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Original scientific paper

RADON (^{222}Rn) AND RADIUM (^{226}Ra) ACTIVITY AND DOSE ASSESSMENT IN SPRING WATERS OF KOSOVO

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Abstract: Radon (^{222}Rn) and radium (^{226}Ra) are naturally occurring radionuclides of the ^{238}U decay series that may contribute to public exposure through drinking water and indoor air due to radon degassing during household water use. Six springs were sampled and analyzed using the pulse-counting ionization chamber (alpha spectroscopy). method with an AlphaGUARD DF2000 monitor coupled to an AquaKIT system. Radon activity concentrations ranged from 0.06 to 10.88 Bq L^{-1}, while ^{226}Ra, indirectly determined after a 30-day decay period of radon, ranged from 0.12 to 0.32 Bq L^{-1}. The total committed effective dose for adult consumers (inhalation and ingestion; ^{222}Rn+^{226}Ra) ranged from 14.35 to 59.72 μSv y^{-1}, remaining well below the WHO reference level of 100 μSv y^{-1}. The results indicate no significant radiological risk and contribute to the existing baseline data on radon and radium in spring waters of Kosovo.

Key words: radon; radium; spring water; AlphaGUARD; Kosovo

1. INTRODUCTION

Radon (^{222}Rn) and radium (^{226}Ra) are naturally occurring radionuclides of the ^{238}U decay series and represent important contributors to natural environmental radioactivity. From a radiation-protection perspective, radon and its short-lived progeny account for a substantial fraction of the effective dose received by the general population, predominantly through inhalation and, to a lesser extent, ingestion (UNSCEAR, 1993). Radon is a chemically inert noble gas characterized by high mobility in soils and rocks, which facilitates its migration from geological formations into groundwater, surface environments, and indoor air. Radium, as the parent nuclide of radon, exhibits distinct environmental behavior due to its chemical reactivity and its involvement in water–rock interaction processes.

The radiological relevance of radon in drinking water arises from two primary exposure pathways: ingestion of dissolved radon and inhalation of radon released into indoor air during domestic water use, such as showering, washing, and cooking (WHO, 2022). Although ingestion contributes to the absorbed dose in the stomach, inhalation of degassed radon typically represents the dominant exposure route, particularly under conditions of limited ventilation (WHO, 2022). In regions where spring waters are widely consumed without centralized treatment, such as Kosovo, the inhalation pathway associated with domestic water use may therefore represent a non-negligible contributor to population exposure, depending on household water-use practices and indoor air exchange rates (Marković et al., 2020). Consequently, even relatively low radon concentrations in water may be of radiological interest when evaluated in the context of real-life consumption patterns.

The occurrence and distribution of radon and radium in groundwater are primarily governed by geological and hydrogeological factors. The uranium-radium content of aquifer materials, mineralogical composition, porosity and permeability, and groundwater residence time all influence radionuclide production, release, and transport mechanisms (Somlai et al., 2002). Groundwater typically exhibits higher radon concentrations than surface waters due to prolonged contact with mineral sources and restricted degassing to the atmosphere. These processes are especially relevant in geologically heterogeneous regions, where localized variations in aquifer composition may result in substantial spatial variability in radionuclide activity concentrations. Such variability highlights the necessity of site-specific assessments rather than reliance on generalized assumptions or regional averages. In addition, physicochemical parameters-including temperature, pH, and electrical conductivity can affect radon solubility and radium mobility, thereby influencing measured activity concentrations in water samples (ISO 13164-3, 2013).

Radium (^{226}Ra) is of particular radiological concern owing to its chemical similarity to calcium, which facilitates its incorporation into bone tissue following ingestion. Unlike radon, radium does not degas from water and therefore contributes exclusively through ingestion pathways. Its concentration in groundwater is controlled by geochemical conditions regulating dissolution, adsorption-desorption, and ion-exchange processes within aquifer materials (WHO, 2022). Long-term ingestion of radium-bearing water may thus represent a chronic exposure scenario, especially in communities relying on untreated groundwater or spring-water sources.

Guideline and regulatory values for radionuclides in drinking water vary among jurisdictions. The World Health Organization recommends a guidance level of 100 Bq′L^{-1} for radon and a reference value of 1 Bq·L^{-1} for ^{226}Ra (WHO, 2022; WHO, 2022). Within the European Union, Council Directive 2013/59/EURATOM establishes a regulatory framework for protection against ionising radiation and promotes risk-based monitoring approaches for naturally occurring radionuclides in water intended for human consumption (EURATOM, 2013). In the United States, the Environmental Protection Agency has proposed a maximum contaminant level of 11.1 Bq·L^{-1} for radon in drinking water (US-EPA, 1999).

Despite the widespread consumption of spring waters for drinking purposes, data on naturally occurring radionuclides in drinking water in Kosovo remain limited and fragmented. Radon and radium activity concentrations in groundwater and drinking-water sources have been previously reported in several studies conducted in the Balkan region, relecting the influence of geological formations and hydrogeological conditions. Studies carried out in Serbia have demonstrated the occurrence of radon in drinking water, including tap water, bottled water, and public fountains, highlighting groundwater as a potential pathway for population exposure (Todorović et al., 2012). Similar investigations in Bosnia and Herzegovina have reported detectable radon activity concentrations in well and spring waters, largely controlled by local geological structures and water–rock interaction processes (Kasić et al., 2016). Research conducted in Croatia has also confirmed the presence of naturally occurring radionuclides such as radium in thermal and mineral waters, emphasizing the importance of monitoring groundwater sources used for human consumption (Bituh et al., 2009). More recent measurements performed in the north of Kosovo have reported radon activity concentrations in alternative drinking-water sources, indicating that groundwater-derived waters may contribute to population exposure through both ingestion and inhalation pathways (Vučković et al., 2023). Despite these regional investigations, systematic assessments of radon and radium activity concentrations specifically in spring waters used for drinking purposes in Kosovo remain limited. In many rural and peri-urban areas, spring waters are consumed directly without centralized treatment or systematic quality control, increasing the relevance of localized geogenic radioactivity for population exposure. Given this widespread reliance on untreated water sources, even moderate activity concentrations of radon and radium may have implications for long-term public health risk, particularly among vulnerable communities. Consequently, further harmonized and site-specific assessments are warranted in order to improve the current evidence base and strengthen radiological risk evaluation at the national level.

Within this context, the present study provides a structured assessment of ^{222}Rn and ^{226}Ra activity concentrations in spring waters from selected locations in Kosovo. Radon was determined through emanometric measurements using an AlphaGUARD DF2000 monitor coupled with an AquaKIT degassing system, following standardized procedures outlined in ISO 13164-3 (2013), while radium activity was assessed indirectly under controlled equilibrium conditions. In addition, the committed effective dose to adult consumers was estimated by accounting for both inhalation and ingestion exposure pathways in accordance with WHO recommendations (WHO, 2022). By establishing reference activity concentrations for radon and rdium in spring waters, this study contributes to the existing body of knowledge and provides an evidence base to support future monitoring programs, radiological risk assessment, and informed decision-making in water resource management and radiological protection in Kosovo.

2. METHODOLOGY

Study area and sampling locations

The study was conducted on natural spring waters used for human consumption at six selected locations in Kosovo: Orllovic village, Shkabaj village, Millosheva village, Obiliq town, Dardishte village, and Fushe Kosova town (Figure 1). These locations were chosen to represent different hydrogeological and lithological settings and to reflect typical groundwater sources used locally for drinking purposes. All investigated springs are accessed directly by the population without centralized treatment, making them relevant for radiological exposure assessment.

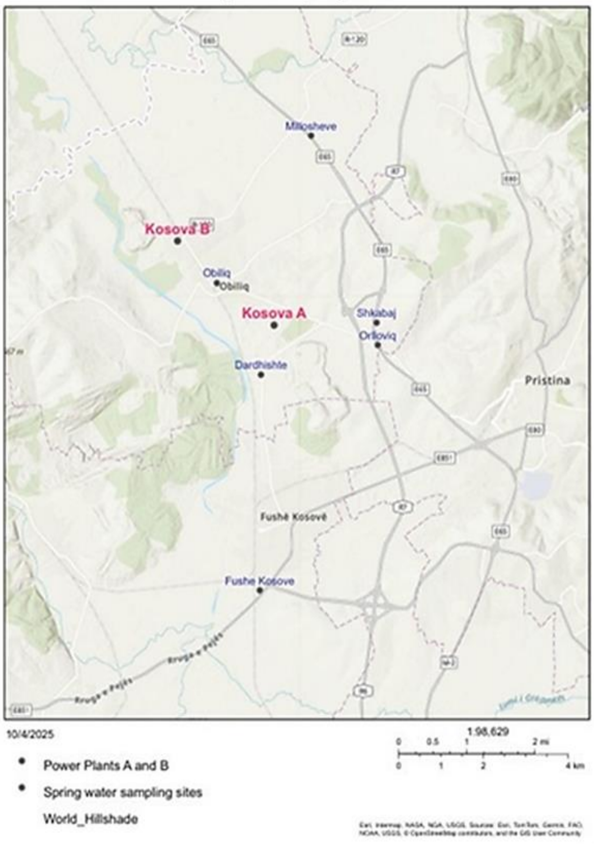

Fig. 1. Map of sampling locations

Sampling locations were distributed across central Kosovo and its surrounding areas, characterized by sedimentary formations interbedded with volcanic and metamorphic units. Such geological diversity is known to influence the occurrence and mobility of uranium-series radionuclides in groundwater systems. Geographic coordinates, local hydrogeological conditions, and usage characteristics were recorded for each sampling site to support interpretation of the results.

Water sampling procedure

Water samples were collected directly at the spring outlets following standardized procedures for radon determination in water. Sampling was performed using radon-tight glass containers with a nominal volume of 100 mL. Particular care was taken to avoid turbulence, air bubbles, and headspace during filling, as these factors can lead to radon loss prior to measurement.

Immediately after collection, the samples were sealed hermetically and transported to the measurement setup. All measurements were performed as soon as possible after sampling to minimize radioactive decay and degassing effects, in accordance with the recommendations of ISO 13164-3 (2013). Duplicate samples were collected at each location for quality control and for subsequent radium determination under equilibrium conditions.

Instrumentation

Radon (^{222}Rn) measurements were performed using an AlphaGUARD DF2000 professional radon monitor (Bertin Instruments), equipped with a gas-tight pulsed ionization chamber with an effective volume of 0.6 liters. The AlphaGUARD system provides high sensitivity and stability, with a measurement range of 2 to 2,000,000 Bq m^{-3} for radon in air and a sensitivity of approximately 1 count per minute at 20 Bq m^{-3}.

For water measurements, the AlphaGUARD monitor was coupled with the AquaKIT accessory, which consists of two degassing vessels (2 × 100 mL) designed for controlled radon transfer from the aqueous phase to the air phase within a closed circulation system. The system allows quantitative dessing of radon from water and homogeneous mixing of air prior to detection.

Measurement principle and emanometric determination of radon

The determination of ^{222}Rn activity concentration in water was based on the emanometric, pulse-counting ionization chamber (alpha spectroscopy) method (ISO 13164-3, 2013). In this approach, radon dissolved in the water sample is transferred into the air phase through controlled aeration within the closed AlphaGUARD–AquaKIT system. During degassing, air is circulated continuously between the degassing vessels and the ionization chamber, ensuring uniform radon distribution.

Before each measurement, the background radon concentration in the system (C_o) was recorded to verify system cleanliness and to correct for residual radon. After degassing, the radon concentration in air (C_{air}) was measured over a defined period, and the average value was used for subsequent calculations.

Water temperature was measured for each sample, as radon solubility in water is temperature dependent. The temperature-dependent water–air distribution coefficient (*k*), according to Weigel, was applied in all calculations, as recommended by ISO 13164-3 (2013).

Calculation of radon concentration in water

The activity concentration of radon in water (C_{water}, Bq·L^{-1}) was calculated using a mass-balance approach that accounts for the radon concentration measured in air after degassing, the background concentration, the internal volume of the system, the sample volume, and the distribution coefficient. The calculation was performed using the following equation:

$$C_{water} = \frac{C_{air}\ x\ \left[\frac{V_{system} - V_{sample}}{V_{sample}} + k\right] - C_o\ x\ \left[\frac{V_{system} - V_{sample}}{V_{sample}}\right]}{1000}$$

Where:

C_{air} – is the radon concentration in air after degassing (Bq m^{-3}),

C_o – is the background radon concentration (Bq m^{-3}),

V_{system} – is the internal volume of the measurement system (mL),

V_{sample} – is the water sample volume (mL),

k – is the water-air distribution coefficient.

Uncertainties in radon concentration were estimated by propagation of the instrumental uncertainty associated with air measurements and statistical variability during the measurement period.

Indirect determination of radium (^{226}Ra)

The activity concentration of radium (^{226}Ra) in water was determined indirectly using the in-growth method based on the decay relationship between ^{226}Ra and its daughter nuclide ^{222}Rn (ISO 13164-3, 2013). Duplicate water samples were stored in hermetically sealed containers for a period of 30 days to allow radon ingrowth and attainment of secular equilibrium.

After this period, radon generated by the decay of dissolved radium was degassed and measured using the same AlphaGUARD–AquaKIT system. Under conditions of secular equilibrium, the measured radon activity is equal to the activity of ^{226}Ra present in the sample. This approach has been widely applied in groundwater studies and is suitable for low-level radium determination when direct radiochemical methods are not employed, as demonstrated in similar applications using the AlphaGUARD–AquaKIT system (Tasev et al., 2021).

Physico-chemical parameters

Basic physico-chemical parameters of the water samples were measured to support interpretation of radionuclide behavior. Water temperature was recorded in situ at the time of sampling. pH and electrical conductivity (EC) were measured using calibrated portable field instruments. These parameters provide information on groundwater chemistry and water–rock interaction processes that may influence radon release and radium mobility.

Committed effective dose assessment

The committed effective dose to adult consumers resulting from ^{222}Rn and ^{226}Ra in drinking water was estimated by considering both ingestion and inhalation pathways. An average daily water consumption of 2 liters per person was assumed.

For radon (^{222}Rn), the ingestion dose was calculated using internationally recommended dose conversion factors, while the inhalation dose was estimated by applying a water-to-air transfer coefficient of 10^{-4}, an indoor occupancy time of 7000 h y^{-1}, an equilibrium factor of 0.4, and an inhalation dose conversion factor of 9 nSv (Bq h m^{-3})$^{-1}$ (WHO, 2022; UNSCEAR, 1993). The ingestion dose from radium (^{226}Ra) was calculated using the appropriate dose conversion factor for adults, assuming direct ingestion of dissolved radium with drinking water (WHO, 2022). The total committed effective dose was obtained as the sum of ingestion and inhalation components and expressed in µSv y^{-1}.

RESULTS AND DISSCUSION

Emanometric measurements of radon in spring-water samples were performed using a closed AlphaGUARD–AquaKIT system with subsequent detection of alpha particles in a pulsed ionization chamber. As defined in standardized emanometric procedures, the efficiency of radon transfer from the aqueous phase to the air phase depends on water temperature, system geometry, and controlled air circulation within the closed system (ISO 13164-3, 2013). To ensure transparency and traceability of the measurements, time-resolved AlphaGUARD logs and the corresponding measurement-course diagrams for each sampling site are presented in Figure 2 (a.b.c.d.e.f.).

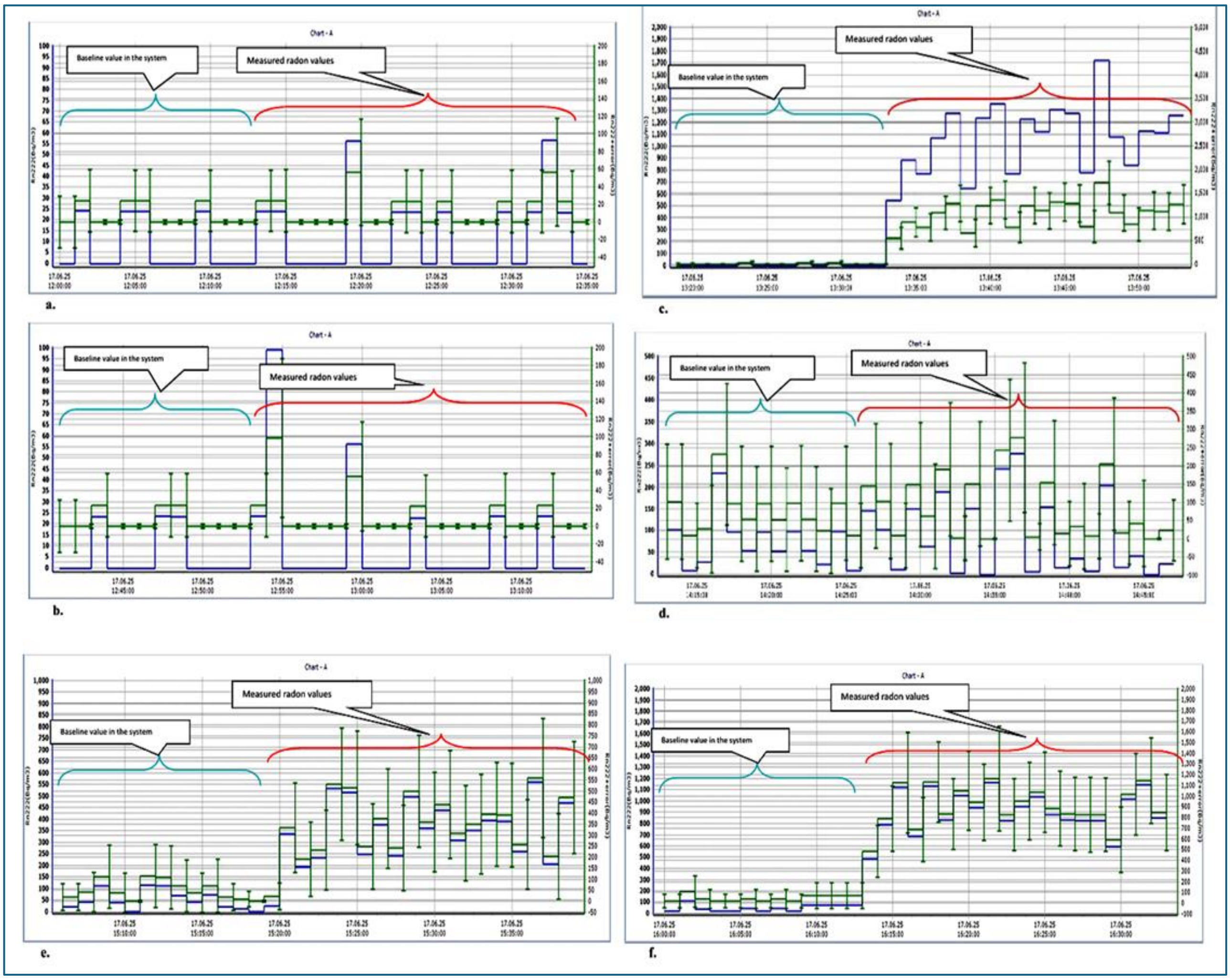

Fig. 2(a.b.c.d.e.f.). Time-resolved diagrams illustrating the course of radon (^{222}Rn) measurements in spring waters from Orllovic village, Shkabaj village, Millosheva village, Obiliq town, Dardishte village, and Fushe Kosova.

Radon activity concentrations were calculated using the measured initial radon concentration in the system (C_0), the radon concentration in air after degassing (C_{air}), the internal volume of the measuring system, the water–air distribution coefficient (*k*, according to Weigel), and the sample temperature. The complete set of parameters used for the calculation of ^{222}Rn activity concentrations at each sampling site, together with associated measurement uncertainties, is summarized in Table 1.

Table 1

Parameters used for the calculation of radon (^{222}Rn) concentration in spring waters from Kosovo (emanometric method; AlphaGUARD–AquaKIT)

Parameter	Orllovic	Shkabaj	Millosheva	Obiliq	Dardishte	Fushe Kosova
Sample volume (mL)	100	100	100	100	100	100
System volume (cm^3)	1150	1150	1150	1150	1150	1150
Water/air distribution coefficient, *k* (Weigel)	0.233	0.229	0.229	0.228	0.228	0.228
Sample temperature (°C)	23.0	24.0	24.0	24.5	24.5	24.5
Measured initial radon concentration in the system, C_0 (Bq m^{-3})	5.66	5.66	5.30	6.87	6.05	6.08
Measured radon concentration in air after aeration, C_{air} (Bq m^{-3})	13.46	12.63	99.73	20.38	36.23	76.43
Error of radon measurements in air (Bq m^{-3})	3.02	3.02	2.57	3.25	3.32	3.99
Radon concentration in the water sample, C_{water} (Bq·L^{-1})	0.09	0.06	10.88	0.55	3.47	8.73
Error of radon measurements in water (Bq·L^{-1})	0.03 (38.12%)	0.03 (43.79%)	0.28 (2.56%)	0.09 (16.91%)	0.18 (5.26%)	0.43 (4.93%)

Table 2

Radon concentrations in waters from Orllovic village, Shkabaj village, Millosheva village, Obiliq town, Dardishte village, and Fushe Kosova town.

Sample/Spring water	Measured value (Bq/L)	MKD action level (Bq/L)	WHO guideline (Bq/L)	US-EPA (Bq/L)
Orllovic village	0.09	1000	100	11.1
Shkabaj village	0.06	100013	100	11.1
Millosheva village	10.88	1000	100	11.1
Obiliq town	0.55	1000	100	11.1
Dardishte village	3.47	1000	100	11.1
Fushe Kosova town	8.73	1000	100	11.1

The calculated ^{222}Rn activity concentrations for the six investigated spring water locations, together with applicable guideline and reference levels, are presented in Table 2, while their spatial distribution is illustrated in Figure 3. Radon activity concentrations ranged from 0.06 Bq·L^{-1} in spring water from Shkabaj village to 10.88 Bq·L^{-1} in Millosheva village. Very low activities measured in Shkabaj and Orllovic are consistent with limited radon generation and/or reduced transfer to groundwater, likely related to local lithology, shorter groundwater residence times, and enhanced natural degassing processes that control radon concentrations in aquifers (Schubert et al., 2012; Vesterbacka et al., 2005). In contrast, elevated activities observed in Millosheva and Fushe Kosova indicate more pronounced water–rock interaction, suggesting the presence of fractured or mineralized aquifer materials that favor radon emanation (Przylibski et al., 2022; Alonso et al., 2015).

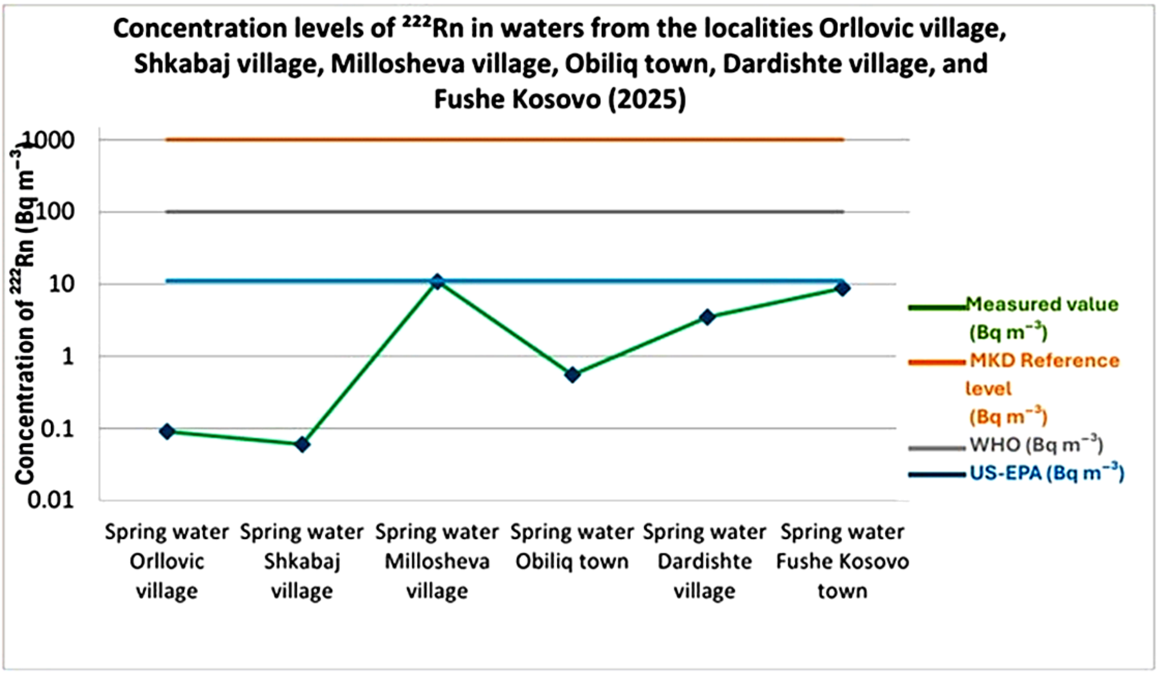

Fig. 3. Diagram of radon concentration in spring waters from Orllovic village, Shkabaj village, Millosheva village, Obiliq town, Dardishte village, and Fushe Kosova town, compared with the reference values, the Macedonian action level (MKD), the values recommended by the World Health Organization (WHO), and the United States Environmental Protection Agency (US-EPA)

The observed spatial variability among the investigated springs reflects natural geological and hydrogeological controls, including lithological composition, fracture density, permeability, and groundwater flow dynamics. Comparable radon ranges have been reported in well and spring waters from Bosnia and Herzegovina, where measured radon concentrations did not exceed the EU reference level for drinking water (Kasić et al., 2016). Similar spatial variability associated with geological features has also been observed in studies focused on radon distribution and geogenic mapping in Croatia, further highlighting the role of local geology in radon behavior (Mostečak et al., 2018). Previous investigations conducted in Kosovo have also reported measurable radon activity concentrations in soil, groundwater, and drinking-water sources, confirming the influence of local geological conditions on radon occurrence and variability across different regions of the country (Elezaj et al., 2025a; 2025b; Marković et al., 2020). From a regulatory and public-health perspective, all measured radon concentrations remain well below the WHO guidance level of 100 $\mathrm{Bq \cdot L^{-1}}$ and below the US-EPA reference value of 11.1 $\mathrm{Bq \cdot L^{-1}}$ applied in drinking-water assessments (WHO, 2022; US-EPA, 2000). The radon activities observed in Kosovo spring waters, within this study, therefore fall within the lower range of values typically reported for groundwater and spring waters in comparable geological environments.

Radium (^{226}Ra) in spring waters

Radium activity concentrations were determined indirectly using the ingrowth method, based on the decay relationship between ^{226}Ra and its daughter nuclide ^{222}Rn. Duplicate water samples were stored in hermetically sealed containers for 30 days to allow radon ingrowth and attainment of secular equilibrium. Radon measured after this period was interpreted as the activity concentration of ^{226}Ra under equilibrium conditions. Similar emanometric approaches based on the ingrowth relationship between ^{226}Ra and its daughter nuclide ^{222}Rn for indirect radium determination in groundwater have been described in earlier analytical and environmental studies (Agency for Toxic Substances and Disease Registry [ATSDR], 1990; Tarim et al., 2011; Martin et al., 2021) and have also been applied in recent investigations using the AlphaGUARD–AquaKIT system (Tasev et al., 2021). Time-resolved measurement logs and the corresponding measurement-course diagrams for the ingrowth measurements are presented in Figure 4 (a.b.s.d.e.f.).

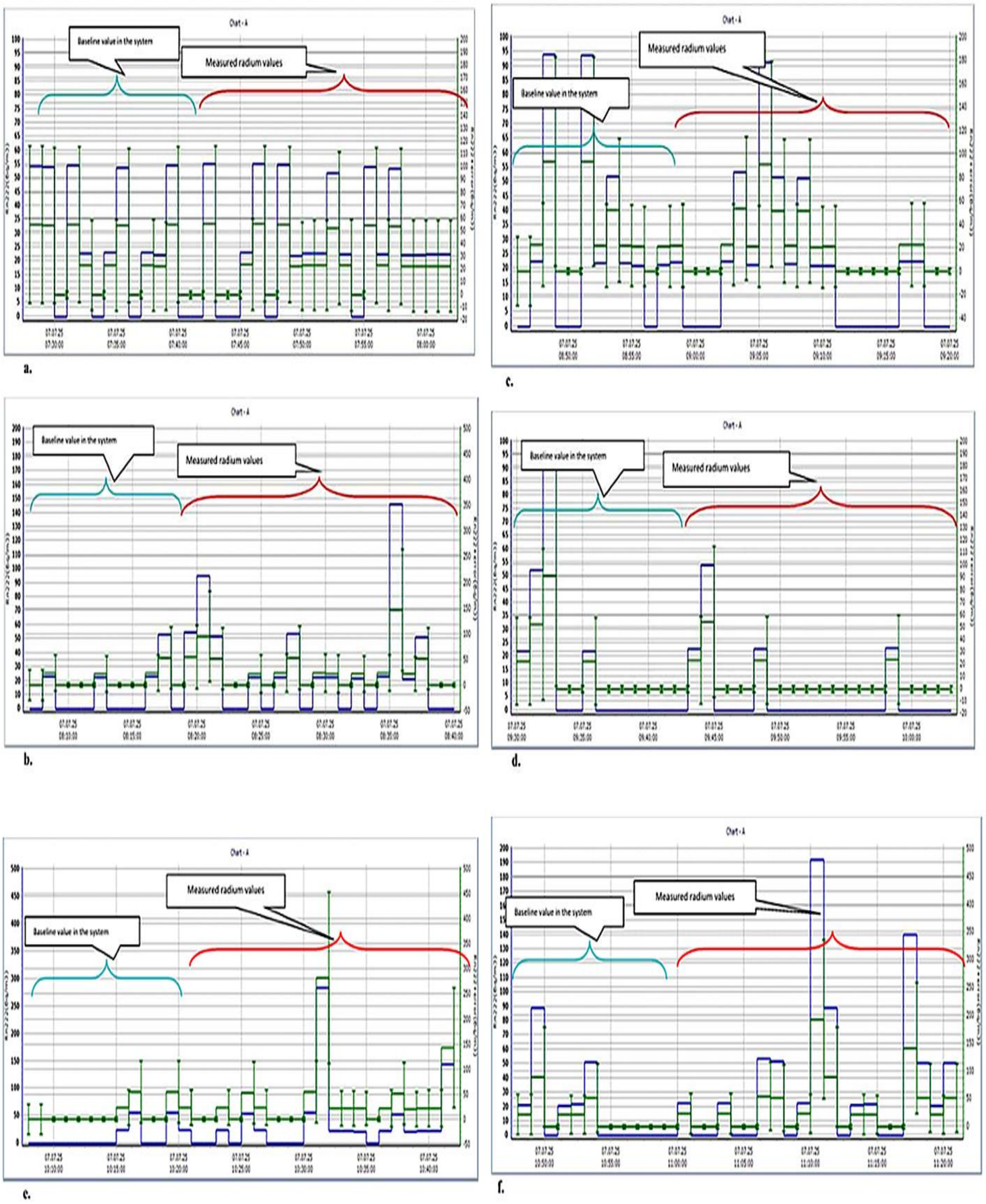

Fig.4 (a.b.c.d.e.f). Time-resolved diagrams illustrating the course of radium (^{226}Ra) measurements in spring waters from Orllovic village, Shkabaj village, Millosheva village, Obiliq town, Dardishte village, and Fushe Kosova.

The parameters used for the calculation of ^{226}Ra activity concentrations, including sample and system volumes, water–air distribution coefficients, sample temperature, and measured radon concentrations before and after ingrowth, are summarized in Table 3. These parameters indicate controlled and comparable measurement conditions across all investigated sites, ensuring consistency of the ingrowth procedure and allowing reliable inter-site comparison of radium activity concentrations.

Table 3

Parameters used for the calculation of radium (^{226}Ra) concentration in spring waters (ingrowth method after 30 days; AlphaGUARD–AquaKIT).

Parameter	Orllovic	Shkabaj	Millosheva	Obiliq	Dardishte	Fushe Kosova
Sample volume (mL)	100	100	100	100	100	100
System volume (cm³)	1150	1150	1150	1150	1150	1150
Water/air distribution coefficient, k (Weigel)	0.204	0.209	0.209	0.209	0.209	0.209
Sample temperature (°C)	28.0	27.0	27.0	27.0	27.0	27.0
Measured initial radon concentration in the system, C_0 (Bq m^{-3})	11.83	8.24	9.23	4.17	7.48	10.35
Measured radon concentration in air after aeration, C_{air} (Bq m^{-3})	27.19	27.34	21.89	15.24	37.24	34.13
Error of measurements in air (Bq m^{-3})	9.34	5.11	4.24	5.41	5.74	5.78
Radium concentration in the water sample (Bq·L^{-1})	0.17	0.21	0.14	0.12	0.32	0.26
Error of radium measurements in water (Bq·L^{-1})	0.10 (59.93%)	0.05 (26.53%)	0.05 (33.02%)	0.06 (48.51%)	0.06 (19.19%)	0.06 (24.10%)

The resulting ^{226}Ra activity concentrations, together with their comparison to the WHO reference level for drinking water (WHO, 2022), are presented in Table 4. According to the United States Environmental Protection Agency (US EPA), regulatory limits for radionuclides in drinking water are also defined based on radiological dose criteria (US EPA, 2023). The spatial distribution of radium activities across the investigated localities is illustrated in Figure 5. Moderate site-to-site variability is observed, with slightly higher radium activity concentrations recorded in Dardishte and Fushe Kosova compared to the remaining sampling locations. This variability is most likely related to local geochemical conditions, such as differences in aquifer mineral composition, water–rock interaction processes, and ion-exchange mechanisms, rather than any anthropogenic influence.

Table 4

Radium concentration in waters in and around Orllovic village, Shkabaj village, Millosheva village, Obiliq town, Dardishte village, and Fushe Kosova town

Sample/Spring water	Measured value ^{226}Ra (Bq/L)	WHO guideline ^{226}Ra (Bq/L)
Orllovic village	0.17	1
Shkabaj village	0.21	1
Millosheva village	0.14	1
Obiliq town	0.12	1
Dardishte village	0.32	1
Fushe Kosova	0.26	1

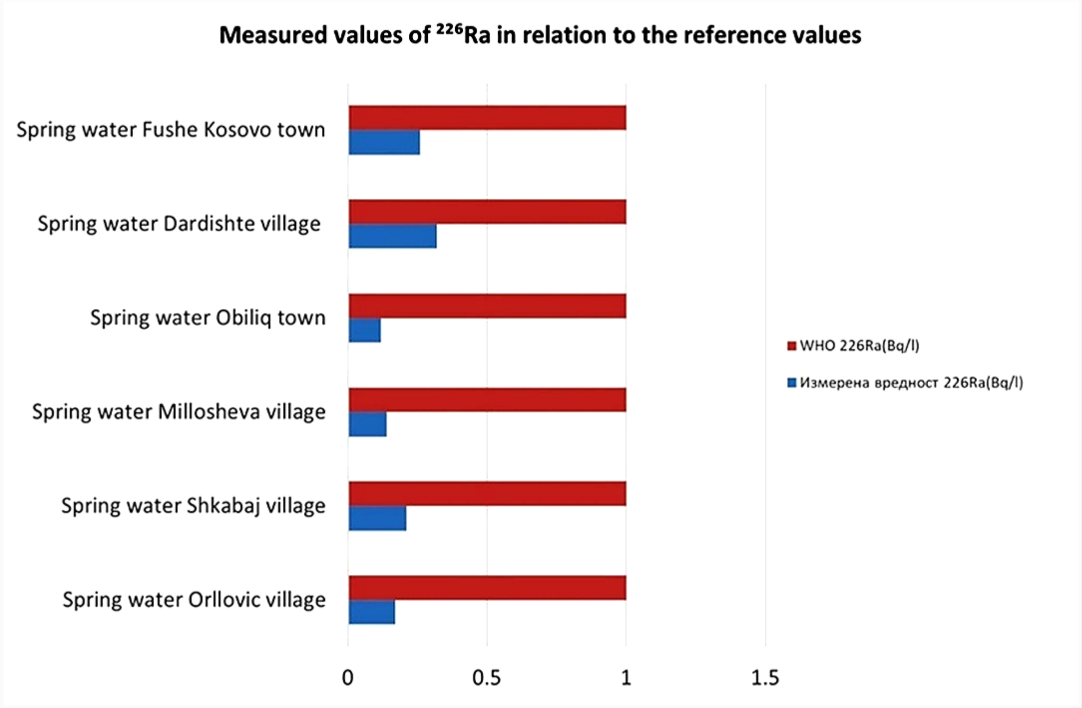

Fig. 5. Measured values of ^{226}Ra in water samples from in and around Orllovic village, Shkabaj village, Millosheva village, Obiliq town, Dardishte village, and Fushe Kosova town, compared with the reference values provided by the World Health Organization (WHO).

Measured ^{226}Ra activity concentrations ranged from 0.12 Bq·L^{-1} in Obiliq town to 0.32 Bq·L^{-1} in Dardishte village. All measured values are below the WHO reference level of 1 Bq·L^{-1}, indicating no exceedance of the principal benchmark used for radiological screening of drinking water (WHO, 2022). Despite their low magnitude, the observed spatial variability highlights the influence of site-specific geochemical conditions, including mineral dissolution, adsorption–desorption processes, and ion-exchange mechanisms, which govern radium mobility in groundwater systems (Somlai et al., 2002; Shivakumara et al., 2014). Radium activity concentrations reported for spring and groundwater systems in southeastern Europe generally remain below international drinking-water guideline values, while still contributing to ingestion dose, which is consistent with the low ^{226}Ra activities observed in the present study (Somlai et al., 2002; Kávási et al., 2010).

Physico-chemical context and committed effective dose

Basic physico-chemical parameters, including pH and electrical conductivity (EC), were measured to support interpretation of radionuclide behavior and are presented together with radionuclide activity concentrations and derived dose estimates in Table 5. The pH values ranged from 7.04 to 7.21, indicating neutral to slightly alkaline groundwater conditions across all investigated spring waters. Electrical conductivity varied between 110 and 810 µS cm^{-1}, reflecting differences in groundwater mineralization and the intensity of water–rock interaction among the sampling sites. In addition to physico-chemical parameters, Table 5 summarizes the activity concentrations of ^{222}Rn (Bq·L^{-1}) and ^{226}Ra (mBq·L^{-1}), as well as the corresponding inhalation and ingestion doses (µSv y^{-1}), total annual effective dose expressed in both µSv y^{-1} and mSv y^{-1}, and the combined inhalation–ingestion dose of ^{222}Rn. Together, these parameters provide essential context for interpreting site-specific variations in radon release, radium mobility, and their contribution to radiation dose.

The committed effective dose to adult consumers was estimated by considering inhalation of ^{222}Rn released into indoor air during household water use and ingestion of ^{222}Rn and ^{226}Ra through drinking water, following internationally recommended assumptions and dose conversion factors (WHO, 2022; UNSCEAR, 2000). The resulting total annual effective dose for each investigated locality is illustrated in Figure 6.

Table 5

Calculated values of exposure due to radon inhalation and ingestion of radon and radium in waters in and around Orllovic village, Shkabaj village, Millosheva village, Obiliq town, Dardishte village, and Fushe Kosova town

Sampling location/ Spring water	Orllovic village	Shkabaj village	Millosheva village	Obiliq town	Dardishte illage	Fushe Kosova town
Number of measurements	34+33	35+35	34+33	34+34	34+34	33+33
pH	7.06	7.1	7.04	7.09	7.15	7.21
EC (μS cm^{-1})	678	810	502	374	475	110
^{222}Rn (Bq·L^{-1})	0.09	0.06	10.88	0.55	3.47	8.73
^{226}Ra (mBq·L^{-1})	170.00	210.00	140.00	120.00	320.00	260.00
Inhalation dose of ^{222}Rn (μSv y^{-1})	0.23	0.15	7.42	1.39	8.74	22.00
Ingestion dose of ^{222}Rn (μSv y^{-1})	0.11	0.08	13.90	0.70	4.43	11.15
Ingestion dose of ^{226}Ra (μSv y^{-1})	17.37	21.46	14.31	12.26	32.70	26.57
TOTAL dose (μSv y^{-1})	17.72	21.69	55.62	14.35	45.88	59.72
TOTAL dose (mSv y^{-1})	0.02	0.02	0.06	0.01	0.05	0.06
TOTAL ingestion dose (mSv y^{-1})	0.02	0.02	0.03	0.01	0.04	0.04
Inhalation and ingestion dose of ^{222}Rn (μSv y^{-1})	0.34	0.23	41.32	2.09	13.18	33.15

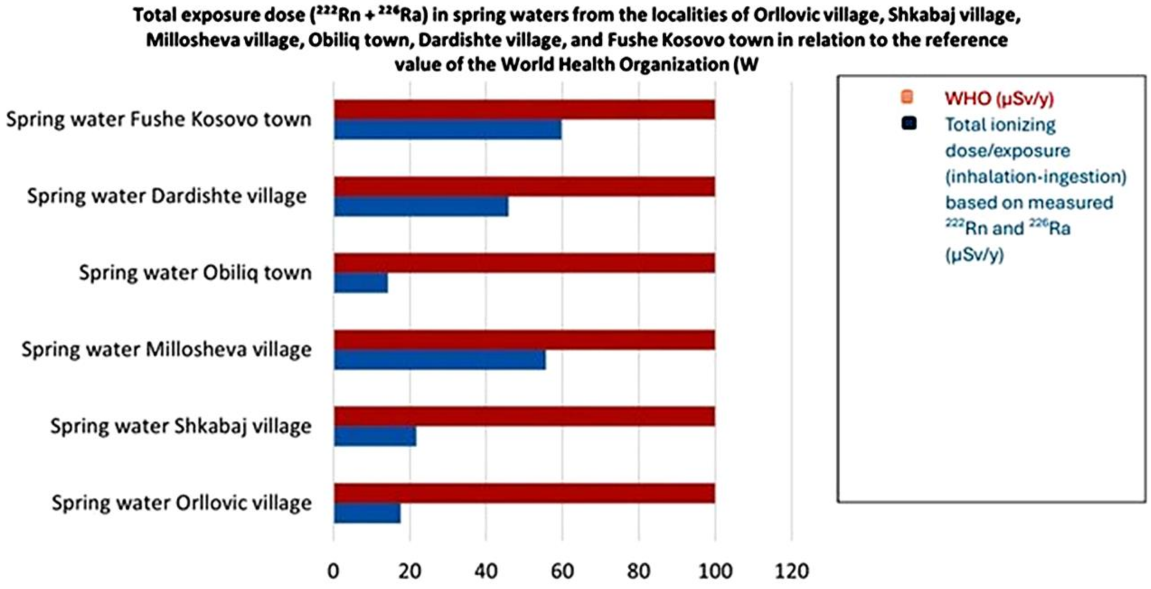

Fig. 6. Calculated values of the total exposure dose from inhalation and drinking/consumption (^{222}Rn + ^{226}Ra) in water samples from in and around the localities of Orllovic village, Shkabaj village, Millosheva village, Obiliq town, Dardishte village, and Fushe Kosova town, compared with the reference values provided by the World Health Organization (WHO)

Across all investigated sites, the inhalation component of ^{222}Rn contributed more to the total dose than the ingestion component of ^{222}Rn, particularly in localities with higher radon activity concentrations such as Millosheva and Fushe Kosova. This pattern is consistent with previous studies demonstrating that radon in water generally contributes more effectively to radiation dose through transfer to indoor air than through direct gastrointestinal uptake, depending on water-use practices and indoor ventilation conditions (WHO, 2022; Öner et al., 2009).

In contrast, ingestion of ^{226}Ra contributed substantially to the total annual effective dose despite its low activity concentrations, reflecting radium's chemical similarity to calcium and its tendency for biological retention following ingestion (WHO, 2022; UNSCEAR, 2000).

The total annual effective dose at all investigated sites ranged from 0.01 to 0.06 mSv y^{-1} and remained well below the WHO reference level of 100 μSv y^{-1}, indicating no significant radiological risk associated with the consumption of these spring waters. Comparable investigations conducted in the Prizren region of Kosovo have also reported radon activity concentrations and associated effective doses within internationally accepted reference limits (Elezaj et al., 2023), further supporting the consistency of the present findings.

CONCLUSIONS

Overall, spring waters from the investigated localities in Kosovo exhibit low activity concentrations of ^{222}Rn and ^{226}Ra, with all measured values and associated dose estimates remaining below internationally accepted reference levels. The observed spatial variability reflects natural geological and hydrogeochemical controls rather than anomalous radiological contamination. This study provides a structured and harmonized baseline dataset for radon and radium in spring waters used for drinking in Kosovo and supports future monitoring, regional comparison, and evidence-based radiological risk management at the national level using standardized emanometric methodology.

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Резиме

АКТИВНОСТ И ПРОЦЕНА НАКОЛИЧЕСТВОТО НА РАДОН (^{222}Rn) И РАДИУМ (^{226}Ra) ВО ИЗВОРСКИТЕ ВОДИ ВО КОСОВО

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Клучни зборови: радон; радиум; изворска вода; AlphaGUARD; Косово

Радонот (^{222}Rn) и радиумот (^{226}Ra) се природно присутни радионуклиди од низата на распад на ^{238}U кои можат да придонесат за изложеност на населението преку водата за пиење и амбиенталниот воздух, како резултат на дегазирање на радонот при употребата на водата во домашни услови. Испитани се шест извори, при што анализите се извршени со еманациска метода со примена на AlphaGUARD DF2000 монитор поврзан со AquaKIT систем. Активностите на ^{222}Rn се движеа во опсег од 0,06 до 10,88 Bq·L^{-1}, додека ^{226}Ra, индиректно определен по 30-дневен период на распад на радонот, се движи од 0,12 до 0,32 Bq·L^{-1}. Вкупната ефективна доза за возрасни лица (вдишување и голтање; ^{222}Rn+^{226}Ra) изнесува од 14,35 до 59,72 µSv y^{-1}, што е значително под референтното ниво од 100 µSv y^{-1}, препорачано од WHO. Резултатите укажуваат на отсуство на значителен радиолошки ризик и придонесуваат кон постојната основна база на податоци за радон и радиум во изворските води во Косово.

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