

A geology-based predictive model for outdoor background gamma radiation in Bulgaria: framework and preliminary spatial assessment

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Abstract. A developed model translates lithology into expected concentrations of ⁴⁰K, ²³⁸U-series, and ²³²Th-series progeny using literature-based transfer functions, and subsequently converts these concentrations into ambient dose equivalent rates. The outdoor radiation background across the territory of Bulgaria was assessed theoretically and mapped in terms of expected gamma dose rates and previously evaluated geogenic radon potential. The results highlight regional-scale variations associated with granite and metamorphic units (elevated values), consolidated and semi-consolidated sedimentary rock (suggested low values), and localized anomalies related to uranium-bearing formations. The model outputs will be validated against data from a planned national survey conducted in the framework of a fundamental scientific project. This integrated, geology-driven approach provides an effective baseline for future evaluation of outdoor radiation background, using integrated systems-radiation surveys in Bulgaria.

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INTRODUCTION

The natural gamma radiation background is an inherent physical characteristic of the environment in which all living organisms on Earth exist. It is commonly quantified by the ambient dose equivalent rate, H*(10), which varies spatially and is specific to each location, area, and region. A major component of this background is terrestrial radiation, which depends strongly on the concentration of naturally occurring radionuclides associated with different rock types (e.g., IAEA, 1990; Shahbazi-

Gahrouei *et al.*, 2013; Bossew *et al.*, 2016). The principal contributors to externally incident gamma radiation are radionuclides from the uranium-238 and thorium-232 decay series, as well as potassium-40 (Saleh *et al.*, 2013; Al-Khawlany *et al.*, 2018; Cinelli *et al.*, 2019). These radionuclides are ubiquitously present in soils and rocks at varying concentrations and have been linked to environmental and biological variability both in Bulgaria and globally (Garnier-Laplace *et al.*, 2013; Del Monte *et al.*, 2024; Nikolova *et al.*, 2024; Aneva *et al.*, 2025). In general, igneous rocks, particularly

granites, are associated with higher radiation levels, whereas sedimentary rocks tend to exhibit lower levels (UNSCEAR, 2000).

In addition to external exposure, natural background radiation also contributes to internal exposure through the inhalation and ingestion of radionuclides. Among these, radon (Rn-222) and its progeny represent the dominant source of internal exposure via inhalation. Radon is a naturally occurring radioactive noble gas with a half-life of 3.8 days, originating from the decay of radium-226 within the uranium-238 series. Due to its inert nature, radon can migrate easily through soils and into the atmosphere, where it may disperse over considerable distances under the influence of meteorological conditions. The release of radon from the earth's surface disrupts the secular equilibrium within its decay chain, thereby contributing to spatial and temporal variations in background radiation levels.

The assessment of natural background radiation is of broad importance for population exposure studies. For the majority of individuals, natural sources constitute the primary contribution to total radiation dose, often exceeding that from anthropogenic sources. Notable exceptions include exposures associated with medical procedures, emergency situations, and certain occupational settings. Consequently, natural background radiation provides a fundamental baseline against which all other sources of ionizing radiation can be evaluated.

The composition and structure of the subsurface exert a strong influence on local levels of natural background radiation, alongside factors such as altitude and climate. Geological and soil-forming processes, operating over timescales ranging from thousands to millions of years, govern the distribution and physicochemical properties of rocks and soils. As a result, geological information can be used to infer large-scale patterns of natural radioactivity. For example, elevated terrestrial gamma dose rates are often observed in mountain ranges associated with the Alpine orogeny, such as the Pyrenees, Alps, Apennines, Dinarides, Hellenides, Carpathians, and the Balkan Mountains, where tectonic processes have led to the exposure of radionuclide-rich lithologies (Cinelli *et al.*, 2019).

In Bulgaria, however, a comprehensive national-scale survey based on integrated measurements of key radiation parameters has not yet been conducted. To address this gap, the project KII-06-H87/3, funded by the Bulgarian Science Fund, aims to develop an integrated methodology for evaluating outdoor radiation background and to generate new insights into the spatial distribution of radiation pa-

rameters. By combining national lithological and subsurface datasets, we aim to develop a predictive spatial model of terrestrial gamma dose rates.

MATERIALS AND METHODS

General geological setting of Bulgaria

According to Dabovski and Zagorchev (2009), Bulgaria is divided into two primary units: The Moesian Platform and the Alpine Orogenic Belt. The Moesian Platform serves as a stable northern foreland, characterized by a Paleozoic basement underlying sub-horizontal Mesozoic and Cenozoic sedimentary successions. The Alpine Orogenic Belt in Bulgaria is a complex, Fold-Thrust Belt of northern vergence, shaped by multiple compressional and extensional phases from the Late Triassic through the Eocene. This belt comprises a negligibly small part the South Carpathian system (noted for Jurassic-Cretaceous flysch in the northwest) and the Balkan Fold-Thrust Belt (The Balkanides). The latter from north to south is further divided into the Balkan Zone, defined by its lack of Mesozoic magmatism; the Srednogorie Zone, dominated by Upper Cretaceous magmatism and volcanic-sedimentary basins; and the Morava-Rhodope Zone, distinguished by its high-grade metamorphic basement and Paleogene magmatism and volcano sedimentary successions. These complex geological settings and rock types control variations in terrestrial gamma dose rates, including the potential for elevated surface gamma dose rates.

Methodology of Terrestrial Gamma Dose Rate assessment and GIS-based Analysis

Naturally occurring radionuclides of terrestrial origin are present to varying degrees in all environmental media. Those radionuclides are called primordial radionuclides because they have a half-life comparable to the age of the Earth. Primordial radionuclides are divided into two groups: those that are single and decay directly to a stable (non-radioactive) element like potassium (K-40), and those that occur in a decay chain (series) like uranium (U-238) and thorium (Th-232). The decay products exist in sufficient quantity and could contribute significantly to population exposure. Due to geological conditions, chemical and physical mobility, and the deposit, the concentration of primordial radionuclides could vary considerably. According to the UNSCEAR, these average and standard er-

ror soil concentrations are: K-40: 400 ± 24 Bq/kg; U-238: 37 ± 4 Bq/kg; and Th-232: 33 ± 3 Bq/kg (UNSCEAR, 2008). Though, rock type concentrations vary based on regional location and local geological features.

The absorbed gamma dose rates in air at 1 m above the ground surface for terrestrial radionuclides were calculated based on coefficients suggested by UNSCEAR (2000) using the following question:

$$D = 0.462 \times C_U + 0.604 \times C_{Th} + 0.0417 \times C_K, [\text{nSv/h}] \quad (\text{Eq. 1})$$

where C_U , C_{Th} and C_K are the average activity concentrations of ^{238}U , ^{232}Th , and ^{40}K in Bq/kg, respectively.

For environmental gamma radiation, the personal dose equivalent, $H_p(10)$ at 10 mm depth can be approximated as equal to the air kerma, *i.e.*, a conversion coefficient of about 1 Sv/Gy is appropriate for external exposure (ICRP, 1996). For the estimation of the effective dose rate, the assumption was made that the radionuclides from the two considered series are in equilibrium. For the calculation of the total dose equivalent rate of an area with different rock types, the terrestrial dose rate was added to the dose equivalent rate from cosmic components of 44 nSv/h as a flat value. The value of cosmic components was estimated by taking the average values of the gamma background in the country according to direct measurement by the National

Automated System for Continuous Control of the Radiation Gamma Background in the Republic of Bulgaria, BULRaMo system (2025), 110 nSv/h, and the assumption of 60% to 40% ratio of terrestrial to cosmic radiation. The BULRaMo system takes a data from 35 measuring stations across the country. The average radionuclide concentrations based on literature sources are presented in Table 1.

The results for ^{40}K in granites are similar to those reported for material from certain localities in West Balkans by Abdulqader *et al.* (2018). The concentrations of U, Th, and Ra radionuclides depend on specific uranium deposits in some locations and may be higher (Abdulqader *et al.*, 2018). Such elevated concentrations are also observed around deposits in Bulgaria (Fig. 1), and there the natural radiation background is locally higher. The geological basis of the present study is based on the Geological Map of Bulgaria at a scale of 1:100 000 (Geological Map), The data used were summarized and provided in digital form by the Japan International Cooperation Agency JICA (2008a; 2008b). The data are organized in a geographic database containing spatial information on the distribution of the main lithological units on the territory of Bulgaria. The GIS-based map comparison is performed using the total dose equivalent rate and the area of each rock type described in Table 1. The comparison represents the contribution of each total dose equivalent rate in regards to its area. The following equation is used:

Table 1
The average radionuclide concentration distributions to lithological units

Geological unit	^{40}K , [Bq/kg]	^{238}U , [Bq/kg]	^{232}Th , [Bq/kg]	Source
Igneous rocks				
Mafic basalts	270	9	8	Jędrzejek <i>et al.</i> (2022)
Mafic gabbro	240	8	12	Jędrzejek <i>et al.</i> (2022)
granites	1300	50	130	Jędrzejek <i>et al.</i> (2022)
granitoids	1000	90	35	Jędrzejek <i>et al.</i> (2022)
Sedimentary rocks				
sandstones	330	15	24	IAEA (1996)
shales	810	15	41	IAEA (1996)
carbonate sediments, <i>e.g.</i> limestones, dolomites	80	15	5.2	IAEA (1996)
unconsolidated and semi-consolidated terrigenous rocks	506	24	42	Alnour <i>et al.</i> (2014)
Metamorphic rock				
Gneisses and meta-granitoids	695	43	51	Dzałuk <i>et al.</i> (2018)
Miscellaneous				
<i>in situ</i> uranium ore deposits	735	73	57	Lazarova <i>et al.</i> (2017)

$$Contribution_i = \frac{TDER_i \times Area_i}{\sum_{j=1}^n (TDER_j \times Area_j)} \quad (\text{Eq. 2})$$

where $TDER_i$ is the total dose equivalent rate for the i^{th} rock type, $Area_i$ is the respective i^{th} rock type spatial size in sq. km, j is the counter for a lithological unit, and n is the total number of the lithological units.

PREDICTED GEOGENIC RADON POTENTIAL ON THE BULGARIAN TERRITORY

As mentioned above, radon is the only inert noble gas of the elements of the radioactive family, therefore it can spread easily in the living environment. A key metric for assessing its impact on an environment or its biota is geogenic radon potential. This potential is determined by both geological factors, such as the radium content of specific rock types, and hydrogeological conditions (*e.g.* Sakoda *et al.*, 2011; Scheib *et al.*, 2013). The gas migrates toward the surface via diffusion and convection through permeable pores and fractures, a process heavily influenced by soil gas movement and moisture saturation levels.

In Bulgaria, complex studies concerning correlation between the measured radon concentrations and bedrock geology in Bulgaria started in the second decade of XXI century (Ivanova *et al.*, 2019; Mutovska *et al.*, 2024). These investigations aim to re-

fine the methodology for calculating the radon index by identifying environmental and structural variables that frequently distort field measurements. Through a synthesis of recent field studies, two primary factors have emerged as critical determinants of soil-gas radon behavior: the degree of subsurface saturation and the presence of tectonic discontinuities.

RESULTS AND DISCUSSION

The object of the analysis is an area of 45 941.38 km², representing part of the territory of the Republic of Bulgaria with a total area of 110 998.42 km². For the remaining part of the territory (65 057.04 km²), the total dose equivalent rate based on the rock types and/or the expected gamma dose rate is the low value range, therefore these areas were not included in the present analysis.

Based on the Eq. 1, the respective total terrestrial dose rate and the total dose equivalent rate were evaluated for the rocks in the country (Table 2).

The total dose equivalent rate is calculated based on the assumption of 60% to 40% ratio between the terrestrial and cosmogenic components of natural background. The variation of the outdoor dose equivalent rate depends on atmospheric conditions and radon and its daughter products concentration. Usually, its range of the total dose equivalent rate is around the 20–40 nSv/h and is due to atmospheric pressure, wind, rain or snow, etc.

Table 2
Rock types and the respective terrestrial dose and total dose equivalent rates

Geological unit	Rock type index	Terrestrial dose rate, nSv/h	Total dose equivalent rate, nSv/h	Range of the total dose equivalent rate, nSv/h
Igneous rocks				
mafic basalts	1	20.25	64.25	50–70
mafic gabbro	2	20.95	64.95	50–70
granites	3	155.83	199.83	180–250
granitoids	4	104.42	148.42	120–160
Sedimentary rocks				
sandstones	5	35.19	79.19	60–90
shales	6	65.47	109.47	80–120
carbonite sediments, <i>e.g.</i> limestones, dolomites	7	13.41	57.41	40–60
unconsolidated and semi-consolidated terrigenous rocks	8	57.56	101.56	80–120
Metamorphic rock				
gneissess and meta-granitoids	9	79.65	123.65	90–130
Miscellaneous				
<i>in situ</i> uranium ore deposits	10	98.80	142.80	120–160

While the total dose equivalent rates for basalts and gabbros are statistically identical in Table 1, they remain categorized separately to facilitate more precise future investigations. This same distinction is applied to ‘granites’ versus ‘granitoids’, and ‘shales’ versus ‘carbonate sediments’, as these groups are expected to exhibit distinct variations in K, U, and Th radionuclide concentrations (*e.g.* [Abbadly et al., 2006](#); [Moura et al., 2011](#); [Bucher and Stober, 2021](#); [Lasheen et al., 2021](#)).

In addition, based on the results of Table 2 a GIS-based map is performed (Fig. 1).

Based on the performed map, the contribution of each rock type is evaluated by using Eq. 2 (Table 3 and Fig. 2). The results show that rock indexes with high TDER but low area occupation have strong local but not dominant effect in regards to the Bulgarian territory. Rock indexes with intermediate TDER but with wide area occupation they possess more dominant effect, although they are not high radioactive ones. Finally, rock indexes with intermediate-

high TDER and wide occupation contribute to a greater extent to the regional radiation background compared to small in area but highly radioactive units.

Preliminary characterization of terrestrial gamma dose rates in Bulgaria indicates that the spatial distribution of radon-prone areas is fundamentally controlled by regional lithology. Two distinct geological zones predominate: an expansive region (~14 500 km²) characterized by unconsolidated and semi-consolidated siliciclastic rocks, and a second zone (~11 652 km²) composed of gneiss. In the siliciclastic terrains, approximately 18% of the area is susceptible to shallow groundwater saturation, posing a significant technical constraint; high moisture content inhibits gas transport, potentially compromising measurement accuracy. Conversely, the gneissic zones exhibit negligible saturation (0.1%). This disparity necessitates a stratified methodology for field investigations. To ensure data integrity, the determination of radon potential and terrestrial gam-

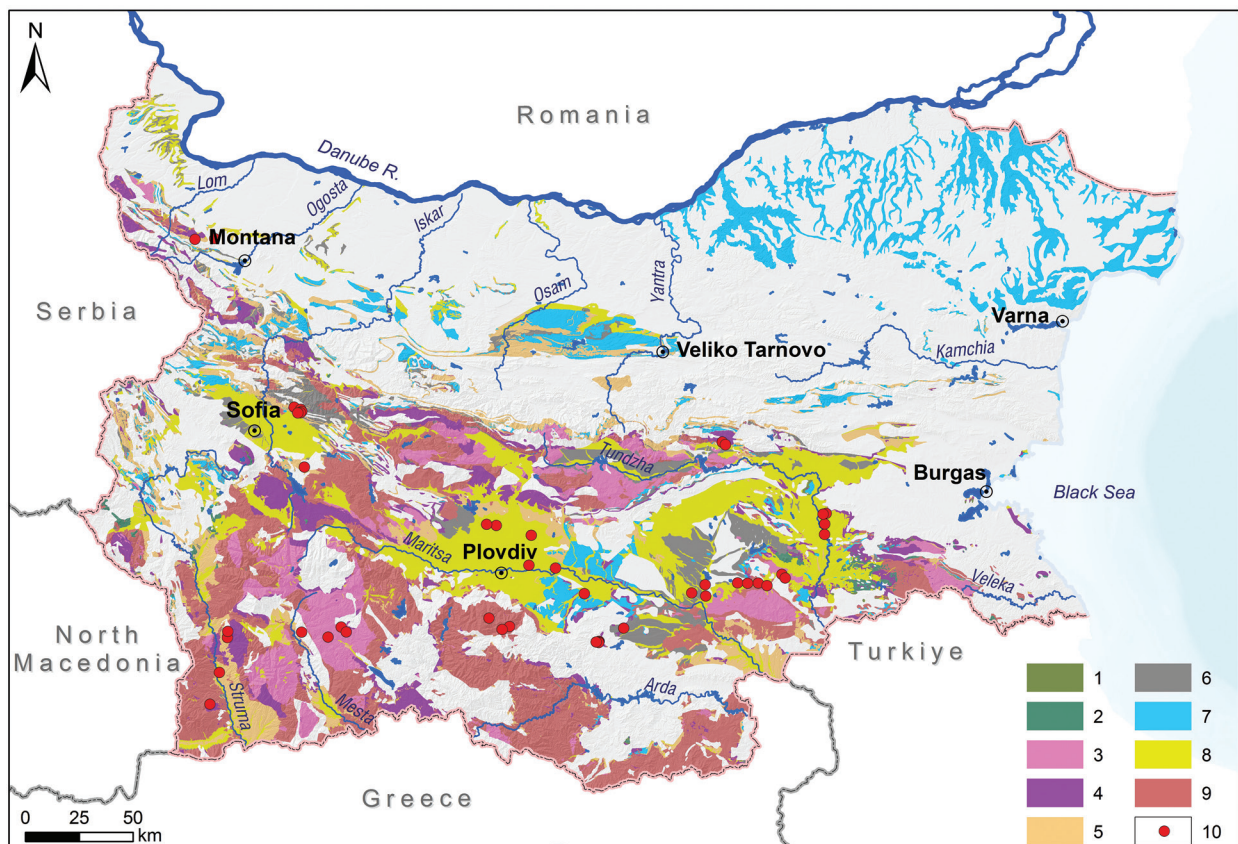


Fig. 1. Map of rock types with evaluated total dose equivalent rate: 1 – mafic basalts; 2 – mafic gabbros; 3 – granites; 4 – granitoids; 5 – sandstones; 6 – shales; 7 – carbonate sediments; 8 – unconsolidated or semi-consolidated terrigenous rocks; 9 – gneisses and meta-granitoids; 10 – main uranium ore deposits.

Table 3
Calculated contribution of each rock type indexes

Rock Index	TDER _i , nSv/h	Area _i , sq. km	TDER _i × Area _i	Contribution, %
1	64.25	62.61	4022.40	0.08
2	64.95	327.34	21260.82	0.42
3	199.83	4353.63	869986.76	17.10
4	148.42	3793.57	563041.50	11.06
5	79.19	5342.19	423048.06	8.31
6	109.47	3182.15	348349.44	6.85
7	57.41	7349.65	421943.19	8.29
8	101.56	10183.58	1034244.48	20.32
9	123.65	11346.67	1403015.99	27.57

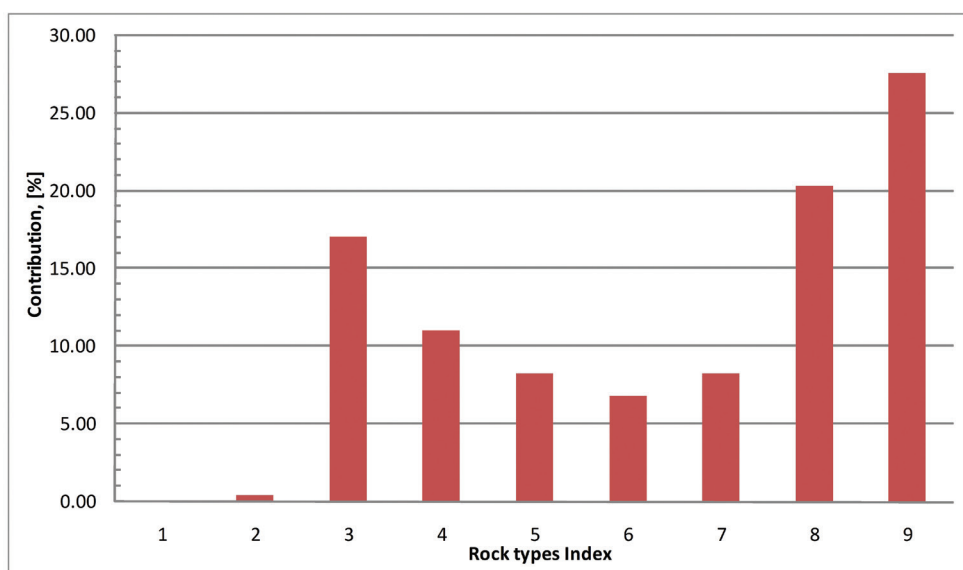


Fig. 2. Graphical comparison of the different rock types dose rate contribution in Bulgaria.

ma dose rates must incorporate site-specific evaluations of groundwater saturation (*e.g.* Antonov *et al.*, 2012; Tsvetkova *et al.*, 2019; Gerginov *et al.*, 2020; Frangov, 2024; Stanchev and Nikolov, 2025; Vasileva, 2025) and contemporary evapotranspiration analyses (Gerginov and Antonov, 2019; Anwar *et al.*, 2024; Nojarov, 2024). Furthermore, this framework must incorporate specialized case studies, specifically regional investigations of mineral waters and preliminary assessments for radioactive waste disposal facilities (Antonov *et al.*, 2020; Tsvetkova, 2022; Hristov *et al.*, 2023), to ensure a comprehensive evaluation of environmental radioactivity.

In addition, the previous radon-prone data reveals significant spatial variability in radon concentrations, even within localized study areas. This phenomenon is most pronounced in regions intensively affected by faulting. These structural features create preferential pathways for radon migration, introducing a probabilistic element to the geological setting. Consequently, the determination of the radon index in these areas cannot rely on isolated samples but must instead account for the complex, non-linear influence of tectonic fragmentation. Thus, an additional more precise investigation must be performed in order to qualify the rock types spa-

tial distribution, including also their composition (e.g. Zagorchev, 2021; Balkanska *et al.*, 2023; Kounov *et al.*, 2025).

CONCLUSION

This study provides a first-order, geology-driven assessment of Bulgaria's outdoor natural gamma radiation background using an integrated methodological framework. By synthesizing national-scale lithological data with literature-based radionuclide activity concentrations and standardized dose conversion coefficients, a preliminary spatial model of terrestrial gamma dose rates was developed and visualized via GIS. The results demonstrate that regional variability in the outdoor dose equivalent rate is governed more by lithology and the areal extent of rock units than by isolated peak concentrations. Specifically, rock types with intermediate radioactivity and broad spatial distribution are the primary contributors to the regional background, whereas highly radioactive units with limited exposure ex-

ert only localized effects. Furthermore, the data suggest a significant correlation between geological setting, geogenic radon potential, and gamma dose rates, with subsurface saturation and tectonic discontinuities serving as critical controls on radon transport. Despite its reliance on generalized concentrations, this mapping provides a fundamental baseline for understanding radiation exposure patterns in Bulgaria. These findings underscore the necessity of integrating also local hydrogeological and structural factors in future research to refine dose assessments and provide a methodological foundation for systematic national-scale population exposure evaluations.

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