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Assessment of natural background radiation in the tourist area of Biserna Cave based on *in situ* measurements

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Abstract: *This study presents the first detailed in situ assessment of natural background radiation in the tourist-accessible portion of Biserna Cave, Bulgaria. Using portable gamma-ray dosimeter and radon detectors, we measured ambient gamma-ray dose rates and radon concentrations along the cave route. Radon was measured at eleven depth-profile points, and a time-weighted average inhalation dose was calculated using a 40% – 20% – 40% time-distribution model (entry – final – travel). The resulting 1-hour inhalation dose (radon) is ~ (3.81 – 10.695) μSv, including a mean gamma-ray component (0.177 μSv/h), the max total is ≈ 10.872 μSv. For a seasonal visitor population of 2,000 – 2,500, the max collective dose is 21.7 – 27.2 mSv. Tour guides, with ~ 115 h exposure annually, receive ~ (0.42 – 1.22 mSv) ± (0.126 – 0.450) mSv. These values lie well below regulatory limits for public exposure, but the elevated radon concentration levels in deeper zones merit attentive occupational monitoring. The study underscores the importance of depth-resolved profiling and site-specific dose modelling in cave ecotourism settings.*

Keywords: radon, gamma-ray background, caves, inhalation dose, occupational exposure

Introduction

Natural background radiation represents the total ionizing radiation originating from cosmic and terrestrial sources, including radionuclides naturally present in the atmosphere, water, and the Earth's crust. The main contributors from terrestrial sources are gamma-ray radiation emitted by uranium (U-238), thorium (Th-232), and their progenies such as radon (Rn-222), as well as other single-decay long-living radionuclides such as potassium

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(K-40). The concentration of these isotopes in geological formations determines the local radiation background, which may vary significantly depending on lithological composition, humidity, and ventilation conditions. According to UNSCEAR and ICRP, radon and its progeny often account for more than 50% of the effective dose from natural sources [1]. Subterranean environments, such as caves, represent unique environments in which radon gas can accumulate to levels much higher than in typical indoor or outdoor settings, depending on ventilation, rock permeability, and hydrology. Some published studies have shown remarkably elevated radon in caves open to the public, sometimes exceeding 25,000 Bq/m³ [2], differ from surface conditions. Radon buildup is particularly typical in karst regions, where porous rocks and underground cavities facilitate gas migration and retention. Measuring natural radioactivity in caves is essential both for scientific purposes (geophysics and radioecology) and for assessing potential health risks to humans, especially in tourist areas with high visitor frequency [3, 4]. Biserna Cave is located in northeastern Bulgaria, within the Shumen Plateau Nature Park. It is one of the most prominent caves in the region, extending over 2.7 kilometers with a complex network of galleries formed in Cretaceous limestones. Owing to its stable temperature (around 11–12°C), high humidity, and unique karst morphology, the cave represents a significant natural and ecological site. In recent years, part of it has been developed and opened for controlled tourist visits around 780 m, making it an ideal location for studying radiation conditions in accessible underground environments. The present study aims to (1) measure ambient gamma dose rates along the tourist route, (2) characterize the radon concentration profile in depth (11 points, Rn1 – Rn11), (3) compute a time-weighted inhalation dose, (4) estimate the collective dose for visitors and the seasonal dose for guides, and (5) discuss implications relative to ICRP and other guidelines. The results are expected to enhance understanding of radiation dynamics in karst environments and to support radiation safety management in underground tourist sites. Prior to this work, no published data existed on the in-depth profile of the internal ambient gamma-rays and radon concentration levels in Biserna Cave.

Materials and Methods

1. Study Area and Access Scheme

Biserna Cave is a karst system with multiple chambers and passages. The tourist route spans about 780 m. For ecological reasons, particularly to protect bat breeding, the cave is open to the public only during two periods each year (1 April – 30 June and 1 September – 15 November). During its everyday operating window per open season, three 1-h tours are run on working days, and four on weekends, by rotating five guides.

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2. Radiation Measurement Instruments

Gamma Radiation: Equivalent ambient gamma dose rates were measured using a portable gamma-ray dosimeter, ATOMEX AT1123 [5, 6], calibrated and certified by the Bulgarian Institute of Metrology. The instrument operates in the photon energy range of 25 keV to 3 MeV and provides high sensitivity with an uncertainty of a few percent. Measurements were conducted in situ along the tourist trail inside the cave, with dose rates recorded in nSv h^{-1} range at multiple points. The dosimeter is accompanied by a valid calibration certificate, ensuring compliance with national and international radiation monitoring standards.

Radon: An AlphaGuard Pro portable ionization chamber, manufactured by Bertin Technologies, capable of continuous monitoring in the range of 10 to 2,000,000 Bq m^{-3}, was used to measure radon concentration at a depth of 430 m from the cave opening. Data for two different time periods at 11 depth-profile points (Rn1–Rn11) along the cave route were obtained from [7]. Continuous radon concentration measurements at two depth-profile locations (430 m and 780 m) were sourced from [8, 9]. Each measurement was reported in Bq m^{-3} with a typical accuracy of ±10%. Environmental parameters, including temperature and relative humidity, were also recorded, as they influence radon diffusion and equilibrium with its decay products.

3. Measurement layout and data processing

Sampling points were selected to represent characteristic sections of the tourist pathway: entrance area, main gallery, midsection, and final chamber. At each point, at least three consecutive measurements were taken, from which mean values and standard deviations were calculated. The obtained results were compared with the typical natural background levels for the Shumen Plateau region and with international reference data (ICRP, UNSCEAR). This methodological framework provides a reliable basis for evaluating dose exposure in underground environments and supports subsequent calculations of the annual effective dose for both visitors and cave personnel.

4. Time-distribution Assumption and Dose Modelling

Because radon and gamma-ray measurement points do not correspond exactly, we adopted a time-weighted exposure model: assume 1 h total, with 40% of time spent during "entry" (divided equally among Rn1–Rn5), 20% at the final point (Rn11), and 40% during "travel" (divided equally among Rn6–Rn10). This 40% – 20% – 40% rule yields appropriate weighting across depth. Dose from radon inhalation was calculated using:

$$\boldsymbol{D_{Rn,i} = C_i . k}$$

where $\boldsymbol{k = Fx9x10^{-3}}\ \frac{\mu Sv}{Bq.h.m^{-3}}$, with equilibrium factor $\boldsymbol{F = 0.4}$. This matches the standard assumption in radon dosimetry under ICRP 137 [10, 11].

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Time-weighted average concentration $C_{avg} = \sum_i C_i t_i$, ($\sum_i t_i = 1h$) then:

$$D_{Rn,1h} = C_{avg}.k$$

An average gamma component (D_γ µSv/h) was added, representing typical ambient gamma background unrelated to radon, based on prior measurements across the cave. Collective visitor dose was computed as:

$$D_{coll} = Nx(D_{Rn,1h} + D_\gamma), (converted\ to\ mSv)$$

5. Occupational Working Hours for guides

Period 1 (1 Apr–30 Jun, 92 days): working days 5/7 × 92 × 3 tours + weekend 2/7 × 92 × 4 tours, divided among 5 guides → 64.46 total hours per guide per period.

Period 2 (1 Sep–15 Nov, 76 days): working days 5/7 × 76 × 3 tours + weekend 2/7 × 76 × 4 tours, divided among 5 guides → 49.9 total hours per guide per period.

Results

1. Gamma-ray Radiation along the Tourist Route

Ambient gamma-ray radiation was measured at nine points (T1 – T9) along the tourist route in 2025: 28 Mar, 31 Mar, 11 Aug, and 19 Sep. (See Table 1). On 11 August, gamma-ray dose increased with depth (T1 = 133.5 nSv/h, T7 = 430 nSv/h). On other dates (28 Mar, 31 Mar, 19 Sep), gamma-ray dose generally decreased with depth. Overall gamma-ray levels remain low to moderate. Point T5 (radon location) shows relatively stable gamma-ray values. This supports the use of average gamma-ray background of 0.177 µSv/h in dose calculations.

Table 1. Gamma-ray Radiation Measurements Along the Tourist Path (2025)

Measurement Point	28/03/2025 Value [nSv/h]	Error [%]	31/03/2025 Value [nSv/h]	Error [%]	11/08/2025 Value [nSv/h]	Error [%]	19/09/2025 Value [nSv/h]	Error [%]
T1	92	6	–	–	133.5	5	103	4
T2	68	3	–	–	206.5	3	–	–
T3	70	5	–	–	240	3	–	–
T4	62	6	–	–	250	3	–	–

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T5(Rn430 m)	69	6	73	2	270	2	77	2
T6	67	5	–	–	340	2	–	–
T7	59	5	–	–	430	5	–	–
T8	60	5	–	–	370	3	–	–
T9	48	5	57	3	340	3	–	–

Note: Measurements were evenly distributed along the route; dashes indicate no measurement. T5 is the main radon point at depth 430 m

2. Radon Concentration Profile and Per-Point Dose

The radon concentrations and uncertainties at 11 points are summarized in Table 2, Table 3 and Table 4. The converted radon dose rate and per-point dose contributions are also shown.

Table 2. Radon in-depth profile and dose contributions (1-hour tour). Average Rn value for Period I (15.08.2019 – 1.11.2019)

Point	**C_i (Bq/m³) ± σ**	**D_Rn,i (μSv/h) ± σ**	**t_i (h)**	**Dose contrib (μSv) ± σ**
Rn1	275 ± 18	0.9900 ± 0.0648	0.08	0.07920 ± 0.00518
Rn2	323 ± 21	1.1628 ± 0.0756	0.08	0.09302 ± 0.00605
Rn3	340 ± 23	1.2240 ± 0.0828	0.08	0.09792 ± 0.00662
Rn4	640 ± 42	2.3040 ± 0.1512	0.08	0.18432 ± 0.0121022
Rn5	725 ± 48	2.6100 ± 0.1728	0.08	0.20880 ± 0.01382
Rn6	765 ± 501	2.7540 ± 1.8036	0.08	0.22032 ± 0.14429

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Rn7	1801 ± 230	6.4836 ± 0.8280	0.08	0.51869 ± 0.06624
Rn8	3016 ± 384	10.8576 ± 1.3824	0.08	0.86861 ± 0.11059
Rn9	7575 ± 9667	27.2700 ± 34.8012	0.08	2.18160 ± 2.78410
Rn10	6179 ± 791	22.2444 ± 2.8476	0.08	1.77955 ± 0.22781
Rn11	6198 ± 785	22.3128 ± 2.8260	0.20	4.46256 ± 0.56520

Table 3. Radon in-depth profile and dose contributions (1-hour tour). Average Rn value for Period II (1.11.2019 – 10.11.2020)

Point	**C_i (Bq/m³) ± σ**	**D_Rn,i (μSv/h) ± σ**	**t_i (h)**	**Dose contrib (μSv) ± σ**
Rn2_1	215 ± 534	0.774 ± 1.923	0.08	0.0619 ± 0.1538
Rn2_2	326 ± 81	1.174 ± 0.292	0.08	0.0939 ± 0.0234
Rn2_3	311 ± 75	1.119 ± 0.270	0.08	0.0895 ± 0.0216
Rn2_4	429 ± 103	1.543 ± 0.370	0.08	0.1234 ± 0.0296
Rn2_5	765 ± 182	2.750 ± 0.655	0.08	0.2200 ± 0.0524
Rn2_6	609 ± 145	2.190 ± 0.521	0.08	0.1752 ± 0.0417
Rn2_7	1729 ± 409	6.210 ± 1.469	0.08	0.4968 ± 0.1175

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Rn2_8	1809 ± 428	6.500 ± 0.08 1.539	0.5200 ± 0.1231
Rn2_9	3598 ± 851	12.940 ± 0.08 3.063	1.035 ± 0.245
Rn2_10	3515 ± 831	12.640 ± 0.08 2.991	1.011 ± 0.239
Rn2_11	3081 ± 729	11.080 ± 0.20 2.621	2.216 ± 0.524

Table 4. Radon profile and dose contributions (1-hour tour) – Period I (15.08.2019 – 1.11.2019) and Period II (1.11.2019 – 10.11.2020)

Point	**C_i (Bq/m³) ± σ (Period I)**	**D_Rn,i (µSv/h) ± σ (Period I)**	**C_i (Bq/m³) ± σ (Period II)**	**D_Rn,i (µSv/h) ± σ (Period II)**
Rn1 / Rn2_1	275 ± 18	0.07920 ± 0.00518	215 ± 534	0.0619 ± 0.1538
Rn2 / Rn2_2	323 ± 21	0.09302 ± 0.00605	326 ± 81	0.0939 ± 0.0234
Rn3 / Rn2_3	340 ± 23	0.09792 ± 0.00662	311 ± 75	0.0895 ± 0.0216
Rn4 / Rn2_4	640 ± 42	0.18432 ± 0.0121022	429 ± 103	0.1234 ± 0.0296
Rn5 / Rn2_5	725 ± 48	0.20880 ± 0.01382	765 ± 182	0.2200 ± 0.0524
Rn6 / Rn2_6	765 ± 501	0.22032 ± 0.14429	609 ± 145	0.1752 ± 0.0417
Rn7 / Rn2_7	1801 ± 230	0.51869 ± 0.06624	1729 ± 409	0.4968 ± 0.1175
Rn8 / Rn2_8	3016 ± 384	0.86861 ± 0.11059	1809 ± 428	0.5200 ± 0.1231
Rn9 / Rn2_9	7575 ± 9667	2.18160 ± 2.78410	3598 ± 851	1.035 ± 0.245
Rn10 / Rn2_10	6179 ± 791	1.77955 ± 0.22781	3515 ± 831	1.011 ± 0.239
Rn11 / Rn2_11	6198 ± 785	4.46256 ± 0.56520	3081 ± 729	2.216 ± 0.524

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Period I corresponds more closely to the actual tourist season Period 2 (September – November) when visitors enter the cave. It reflects the short-term peak radon exposure during active cave visits.

Period II represents an annual average for the entire year, including off-season periods when the cave is closed and ventilation may differ. Radon concentrations and doses are lower than in Period I.

This comparison highlights the importance of seasonal and depth-resolved radon profiling for accurate assessment of public and occupational exposure in cave ecotourism.

The relatively large standard deviations observed in Tables 2, 3 and 4 reflect the pronounced spatial and temporal variability of radon concentration measurements inside the cave. Such variations are mainly due to changing microclimatic conditions (temperature, humidity, air exchange) and the heterogeneous geometry of the underground passages. In addition, Table 3 represents annual mean values at each measurement point, which further increases the apparent dispersion, since as shown in Figure 2, even within short periods the radon concentration can fluctuate by several orders of magnitude. Therefore, the reported standard deviations represent genuine environmental variability rather than instrumental uncertainty.

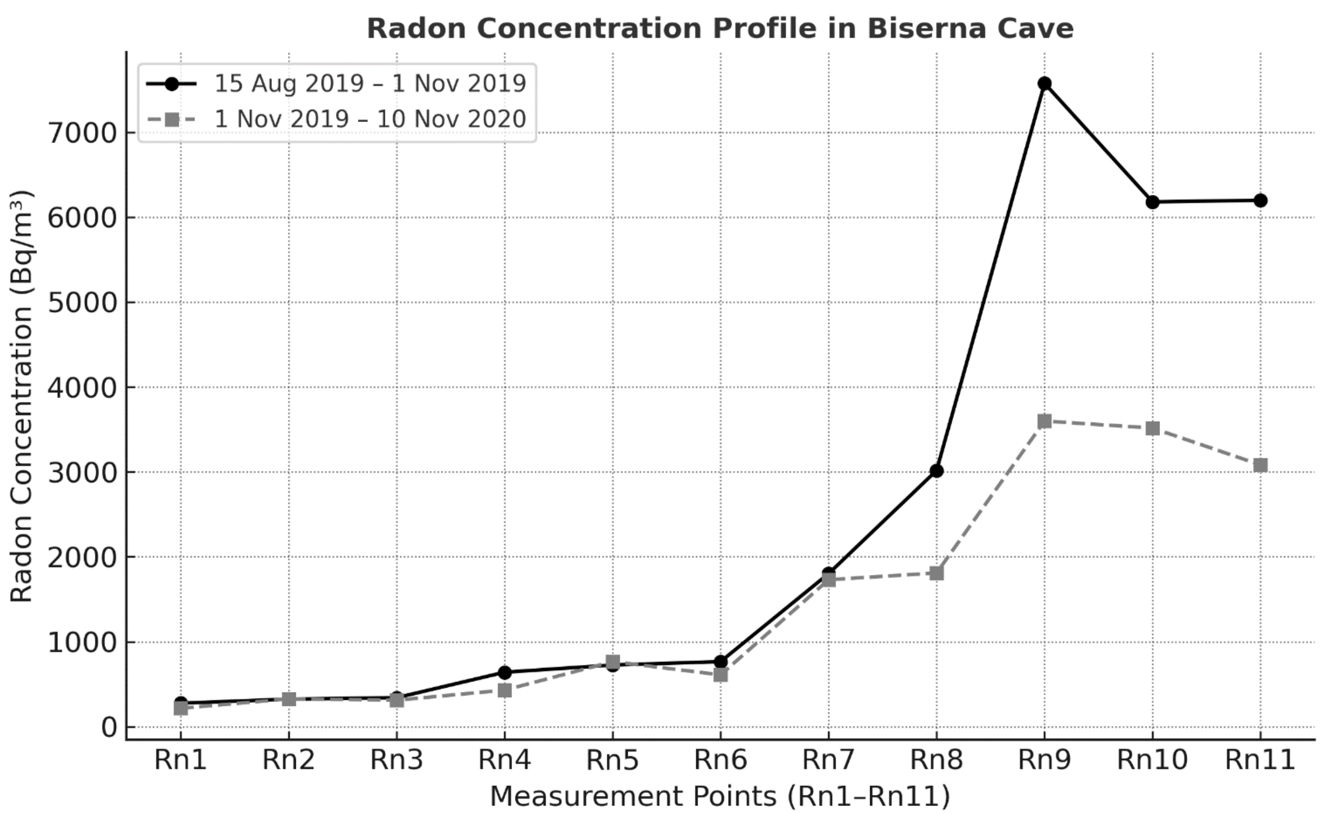

Figure 1. Radon profile – Period I (15.08.2019 – 1.11.2019) and Period II (1.11.2019 – 10.11.2020)

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Table 5. Summary of radon concentration statistics at two depths (Rn_430 m and Rn_780 m) for different measurement periods (2022 – 2025)

Year	Period	Depth (m)	Mean (Bq/m³)	SD (Bq/m³)	Median (Bq/m³)	Mode (Bq/m³)
2022	Period 2	430	521	619	227	86
		780	1702	1192	1164	654
2023	Period 1	430	479	455	317	224
		780	4341	2098	4735	1945
	Period 2	430	864	792	517	438
		780	8269	1586	8796	9061
2024	Period 1	430	606	600	422	326
		780	5064	2303	5277	6616
	Period 2	430	866	841	582	494
		780	—	—	—	—
2025	Period 1	430	490	477	344	244
		780	—	—	—	—
	Period 2	430	883	524	514	403
		780	—	—	—	—

Data compile from [7] and [8]

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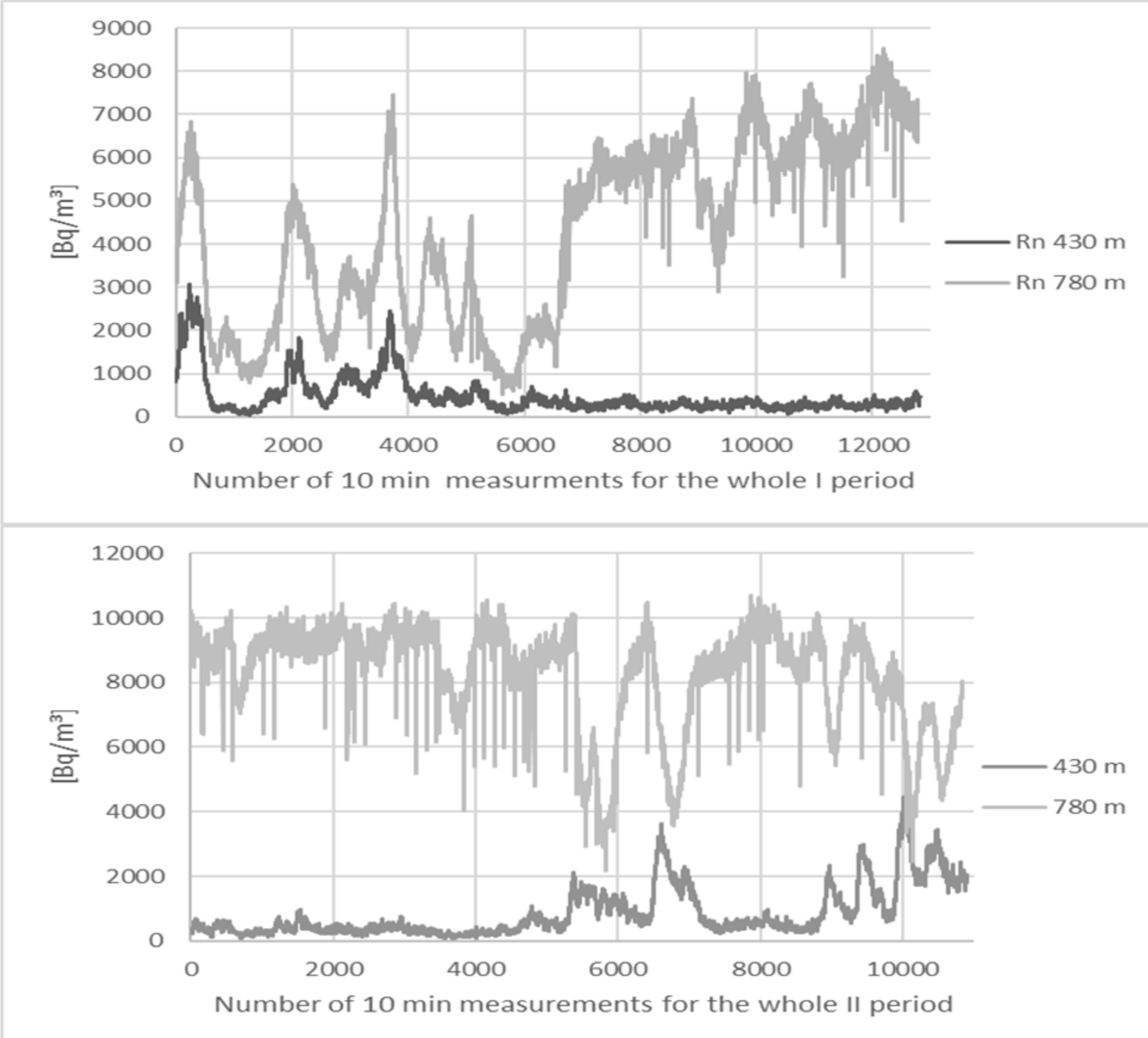

Figure 2. Radon profile – Period I (1.04.2024 – 30.06.2024) and Period II (1.09.2024 – 15.11.2024)

The multi-year dataset reveals a clear pattern: Radon concentrations increase with depth, with Rn_780 m consistently showing much higher means and modes when data are available. Seasonal variation is evident: Period 2 (autumn) generally shows higher radon levels than Period 1 (spring), consistent with lower ventilation and higher humidity during cooler months. 2023 Period 2 stands out with exceptionally high values (>8 k Bq/m³) at 780 m, suggesting limited air exchange during that time. Missing data for deeper zones (2024 – 2025) highlight the need for continuous or automated monitoring to better capture annual variability and long-term trends.

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Table 6. Radon Concentrations by Year and Period with linear estimation of missing data

Year	Period	Depth (m)	Mean (Bq/m³)	SD (Bq/m³)	Median (Bq/m³)	Mode (Bq/m³)
2019	2 (autumn)	430	765	501	-	-
		780	6198	785	-	-
2020	Annual mean	430	609	145	-	-
		780	3081	729	-	-
2022	2 (autumn)	430	521	619	227	86
		780	1702	1192	1164	654
2023	1 (spring)	430	479	455	317	224
		780	4341	2098	4735	1945
	2 (autumn)	430	864	792	517	438
		780	8269	1586	8796	9061
2024	1 (spring)	430	606	600	422	326
		780	5064	2303	5277	6616
	2 (autumn)	430	866	841	582	494
		780	1487	-	-	-
2025	1 (spring)	430	490	477	344	244
		780	735	655	-	-
	2 (autumn)	430	883	524	514	403
		780	1521	823	-	-

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Table 7. Occupational Dose Estimation

Year	Period 1 Dose (mSv)	Period 2 Dose (mSv)	Annual Dose (mSv)
2019	0.69 ± 0.254	0.53 ± 0.196	1.22 ± 0.450
2020	0.39 ± 0.101	0.30 ± 0.079	0.69 ± 0.180
2022	0.24 ± 0.071	0.18 ± 0.055	0.42 ± 0.126
2023	0.51 ± 0.113	0.65 ± 0.071	1.16 ± 0.184
2024	0.53 ± 0.123	0.41 ± 0.096	0.94 ± 0.219
2025	0.50 ± 0.245	0.18 ± 0.0378	0.68 ± 0.283

3. Interpretation and Legal Considerations

Annual guide doses (0.42 – 1.22 mSv) are below the 6 mSv occupational limit. However, Bulgarian law and ICRP guidance [12] require a radiation protection program when annual doses exceed 1 mSv. Measures include:

- Continuous radon monitoring in workplaces;
- Assessment of exposure pathways and mitigation;
- Personal protective equipment if needed;
- Worker training on radiation safety;
- Regular review of the protection program.

Conclusions

The present study provides the first depth-profiled assessment of ambient gamma-ray radiation in Biserna Cave, as well as the first multi-year depth-profiled evaluation of radon concentrations. The results indicate that the time-weighted effective dose per one-hour tourist tour ranges from approximately 3.8 to 10.9 µSv, accounting for both radon and gamma-ray components. The collective seasonal dose for visitors is estimated at 22–27 mSv, while the annual occupational dose for cave guides remains below 6 mSv. However, given that the dose with associated uncertainties occasionally exceed 1 mSv, the implementation of a radiation monitoring plan in accordance with regulatory requirements is recommended. Ambient gamma-ray radiation levels along the tourist route are generally

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low to moderate, showing only minor seasonal variations. Overall, the multi-year dataset establishes a valuable baseline for future occupational and public radiological protection measures in Biserna Cave.

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