DEPENDENCE OF CONCENTRATION OF RADON ON ENVIRONMENTAL PARAMETERS – MULTIPLE LINEAR REGRESSION MODEL

Anita Ptiček Siročić [1*], Sanja Kovač [1], Davor Stanko [1], Iva Pejak [1]
[1] *University of Zagreb, Faculty of Geotechnical Engineering, Hallerova aleja 7, HR42000, Varaždin, Croatia*
*E-mail of corresponding author: anitaps@gfv.unizg.hr

Abstract: *Radon (^{222}Ra) is a colourless and odourless natural radioactive element in gaseous state. The concentration of radon in the air is usually low, but it can be very high inside of a living space, because of its possibility to penetrate from a foundation soil over a basement into a building itself. People are daily exposed to a certain concentration of radon that is found in soil, water, air and food. This paper shows a correlation analysis of environmental parameters by using the model of multiple regressions. It defines certain statistical relations between environmental parameters such as temperature, humidity, and atmospheric pressure with measured values of radon concentrations. Measurements were carried out at several locations in various residential buildings in north-western Croatia. The results indicated that individual environmental parameters and radon concentration at individual locations were connected. For example, at one location the concentration of radon was decreasing if atmospheric pressure was increasing. Measurements at another location indicated that the concentration of radon was increasing if air humidity was increasing. Due to large number of different parameters affecting the concentration of radon in residential buildings, a satisfactory statistical model to predict the concentration of radon with environmental parameters is not easy to achieve since it was observed variability of radon concentrations with environmental parameters within different local sites. It is necessary to consider a longer period to determine with certainty a mathematical model that would give the most accurate prediction of radon concentration dependence on environmental parameters which can affect human health and quality of life.*
Keywords: *radon, temperature, humidity, regression model*

Received: 06.11.2020. / Accepted: 05.02.2021.
Published online: 01.12.2021.

Original scientific paper
https://doi.org/10.37023/ee.8.1-2.3

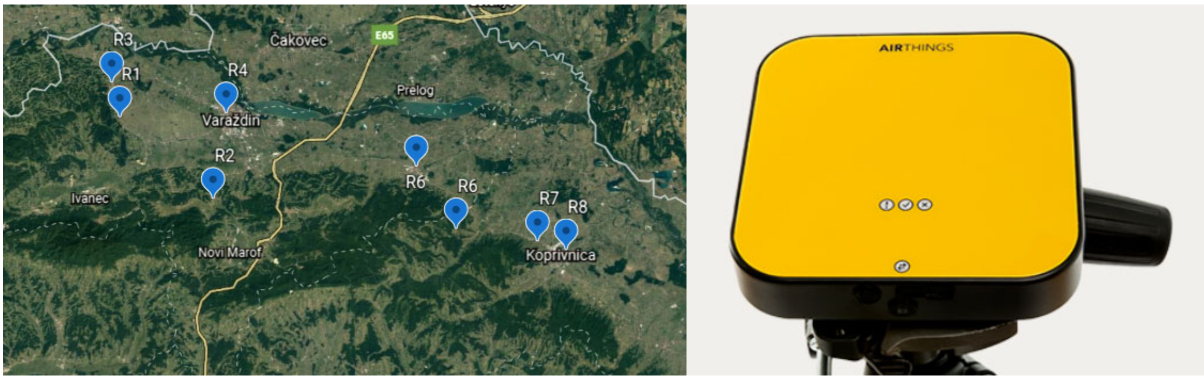
1. INTRODUCTION

Radon (222Rn) is a natural noble radioactive gas, whose main source is soil. Radon is formed as a progeny in the radioactive series of uranium, which is found in the Earth's crust. On its way to the atmosphere, radon mixes with the air that people inhale and take into the body (James 1988). The main consequence of the presence of high concentrations of radon in the environment is the development of deadly lung cancer (by inhalation) and gastric cancer (by ingesting water). Radon concentrations change significantly over time, and thus throughout the year. For a more reliable estimate of the radiation dose of radon and its short-lived offspring in the environment, it is necessary to perform measurements for at least one year. The measurement is performed using specially developed nuclear trace detectors that are exposed in the environment where people live every day (Zeeb et al. 2009). In accordance with (Council Directive 2013/59 Euroatom) on the basic safety standards for protection against the dangers arising from exposure to ionizing radiation for EU Member States, it has been established that the reference level of radon for indoor and workplace should not exceed 300 Bq/m^3. This reference level has also been transposed into Croatian legislation by the Ordinance on radiation limits, the recommended dose limit and the assessment of personal radiation (Official Gazette 38/18). According to research conducted in residential areas of the Republic of Croatia, the concentration of radon varies from county to county (Radolić et al. 2006; Mostečak et al. 2018). For example, Istria, Karlovac or Lika-Senj counties are the counties with the highest measured radon concentration in the range of 101-200 Bq/m^3, while in Baranja, Požega - Slavonia County radon concentrations are lower and amount to 51-100 Bq/m^3 (Radolić et al. 2006).

Correlation between the hourly indoor radon variations with environmental parameters indicated that indoor radon concentrations may be affected by both indoor-to-outdoor temperature, humidity and pressure differences (Steck 2009; Xie et al. 2015). The aim of this study was to investigate the relationship between environmental parameters and temperature, humidity and atmospheric pressure with the concentration of radon in the air indoors at several locations in north-western Croatia.

2. EXPERIMENTAL PART

Radon concentrations were measured at 8 locations in the Varaždin and Koprivnica-Križevci counties (north-western Croatia) in the period between 2018 and 2020 within 7 to 14 days measurements, **Figure 1.** Radon concentration measurements were performed with an Airthings Corentium Pro measuring instrument (https://www.airthings.com/pro). Corentium Pro contains four radon chambers that work in parallel to obtain the most accurate and accurate results. The principle of operation is as follows: the device causes indoor air through a passive diffusion chamber and accurately calculates the radon level using alpha spectrometry. Radon is identified by silicon photodiodes for measuring energy and counting α particles derived from the decaying chain of radon. The measuring instrument is calibrated for reference instruments in accredited laboratories and is AARST-NRPP certified (certified by the American Association of Radon Technologists and Scientists). In addition to four radon chambers, the instrument also has sensors for measuring temperature, pressure and humidity.



a) **b)**

Figure 1. *a) Map of measurement location b) Airthings Corentium Pro measuring instrument*

3. RESULTS AND DISSCUSSION

The values of radon concentration, temperature, humidity and atmospheric pressure were measured at the different locations (**Figure 1**). **Tables 1-4** show the values of individual measured parameters. **Table 1** shows the minimum; maximum and average values of radon concentration and it can be seen that the radon concentration is lower on the ground floor and on the first floor compared to the basement. The values of radon concentration obtained at location 7. show a deviation from other measurements and it is possible to assume that the basement rooms of this location have good ventilation and the concentration of radon is significantly lower than on the ground floor.

Table 1. Radon concentration values (min., max. and average)

Location	c_{MIN} [Bq/m^3]	c_{MAX} [Bq/m^3]	c_{av} [Bq/m^3]
LOCATION 1 – basement	9.00	123.00	46.20
LOCATION 1 – ground floor	9.00	72.00	21.70
LOCATION 2 – basement	2.17	207.00	70.00
LOCATION 3 – ground floor	1.85	232.00	56.00
LOCATION 4 – 1st floor	0.54	154.00	52.20
LOCATION 5 – 1st floor	2.95	363.00	132.00
LOCATION 6 – basement	2.49	220.00	83.00
LOCATION 7 – basement	1.35	68.00	16.00
LOCATION 7 – ground floor	0.89	112.00	36.00
LOCATION 8 – basement	1.45	262.00	87.00
LOCATION 8 – 1st floor	0.80	112.00	36.00

Table 2 shows the temperature values for individual locations. The results show that the temperature values in the basement and ground floor are approximately the same at most locations, if the average measured temperatures are observed, except at location 8, where there is a significant difference in the average measured values. It is to be assumed that deviations are present due to measurements during the winter months when the heating of the rooms in which people stay is increased (Ptiček Siročić et al. 2020).

Table 3 shows the results of the minimum, maximum and average values of humidity parameters. The measured values of the environmental humidity parameter range from 39 to 75 %, depending on the location and the period of the year. If we compare the values from **Tables 1-3,** the radon concentration is higher if the humidity is lower, but only in the case of measurements in the basement and ground floor.

Table 2. Temperature values (min., max. and average)

Location	T_{MIN} [°C]	T_{MAX} [°C]	T_{av} [°C]
LOCATION 1 – basement	21.0	24.6	22.5
LOCATION 1 – ground floor	21.0	23.6	22.8
LOCATION 2 – basement	21.4	24.4	23.6
LOCATION 3 – ground floor	13.1	26.8	23.6
LOCATION 4 – 1st floor	24.9	30.6	27.3
LOCATION 5 – 1st floor	17.4	26.2	20.4
LOCATION 6 – basement	14.6	19.4	16.1
LOCATION 7 – basement	15.0	19.4	16.9
LOCATION 7 – ground floor	19.8	30.2	25.1
LOCATION 8 – basement	15.2	19.2	16.8
LOCATION 8 – 1st floor	14.2	19.2	16.8

Table 3. Values of the environmental humidity parameter (min., max. and average)

Location	H_{MIN} [%]	H_{MAX} [%]	H_{av} [%]
LOCATION 1 – basement	39.9	52.2	44.3
LOCATION 1 – ground floor	55.8	62.1	59.4
LOCATION 2 – basement	32.0	47.0	39.0
LOCATION 3 – ground floor	44.0	86.9	53.0
LOCATION 4 – 1st floor	46.0	61.9	53.8
LOCATION 5 – 1st floor	41.0	62.0	54.0
LOCATION 6 – basement	50.0	96.0	75.0
LOCATION 7 – basement	43.0	60.0	52.0
LOCATION 7 – ground floor	33.0	52.0	41.0
LOCATION 8 – basement	48.0	67.0	62.0
LOCATION 8 – 1st floor	43.0	64.0	55.0

Table 4 shows the minimum, maximum and average values of atmospheric pressure. Atmospheric pressure values generally depend on altitude, and the higher it is, the lower the pressure. The values of the measured atmospheric pressure at individual locations range from 98 to 102 kPa. The results show that the radon concentration is higher at the locations where the lowest value of atmospheric pressure was measured (**Tables 1 and 4**). Namely, at location 5, the average measured radon concentration was 132 Bq/m^3 and the average atmospheric pressure was 99.96 kPa.

4. ESTABLISHMENT OF A MULTIPLE LINEAR REGRESSION MODEL

Based on the measured values of radon concentration and the environmental parameters (temperature, humidity, atmospheric pressure), the statistical correlation between the above indicators was determined. In other words, an attempt was made to determine whether there was a relationship between radon concentration and environmental parameters (Steck 2009; Xie et al. 2015). Using a univariate linear regression technique, a correlation (dependence) between the radon concentration and the environmental parameter was established. The technique of determining the correlation coefficient between two quantities, i.e. between the radon concentration and each individual environmental parameter was used (Roselund et al. 2008).

Table 4. Atmospheric pressure values (min., max. and average)

Location	p_{MIN} [kPa]	p_{MAX} [kPa]	p_{av} [kPa]
LOCATION 1 – basement	98.57	100.51	99.21
LOCATION 1 – ground floor	98.61	99.41	99.08
LOCATION 2 – basement	98.44	101.06	99.69
LOCATION 3 – ground floor	98.34	100.60	99.53
LOCATION 4 – 1st floor	97.46	99.74	98.73
LOCATION 5 – 1st floor	98.00	101.23	99.96
LOCATION 6 – basement	98.37	100.14	99.16
LOCATION 7 – basement	96.83	100.66	98.90
LOCATION 7 – ground floor	100.50	102.09	101.36
LOCATION 8 – basement	99.54	101.32	100.48
LOCATION 8 – 1st floor	99.69	101.80	100.67

Figures 2 and 3 show the scatter plots for radon concentration and individual environmental parameters (humidity and pressure) and the regression direction is plotted with the indicated calculated Pearson correlation coefficient. **Figure 2** shows the scatter plot for the ratio of radon concentration to humidity parameter at location 6 - basement, with a calculated decreasing Pearson correlation coefficient of -0.12 and a plotted regression direction that is decreasing. In cases of connection between radon concentration and humidity parameters, the obtained correlation coefficients are negative, and a negative correlation was observed between the radon concentration and the environmental humidity parameter. The ratio of radon concentration and pressure for location 3, ground floor is shown in **Figure 3**, with a scattering diagram with the calculated corresponding correlation coefficient and plotted ascending regression direction. Pearson's correlation coefficient is positive and amounts to 0.23, and the correlation between radon concentration and pressure is positive. From the above relations it can be concluded that there is a proportional relationship between air pressure and radon concentration, i.e., the higher the air pressure, the higher the radon concentration. **Table 5** shows the values of all correlation coefficients between radon concentration and environmental parameters (temperature, humidity, and atmospheric pressure) at individual locations.

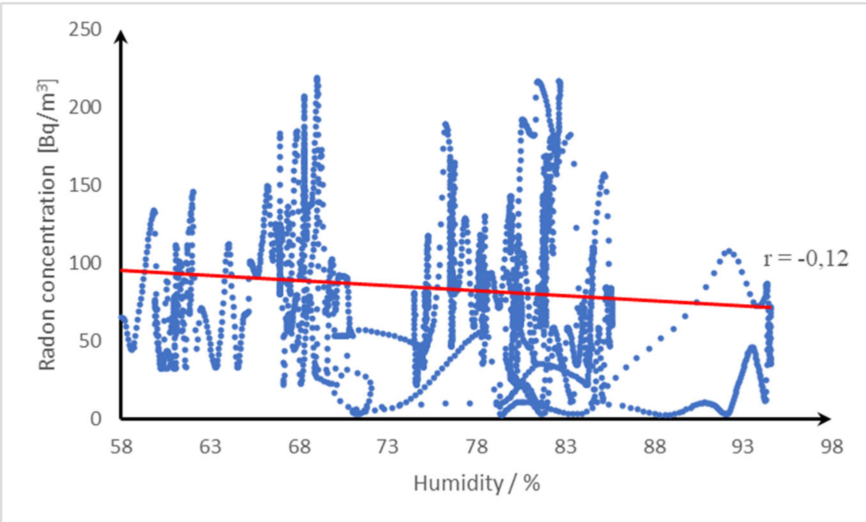


Figure 2. *Humidity - radon concentration scattering diagram, location 6 - basement*

Since all calculated correlation coefficients at absolute value are less than 0.5, these results indicate that a weak correlation was found in all interrelationships between radon concentration and environmental parameters. In this situation, it is advisable for each radon concentration to take those environmental parameters for which $| r | \geq 0.25$, i.e. which have a significant impact on them. For this reason, these indicators were taken as independent variables in multiple regression analysis (Roselund et al. 2008).

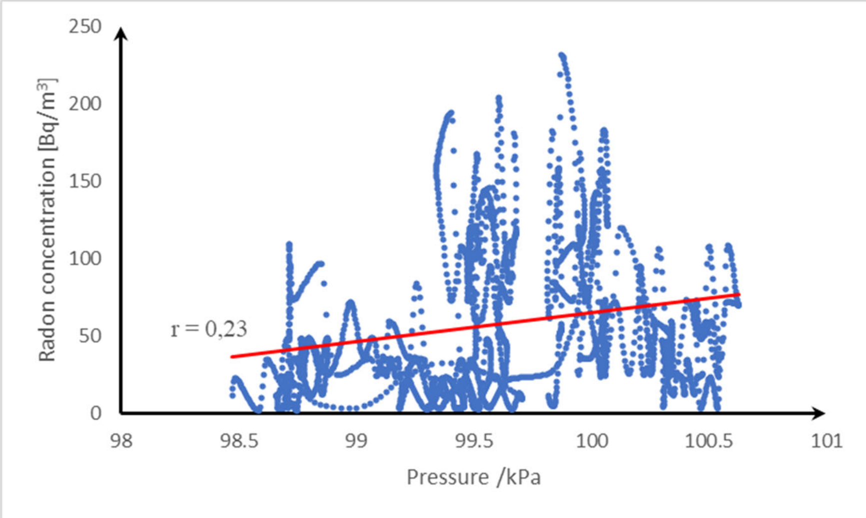


Figure 3. *Pressure scattering diagram - radon concentration, location 3 – ground floor*

Table 5. Correlation coefficients of radon concentration and environmental parameters

Location	Temperature [°C]	Humidity [%]	Pressure [kPa]
LOCATION 1 – basement	0.23	-0.17	0.11
LOCATION 1 – ground floor	0.13	-0.05	0.23
LOCATION 2 – basement	**-0.32**	0.16	**-0.30**
LOCATION 3 – ground floor	**0.33**	**-0.35**	0.23
LOCATION 4 – 1st floor	0.03	0.05	**-0.34**
LOCATION 5 – 1st floor	-0.17	**0.43**	-0.03
LOCATION 6 – basement	-0.08	-0.12	**-0.26**
LOCATION 7 – basement	0.11	0.23	0.11
LOCATION 7 – ground floor	-0.17	**0.28**	-0.20
LOCATION 8 – basement	0.19	0.21	**-0.37**
LOCATION 8 – 1st floor	-0.08	**0.38**	**-0.27**

At location 1, there is no significant influence of environmental parameters on the radon concentration, more precisely, the correlation coefficients in absolute value are less than 0.25. At location 2, temperature (r = -0.32) and atmospheric pressure (r = -0.30) have a significant influence on the radon concentration. Significant influence of temperature (r = 0.33) and humidity (r = -0.35) on radon concentration was obtained by correlation analysis at location 3. Correlation analysis also determined a significant influence of atmospheric pressure on radon concentration at location 4, where is r = -0.34. A significant influence of the environmental parameter of air humidity on the radon concentration at location 5 was calculated (r = 0.43), while the influence of pressure on the radon concentration at the same location was extremely low (r = 0.03), in contrast to the recorded influence of pressure at location 6. (r = -0.26). It is interesting to note that for the basement at location 7 there is no significant influence of environmental parameters on the radon concentration, but on the ground floor the influence of humidity was recorded (r = 0.28). At location 8, a significant influence of atmospheric pressure was recorded in the basement (r = -0.37) and on the first floor (r = -0.27). Also, on the first floor, the influence of humidity (r = 0.38) on the radon concentration is visible.

In general, an attempt was made to formulate a model of multiple linear regression of shapes according to the equation:

$$y = a_1x_1 + a_2x_2 + \cdots + a_nx_n \quad (1)$$

where y is the radon concentration, x_1, …, x_n are independent variables (environmental parameters that have a significant impact on radon concentration) and a_1,…, a_n are …. (Roselund et al. 2008).

For the application of the multiple linear regression model, 3 locations were considered, namely: a) location 2, b) location 3 and c) location 8, because at those specified locations two absolute values of the correlation coefficients are greater than 0.25. In other words, the influence of certain environmental parameters on radon concentration is statistically significant at these locations. In addition to the equations of the multiple regression model, scatter plots are also shown.

a) For location 2, the following multiple regression model was obtained, equation (2):

$$y = 1221{,}78 - 8{,}62 * T - 9{,}53 * p \tag{2}$$

where *T* is the value of the ambient temperature parameter and *p* is the value of the ambient pressure environmental parameter. It can be seen from the obtained model that the value of radon concentration (*y*) is inversely proportional to the values of the ambient temperature and pressure parameters. In other words, the higher the value of temperature and pressure, the lower the concentration of radon in the air. This conclusion is confirmed by the negative signs in front of the environmental parameters of temperature and pressure. Furthermore, the obtained results are confirmed by the descending directions (**Figures 4 and 5**), which confirm the inverse proportionality of radon concentration and temperature, i.e. radon concentration and pressure.

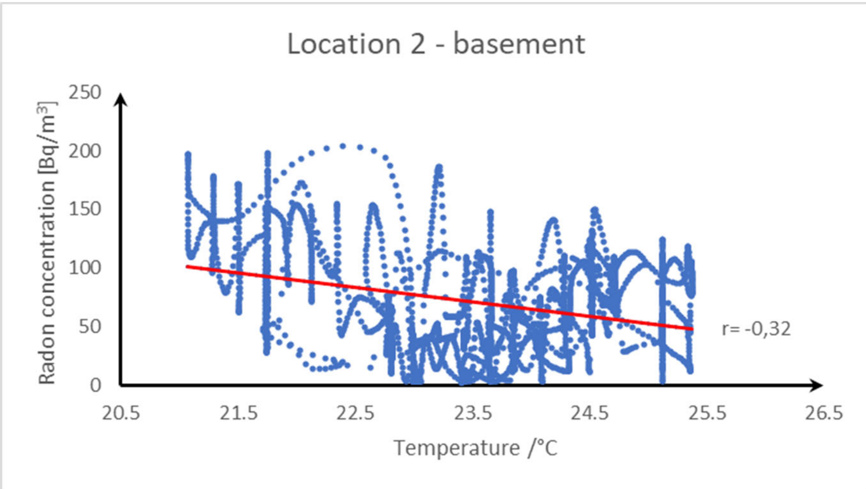


Figure 4. *Scattering diagram with plotted regression direction between radon concentration and temperature*

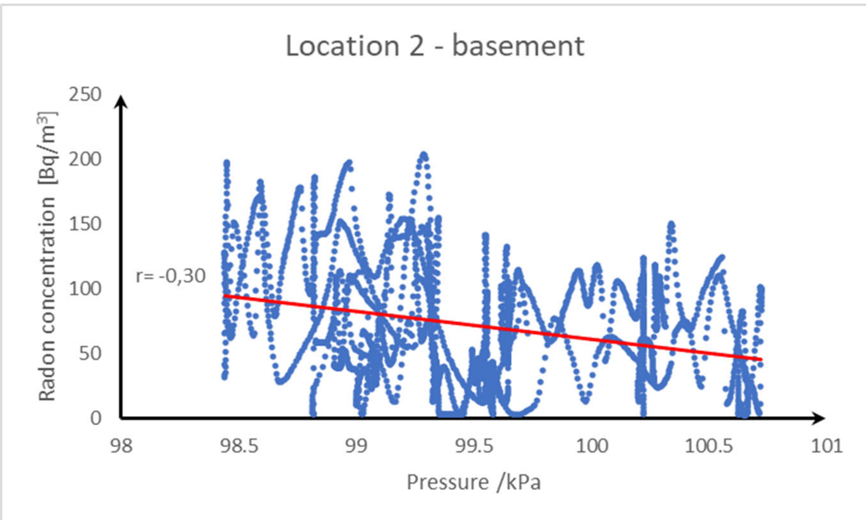


Figure 5. *Scattering diagram with plotted regression direction between radon concentration and pressure*

b) For measurement at location 3, the following multiple regression model was obtained, equation (3):

$$y = 63{,}11 + 1{,}85 * T - 0{,}93 * H \tag{3}$$

where T is the value of the ambient temperature parameter and H is the value of the ambient humidity parameter. It can be seen from this model that the value of radon concentration (y) is proportional to the value of the environmental temperature parameter and inversely proportional to the value of the environmental humidity parameter. This indicates that with increasing temperature, the concentration of radon in the air increases. Conversely, the higher the humidity parameter value, the lower the radon concentration in the air. This is confirmed by the results in **Figures 6 and 7** where one ascending direction and one descending direction are visible. In the single model, a positive correlation was obtained in relation to radon concentrations and temperature, while in relation to radon concentration and humidity, the correlation was negative, which is confirmed by the negative sign in front of the H parameter.

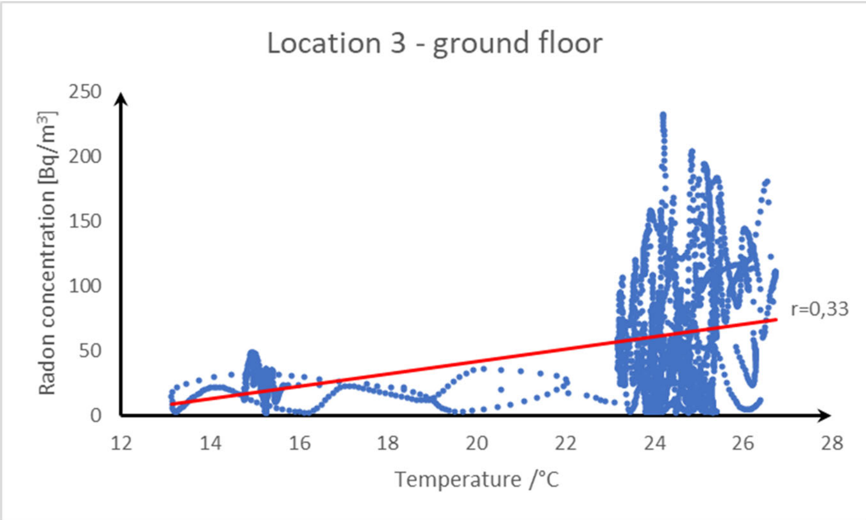


Figure 6. *Scattering diagram with plotted regression direction between radon concentration and temperature*

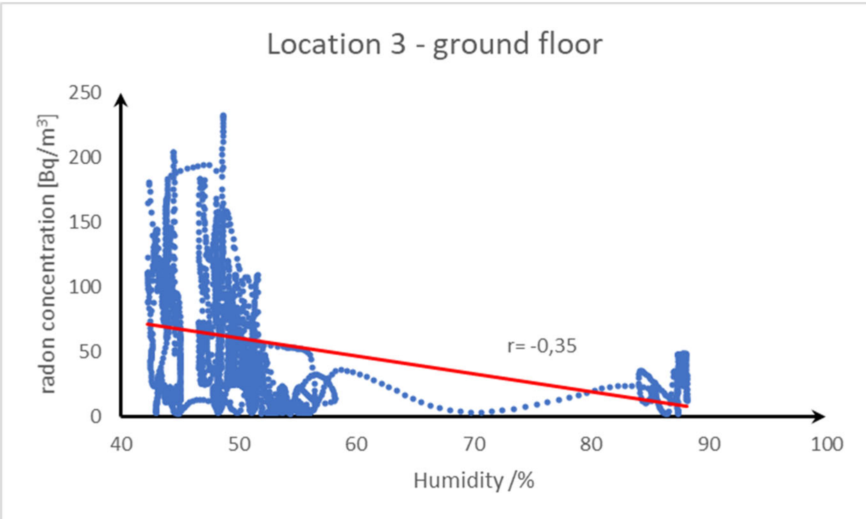


Figure 7. *Scattering diagram with plotted regression direction between radon concentration and humidity*

c) For the measurement at location 8, the following multiple regression model was obtained, equation (4):

$$y = 297{,}38 + 2{,}27 * H - 3{,}79 * p \quad (4)$$

where H is the value of the ambient humidity parameter and p is the value of the atmospheric pressure environmental parameter. It can be seen from this model that the value of the radon concentration (y) is proportional to the humidity value, i.e., the radon concentration increases with increasing humidity. However, the concentration of radon is inversely proportional to the value of atmospheric pressure, and as the atmospheric pressure increases, the concentration of radon in the air decreases. Observing the single regression model (**Figure 8 and Figure 9),** the correlation coefficient is positive, and this is confirmed by the positive sign in front of the humidity parameter value. However, in **Figure 9** the correlation coefficient is negative which confirms the negative sign in front of the atmospheric pressure parameter.

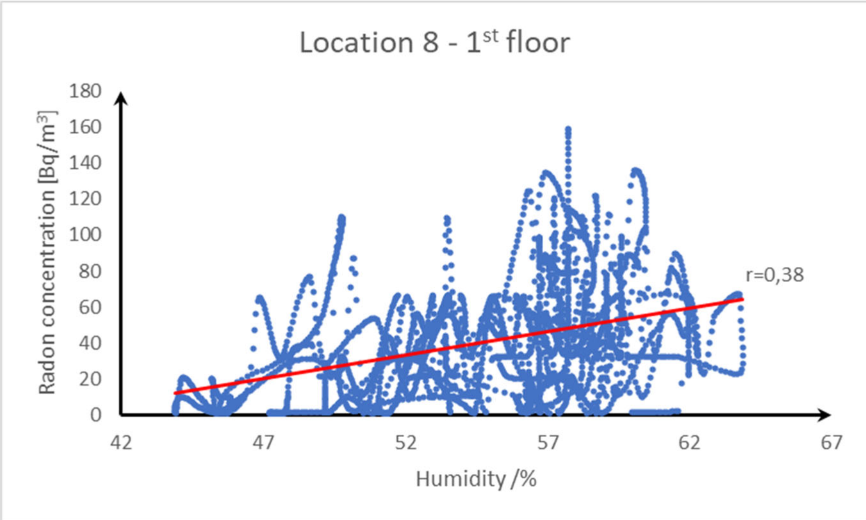


Figure 8. *Scattering diagram with plotted regression direction between radon concentration and humidity*

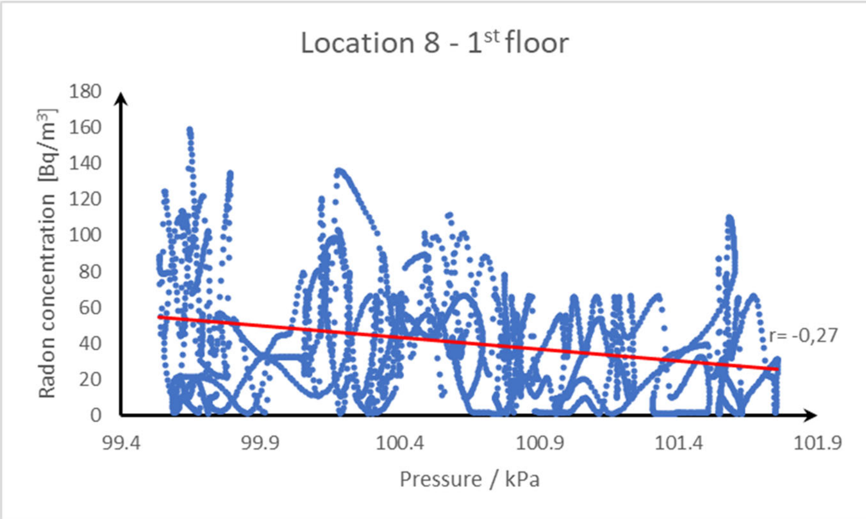


Figure 9. *Scattering diagram with plotted regression direction between radon concentration and pressure*

The obtained models can be used for the purpose of predicting radon concentrations at individual locations, which means that from the given equations for given values of input (independent) variables, it is possible to calculate or predict the radon concentration at an individual location (Roselund et al. 2008). At location 2, if we take the average values of the parameter T = 23,6 °C and the parameter p = 99,69 kPa, the radon concentration will be 68,30 Bq/m^3, as can be seen from equation 5 where the parameter values are included in equation (2):

$$\begin{gathered} y = 1221{,}78 - 8{,}62 * T - 9{,}53 * p \\ y = 1221{,}78 - 8{,}62 * 23{,}6 - 9{,}53 * 99{,}69 \\ y = 1221{,}78 - 203{,}43 - 950{,}05 = 68{,}3\ \mathrm{Bq/m^3} \end{gathered} \quad (5)$$

The average value of the measured radon concentration at location 2 is 70 Bq/m^3. Likewise, the radon concentration for location 3 can be calculated using equation (3). If we consider the average value of T= 23,6 ° C, and the average value of H (humidity) 53 %, we get the value of radon concentration which is 57,48 Bq/m^3, and the procedure of obtaining radon concentration can be seen in equation (6):

$$\begin{gathered} y = 63{,}11 + 1{,}85 * T - 0{,}93 * H \\ y = 63{,}11 + 1{,}85 * 23{,}6 - 0{,}93 * 53 \\ y = 63{,}11 + 43{,}66 - 49{,}29 = 57{,}48\ \mathrm{Bq/m^3} \end{gathered} \quad (6)$$

The average value of the measured radon concentration at location 2 is 56 Bq/m^3. If at location 8 on the 1st floor the average humidity parameter is 55 % and the average atmospheric pressure is 100.67 kPa. The equation (4) of the multiple models is considered. The result is a radon concentration value of 40,69 Bq/m^3, equation (7):

$$\begin{gathered} y = 297{,}38 + 2{,}27 * H - 3{,}79 * p \\ y = 297{,}38 + 2{,}27 * 55 - 3{,}79 * 100{,}67 \\ y = 297{,}38 + 124{,}85 - 381{,}54 = 40{,}69\ \mathrm{Bq/m^3} \end{gathered} \tag{7}$$

The average value of the measured radon concentration of radon at location 8 is 36 Bq/m^3. If calculated results of the concentration of the Radon are compared with the measured values, it is obvious that there is very small difference between them. This observation led to the conclusion that mathematical models of predicting the value of the concentration of Radon are accurate and can be used in practice.

5. CONCLUSION

Radon as a radioactive element contributes the most to natural radiation on Earth. In the open air, radon concentrations are low and harmless to human health, while indoors they can be elevated and as such dangerous to human health. In the Republic of Croatia, i.e., in Varaždin and Koprivnica-Križevci counties, at measuring locations, most households are not exposed to too high values of radon concentration. Since most radon comes from ground soil, the highest radon concentrations were measured in basements. By applying multiple regression analysis and establishing a mathematical model, it is possible to determine the statistical relationship between individual environmental parameters and radon concentration. The univariate model between the radon concentration and each environmental parameter and the obtained correlation coefficient also help to establish a multiple linear regression. For example, if the calculated correlation coefficient for certain parameters in a univariate model is the correlation coefficient is negative, the multiple regression model will show the inverse proportionality of the radon concentration to the value of a certain environmental parameter. The results indicate different relationships between radon concentration and temperature, humidity and atmospheric pressure at individual measurement sites. At all locations where the correlation coefficient between radon concentration and atmospheric pressure in absolute value is greater than 0.25, there is a negative correlation between these two quantities, i.e., the radon concentration decreases with increasing atmospheric pressure.

The main issue of obtaining a mathematical model capable of predicting radon concentration dependence on the environmental parameters for all locations and especially for certain region is hard to achieve as it was observed to be a local site function. However, given the change in climatic conditions at measuring sites, it is necessary to consider a longer period to determine with certainty a mathematical model that would give the most accurate prediction of radon concentration dependence on the environmental parameters which can affect human health and quality of life at these sites.

6. REFERENCES

Council Directive 2013/59/EURATOM
https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2014:013:0001:0073:EN:PDF
https://www.airthings.com/pro

James A (1988) Radon and its decay products in indoor air: An Overview. John Wiley & Sons, New York

Mostečak A, Perković D, Kapor F, Veinović Ž (2018) Radon mapping in Croatia and its relation to geology. MGPB, 33:1-11

Ordinance on dose limits, dose constraints and assessment of individual doses (Official Gazette 38/18)

Ptiček Siročić A, Stanko D, Sakač N, Dogančić D, Trojko T (2020) Short-Term Measurement of Indoor Radon Concentration in Northern Croatia. Appl Sci 10(7),2341: 1-13

Radolic V, Vukovic B, Stanic D, Katic M, Faj Z, Lukacevic I, Planinic J, Suveljak B, Faj D, Lukic M (2006) National survey of indoor radon levels in Croatia. J Radioanal Nucl Ch, 269:87-90

Rosenlund M, Forastiere F, Stafoggia M, Porta D, Perucci M, Ranzi A, Nussio F, Perucci C.A (2008) Comparison of regression models with land-use and emissions data to predict the spatial distribution of traffic-related air pollution in Rome. J Expo Sci Env Epid,18:92–199

Steck D.J (2009) Annual average indoor radon variations over two decades. Health Phys, 96:37-47

Xie D, Liao M, Kearfott K.J (2015) Influence of environmental factors on indoor radon concentration levels in the basement and ground floor of a building – A case study. Radiat Meas, 82:52-58

Zeeb H, Shannoun F (2009) WHO handbook on indoor radon: a public health perspective, WHO Press, Geneva