Fuzzy Radon Hazard Index Assessment for Stochastic Environmental Health Risk Evaluation of Urban Scale Building

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Abstract

Radon gas emission is an emerging phenomenon that modern lifestyles have become a potential danger to humans. So, stochastic evaluation of the amount of this hazardous gas in urban scale and residential buildings can be critical in identifying environmental health risks. A novel fuzzy Radon Hazard Index is proposed in this research to assess statistical radon environmental health risks. The output index FRHI ranges from 0 (No Hazard) to 100 (The highest degree of hazard). The approach can serve as a circumstantially integrated standard for stochastic radon risk assessment and management because innovation fuzzifies this field's most important stochastic standards. In this study, first, Radon was measured in the urban scale building, and then, Arc GIS software prepared natural Radon emission zoning maps at urban and geological scales. A residential building unit in one of the critical areas has been selected. Some corrective actions have been adopted to reduce Radon in urban building units. The FRHI Assessment for stochastic environmental health risk evaluation shows that the initial fuzzy level for the mean value of FRHI is Hazardous (for FRHI value equal to 60.1) determined by Red color. This is while the Maximum FRHI level for 48 hours after installation is Rather Hazardous (for FRHI value equal to 44.8) determined with orange color, and the maximum statistical environmental health risk after steady-state installation would fall into an improved category. So identifying critical areas can provide exceptional control at the urban scale building that reduces the risks of natural Radon.

Introduction

Natural Radon gas is formed as a byproduct in rocks (Przylibski et al. 2004). Natural Radon is emitted from the subsoil and is most concentrated in enclosed spaces (Meyer 2019), and Since Radon 222 has a half-life of around 3.82 days (Kulal et al. 2018), it can be stored in closed structures and remain in the air for many days (Chilingarian et al. 2021). So, homes and workplaces must be adequately ventilated (Mainardi et al. 2018). Natural elements are responsible for three-quarters of the radioactivity in the environment (Udovicic et al. 2020). Radon is the most abundant natural radioactive source (McGrath and Byrne 2020). The public health issue that its concentration causes both within buildings and drinking water necessitates consideration for evaluation (Alonso et al. 2019).

Radon decays result from ionizing radiation. As it penetrates matter (Usikalu et al. 2017), it usually draws electrons from the surrounding atoms in ionization mechanisms (Boerma et al. 2016). Suppose the material is a biological structure with high water content. In that case, the ionization of water molecules can produce so-called free radicals with a high degree of chemical activity, enough to change essential molecules found in living organisms' cells (Ravanat et al. 2021; Blundell, 2015). Chemical modifications in DNA, the essential organic molecule that is part of the cells that make up our bodies, may be among these alterations (Magalhães et al. 2003; Brenner 1994). These modifications can have biological consequences, such as irregular cell growth. (Stanley et al. 2021; Gesell 1983), these changes can be more or less severe, depending on the dosage of radiation received (Abaszadeh Fathabadi et al. 2020). The most serious hazard posed by Radon in enclosed spaces is inhalation (Lopes et al. 2021). Radon gas releases -particles that cannot migrate through lung tissues (Curado et al. 2021) and, as a result of their toxic effects, settle on them and cause damage to these tissues (Nguyen et al. 2021). The presence of people inside a building promotes air circulation and, as a result, reconstruction (Kladder 1995; Yarmoshenko et al. 2021). However, if the accumulation values are high, further disciplinary steps can be taken (Sciences 2021). This radioactive gaseous element is used in nearly all building materials and the soil where buildings are installed (Nastro et al. 2018; Rizo-Maestre and Echarri-Iribarren 2020). There are various Radon measurement instruments available. Some are operational, demand energy, and have a continuous record of Radon gas concentration and variations throughout the measurement time (Li et al. 2019; Hu et al. 2018). Others are passive, requiring no electricity to run in the sampling area (Sherafat et al. 2021). Radon detectors, alpha detectors, electrical ion detectors, and continuous controllers can measure Radon in suburban areas (Sainz et al. 2021; Bekteshi et al. 2021). A sensor made of activated carbon (coal) is used for short-term calculation in this study (Sainz et al. 2021). Since the maximum Radon concentration is achieved while the space in question is devoid of air ventilation (for example, when all windows and joints are closed), the brief measurement taken during this time should be considered more significant than the average annual Radon amount (Ahmad et al. 2021).

The earth is the most significant source of Radon in isolated structures or on the ground floor of buildings. The radio concentration in the ground ranges between 10 and 50 Bq/m3, with far higher values possible. The average value is approximately 40 Bq/m3 (Fard et al. 2021). Radium-226 determines the Radon level that reaches a building from the earth in the subsoil and its soil permeability (Maestre et al. 2021). Many countries have Radon content predictive charts, which primarily reflect the igneous makeup of the soil (Cambeses et al. 2016; Bochicchio et al. 2014; Spengler and Adamkiewicz 2009; Vimercati et al. 2021). Sweden, for example, has created maps focused on the calculation of Radon's geo-genic potential, which shows the danger level by zone based on the concentration of Radon in the ground at 1 m depth, Field Studies of Radon in Rocks, Soils, and Water – 1st Edition - Gu, (Maestre et al. 2021; Borgoni et al. 2011; Ielsch et al. 2010).

Similarly, the utility of approaches dependent on other factors, such as soil radio-226 concentration, has been investigated. In France, for example, the national map was created using geological maps and the average natural radon elements content of each geological unit (Bard 2017; Kemski et al. 2001). The German and Czech maps were both created using Radon's geo-genic ability. Both Radon gas predictive maps show granitic soils as the most dangerous in concentrations (Neznal et al. 2004; Neznal and Corp 2021; Francisco et al. 2017). There are various theories and structures for hazard identification and risk analysis that can focus on safety (Sarkheil and Rahbari 2016; Sarkheil et al. 2016) as well as health and environmental aspects (Sarkheil et al. 2020; Sarkheil 2021) so that by considering them, the risk of hazards arising from Reduced natural radon emissions.

Because of the role of this gas in community health, the amount of natural Radon gas released from various geological rocks and its impact on improving population distribution and residential and commercial places in the case study, were explored in this research. A location is surveyed, and multiple natural Radon inhibition procedures are investigated, with the findings interpreted and compared.

Materials And Methods

Natural Radon data emission/collection in the case study

Because of the importance of the case study region and its social and economic status in the country, natural Radon fertilization impressions have been performed in the urban scale (Fig. 1). The harvests performed have almost the same harvesting conditions as mentioned below. Data collection was performed during the three months and in the fall. The data were taken from closed places, the temperature and humidity conditions were constant and the same. Temperature ranges from 12 to 18 (dC) degrees Celsius, and humidity degrees were very low due to the climate of the case study and in the range of 10 to 17 percent. There are 145 neighborhoods in the urban scale of the case study, and we had at least one harvest in each neighborhood. It is considered the most critical in neighborhoods where more than one harvest has taken place. All data were collected from the basements of residential, commercial, or office units located in different parts of the city. Some of these basements were related to existing parking lots, and some were in buildings. In this study, an attempt has been made to take public places so that places where people are inevitably present, and the control of the situation is not in their hands has been examined. Places around the critical buildings and its underpasses have been taken several times, the most critical of which is considered. Below is a map of the different neighborhoods of the case study.

The Radon value was measured using a KATA Radon-Box/10 device (Tanaka et al. 2017). The accuracy of this device is acceptable, and for this reason, it has been used to measure Radon values in different parts of the city. The Radon-Box is made of metal and is filled with activated carbon. This device can be placed in the room for seven days to collect Radon. After this period, the device is analyzed using the analysis software available in the DGM-1500 (Sarén et al. 2016). The final result shows the amount of Radon in Bq/m^3.

Natural Radon distribution zoning maps for the urban areas were obtained using Arc GIS software and the geostatistical analysis tool (Qiu et al. 2012; Pulido-Bosch et al. 2015). Kriging, Areal, IDW, and co-kriging (Zhao et al. 2019; Gong et al. 2021) to achieve the most optimal Radon gas zonation, and parameters such as mean error and RMSE were used to compare them (Ćalasan et al. 2021).

Fuzzy Radon Hazard Index (FRHI)

In this study, a novel fuzzy attitude is conducted in continue of these studies: Sarkheil and Rahbari 2016a; Sarkheil and Rahbari 2016b; Sarkheil et al. 2018a; Sarkheil et al. 2018b; Sarkheil et al. 2018c; Sarkheil and Rahbari 2017; Sarkheil and Rahbari 2015; Sarkheil et al. 2021a; Sarkheil et al. 2021b; Sarkheil et al. 2019. This part proposes a comprehensive index via a fuzzy inference system for assessing health problems caused by emissions of radon gas. For this aim, some essential criteria are studied, which are listed in Table 1 and schematically presented in Fig. 2.
Regarding non-linearity of output FRHI, it is highlighted that the curves are calibrated. The main attitude is overestimating, i.e., for levels above less hazardous, the FRHIs rise sharply just after category start point (critical points recommended by standards) while smoothing down before the category endpoint. This

notion satisfies the rigor required for an accepted worldwide standard. For non-hazardous and less hazardous levels, the pattern is smoothing after start points while accelerating before endpoints. Because the lower amounts are not so crucial, while critical values are those close to higher bounds, this is a significant advantage of the novel fuzzy method introduced in this study. Indeed this fuzzy approach identifies the critical conditions well and can address corresponding health recommendations.

The produced FIS for FRHI has 5 Gaussian MFs for both input and output, demonstrated in Figs. 3a & b. The prepared FIS can be extracted from Appendix 1.
It is highlighted that the output received by FRHI is very trustworthy because it is constructed upon integration of four reputed international standards, and it can be widely accepted by many studies just as the results of the present study in followings. Fuzzy perceptions help researchers to conceptualize the fuzzy radon health risk better because the main body of the hazards and health and environmental risks are non-linear and too complex

Management Of Radon Risk:

After a thorough risk assessment is performed, it should be devoted to continuing risk management. The most critical risk management methods are generally stated as follows (Sarkheil and Rahbari 2016):

- Risk Elimination/Decrease
- Risk Control by engineering acts
- Risk Mitigation
- Risk Transfer
- Risk Substitution
- Endorsing PPEs[4]

Among the above general list, steps 1 and 2 are precisely the most proper and effective methods for Radon emission risk management because radon emissions have natural radix and vary from site and time to another site and time. Health masks are suitable only for temporarily outdoor conditions and may not be useful for indoor and long-time consumption.

So for decreasing health risk problems of radon emissions, it is highly advised to decrease indoor radon concentration by engineering methods.

The essential engineering methods are as follows:

- Closing of Radon inlets to indoors after finding the natural emission primary way. Most radon emissions happen through microscopic and macroscopic holes on the ground surface. It is advised to use proper insulations for floors, usually made of rubber or slurry
- We are utilizing proper free or forced ventilation for rooms by canals or fans.
- Soil Suction from underground spaces by proper pipelines attached to the suction motor

- Pressurize the indoor space with proper blowers, fans, coolers, etc., to reduce the emission driving force.
- Using impermeable paints for walls

A case study for proper ventilation is studied as follows. A twenty-four-year residential unit with a total area of 224 square meters and 178 square meters of infrastructure was selected, implemented on one floor with a basement and a gabled roof. Materials and hand concrete have been used to build this building. The window frames of this residential unit are made of metal, and single-pane glass is used for doors and windows. This residential unit is located in the Kuh-e-sangi area, 20th Kuh-e-sangi street, No. 27 (located in the southern part of the city - an area with high Radon pollution and worn texture), and currently, four people live in it. Radon values have been measured in ten points by the Radon Box-10 device to evaluate the Radon values in this residential unit. There are four ways to reduce Radon concentrations inside buildings:

- Ventilate air rich in Radon.
- Reduce Radon input.
- Radon emission sources should be shifted.
- Radon and its derivatives should be removed or eliminated in some way (Skeppström et al. 2021)

Ventilation methods cause Radon-filled air to escape, and Radon accumulation will be prevented by entering the outside air. The quality of the walls and floor also plays a vital role in preventing Radon from entering and blocking cracks and holes in the Radon concentration. Theoretically, it is possible to pass indoor air through a type of filter so that Radon and its derivatives are absorbed by the filter and separated from the indoor air (Cooper et al. 2021).

Then, using the method of reducing the pressure under the slab, Radon was repelled in this residential unit. Additional drainage wells and concrete adhesive sealing foundation and body cracks have been used to make this method more efficient. (Yuan et al. 2019)To better evaluate the performance of the Radon correction method, measurements and diagrams of its changes have been drawn every 12 hours and four times.

To improve the efficiency of the Radon correction system using the method of reducing the air pressure under the slab, the method of drilling the Radon absorption well and repairing the cracks in the body and foundation in the basement has been used. For this purpose, all cracks and crevices in the floor, walls, and corners of rooms and basements were first identified and repaired with concrete adhesive. For this purpose, Faber concrete adhesive is used to repair superficial and deep damage. Faber concrete adhesive has different uses. Faber concrete adhesive is without the need to add water and is homogeneous. Faber concrete adhesive has high tensile and flexural strength and effectively increases gypsum and lime concrete durability. Most of the use of concrete adhesive is related to repair work because this additive with mortar forms a harmonious and homogeneous mixture and at the same time prevents water seepage and separation of fine and coarse grains. The physical state of concrete adhesive in liquid form and color of this concrete adhesive is a milky color. The weight of Faber 1 concrete adhesive is 3gr / cm, and Faber concrete adhesive does not contain chlorine. The concrete adhesive is packed in 4 and 20-liter plastic containers (Fuente et al. 2021).

[4] Personal Protective Equipment

Results And Discussions

Stochastic evaluation of Radon zoning

Based on the mean error values and RMSE, the kriging method was selected as the most optimal method. In this study, Radon levels were measured in 145 neighborhoods of the city. Then, Radon zoning was performed by four interpolation methods based on the measured values. As expected, the kriging method was selected as the most optimal method. The population density map of the city, the zoning map by kriging method, and the map of places and streets of the study area were used to evaluate the zoning results on an urban scale. The results are shown in Table 1. The column FRHI in Table 1 denotes the amounts of fuzzy Radon Hazard Index contrasted by predefined colors. As it is derived from FRHI columns for 159 stations, only 9 stations (about 5.6%) are categorized in Very Hazardous Level by Purple color, 89 stations (about 55.9%) are categorized in Non-Hazardous Level by Green color, 45 stations (about 28.3%) are categorized in Less-Hazardous Level by Yellow color, 7 stations (about 4.4%) are categorized in Rather Hazardous Level by Orange color, and nine stations (about 5.6%) are categorized in Hazardous Level by Red color. Fortunately, the majority of stations, 55.9%, receive non-hazardous exhibits; the city has good radon environmental health assessment conditions. For hazardous and very hazardous stations, environmental and health management methods should efficiently be employed in order to improve the radon hazard index. Table 2 also shows the measured quantities of Radon gas in each of them.

The most polluted areas of Radon in the city are region 8 in areas 1, 2, region 12 in area 2, region 12 in area 3, region 6 in area 3, and region 5 in area 3. The cause of pollution regions 8 in areas1 and two are being within the shrine's traditional texture and not observing urban planning principles and poor air conditioning in these areas. Region 12 in area 3 includes the Asian Highway, which is the busiest entrance road to the city from Tehran. Also, in this zone, geological formations naturally emit high amounts of Radon. Region 12in area 2 is located in near Industrial Town, which is likely to have high radon levels due to many industrial units in the area. Region 6 in area 3 is located in the adjacent of power plant, where the Radon released from its activity is the primary possibility for high amounts of Radon and can be the main reason for observing higher Radon levels in this area. The rest of the study area is within the Radon limit. The cleanest areas are region 9 in area 2, region 11 in area 2, region 12 in area 1, region 7 in area 3, region 2 in area 5, area 6, and region 2 in area 6. Also, in area 2 and region11 in area 2, there is the Great Nation Park, which has caused the Radon values in this zone to remain much lower than the permissible limit. Radon values are very high around region 12 in area 1, but in the middle of this area, due to green space (Vakilabad Park), Radon values are within the permissible range. In region

7 in area 3, Tough Forest Park is the main factor in the permissibility of Radon gas. In region 2 in areas 5, 6, and region 6 in area 2, due to very low population density and its geological structure, Radon values are within the allowable range (Fig. 4).

Four interpolation methods, such as areal, IDW, Kriging, and Co-Kriging, were used to model spatial variations (Table 3). Kriging and co-kriging methods are based on the definition of the variogram, and the success of the method depends on choosing the appropriate or optimal variogram model. In this method (IDW), the weights are determined only according to the distance of each known point from the unknown point, without considering the distribution of points around the estimated point. Nearby points are given more weight, and farther points are given less weight. R2, ME, and RMSE indices are used to compare the accuracy of kriging, co-kriging, IDW, and Areal interpolation methods (Warrick et al. 2021).

Table 3
Comparison of interpolation methods for Radon zoning measured at the urban scale

Interpolation Method	Average Error (%)	RMSE (%)	Number of Samples
Areal	13.28	12.70	145
IDW	11.25	24.23	145
CO-Kriging	10.49	14.40	145
Kriging	5.46	17.45	145

The Results Of The Implementation Of The Method In The Selected Residential Unit

After repairing the cracks, and absorption well was dug in the building area at a distance of 1.5 meters from the sidewall of the foundation, with a depth of 3 meters and a diameter of 30 cm. Used to hold the fan steady. For this purpose, a 20-watt blowing shaft fan with an airflow rate of 100 cubic meters per hour was used. The good chamber was covered with aluminum foil, and a hole with a diameter of 7.5 cm was passed in the center to expel the air. The area around the well was covered with concrete adhesive, and the perimeter of the PVC pipe was covered with glass adhesive to prevent air leakage. Then, using a Hilti device, a hole was dug to a depth of 25 cm below the slab and a diameter of 7.5 cm in the corner of the main corridor of the basement. Then it was connected to the air transfer pipe installed outside the building by an elbow pipe. In the first 30 cm of the buried pipe, holes were made under the slab at intervals of one centimeter to facilitate air passage. The PVC pipe used continued to the roof level, then was connected to the suction system installed in the roof by a flexible plastic pipe, and thus the air containing Radon was transferred out of the building. The suction system includes two 15-watt axial suction fans with an efficiency of 85 and a percentage placed in parallel (Appendix 2).

The measurement time at each harvest point was about ten minutes every twelve hours and up to 48 hours after installing the Radon disposal system. In total, 50 measurements of Radon gas have been taken in this residential unit. The maximum registered amount is equal to 219 Becquerel's per cubic meter for the basement, and the minimum amount is equal to 86 Becquerel's per cubic meter for the attic. As in previous sections, the Radon limit is set at 147 Becquerel's per cubic meter (EPA). Table 4 shows the measured values.

Table 4
Natural Radon measured values in different parts of the residential unit Bq/m^3.

Sampling location	Floor	Initial value	12 hours after installation	24 hours after installation	36 hours after installation	48 hours after installation
Hallway	Basement	127	119	112	108	101
WC No.2	Basement	219	189	168	139	112
The main room	Basement	179	167	159	146	132
Living room	1st floor	168	153	149	135	121
kitchen	1st floor	156	147	138	127	113
Attic	1st floor	86	85	83	82	79
Bedroom	1st floor	119	113	106	100	97
Child room	1st floor	138	124	119	115	110
WC	1st floor	163	157	138	121	119
Guest room	1st floor	114	110	108	105	98
Average	Both	146.9	136.4	128	117.8	108.2

In Table 4, natural Radon emission was measured at known points, and its values were assumed to be the initial value. After installing the Radon reduction system, it was measured continuously and every 12 hours. The Radon values were reduced alternately in all measurements, reflecting the positive result of this corrective method.

As expected, the toilets had the highest, and the gables had the lowest recorded value due to their adequate ventilation and the physical nature of the Radon accumulation in the lower floors and heights, as below Eq. (1).

$y = 150.84 X^{(-0.182)}$ (1)

Where y, is the amount of Radon over time X (one unit is half a day or 12 hours).

The cost of implementing this correction method is estimated at 100 USD, which is very small compared to Radon-related therapeutic costs. To further reduce the amount of Radon, the building owner uses a package and a wall-mounted radiator instead of a heating system.

In the bathroom and toilet area, use more robust artificial ventilation and seal the doors and windows in winter, improving natural ventilation. It is better to open all the doors and windows and change the air inside the building in some cases.

The diagrams in Figs. 5a, b and c show that the efficiency of the Radon ventilation system will reach its maximum value after about one week. It is better to use auxiliary sensors to optimize power consumption. For this purpose, a system can be used that starts working from a specific limit if the Radon values rise and stay in standby mode when unnecessary.

It is important to note that the initial fuzzy level for the mean value of FRHI is Hazardous (for FRHI value equal to 60.1) determined by Red color. This is while the Maximum FRHI level for 48 hours after installation is Rather Hazardous (for FRHI value equal to 44.8) determined with orange color. This matter expresses that the maximum statistical environmental health risk after steady-state installation would fall into an improved category exhibiting hazards instead, however, for mean values, this level would fall into less hazardous, which meets all three recommendations of ICRP, USEPA, and WHO.

The interesting point, in this case, is that the owner of the building initially opposed the installation of the system. Still, after learning about Radon gas's very dangerous harms and the relatively high amounts of Radon in his home, he agreed to adopt this system and cooperated in all stages. It can be concluded that most people, even the educated, are not sufficiently aware of Radon gas and its harms, and it is better to cultivate this issue first. When this issue is implemented, the people themselves tend to adopt corrective methods.

Conclusion

Based on the mean error values and RMSE, the kriging method was selected as the most optimal method. A significant result obtained in this section of the urban-scale Radon zoning assessment is that green spaces in the city reduce air pollution and prevent it from condensing in one place by creating a natural airflow. Therefore, it can be suggested to create urban green spaces in polluted areas of the city. It is better to expand the city and buildings in the northern and southern parts of the study area, where the Radon emissions levels are low. It is better to conduct a comprehensive assessment in hotels and inns of the city. If necessary, a correction system for Radon values should be adopted. Carefully in the population density map of the study area, it is concluded that there is a direct relationship between population density and increase in Radon values, so another way to reduce Radon values is to reduce population density in an area.

In this study, to reduce the Radon values in a residential unit, reducing the pressure under the slab, along with two other auxiliary methods, was used. Radon values were collected at 5 points before installing the system to evaluate the system's performance. Due to Radon's accumulation at lower levels and poor ventilation in the basement, the values recorded in this area were higher than those recorded on the first floor. In the basement, the bathroom and the main room show the highest amounts of Radon. On the main floor of this studied building, the bathroom, kitchen, and children's room show the highest values. The reason for this is the release of Radon in the kitchen. In contrast, they were burning gas for cooking and appliances such as washing machines, refrigerators, and freezers. In other areas, lack of proper ventilation has been recorded as the leading cause of the increase. Given that the measurements were made in the fall, it is likely that Radon levels in the winter will increase due to heaters and sealing of doors and windows, consequently reducing natural ventilation. If the residents do not install a healthy correction system, they will probably be in danger.

The average of the initial recorded values was equal to 146.9 Becquerel's per cubic meter to evaluate the system's performance, which decreased the Radon values every 12 hours after installing the system. According to the information in the tables, it was determined how the system efficiency increases. Within 48 hours, the system's efficiency increased to 28%, which means that after 48 hours, the amount of Radon reached 72%. This value is expected to increase to 50% in the long run and remain constant after that. To obtain the average long-term Radon, we also obtained a fitting line based on the measured values, which will be obtained by Eq. 1 of the long-term Radon values (Table 5).

Table 5
Measured Radon values and increase in system efficiency percentage over time.

	Initial value	12 hours after installation	24 hours after installation	36 hours after installation	48 hours after installation
The amount of Radon	146.9	136.4	128	117.8	108.2
Decreased Ratio	1	0.92852	0.87134	0.80191	0.73656
System Efficiency (percentage)	0	7.14772	12.8652	19.8094	26.3445

As mentioned, natural radon emissions from subsurface rocks and fractures are present in all parts of the world. So identifying critical areas (with high radon emissions) can provide special control measures at the local and site scale buildings that reduce the risks of this natural gas.

Declarations

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Conflict of interest

The authors have no relevant financial or non-financial interests to disclose. The authors have no conflicts of interest to declare that are relevant to the content of this article.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

References

1. Abaszadeh Fathabadi Z, Ehrampoush MH, Mirzaei M, Mokhtari M, Sakhvidi MN, Rahimdel A, Dehghani Tafti A (2020) The Relationship of Indoor Radon Gas Concentration with Multiple Sclerosis: A Case-Control Study. Environ Sci Pollut Res 27 (14): 16350–61. https://doi.org/10.1007/s11356-020-08147-y.
2. Ahmad N, Khan IU, Rehman UR J, Nasir T (2017) An Overview of Radon Concentration in Malaysia. J Radiat Res, Accessed May 14, 2021. https://www.sciencedirect.com/science/article/pii/S168785071730095X.
3. Alonso H, Rubiano JG, Guerra JG, Arnedo MA, Tejera A, Martel P (2019) Assessment of Radon Risk Areas in the Eastern Canary Islands Using Soil Radon Gas Concentration and Gas Permeability of Soils. Sci Total Environ 664 (May): 449–60. https://doi.org/10.1016/j.scitotenv.2019.01.411.
4. Bard D (2017) Commentaries. Environnement, Risques et Sante. John Libbey Eurotext. https://doi.org/10.3390/ijerph14040344.
5. Bekteshi S, Kabashi S, Ahmetaj S, Xhafa B (2017) Radon Concentrations and Exposure Levels in the Trepça Underground Mine: A Comparative Study. J Clean Prod, 155(1): 198-203. https://www.sciencedirect.com/science/article/pii/S0959652616317632.
6. Blundell M (2015) Naturally Occurring Radioactive Materials. In Proceedings of the American Gas Association, Operating Section, 1:490–502. American Gas Association. https://doi.org/10.1201/9780203746042.
7. Bochicchio F, Žunić ZS, Carpentieri C, Antignani S, Venoso G, Carelli V, Cordedda C, Veselinović N, TollefsenT, Bossew P (2014) Radon in Indoor Air of Primary Schools: A Systematic Survey to Evaluate Factors Affecting Radon Concentration Levels and Their Variability. Indoor Air 24 (3): 315–26. https://doi.org/10.1111/ina.12073.

8. Boerma M, Vijayalakshmi S, Xiao WM, Gregory A, Nelson, Amrita KC, Koturbash I, Singh SP, Tackett AJ, Hauer-Jensen M (2016) Effects of Ionizing Radiation on the Heart. Mutat Res Rev Mutat Res 770 (Pt B): 319–27. https://doi.org/10.1016/j.mrrev.2016.07.003.
9. Riccardo B, Tritto V, Bigliotto C, de Bartolo D (2011) A Geostatistical Approach to Assess the Spatial Association between Indoor Radon Concentration, Geological Features, and Building Characteristics: The Case of Lombardy, Northern Italy. Int J Environ Res 8 (5): 1420–40. https://doi.org/10.3390/ijerph8051420.
10. Brenner D J (1994) Protection against Radon-222 at Home and at Work. ICRP Publication 65. Int J Radiat Biol 66 (4): 413–413. https://doi.org/10.1080/09553009414551371.
11. Ćalasan M, Aleem SHEA, Zobaa AF (2020) On the Root Mean Square Error (RMSE) Calculation for Parameter Estimation of Photovoltaic Models: A Novel Exact Analytical Solution Based on Lambert W Function. Energy Convers Manag https://www.sciencedirect.com/science/article/pii/S0196890420302545.
12. Cambeses A, Garcia-Casco A, Scarrow JH, Montero P, Pérez-Valera LA, Bea F (2016) Mineralogical Evidence for Lamproite Magma Mixing and Storage at Mantle Depths: Socovos Fault Lamproites, SE Spain. Lithos 266–267 (December): 182–201. https://doi.org/10.1016/j.lithos.2016.10.006.
13. Chilingarian A, Hovsepyan G, Sargsyan B (2021) Circulation of Radon Progeny in the Terrestrial Atmosphere during Thunderstorms. Geophys Res Lett, Blackwell Publishing Ltd. https://doi.org/10.1029/2020GL091155.
14. Cooper A, Le TN, Iimoto T, Kosako T (2011) Temperature Calibration Formula for Activated Charcoal Radon Collectors. J Environ Radioact, Accessed May 14, 2021. https://www.sciencedirect.com/science/article/pii/S0265931X10002031.
15. Curado A, Silva JP, Lopes SI (2020) Radon Risk Assessment in a Low-Energy Consumption School Building: A Dosimetric Approach for Effective Risk Management. Energy Rep, Accessed May 14, 2021. https://www.sciencedirect.com/science/article/pii/S2352484719312739.
16. EPA (2012) A citizen's guide to Radon: The guide to protecting yourself and your family from Radon. Washington, DC: United States Environmental Protection Agency.
17. USEPA (1992) Radon decay product measurement device protocols. Washington DC: United States Environmental Protection Agency.
18. Fard ZD, Rahimi M, Malakootian M, Javid N (2021) Studying Radon Concentration in Drinking Water Resources in Zarand City (Iran) and Its Villages. J Radioanal Nucl Chem, Accessed May 14, 2021. https://link.springer.com/article/10.1007/s10967-020-07349-5.
19. Francisco PW, Jacobs DE, Targos L, Dixon SL, Breysse J, Rose W, Cali S (2017) Ventilation, Indoor Air Quality, and Health in Homes Undergoing Weatherization. Indoor Air 27 (2): 463–77. https://doi.org/10.1111/ina.12325.
20. Fuente M, Rábago D, Goggins J, Fuente I (2019) Radon Mitigation by Soil Depressurisation Case Study: Radon Concentration and Pressure Field Extension Monitoring in a Pilot House in Spain. Sci

Total Environ, Accessed May 14, 2021. https://www.sciencedirect.com/science/article/pii/S004896971933685X.

21. Gesell Thomas F (1983) Background Atmospheric 222Rn Concentrations Outdoors and Indoors: A Review. Health Physics 45 (2): 289–302. https://doi.org/10.1097/00004032-198308000-00002.
22. Gong G, Mattevada S, O'Bryant SE (2014) Comparison of the Accuracy of Kriging and IDW Interpolations in Estimating Groundwater Arsenic Concentrations in Texas. Environ Res, Accessed May 14, 2021. https://www.sciencedirect.com/science/article/pii/S0013935113002065.
23. Jun H, Yang G, Hegedűs M, Iwaoka K, Hosoda M, Tokonami S (2018) Numerical Modeling of the Sources and Behaviors of 222Rn, 220Rn and Their Progenies in the Indoor Environment—A Review. J Environ Radioact, https://doi.org/10.1016/j.jenvrad.2018.03.006.
24. ICRP (1995) ICRP Publication 69: Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 3 Ingestion Dose Coefficients. The Netherlands: Elsevier Health Sciences.
25. Welsch G, Cushing ME, Combes P, Cuney M (2010) Mapping of the Geogenic Radon Potential in France to Improve Radon Risk Management: Methodology and First Application to Region Bourgogne. J Environ Radioact 101 (10): 813–20. https://doi.org/10.1016/j.jenvrad.2010.04.006.
26. Kemski J, Siehl A, Stegemann R, Valdivia-Manchego M (2001) Mapping the Geogenic Radon Potential in Germany. Sci Total Environ 272:217–30. https://doi.org/10.1016/S0048-9697(01)00696-9.
27. Kladder Douglas L (1995) Protecting Your Home from Radon : A Step-by-Step Manual for Radon Reduction /. Colorado Vintage Companies, Inc.
28. Feride K, Akkurt İ, Özgür N, Sezer M (2018) The Correlation of the Seismic Activities and Radon Concentration in Soil Gas. Arab J Geosci 11 (16). https://doi.org/10.1007/s12517-018-3743-8.
29. Peng L, Zhang R, Gu M, Zheng G (2018) Uptake of the Natural Radioactive Gas Radon by an Epiphytic Plant. Sci Total Environ 612: 436–41. https://doi.org/10.1016/j.scitotenv.2017.08.253.
30. Lopes SI, Silva J, Antão A, Curado A (2018), Short-Term Characterization of the Indoor Air Radon Concentration in a XII Century Monastery Converted into a School Building. Energy Proscenia, https://www.sciencedirect.com/science/article/pii/S1876610218308488.
31. Maestre C R, Iribarren VE (2018) The Radon Gas in Underground Buildings in Clay Soils. The Plaza Balmis Shelter as a Paradigm. Int. J. Environ. Res. Public Health 2018. https://www.mdpi.com/1660-4601/15/5/1004.
32. Magalhães MH, Amaral ECS, Sachett I, Rochedo ERR (2003) Radon-222 in Brazil: An Outline of Indoor and Outdoor Measurements. J Environ Radioact 67 (2): 131–43. https://doi.org/10.1016/S0265-931X(02)00175-3.
33. Mainardi AS, Redlich CA (2018) Indoor Air Quality Problems at Home, School, and Work. Am. J. Respir. Crit 198 (1). https://doi.org/10.1164/rccm.1981P1.
34. McGrath James A, Byrne MA (2020) An Approach to Predicting Indoor Radon Concentration Based on Depressurisation Measurements. Indoor and Built Environment. https://doi.org/10.1177/1420326X20924747.

35. Winfried Meyer (2019) Impact of Constructional Energy-Saving Measures on Radon Levels Indoors. Indoor Air 29 (4): 680–85. https://doi.org/10.1111/ina.12553.
36. Nastro V, Carnì DL, Vitale A, Lamonaca F, Vasile M (2018) Passive and Active Methods for Radon Pollution Measurements in Historical Heritage Buildings. J Int Meas Confed 114 (January): 526–33. https://doi.org/10.1016/j.measurement.2016.09.002.
37. Neznal M, Matolin M, Barnet I, Miksova J (2004) The New Method for Assessing the Radon Risk of Building Sites. http://c14.kiev.ua/pdf/method.pdf.
38. Matěj N, Neznal M (2021) Reliability of the new Method for Assessing the Radon Risk-gas Permeability Classification. Radon Vos Cz, https://radon-vos.cz/pdf/permeability_class.pdf.
39. Nguyen PTH, NB Vu, Le Cong H (2021) Soil Radon Gas in Some Soil Types in the Rainy Season in Ho Chi Minh City, Vietnam. J Environ Radioact, https://www.sciencedirect.com/science/article/pii/S0265931X17310676.
40. Andrzej Tadeusz P, Mamont-Cieśla K, Kusyk M, Dorda J, Kozłowska B (2004) Radon Concentrations in Groundwaters of the Polish Part of the Sudety Mountains (SW Poland). J Environ Radioact 75 (2): 193–209. https://doi.org/10.1016/j.jenvrad.2003.12.004.
41. Pulido-Bosch A, Rigol-Sanchez JP, and Stuart N)2015) Arc Geomorphometry Arc Geomorphometry: A Toolbox for Geomorphometric Characterisation of DEMs in the ArcGIS environment, https://doi.org/10.1016/j.cageo.2015.09.020.
42. Fang Q, Zhang C, Zhou Y (2012) The Development of an Areal Interpolation ArcGIS Extension and a Comparative Study. Taylor & Francis 49 (5): 644–63. https://doi.org/10.2747/1548-1603.49.5.644.
43. Ravana JL, Douki T (2021) UV and Ionizing Radiations Induced DNA Damage, Differences and Similarities. Radiat Phys Chem, https://www.sciencedirect.com/science/article/pii/S0969806X1630216X.
44. Rizo-Maestre C, and Echarri-Iribarren V (2020) Radon Gas in the City of Alicante. High Risk of Low Indoor Air Quality in Poorly Ventilated Buildings. Int J Environ Res 17 (23): 1–25. https://doi.org/10.3390/ijerph17238762.
45. Sainz C, Rábago D, Celaya S, Fernández E, Quindós J, Quindós L, Fernández A, Fuente I, Luis Arteche J, Santiago Quindós L (2018) Continuous Monitoring of Radon Gas as a Tool to Understand Air Dynamics in the Cave of Altamira (Cantabria, Spain). Sci Total Environ, https://www.sciencedirect.com/science/article/pii/S0048969717335726.
Sarén J, Tuunanen J, Uusitalo J (2016) High Voltage Conditioning of the Electrostatic Deflector of MARA. Nucl Instrum Methods Phys Res B 376: 353–56. https://doi.org/10.1016/j.nimb.2015.11.025.
46. Sarkheil H, Rahbari S (2016) HSE key performance indicators in HSE_MS establishment and sustainability: a case of south pars gas complex, Iran, Int J Occup Hyg 8 (1): 52–60.
47. Sarkheil H, Tavakoli J, Rezvani S (2016) Inherent safety process assessment in the initial phase of the chemical design process: the case of acetic acid production process, Safety Promot Inj Prev 4 (1): 207–212.

48. Sarkheil H, Tahery B, Rayegani B, Ramezani J, Goshtasb H, Jahani A)2020(Evaluating the current status of the national health, safety, and environment management system for integration, harmonization, and standardization of environmental protection, Health Risk Anal 1, 18–24, https://doi.org/10.21668/ health.risk/2020.1.02.eng.
49. Sarkheil H)2021(Risk and incident analysis on crucial safety performance indicators and anomalies feedback in south pars gas complex, Results in Engineering, Results Eng 9:100210, https://doi.org/10.1016/j.rineng.2021.100210
50. Sarkheil H, Azimi Y, Rahbari S (2018) Fuzzy wastewater quality index determination for environmental quality assessment under uncertain and vagueness conditions. Int J Eng-Transact B 2018; 31(8):1196–204 .
51. Sarkheil H, Rahbari S, Tavakoli J, Shayanfard P (2018) Evolving Principle-Based Fuzzy Inherently Safer Design Index (FISDI) for ISD assessment, case study for acetic acid production plant. Int J Occup Hyg 2018;10(1) .
52. Sarkheil H, Rahbari S (2016) Development of case historical logical air quality indices via fuzzy mathematics (Mamdani and Takagi–Sugeno systems), a case study for Shahre Rey Town. Environ Earth Sci 2016;75(19):1319 .
53. Sarkheil H, Azimi Y, Rahbari S (2015) Modelling environmental air quality index assessment of using fuzzy logic in South Pars especial economic and energy zone, the case of Assaluye, Bidkhun, and Shirino. J Environ Sci Technol 2015 .
54. Sarkheil H, Rahbari S (2015) RRR (Reclamation, Remediation and Recovery): Green Phases of Mining and Drilling Lifecycle Influence on and/or Influenced by Sustainable Development. Eur. Online J Nat Soc 4, dec. 2015. https://european-science.com/eojnss/article/view/2971
55. Sarkheil H, Rahbari Sh, (2017) Environmental Performance Assessment and Management of the South Pars Gas Complex, Comparing Refineries: One and 9-10. J Environ Sci Technol, doi: 10.22034/jest.2019.13698
56. Sarkheil H, Azimi Y, Rahbari Sh (2019) Fuzzy Wastewater Quality Index (FWWQI) for Environmental Quality Assessment of Industrial Wastewater, a Case Study for South Pars Special Economic and Energy Zone. Journal of Civil and Environmental Engineering 51.2 (103): 153-160. doi: 10.22034/jcee.2019.9101
57. Sarkheil H, Rahbari Sh, Azimi Y (2021) Fuzzy-Mamdani environmental quality assessment of gas refinery chemical wastewater in the Pars special economic and energy zone. Environmental Challenges 3, 100065. https://doi.org/10.1016/j.envc.2021.100065
58. Sarkheil H, Rezaei HR, Rayegani B, Khorramdin S, Rahbari Sh (2021) Fuzzy dynamic system analysis of pollution accumulation in the Anzali wetland using empirical-nonlinear aspects of an economically-socio-environmental interest conflict. Environmental Challenges 2, 100025. https://doi.org/10.1016/j.envc.2021.100025
59. Gulan L, (2021) An Analysis of Factors Affecting the High Radon Concentration in Different Types of Houses. Scindeks.Ceon.Rs. The University Thought - Publication in Natural Sciences 7 (1): 51-54.

http://scindeks.ceon.rs/article.aspx?artid=1450-72261701051G.

60. Sherawat S, Mansour SN, Mosaferi M, Aminisani N, Yousefi Z, Maleki Sh (2021) First Indoor Radon Mapping and Assessment Excess Lifetime Cancer Risk in Iran. MethodsX 6: 2205-2216, https://www.sciencedirect.com/science/article/pii/S2215016119302523.
61. Skeppström K, Olofsson B (2021) A Prediction Method for Radon in Groundwater Using GIS and Multivariate Statistics. Sci Total Environ, https://www.sciencedirect.com/science/article/pii/S0048969706001896.
62. Spengler J, Adamkiewicz G (2009) Indoor Air Pollution: An Old Problem with New Challenges. Int J Environ Res Public Health 2009, 6(11): 2880-2882. https://www.mdpi.com/1660-4601/6/11/2880.
63. Stanley FKT, Zarezadeh S, Dumais CD, Dumais K (2017) Comprehensive Survey of Household Radon Gas Levels and Risk Factors in Southern Alberta. CAMJ Open 5(1): 255-264. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5378506/.
64. Aya T, Minami N, Yasuoka Y, Iimoto T, Omori Y, Nagahama H, Muto J, Mukai T (2017) Accurate Measurement of Indoor Radon Concentration Using a Low-Effective Volume Radon Monitor. Radiat Prot Dosim 177 (3): 324–30. https://doi.org/10.1093/rpd/ncx050.
65. Udovicic V, Veselinovic N, Maletic D, Banjanac R, Dragic A, Jokovic D, Savic M, Knezevic D, Eremic Savkovic M (2020) Radon Variability Due to Floor Level in Two Typical Residential Buildings in Serbia. Nukleonika 65(2): 121-125, https://doi.org/10.2478/nuka-2020-0019
66. Usikalu MR, Olatinwo V, Akpochafor M, Aweda MA, Giannini G, Massimo V (2017) Measurement of Radon Concentration in Selected Houses in Ibadan, Nigeria. In Journal of Physics: Conference Series. Vol. 852. Institute of Physics Publishing. https://doi.org/10.1088/1742-6596/852/1/012028.
67. Luigi V, Fucilli F, Cavone D, De Maria L, Birtolo F, Ferri MG, Soleo L, Lovreglio P (2018) Radon Levels in Indoor Environments of the University Hospital in Bari-Apulia Region Southern Italy. Int. J. Environ. Res. Public Health 2018, 15(4): 694, https://doi.org/10.3390/ijerph15040694.
68. Warrick AW, Zhang R, Moody MM, Myers DE (1990) Kriging versus Alternative Interpolators: Errors and Sensitivity to Model Inputs. Field-Scale Water and Solute Flux in Soils. https://doi.org/10.1007/978-3-0348-9264-3_17
69. WHO (2009) WHO Handbook on Indoor Radon: A Public Health Perspective. Geneva: World Health Organization.
70. Yarmoshenko IV, Onishchenko AD, Malinovsky GP (2021) Radon Concentration in Conventional and New Energy Efficient Multi-Storey Apartment Houses: Results of Survey in Four Russian Cities. Nature Com 2021. https://www.nature.com/articles/s41598-020-75274-4.
71. Li Y, Geng S, Mao J, Wang Q (2019) Investigating the Mitigation Effects of Radon Progeny by Composite Radon Removal Device. J. Radioanal. Nucl. Chem 319 (1): 205–11. https://doi.org/10.1007/s10967-018-6340-0.
72. Wenju Z, Cao T, Li Z, Sheng J (2019) Comparison of IDW, Cokriging and ARMA for Predicting Spatiotemporal Variability of Soil Salinity in a Gravel–Sand Mulched Jujube Orchard. Environ. Monit. Assess. https://doi.org/10.1007/s10661-019-7499-8.

Tables

Table 1 and 2 are available in the Supplementary Files section.

Figures

Figure 1

Location and population density of the case study

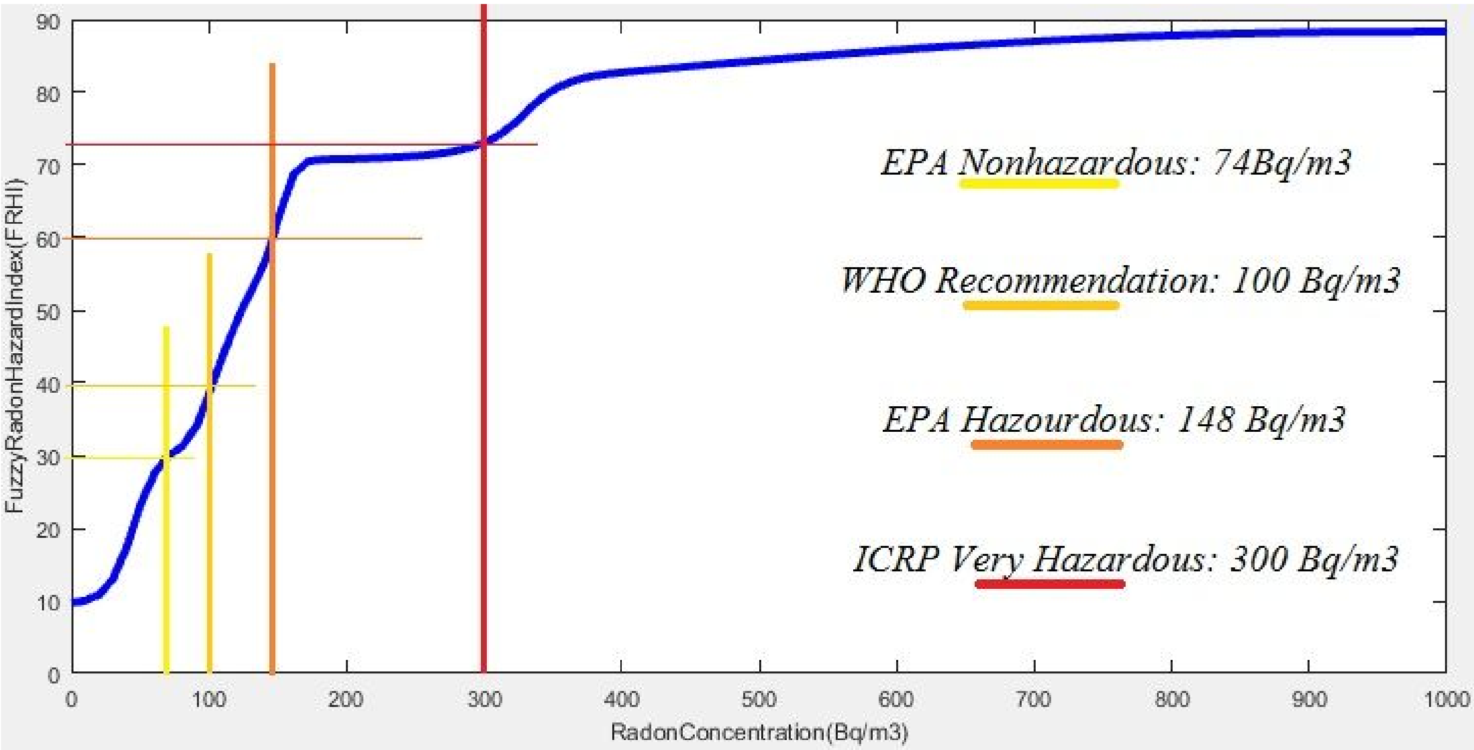

Figure 2

Input/Output non-linear transaction for FRHI

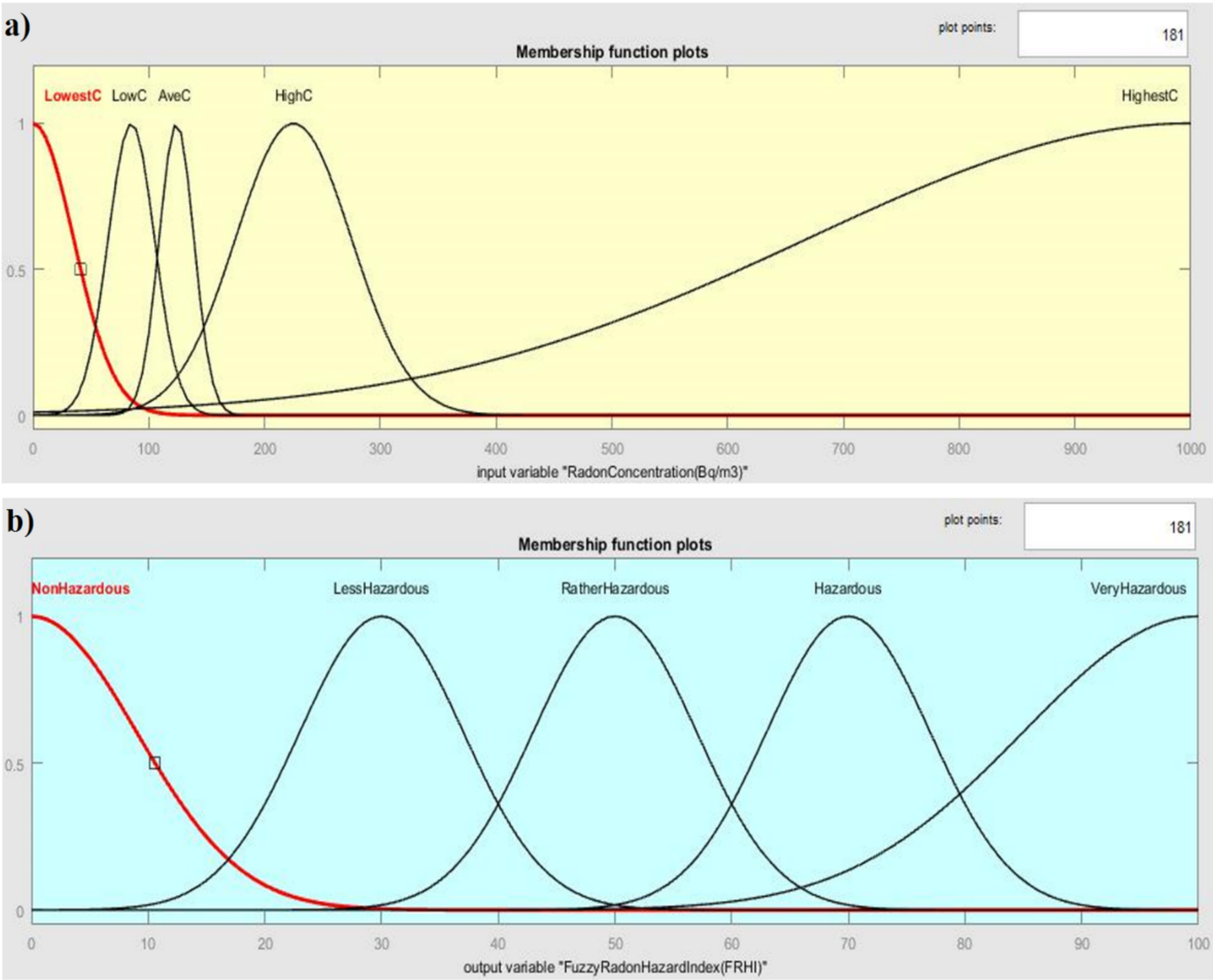

Figure 3

a) Membership function attribution for input: Radon Concentration. b) Membership function attribution for input: FRHI

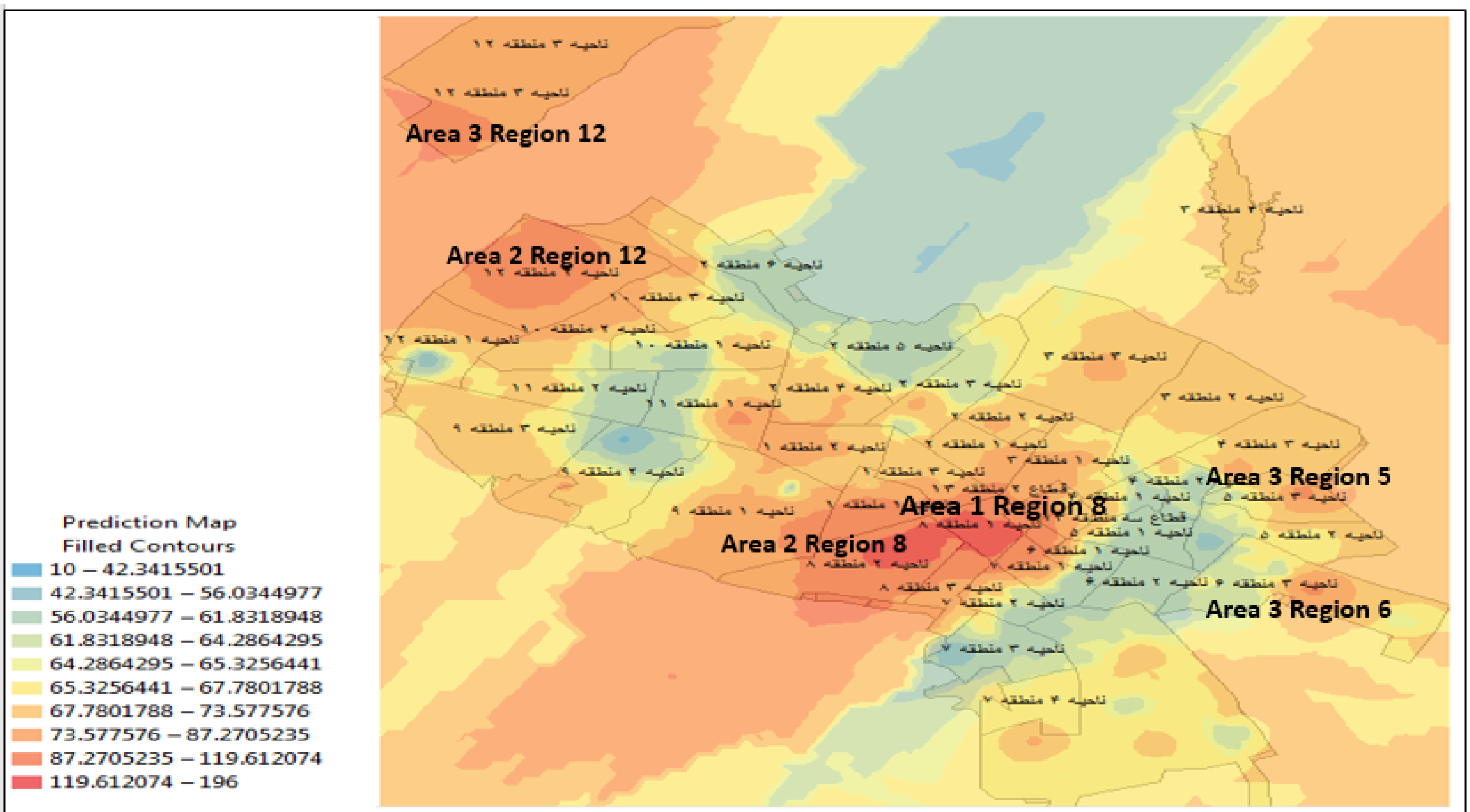

Figure 4

Radon zoning on an urban scale by the Kriging interpolation method in the case study

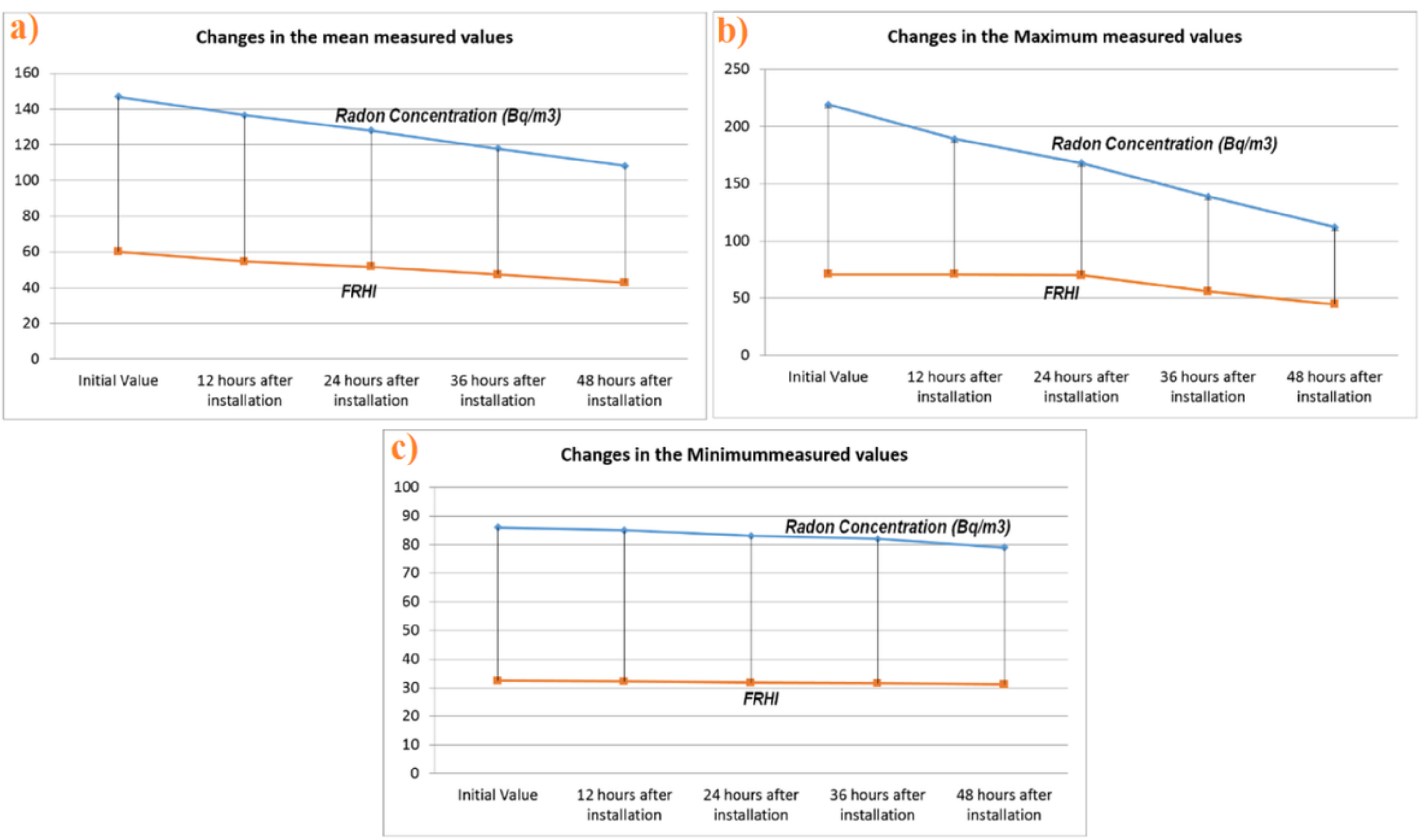

Figure 5

a) Changes of the mean of the measured values of Radon concentration measured. b) Changes in the maximum measured values of Radon concentration measured. c) Changes in the minimum measured value of Radon concentration measured.

Supplementary Files

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