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Research Article

Spatial Distribution of the Geogenic Radon Gas in Soils Near a Small Town and a Prospective Uranium Mine, Western Black Hills, Wyoming, USA

Ümit YILDIZ

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e-mail: umit.yildiz@sdsmt.edu
Institution: South Dakota School of Mines and Technology

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ABSTRACT

Natural radiation, which derives from uranium, thorium, and potassium, exists in a variety of geological environments including soils, rocks, plants, water bodies, and air, and is widely distributed in the Earth's crust. Regions with uranium-rich soil or rock typically have very high radon levels and it is a known fact that radon gas is the leading cause of lung cancer among non-smokers and it ranks as the second most common cause of lung cancer overall. This study aimed to create spatial distribution maps of radon gas concentrations in the soils close to a small town and a prospective uranium mine located in the western flank of the Black Hills uplift, Wyoming, to determine the potential health risks of the area. During this study, 204 in-situ measurements of the radon soil gas concentration in the soil were conducted within a study area of about 114 km^2, which is located near Moorcroft, Crook County, Wyoming, United States. The concentrations for radon soil gas ranged from 1.1 kBq/m^3 to 371.3 kBq/m^3 with an average of 53.5 kBq/m^3. In addition, a spatial distribution map was created for the soil gas radon concentrations. Based on this map, elevated concentration values appeared to be in the Moorcroft town center and the southeastern and southwestern portions of the study area. The northern part of the study area, which is closer to the prospective uranium mine, also shows east-west trending elevated values. The presence of the high-risk soil gas radon activity concentrations within the study area can be explained by the presence of the roll front type uranium mineralization in the northern part of the research area. 40% of the sites, with radon levels exceeding 50 kBq/m^3, indicated high risk in the region.

Küçük Bir Kasaba ve Uranyum Madeni Yakınındaki Topraklardaki Jeojenik Radon Gazının Mekansal Dağılımı, Batı Black Hills, Wyoming, ABD

ÖZET

Uranyum, toryum ve potasyumdan kaynaklanan doğal radyasyon, toprak, kaya, bitki, su kütleleri ve hava dahil olmak üzere çeşitli jeolojik ortamlarda bulunur ve yer kabuğuna yaygın olarak dağılmıştır. Uranyum açısından zengin toprak veya kayaçlara sahip bölgeler tipik olarak çok yüksek radon seviyelerine sahiptir ve radon gazının sigara içmeyenler arasında akciğer kanserinin önde gelen nedeni olduğu ve genel olarak akciğer kanserinin en yaygın ikinci nedeni olduğu bilinen bir gerçektir. Bu araştırma, çalışma bölgesinin potansiyel sağlık risklerini belirlemek

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için küçük bir kasabaya ve Wyoming'deki Black Hills'ların batı kanadında yer alan olası bir uranyum madenine yakın topraklardaki radon gazı konsantrasyonlarının mekansal dağılım haritalarını oluşturmayı amaçlamıştır. Bu çalışma sırasında, Moorcroft, Crook County, Wyoming, Amerika Birleşik Devletleri yakınlarında bulunan yaklaşık 114 km^2'lik bir çalışma alanında topraklardaki radon toprak gazı konsantrasyonunun 204 adet yerinde ölçümü yapılmıştır. Radon toprak gazı konsantrasyonlarının ortalaması 53,5 kBq/m^3 `tür ve değerler 1,1 kBq/m^3 ile 371,3 kBq/m^3 arasında değişmiştir. Ayrıca toprak gazı radon konsantrasyonları için mekansal dağılım haritası oluşturulmuştur. Bu haritaya göre, yüksek konsantrasyon değerlerinin Moorcroft kasaba merkezinde ve çalışma alanının güneydoğu ve güneybatı kısımlarında olduğu ortaya çıkmıştır. Çalışma alanının muhtemel uranyum madenine daha yakın olan kuzey kısmı da doğu-batı yönlü yüksek değerler göstermektedir. Çalışma alanı içinde yüksek riskli toprak gazı radon aktivite konsantrasyonlarının varlığı, araştırma alanının kuzey kesiminde roll-front tipi uranyum cevherleşmesinin varlığı ile açıklanabilir. Radon konsantrasyonlarının %40'ı 50 kBq/m^3'ü aştığı için bu sahaların bölgede daha yüksek riskli olduğunu göstermiştir.

1. INTRODUCTION

Natural radiation, which derives from uranium, thorium, and potassium, exists in a variety of geological environments including soils, rocks, plants, water bodies, and air, and is widely distributed in the Earth's crust. Uranium is a naturally occurring toxic heavy metal that is found in nearly all types of rocks, soils, sands, and water in trace amounts [1]. In the earth's crust (continental and oceanic) the average concentration of uranium is 2.3 ppm [2]. Where the geological conditions are favorable, deposits of uranium may occur in higher concentrations. Similarly, soil, water, and air all contain small levels of radon gas and radon progeny. Radon's daughter products, often known as "progeny," are several radioactive compounds that it generates together with alpha particles. Uranium-234, Thorium-230, Radium-226, and Radon-222 are intermediate products in the decay chain that starts with natural Uranium-238 and ends with Lead-206 [3] (Figure 1). Radon is a radioactive gas that is colorless, invisible, odorless, and tasteless and is produced by the naturally occurring radioactive decay of uranium [4]. Radon is the heaviest noble gas (4.4 gr/cm^3) and element of group 8A of the periodic table with an atomic number of 86. It is the only radioactive gas that emits alpha particles and has a half-life of 3.8 days [5]. Regions with uranium-rich soil or rock typically have very high radon levels.

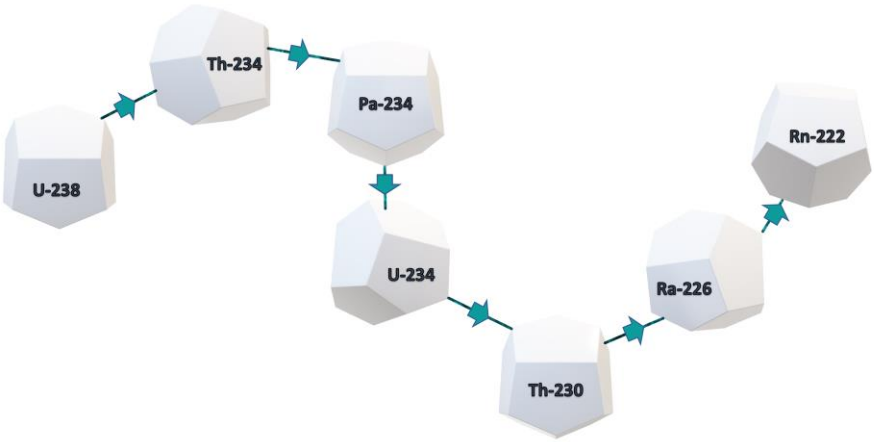

Figure 1. The image illustrates the main decay chain of Uranium 238.

The International Agency for Research on Cancer (IARC) has categorized radon as a Category 1 carcinogenic to humans [6, 7]. Lung cancer risk is increased by radon progeny inhalation. Data from studies

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of lung cancer mortality among uranium miners and other workers exposed to extremely high levels of radon progeny served as the initial foundation for the association between the concentration of radon progeny in the air and the risk of lung cancer [8, 9]. Furthermore, radon is the leading cause of lung cancer among non-smokers and it ranks as the second most common cause of lung cancer overall [5]. Many lung cancer fatalities are attributed to radon each year in the US alone, according to estimates. Small radioactive particles created by the decay of radon gas can be ingested into the lungs, where they can affect lung tissue and raise the risk of lung cancer, especially in smokers and people with chronic respiratory disorders [8]. The exposure to radon has also been connected to various respiratory medical conditions. Radon and its decay products can irritate the respiratory tract lining, causing inflammation and potentially aggravating asthmatic symptoms [9]. Although the evidence is not as strong as it is for lung cancer, there is evidence that radon exposure may be linked to an increased risk of other cancers, such as leukemia [5].

Decisions about whether more dwelling radon measurements are required in areas of projected development can be supported by knowledge of a region's potential radon gas concentrations in soil [10]. The purpose of this study was to create spatial distribution maps of radon gas concentrations in the soil close to a small town and a prospective uranium mine located in the western flank of the Black Hills uplift, Wyoming, in order to determine the health risks of the area.

1.1. Study Area

The study was conducted in a 114 km^2 area which is located near Moorcroft, Crook County, Wyoming, United States (Figure 2). Based on the Köppen-Geiger [11] climate classification scheme, Wyoming's climate is classified as cold semi-arid where summers are hot and dry and winters tend to have cold and possibly freezing temperatures. The study area is located on rugged terrain with an average 1200 meters elevation above sea level. The area is situated in the resourceful Powder River Basin which is located on the western flanks of the Black Hills. The Powder River Basin is known to be one of the most favorable basins in the United States for uranium mineralization. In 1952, the first uranium mineral (uraninite) was detected in the Cretaceous fluvial sandstones of the Inyan Kara Group in Crook County, near the northeastern flank of the Black Hills. In the late 1970s, Nubeth Joint Venture discovered uranium mineralization in the Powder River Basin, located 30 km north of the study area. Nowadays, uranium exploration and mining activities are continuing in the area.

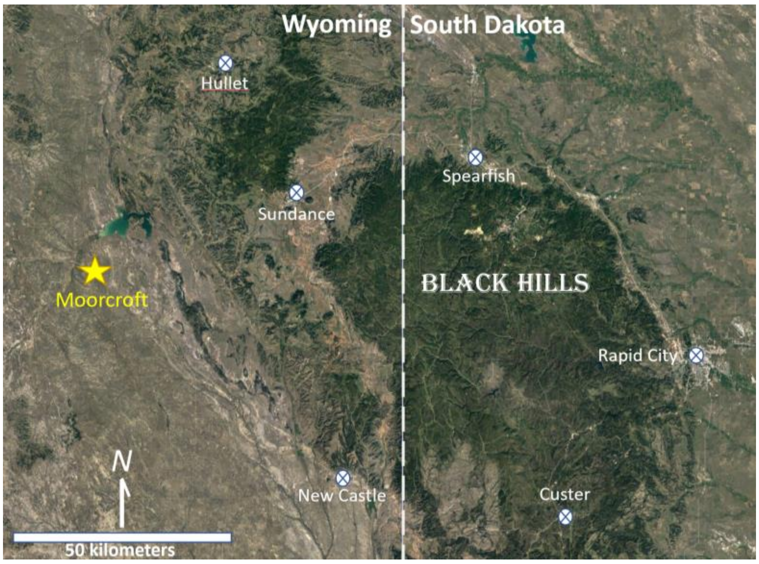

Figure 2. Satellite imagery showing the location of the study area.

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2. GEOLOGIC SETTINGS

Northeastern Wyoming is located in the Powder River Basin, a significant intermontane basin formed during the Laramide Orogeny in the northeasternmost Rocky Mountains (Figure 3). It makes up the majority of the surrounding province and, along with a section of the adjacent uplifts (Black Hills and Big Horns uplifts), covers an area of about 88,000 km^2. The Powder River Basin is an asymmetric, relatively less deformed, northeasterly trending syncline that is 400 km long and 180 km wide [12]. A thick succession of Phanerozoic strata, measuring more than 5000 meters thick in the basin axis, overlies the entire crystalline basement rocks. The Paleozoic shelf carbonates, sandstones, and mudstones that make up this sequence are relatively thin, rarely eclipsing 700 meters, and are overlain by a very thick succession of Mesozoic and early Tertiary terrestrial rocks that document the formation, filling, and destruction of the Western Interior seaway as well as the uplift of the western Cordillera, the development of regional uplifts, and the formation of the Powder River Basin [12]. Most uranium mineralization occurs as roll-front-type deposits in the fluvial sandstones of the Upper Cretaceous Fox Hills, and Paleocene Lance formations.

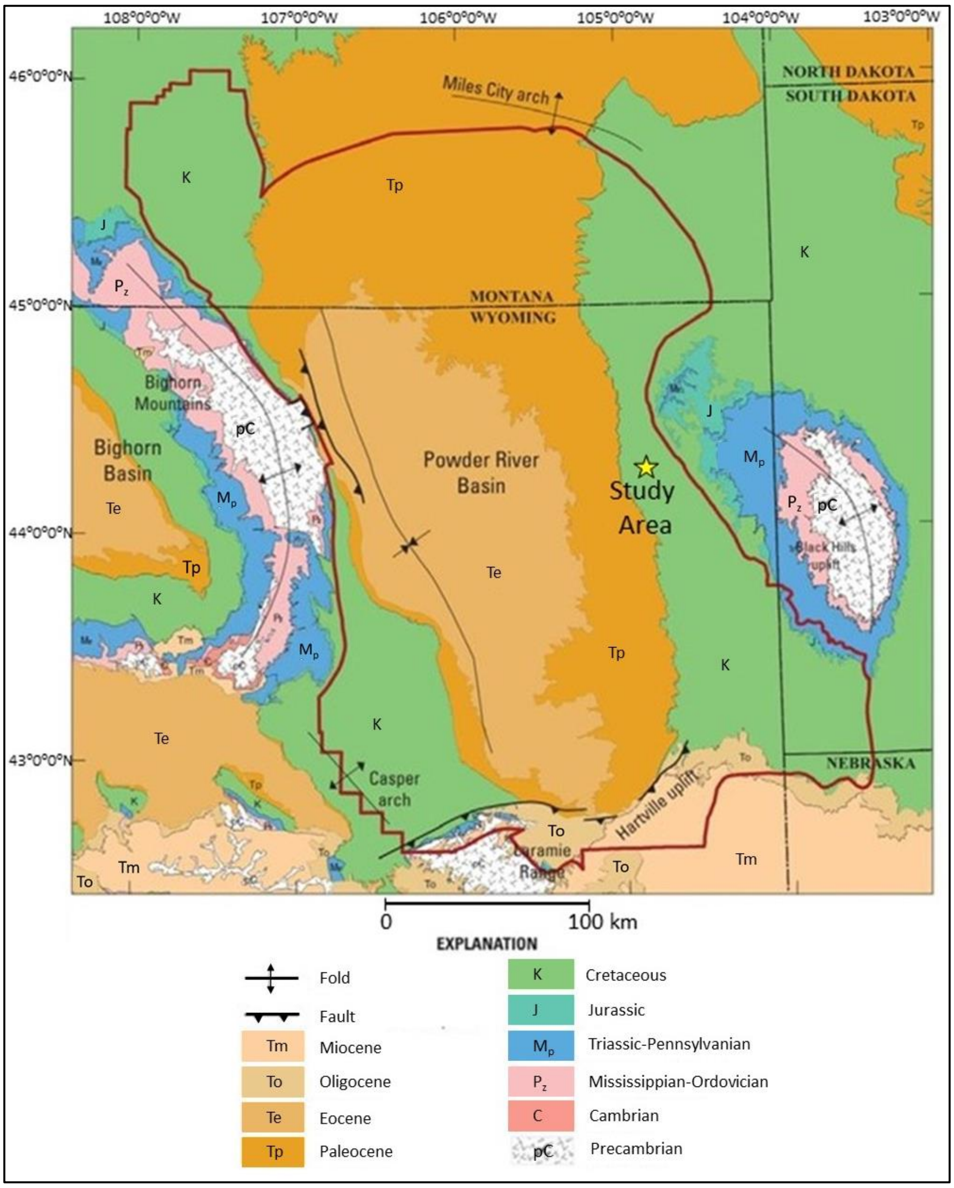

Figure 3. Geological map of the Powder River Basin and surroundings [13]. The study area is marked by a yellow star.

3. METHODS

Field measurements for soil gas radon activity concentrations were conducted over 14 consecutive days period in March 2014. To ensure that the study area was evenly dispersed throughout, 204 in-situ measurements of the radon concentration in the soil were conducted. A portable Garmin E-Trex GPS unit was used to record geographic coordinates. The sampling was conducted over three lithologies found in the surficial geology of the study area. These are the Late Cretaceous Fox Hills Formation, the Paleocene Lance Formation, and the Quaternary alluvial sediments. The soil gas radon concentration was measured using a RAD7 electronic radon detector manufactured by Durridge Corporation, U.S.A. The state-of-the-art RAD7 detector system has a cylindrical sampling chamber with a capacity of 0.7 liters. Alpha radiation is directly converted into an electrical signal by its detectors [14]. During this research, a stainless steel soil gas probe provided by the manufacturer was used. The probe was implanted into the soil, and the air was sucked up by the hollow tube and eventually into the RAD7. The probe had sampling ports near the tip. The average depth of the soil was 1.8 meters. The RAD7 has the capacity to determine each particle's energy, allowing it to identify the different isotopes that are produced when uranium decays [15]. As a result, it can distinguish between various daughter products and signals from noise. After 5–10 minutes of closed-circuit air circulation, and the radon was evenly mixed with the air, the resulting alpha activity was measured. The RAD7 finally determines the radon soil gas concentration. The Grab protocol software then takes a half-hour to process all sampling points. For QA/QC assurance, four measurements were taken at each site, and the mean of the four values was recorded in the database. Later, the radon concentration values were transferred into a computer for further analysis. The kriging interpolation algorithm on ArcMap 10.7.1 platform was employed to produce a spatial distribution map of the radon concentrations. For input, mean radon concentration values in kBq/m3 (kilo becquerel/cubic meter) were used. UTM (Universal Transverse Mercator) Zone 13N coordinate system with NAD (North American Datum) 1927 datum was used for all geostatistical processes.

4. RESULTS and DISCUSSIONS

A statistical summary of soil gas radon activity concentrations along with sampling depth, CO_2, O_2, and CH_4 was presented in Table 1. The concentrations for radon soil gas ranged from 1.1 kBq/m^3 to 371.3 kBq/m^3 with an average of 53.5 kBq/m^3. Seven very high outliers are present in the data (higher than 150 kBq/m^3). Six of these outliers are in Quaternary alluviums, and one is in the Paleocene Lance Formation which consists mainly of fluvial sediments. Figure 4 illustrates soil gas radon activity concentration values and the number of samples.

Table 1. Statistical summary of the sampling depth, soil gas radon activity concentrations, CO_2, O_2, and CH_4.

	Sampling Depth (m)	Concentration (kBq/m^3)	CO_2 (%)	O_2 (%)	CH_4 (ppm)
Mean	1.85	53.5	0.29	19.84	4.05
Median	1.83	43.8	0.20	19.90	1.00
Min.	0.61	1.1	0	16.10	0
Max.	2.21	371.3	1.70	21.50	53.00
Skewness	-1.32	2.9	2.37	-0.88	3.66
St. Dev.	0.27	51.2	0.22	0.70	7.12

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According to Eisenbud and Gesell [16] classification, soils with radon concentrations below 10 kBq/m^3 are considered low-risk, those with values between 10 and 50 kBq/m^3 are categorized as normal risk whereas those with values exceeding 50 kBq/m^3 are classified as high risk [14, 17]. Based on this classification, 13% of the sampling sites suggested low-radon risk, 47% of the sites indicated a normal risk, and 40% of the sampling sites showed regions of potentially high risk within the study area.

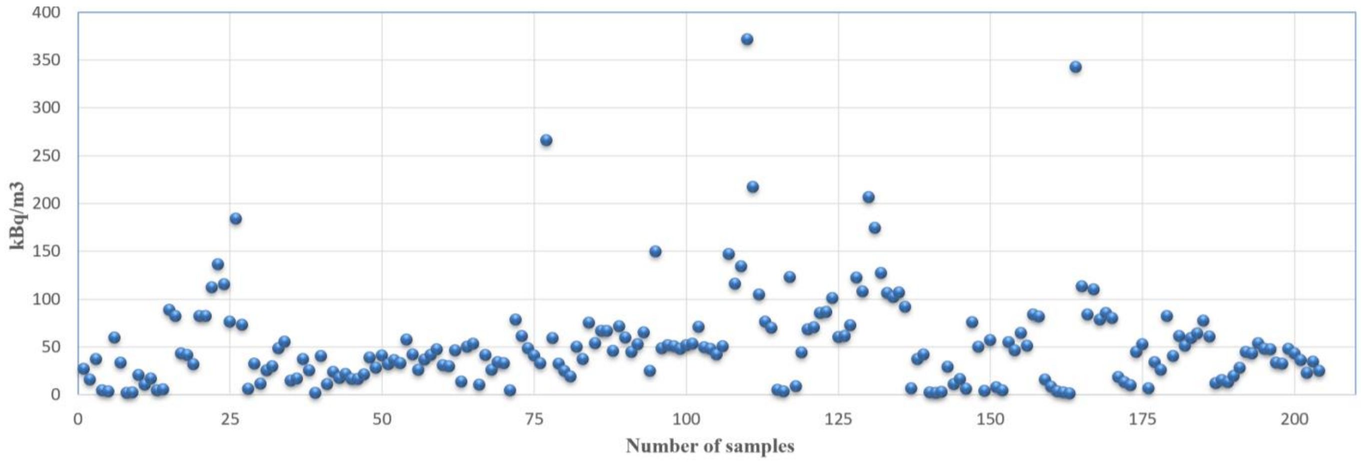

Figure 4. Chart illustrating soil gas radon concentrations and the number of samples.

Furthermore, a spatial distribution map was created for the soil gas radon concentrations within the study area (Figure 5). Based on this map, elevated concentration values appeared to be in the Moorcroft town center and the southeastern and southwestern portions of the study area. The northern part of the study area, which is closer to the prospective uranium mine, also shows east-west trending elevated values. The presence of the high-risk soil gas radon activity concentrations within the study area can be explained by the presence of the roll front type uranium mineralization in the northern part of the research area. The varying quantities of in-situ geogenic uranium minerals in Fox Hills and Lance formations are what cause the variability in natural radioactivity levels at various sampling locations.

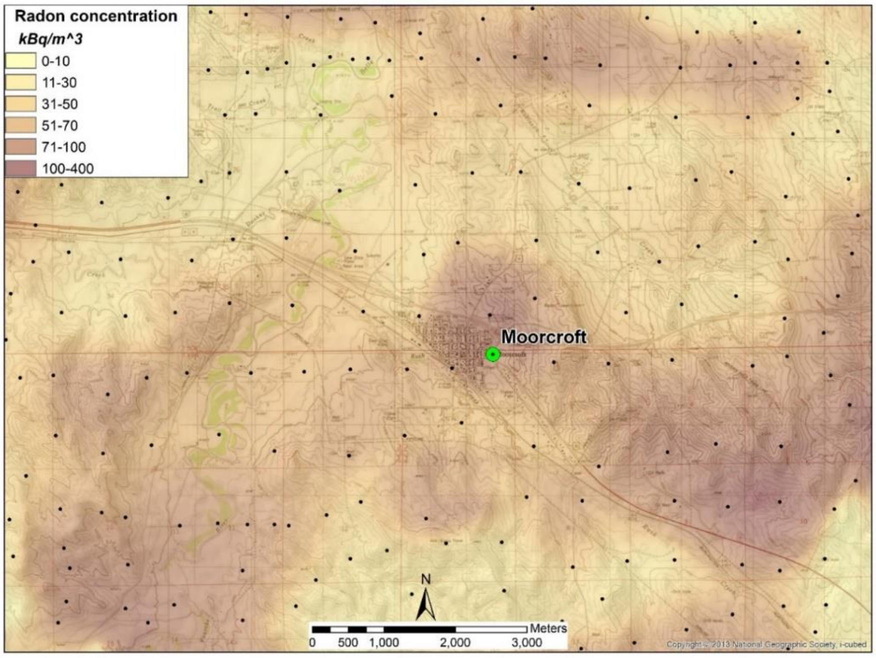

Figure 5. Spatial distribution map showing the soil gas radon concentrations within the study area. Sampling locations were marked by black dots.

5. CONCLUSIONS

The local geology and properties of the soil can have a significant impact on the radon concentrations in soil gas. While radon levels in soil gas may be naturally high in some places, they may be low or nonexistent in other places. The spatial distribution of radon in soils can be influenced by a variety of geological aspects, including the presence of uranium-bearing rocks, soil permeability, and groundwater conditions.

A total of 204 radon soil measurements were taken within the study area. Between 1 and 370 kBq/m^3, the study area's soil gas radon concentrations show a significant variation. 40% of the sites indicated a high risk of radon level. The spatial distribution map for radon concentrations will serve as a useful tool for the determination of new dwelling sites in the research area and as a guide for future remediation efforts.

In the future, systematic radon surveys and mapping can be conducted in the study area, thus areas with high soil gas radon concentrations can be located, and suitable mitigation measures can be put in place to lower radon exposure and protect human health.

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors

Author's Contribution

The first author contributed 100% of the entire study.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research And Publication Ethics

The author of the paper declares that he complies with the scientific, ethical, and quotation rules of ETOXEC in all processes of the paper and that he does not make any falsification of the data collected. In addition, he declares that Environmental Toxicology and Ecology and its editorial board have no responsibility for any ethical violations that may be encountered and that this study has not been evaluated in any academic publication environment other than Environmental Toxicology and Ecology.

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