3}, recommended by WHO. The calculated annual effective doses for inhalation of the radon in indoor air were also found to be 0.26 μSv for the minimum and 4.36 μSv for the maximum. The parametric distribution analysis is also performed with 3-parameter Weibull distribution and some remarks are provided on radon concentration activity.

Key words: annual effective dose, Ilgin active fault, indoor radon, statistical modelling, Weibull distribution

INTRODUCTION

Radon (Rn-222) is the most common radon isotope and radon and its decay products are the first and the most important natural radiation sources to which people are exposed. It is generated by radioactive transformation of radium (Ra-226), found in natural decay chain of uranium (U-238) in rocks and soil from the earth's crust. Radon, generated in the natural decay chain, escapes easily from rocks and soil into the air and contributes to indoor radon concentration in enclosed spaces such as schools, houses, underground mines and other buildings. The magnitude of indoor radon concentration depends primarily on a building's construction methods (including architectural design, quality-amount of used materials such as steel, concrete, dimension stones) and the amount of radon in the underlying soil. This gas can enter a building from the soil through cracks in concrete floors and walls, floor drains, sump pumps, construction joints, and tiny cracks or pores in hollow-block walls and because of that, radon levels are generally highest in basements and ground floor rooms that are in contact with the soil. Dai *et al*. stated that the fault zones should have a priority for monitoring radon concentration level in settlement areas [1]. Radon is also soluble in water and its solubility increases rapidly with decreasing temperature. The radon gas later escapes from water and goes into the air, raising the room's radon content. An average concentration of radon in water of 10 kBqm^{-3} implies a contribution of 1 Bqm^{-3} to radon in air. It is well known that there is a relationship between indoor radon concentration and geological settings of the region, especially tectonic regime directly affects the radon concentrations [2].

It is well-known that the relation exists between radon gas-fault zones and thermal springs. Extensional and tensional tectonic regimes control the development of any active faults on earth surface independent whether it is below sea level or not [3-6]. Produced radon gas within underground formations is initially a mixture with underground water including hot meteoric water. When these waters find hydraulic channels within the geological formations, they are actually transferred trough the surface along the fault zones.

Radon decays with a 3.8 days half-life into the short-lived radioactive elements like Po-218, Pb-214, Bi-214, and Po-214 [2]. Radon and its short-lived decay products, especially Po-218 and Po-214 in solid form, are also alpha emitters and may attach to aerosol particles like dust in the atmosphere. When they are inhaled, the densely ionizing alpha particles, emitted by unat-

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tached or attached to the surface of aerosols, can interact with biological tissue in the lungs leading to DNA damage [7]. For this reason, radon and decay products have a risk of cancer, especially for lung cancer and it is also well known that radon exposure is the second leading cause of lung cancer, after smoking [8].

Indoor radon activity measurements are very important in school buildings, as well as all indoor environment where people live, in order to determine the radon exposure of students, teachers and staff. Such surveys have been carried out in schools and thermal spas in Turkey [9, 10] and various countries of the world [11-15]. In the present work, we have obtained the results of the indoor radon activity concentrations and the effective dose rates of radon exposure, measured in some schools of Ilg?n district of Konya province.

MATERIAL AND METHOD

Geological setting of study area

Ilgin is a district of Konya province located in the central part of Turkey. The study area is tectonically located in Kutahya-Bolkardag Belt [16]. In this belt, various rocks units including crystalized limestones, dolomites, phillites, metamorphosed conglomerates and sandstones are widespread at different age. A detailed geological description can be found in Hüseyinca and Eren [17]. In terms of development of the thermal springs in the region, perhaps, the Neogene tectonic regimes played the most important role. This recent tectonic regime caused the formation of still active faults in and around the town of Ilgin. The area still suffers from the sometimes deadly earthquakes. The best known active fault in the region is called *Ilgin Fault* which developed as normal fault – a result of gravity driven fault type. The Ilgin thermal baths are situated at the southern tip of this fault which is still playing an active channel way to the heated meteoric water in depth. The active fault systems often gave rise to development of thermal springs in many localities in Turkey and in the world. It is expected that the radon concentration could be reasonably high in indoors of Ilgin region, since the area has both active faults and thermal springs which could cause high radon production from depth. When radon concentration levels exceed 200 Bqm^{-3} in basements and first floors, it is suggested to use automatically activated electric fan for lowering radon concentration, as in Norwegian cities, as well as constructing a radon membrane for buildings [18].

Measurement equipment

The indoor radon activity concentration measurements were performed at the ground floor and basements, for three days, in some schools and thermal spas in the Ilgin district of Konya province. Sort-term measurements of the indoor radon activity levels were performed using a portable AlphaGUARD PQ2000 PRO radon monitoring detector. The detector uses the proven principle of the puls ionization chamber (alpha spectroscopy). The ionization chamber is designed for the continuous measuring of radon and radon progeny concentration in air, water and soil gas [19].

Dose estimation

The average annual effective doses (AED) in mSv units, received by students in the schools and staff in the thermal spas, due to the indoor radon measured at these locations, were estimated using the following formula [2]

$$AED \quad C_{\rm Rn} FTD_{\rm CF} \ \ 10^{\ \ 6} \qquad (1)$$

where $C_{\rm Rn}$ [Bqm^{-3}] is the average indoor radon activity concentration, F – the equilibrium factor between radon and it's progeny and it is equal to 0.4, $D_{\rm CF}$ – the dose conversion factor and its value is 9 $nSvh^{-1}$ per Bqm^{-3}, and T – the time spent annually inside the schools and thermal spas and it is 2000 hours for students and staffs in schools and thermal spas. According to these data, AED values were calculated using eq. (1) for teachers, students and staff and are shown in tab.1 and tab. 3.

RESULTS AND DISCUSSION

Radon activity concentrations and effective doses at various schools

We performed the indoor radon activity concentration measurements at the ground floor classrooms of 19 schools (high school, secondary school, primary school, and kinder garden) as well as at the basement floor classrooms of four of these schools, as shown in fig. 1. The Annual effective doses, due to the radon activity values, were also estimated by taking into account the fact that a teacher, student and staff spent 8 hours a day at the schools, as shown in tab. 1.

In tab. 1, while HS, SS, and PS codes are shown for high school, secondary school, and primary school, respectively, a and b codes indicate ground and basement of schools, as shown in tab. 1. Frequencies of different levels of schools are also shown in tab. 2. According to the results, the highest value of the radon concentration and *AED* were found to be 382 Bqm^{-3} and 4.02 mSv, respectively, in the school coded with HS 1. This situation can be related to the construction quality of the schools and their connection to the ground. The lowest value of radon concentration and AED was also measured as 25 Bqm^{-3} and 0.26 mSv, respectively, in school coded with PS 7. It is also seen, that radon ac-

Table 1. Radon activity concentration values and AED for teachers, students, and staffs of the schools in the region of Ilgin

No	Code	Location name	Radon activity [Bqm^{-3}]	AED [mSv]
1	SS 1	Yunus Emre Secondary School (Ground)	35	0.37
2	PS 1	Irfan Yayla Primary School (Ground)	101	1.06
3	PS 2	Atatürk Primary School (Ground)	107	1.12
4	SS 2	Cansu Simsek Secondary School (Ground)	90	0.95
5	PS 3	Cumhuriyet Primary School (Ground)	57	0.60
6	HS 1	Huseyin Aksoy High School (Ground)	382	4.02
7	SS 3a	75.YIL Secondary School (Ground)	28	0.29
8	SS 3b	75.YIL Secondary School (Basement)	43	0.45
9	PS 4	Inonu Primary School (Ground)	124	1.30
10	HS 2	Ticaret Borsasi Science High School (Ground)	100	1.05
11	HS 3	Imam Hatip High School (Ground)	31	0.33
12	SS 4	Imam Hatip Secondary School (Ground)	27	0.28
13	SS 5	Mehmet Akif Ersoy Secondary School (Ground)	61	0.64
14	PS 5a	Ahmet Ali Gezgin Primary School (Ground)	38	0.40
15	PS 5b	Ahmet Ali Gezgin Primary School (Basement)	81	0.85
16	HS 4	S.B.H. Coban Vocational and Technical High School (Ground)	118	1.24
17	HS 5	Seker-Is Sendikasi Voc. and Technical High School (Ground)	107	1.12
18	PS 6	Halil Ozkan Primary School (Ground)	71	0.75
19	PS 7	S.M. Deniz Kagnici Primary School (Ground)	25	0.26
20	KG 1a	Elif Kindergarden (Ground)	57	0.60
21	KG 1b	Elif Kindergarden (Basement)	113	1.19
22	PS 8a	100. YIL Primary School (Ground)	32	0.34
23	PS 8b	100. YIL Primary School (Basement)	324	3.41

Table 2. Frequencies of different modes of schools

Number of Kindergardens	2
Number of Primary schools	10
Number of Secondary schools	6
Number of High Schools	5

tivity values of the basement floors (SS3b, HS4b, PS5b, KG1b, PS8b) were higher than ground floor values (SS3a, HS4a, PS5a, KG1a, PS8a) in the schools. This can also be related to the fact that radon gas is about eight times heavier than air. While all the average values of the radon concentration in the schools are below the Turkish action level of 400 Bq per year, these values measured in 9 of these schools (PS1, PS2, HS1, PS4, HS4, HS5, HS6, KG1b, PS8b) are above the reference level of 100 Bqm^{-3}, recommended by WHO [7, 20]. When radon activity data, taken from each measurement location, are analysed, it is seen that the activity overnight is higher than during the day, which may be due to daytime ventilation of schools.

Statistical analysis

Twenty three schools were surveyed and frequencies of different modes of schools are given in tab. 2. In tab. 3, sample min, max, mean, standard deviation, median, first (Q1) and third (Q3) quartile, interquartile range (IQR), skewness and kurtosis, are given. Even though the mean radon activity was less than 100 Bqm^{-3}, standard deviation 88.7 indicates that variation of radon activity is too large from school to school. From tab. 3, the positive value of the skewness coefficient indicates an asymmetric distribution of radon average concentrations with the right tailed. The estimate of kurtosis 6.04 also indicates that the distribution, where the real data comes from, is heavy-tailed. It is a consequence of the observed two abnormal radon values of 324 Bqm^{-3} and 382 Bqm^{-3}. These values were not considered as outliers, because our measurements of the the radon activity concentrations were highly sensitive.

In nature, there are two types of phenomena which are deterministic and stochastic. Stochastic phenomenas obey a laws and these laws are descibed by a function called probability density function in statistical theory. If a random phenomena is modelled by a statistical distribution, one can easily understand the whole behavior of the phenomena. Since the sample size is good enough to study with parametric distribution, the parametric distribution analysis is peformed hereafter.

In the analysis, we recognize that the three-parameter Weibull distribution gives a better fit of the radon activity data. Weibull distribution is one of the most popular statistical distributions in reliability theory and survival analysis. It can also be used for modelling several random phenomena including radon activity. The

Table 3. The non-parametric descriptive statistics for indoor radon concentrations in 23 locations of schools

Variable	Mean	St. Dev.	Minimum	Q1	Median	Q3	Maximum	IQR	Skewness	Kurtosis
Radon activity	93.6	88.7	25	35	71	107	382	72	2.44	6.04

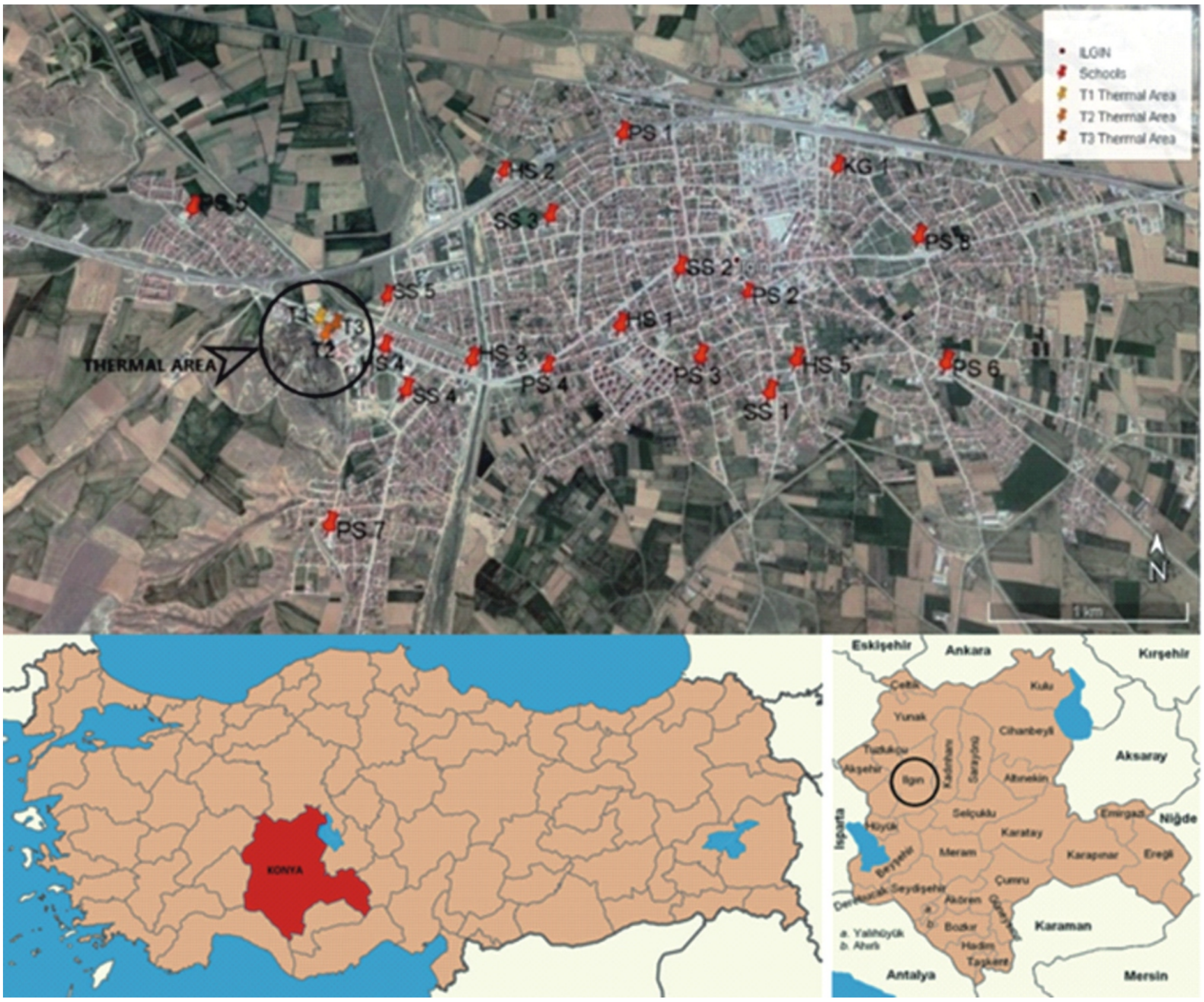

Figure 1. Schools and thermal spas in the study area

probability density function of three-parameter Weibull distribution is given in eq. (2)

$$f(x,\alpha,\lambda,\beta) = \frac{\beta}{\alpha^{\beta}}(x-\lambda)^{\beta-1}\exp\left[-\left(\frac{x-\lambda}{\alpha}\right)^{\beta}\right] I_{(\lambda,\infty)}(x) \tag{2}$$

where $\alpha > 0, \beta > 0$ and $\lambda > 0$ are shape, scale and threshold parameters, respectively and $I_{(a,\,b)}(x)$ is indicator function defined by

$$I_{(a,\,b)}(x) = \begin{cases} 1, & x \in (a,b) \\ 0, & x \notin (a,b) \end{cases}$$

Expected value (E) and variance (Var) of random variable X having three-parameter Weibull distribution are given in eqs. (3) and (4)

$$E(X) = \lambda + \alpha\Gamma\left(1+\frac{1}{\beta}\right) \tag{3}$$

$$Var(X) = \alpha^2\left[\Gamma\left(1+\frac{2}{\beta}\right) - \Gamma^2\left(1+\frac{1}{\beta}\right)\right] \tag{4}$$

respectively, where $\Gamma(.)$ is well-known Gamma function [21]. More details on Weibull distribution, can be found in references [21-23].

From fig. 2, it can be concluded that three-parameter Weibull, three-parameter log-normal, three-parameter log-logistic and two-parameter exponential distributions, are candidates for modelling radon data.

Because all the data points were between confidence limits for all distributions in PP-Plot. The likelihood values for these distributions are obtained by –120.479, –120.665, –120.899, and –121.261, respectively. The maximum values are obtained for three-parameter Weibull with –120.479, as desired. It is noted that p value of Anderson-Darling (AD) test for two-parameter exponential distribution is greater than 0.25 and 95 % confidence interval (CI) of shape parameter (see tab. 4) of three-parameter Weibull distribution contains 1, radon concentration data can also be modelled by two-parameter exponential distribution. Nevertheless, we consider the three-parameter Weibull distribution in the parametric data analysis since it has highest log-likelihood for the data. Empiri-

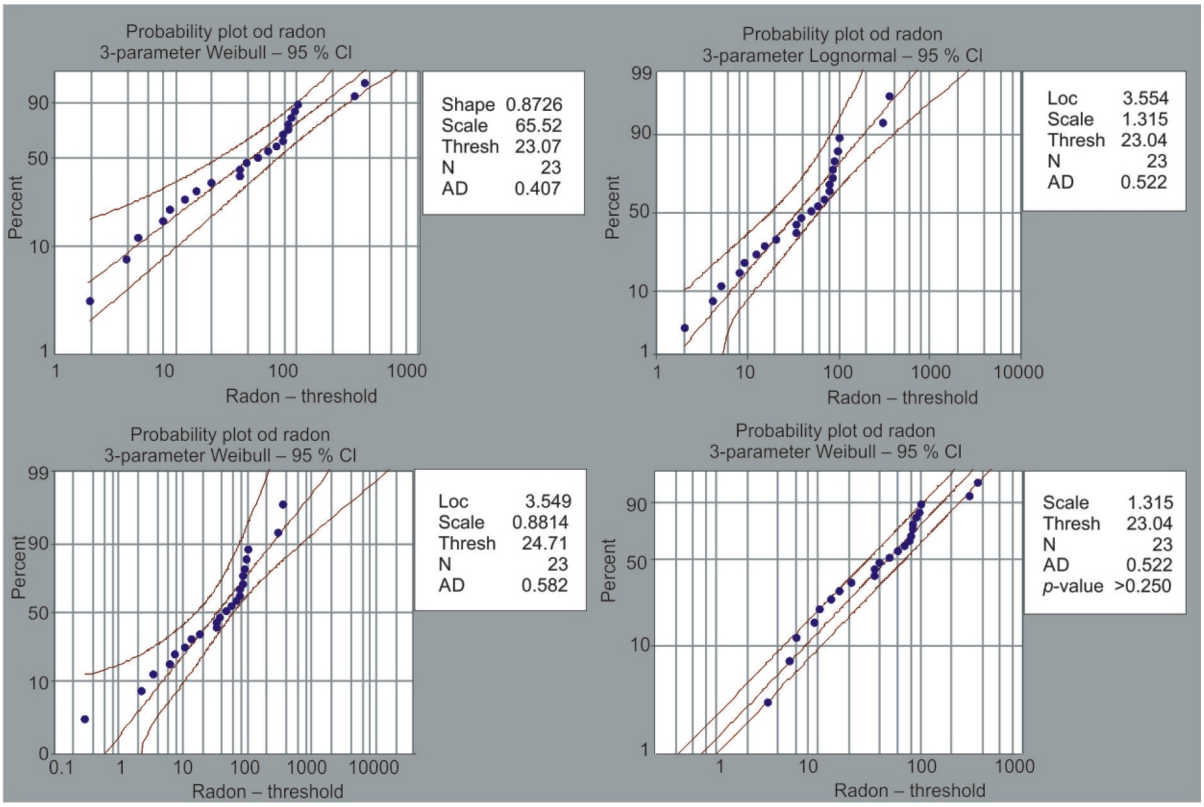

Figure 2. Probability plots for radon activity concentration data

Table 4. Parameter estimates of three-parameter Weibull distribution

Parameter	Estimate	Standard Error	95 % Normal CI	
			Lower	Upper
Shape	0.8726	0.1382	0.6397	1.1903
Scale	65.5174	16.5431	39.9418	107.469
Threshold	23.0698	0	23.0698	23.0698

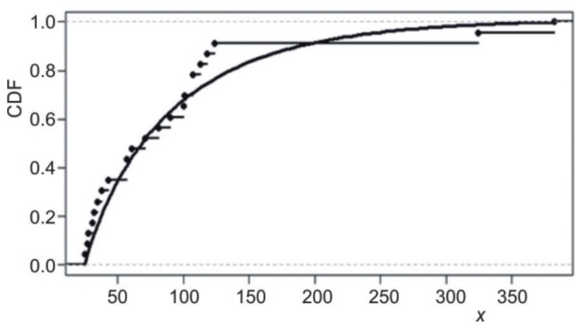

Figure 3. Empirical and fitted cumulative distribution functions (CDF). The solid curve is fitted CDF and *x* [Bqm^{-3}] represents the radon activity

cal and fitted cumulative distribution functions are given in fig. 3 and it is observed that three-parameter Weibull distribution fits well to radon concentration data. In this case, three-parameter Weibull distribution is a good choice for modelling radon concentration data.

Three-parameter Weibull distribution has also minimum Anderson-Darling statistic value of 0.407, as desired. Anderson-Darling goodness of fit test, based on radon concentration data for three-parameter Weibull distribution, gives p-value as $0.376 > 0.05$. It can also be concluded that the null hypothesis cannot be rejected with significance level 0.05, where the null hypothesis is that the radon data come from three-parameter Weibull distribution.

In tab. 4, the maximum likelihood estimates of shape, scale and threshold parameters are given for three-parameter Weibull distribution. The 95 % confidence intervals for parameters are also given in tab. 4. The length of confidence interval for scale parameter is large, as expected, since the sample size is small and sample variance is too large.

In tab. 5, estimated mean, standard deviation, median, first and third quartile and interquartile range, as well as its 95 % confidence intervals, are given. It is observed that parametric inference coincides with non-parametric inference given in tab. 3.

Table 5. Characteristics of three-parameter Weibull distribution

	Estimate	Standard Error	% 95 Normal CI	
			Lower	Upper
Mean	93.2231	16.7820	65.5074	132.665
Standard deviation	80.6283	23.9769	45.0153	144.416
Median	66.1178	12.1027	46.1857	94.6518
First quartile (Q1)	38.7845	6.12303	28.4627	52.8494
Third quartile (Q3)	118.331	22.8612	81.0302	172.801
Interquartile range (IQR)	79.5461	19.1991	49.5648	127.663

From tab. 5, it can be seen that sample mean is greater than sample median. These results are expected for the positively skewed data. It can be concluded that the location of distribution is near the sample median 66.1178 but, we should know that one can observe large values of radon construction activity with a small positive probability. This situation can be observed when the distribution is rightly skewed. For this reason, the median can be used for the interpretation of location of radon values instead of mean. Using the first and third quartiles, it can be also said that in schools, the probability for radon activity values between 38.7845 and 118.331, is 0.5.

From tab. 5, it can also be concluded that radon activity concentrations are located between 46.1857 and 94.6518 with 95 % confidence level.

The percentiles of distribution with confidence intervals are given in tab. 6. From tab. 6, it can be said that the school has radon activity value less than 104.117 with probability 0.70, as an example.

Radon activity concentrations and effective doses at various thermal spas

The indoor radon activity concentration measurements were performed in three different blocks of the thermal spa operated by the municipality of Ilgin. The measurements were performed in the changing rooms at the entrances of the buildings. The three blocks of thermal spas, in the study area, are shown in the circle in fig. 1. The radon activity concentration varied from 47 Bqm^{-3} to 415 Bqm^{-3}, as given in tab. 7. The AED, due to the radon activity values, were also estimated by taking into account the fact that staffs spent 8 hours a day at the thermal spa as shown in tab. 7.

According to the results, while two blocks of average values of radon concentration in the thermal spa are below the Turkish action level of 400 Bqm^{-3}, these values measured in two blocks of the spa (T1, T2) are above the reference level of 100 Bqm^{-3}, recommended by WHO. The distance from the thermal pool is closely related to the location of measurement point, since there have been a positive correlation between the radon level and the distance. In tab. 7, the code T1 is the closest measuring point to the pool, which has the highest indoor radon concentration. Radon dissolved in thermal waters escapes to air in the ratio of 1/10000 (2) therefore, indoor radon concentration at the measurement locations can increase because Erdogan et. al reported that radon concentration of the thermal water is ranged about 15 to 70 kBqm^{-3} for the region [24]. Diaz Lagos *et al*. also reported high radon concentrations in spas at Boyaca, Colombia [25].

Table 6. Fitted distribution percentiles

Percent	Percentile	Standard Error	95.0 % Normal CI Lower	95.0 % Normal CI Upper
10	28.0404	2.71018	23.2014	33.8887
20	34.8154	5.01537	26.2513	46.1735
30	43.1741	7.22978	31.0946	59.9463
40	53.4126	9.52430	37.6583	75.7576
50	66.1178	12.1027	46.1857	94.6518
60	82.3417	15.2961	57.2134	118.507
70	104.117	19.7514	71.7869	151.007
80	136.099	27.0131	92.2379	200.818
90	193.455	42.4126	125.883	297.301
95	253.425	61.3408	157.696	407.268
99	400.116	116.426	226.205	707.733

Table 7. Radon activity concentration value and AED for staff in the thermal spa

Number	Code	Location name	Mean radon activity [Bqm^{-3}]	AED [mSv]
1	T 1	Thermal spa (A block)	415	4.36
2	T 2	Thermal spa (B block)	147	1.55
3	T 3	Thermal spa (C block)	47	0.49

CONCLUSIONS

The short-term indoor radon activity concentration measurements, at the ground floor classrooms, of 19 schools and also basement floor classrooms of four of these schools, as well as the indoor radon measurements which were performed in three different blocks of the thermal spa operated by the municipality of Ilgin. The annual effective doses, due to the radon activity values, were also estimated by taking into account the fact that teachers, students and staff spent 8 hours a day at the schools. While radon concentration, for only one location in total, which is a thermal spa, is above the Turkish action level of 400 Bqm^{-3}, the value for 10 locations are above the reference level of 100 Bqm^{-3}, recommended by WHO. The high radon values could be related to the well-known active Ilgin Fault, which gives raise to the occurrence of thermal exhalations in the region. However, the spas are distributed in and around this fault zones in the area.

The distribution of radon concentration is modelled by three-parameter Weibull distribution. This fitted model can be used to caluclate any probability of interest. According to our knowledge, radon activity concentration data are for the first time modelled with a statistical distribution in the literarture. In this manner, our approach could inspire authors to use the statistical distribution for modelling radon activity concentrations.

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AUTHORS' CONTRIBUTIONS

The idea for research of indoor radon in schools was suggested by M. Erdogan. Measurements were performed by M. Abaka and M. Erdogan. Statistical analysis was carried out by C. Kus and geological contribution of the study region was carried out by V. Zedef. Analysis, discussion and writing of the manuscript was carried out by M. Erdogan, K. Manisa, V. Zedef, C. Kus, and H. Bircan.

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**Мехмет ЕРДОГАН, Мурат АБАКА, Кан МАНИСА,
Хасан БИРЏАН, Џоскун КУС, Вејсел ЗЕДЕФ**

КОНЦЕНТРАЦИЈА АКТИВНОСТИ И ЈАЧИНА ЕФЕКТИВНЕ ДОЗЕ РАДОНА У ШКОЛАМА И ТЕРМАЛНИМ БАЊАМА ИЛГИНА, ТУРСКА

Концентрације активности радона у затвореном простору и дозе радона у приземљу и подруму 19 школа (вртића, основних и средњих школа) и термалних бања у округу Илгин у Конији мерене су три месеца помоћу AlphaGUARD PQ 2000PRO детектора радона, у првој половини 2016. године. Према резултатима, док је концентрација радона у затвореном простору за само једну локацију од свих изнад турског нивоа акције од 400 Bqm^{-3}, вредност за 10 локација је изнад референтног нивоа од 100 Bqm^{-3} који препоручује Светска здравствена организација. Израчунате годишње ефективне дозе удахнутог радона из ваздуха у затвореном простору такође су добијене у опсегу од минималних 0,26 Sv до максималних 4,36 Sv. Анализа параметарске расподеле извршена је са тропараметарском Вејбуловом расподелом и дате су неке напомене о концентрацији активности радона.

Кључне речи: годишња ефективна доза, активни расед у Илгину, радон у затвореном простору, статистичко моделовање, Вејбулова расподела