RADIOACTIVITY IN SOIL FROM MOJKOVAC, MONTENEGRO, AND ASSESSMENT OF RADIOLOGICAL AND CANCER RISK

by

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Soil samples from Mojkovac, Montenegro, were analyzed by standard gamma-spectrometry for radioactivity due to ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs. Average activity concentrations have been found to be 28.6, 43.1, 620.8, and 55 Bq/kg, respectively. In order to evaluate the radiation hazard, radium equivalent activity, absorbed dose rate, annual effective dose, external and internal hazard indexes, and the annual gonadal dose equivalent were determined and found to be at an average of 133.79 Bq/kg, 65.18 nGy/h, 79.93 μSv/y, 0.37, 0.45, and 0.46 mSv/y, respectively. With life expectancy taken to be 70 years, a mean lifetime outdoor gamma radiation was calculated as 5.6 mSv, yielding a lifetime cancer risk of 2.8 10^{-4}.

Key words: soil-radioactivity, radiological hazard, cancer risk

INTRODUCTION

Natural background radiation makes up approximately 80% of the total radiation dose a person receives in a year [1], with soil radionuclide activity concentration as one of the main contributors. This radiation was formed by the process of nucleosynthesis, but only radionuclides with half-lives comparable to the Earth's age, such as ^{40}K and radionuclides from the uranium and thorium series, can still be found in different geological materials. A majority of them can be considered as γ-emitting radionuclides. Namely, ^{40}K decays by electron capture and β^+-decay to stable ^{40}Ar (10.7%) (with an emission of 1460.83 keV γ-ray), and by β^--decay to stable ^{40}Ca (89.3%) [2]; ^{238}U series contains 18 daughter radionuclides (including ^{226}Ra, with a half-life of 1600 years), and ends with stable lead – ^{206}Pb [2] (radioecological importance of ^{226}Ra is mostly related to its decay product radon (^{222}Rn) which contributes about 50% to the average annual effective dose that the human population receives from all natural radiation sources [3]); ^{232}Th series contains 10 daughter radionuclides and ends with stable ^{208}Pb [2]. Their gamma radiation (following decays of ^{40}K and daughters in the uranium and thorium series) represents the main external source of irradiation and can be considered as the largest contributor to the external dose absorbed by the world population. Total external exposure rates from terrestrial gamma radiation worldwide showed the absorbed dose rates median of 57 (18-93) nGy/h and a population-weighted average of 59 nGy/h. The median value of the absorbed dose rates in air from radionuclides of the ^{238}U series has been found to be 16 nGy/h, with a population-weighted value of 15 nGy/h, as is the case with radionuclides of the ^{232}Th series – 18 nGy/h, with a population-weighted value – 27 nGy/h [4].

Potassium-40 activity concentrations in soil worldwide showed medians in the range from 140 to 850 Bq/kg, with a mean of 400 Bq/kg, whilst ^{226}Ra activity medians ranged from 17 to 60 Bq/kg, with a mean of 35 Bq/kg, and those of ^{232}Th – from 11 to 64 Bq/kg, with a mean of 30 Bq/kg [4].

On the other hand, soil radioactivity is also affected by artificial radionuclides, in particular by ^{137}Cs (a fission product with a half-life of 30.1 years) formed through nuclear tests and accidents. This is why soil samples from Mojkovac, Montenegro, have for the first time been analyzed for radioactivity due to ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs.

In order to evaluate the health hazards of natural radioactivity, radium equivalent activity, gamma-absorbed dose rate, annual effective dose, hazard index (external and internal), annual gonadal dose equivalent and the excess lifetime cancer risk were also estimated and presented here.

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MATERIALS AND METHODS

Sampling and sample preparation

A map of the study area (Mojkovac) with 13 soil sampling locations (tab. 1) is shown in fig. 1.

The town of Mojkovac, with a population of 10000 (census of population, households, and dwellings in the Republic of Montenegro in 2003), lies on the west bank of the Tara River, between mountains Bjelasica and Sinjajevina. It is located around 850 m above sea-level, and the geology of the region is characterized by marl, sandstone, and schist, Triassic limestones with chert, keratophyre, quartz keratophyre and tuffs, and Quaternary alluvium.

In addressing environmental problems in Montenegro, Mojkovac was marked as an ecological hot spot, mostly due to the waste storage site ("Jalovište" in fig. 1, separated from the town only by a road) of flotation sludge from re-processing of Pb-Zn of the Brskovo mine (closed in 1991). Therefore, ecological hazards (including impact upon the ecosystem of the National park Durmitor) were considered in many studies (particularly in those dealing with heavy metals) but, until now, there has not been a study evaluating environmental risk due to radioactivity in soil.

A standard procedure for soil sampling [5] has been applied in the present study. The surface (0-5 cm) of uncultivated soil has been taken (from a frame of 25 cm 25 cm), foreign bodies were removed and the remaining soil placed in clean bags. The samples were dried at room temperature, passed through 2 mm sieves, weighed, placed in Marinelli beakers and kept for around 40 days before the analysis at airtight conditions, so as to allow secular equilibrium between radium and its daughters.

Determination of radionuclide activity concentrations and radium equivalent activity

Gamma-spectrometry is a standard procedure for ^{40}K and ^{137}Cs measurements, but is widely used for various radium and thorium measurements, as well. So, the soil samples from Mojkovac were measured using the coaxial HPGe detector (ORTEC – GEM-40190, relative efficiency – 40%, FWHM – 1.80 keV at 1.33 MeV, FWHM – 840 eV at 122 keV; background – 1.23 cps; software – Gamma Vision 32 A66-B32 V 4.12 and Gamma Vision 32 A66-B32 V 5.2), calibrated using standard mixtures of gamma emitting isotopes in Marinelli beakers (Czech Metrological Institute). The soil samples were measured over different live measuring times (from 23 156 s /Školski centar/ to 64 747 s /Mala škola/), and activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs were determined by using intensive photopeaks – ^{226}Ra (295.22 keV, 351.93 keV, 609.31 keV, 1120.2 keV, 1764.4 keV), ^{232}Th (338.32 keV, 911.20 keV), ^{40}K (1460.83 keV), and ^{137}Cs (661.62 keV), in a standard procedure (based on the to-

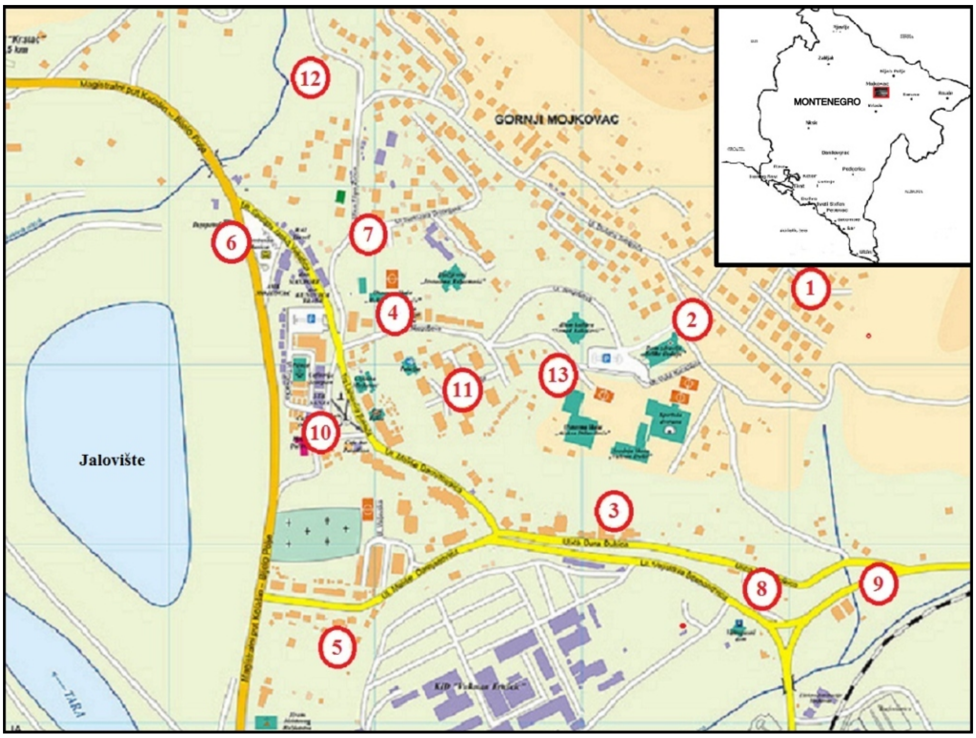

Figure 1. Soil sampling locations

tal net counts under the selected photopeaks, live measuring time, photopeak efficiency, gamma ray intensity, and weight of the sample).

The radium equivalent activity (Ra_{eq}) in Bq/kg represents the uniformity with respect to exposure to radiation, as the distribution of ^{226}Ra, ^{232}Th, and ^{40}K in soil is not uniform. It was calculated by the relation [6]

$$Ra_{eq} = A_c(^{226}Ra) + 1.43A_c(^{232}Th) + 0.07A_c(^{40}K) \quad (1)$$

where $A_c(^{226}Ra)$, $A_c(^{232}Th)$, and $A_c(^{40}K)$ [Bqkg^{-1}] are the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, respectively, in soil samples. At the base of calculating Ra_{eq} *i. e.*, eq. (1) is the assumption that 370 Bq/kg of ^{226}Ra or 259 Bq/kg of ^{232}Th or 4810 Bq/kg of ^{40}K produce the same γ-dose rate.

Absorbed and effective dose rate

The gamma absorbed dose rate in air at 1 m above the ground level, D [nGyh^{-1}] was calculated using the equation

$$D = A_c(^{226}Ra)0.462 + A_c(^{232}Th)0.604 + A_c(^{40}K)0.0417 \quad (2)$$

where $A_c(^{226}Ra)$, $A_c(^{232}Th)$, and $A_c(^{40}K)$ are activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, respectively, and 0.462, 0.604, and 0.0417 (nGy/h)/(Bq/kg), respectively, are corresponding dose coefficients [4]. In eq. (2), it is assumed that all decay products of ^{226}Ra and ^{232}Th are in radioactive equilibrium with their precursors.

The annual effective dose rate, E was estimated by equation

$$E = D\,[\text{nGyh}^{-1}]\ \ 8760\ \text{h}\ \ 0.2\ 0.7\ \text{Sv/Gy}^{-1} \quad (3)$$

where the dose conversion factor (0.7 Sv/Gy), outdoor occupancy factor (0.2) and time (8760 hours per year) are taken into account, as proposed by the UNSCEAR [4].

Hazard index, annual gonadal dose equivalent and excess cancer risk

The external hazard index (H_{ex}) was calculated by [6]

$$H_{ex} = A_c(^{226}Ra)/370 + A_c(^{232}Th)/259 + A_c(^{40}K)/4810 \quad (4)$$

The maximum value of this index equal to *unity* corresponds to the upper limit of radium equivalent activity (370 Bq/kg).

As it is known, radon and its short-lived products are also hazardous for respiratory organs. The internal hazard index H_{in} (quantifying the internal exposure to radon and its decay products) is given by the equation [7, 8]

$$H_{in} = A_c(^{226}Ra)/185 + A_c(^{232}Th)/259 + A_c(^{40}K)/4810 \quad (5)$$

It is important to point out that the values of indices H_{ex} and H_{in} must be less than *unity* for the radiation hazard to be negligible. For a safe use of a material in the construction of dwellings, the index H_{in} should be less than *unity* and its maximum value needs to be less than *unity* [7].

The gonads, active bone marrow and bone surface cells are considered as the organs of interest by the UNSCEAR [3]. Thus, the annual gonadal dose equivalent (G) in μSv/y due to ^{226}Ra, ^{232}Th, and ^{40}K activity concentration was calculated using [9]

$$G = A_c(^{226}Ra)3.09 + A_c(^{232}Th)4.18 + A_c(^{40}K)0.314 \quad (6)$$

Moreover, excess lifetime cancer risk (CR) was calculated by [10]

$$CR = E\ T\ RF \quad (7)$$

where, E is the annual effective dose rate, T – the lifetime (70 years), and RF – the risk factor [Sv^{-1}], fatal cancer risk per Sievert. For stochastic effects, the ICRP 60 recommended a value of 0.05 for the public [11]. On the other hand, taking the fatal cancer risk for a population of all ages, the ICRP 103 uses a value of 0.04 [12], and its detriment-adjusted nominal risk coefficients for stochastic effects after exposure to radiation at low dose rate (derived from incidence data), differ from those given in the ICRP 60 (derived from mortality data).

RESULTS AND DISCUSSION

Radionuclide concentration and radium equivalent activity

The results of soil measurements, *i. e.*, ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs activity concentrations in the 13 samples from Mojkovac, as well as radium equivalent activities calculated by eq. (1), are given in tab. 1. A cumulative activity concentration at each location is shown in fig. 2.

Minimum detectable activities ranged from 0.47 Bq/kg (Rudnica 1) to 2.25 Bq/kg (Školski centar) – for ^{226}Ra; from 1 Bq/kg (Rudnica 1) to 3.65 Bq/kg (Mikronaselje) – for ^{232}Th; from 2.6 Bq/kg (Rudnica 1) to 10.9 Bq/kg (ul. Dušana Tomovića) – for ^{40}K; and, from 0.29 Bq/kg (Braunovići) to 1 Bq/kg (Rudnica) – for ^{137}Cs. From the data in tab. 1, it follows that ^{226}Ra activity concentrations in sampled soil ranged from 20.5 to 38.3 Bq/kg, with a mean, standard deviation and a median of 28.6, 4.3, and 28.6 Bq/kg, respectively. This average value is in accordance with a mean

Table 1. Radionuclide activity concentrations and radium equivalent activities

	Location	Activity concentration [Bq/kg]				
		^{226}Ra	^{232}Th	^{40}K	^{137}Cs	Ra_{eq}
1	Braunovići	26.42 0.29	47.68 1.73	614.64 20.21	4.94 0.22	137.63
2	ul. Dušana Tomovića	30.05	42.95 2.70	567.60 21.94	28.64 1.22	131.2
3	ul. Svetozara Drobnjaka	38.26 1.36	39.30 2.52	517.63 19.81	80.36 2.82	130.73
4	Mala škola	25.56 1.08	38.46 1.82	515.61 17.84	66.03 2.21	117.65
5	Park	26.97	47.17 2.51	678.86 24.06	1.26 0.35	141.94
6	Pumpa	26.13 1.04	39.70 1.80	753.41 25.60	33.60 1.18	135.64
7	Ilići	33.56 1.39	56.33 2.52	598.05 21.02	8.32 0.47	155.97
8	Rudnica 1	20.49 0.74	31.24 1.22	575.21 18.90	6.50 0.26	105.43
9	Rudnica	29.92 1.38	33.98 2.03	674.11 24.01	276 9	125.69
10	Hotel Sinjajevina	28.59 1.48	41.77 2.73	565.96 21.58	79.17 2.80	127.94
11	Mikronaselje	30.86 1.56	44.63 2.79	632.21 23.88	41.34 1.62	138.93
12	Juškovića potok	24.78 1.09	45.16 2.11	692.89 23.85	4.78 0.36	137.86
13	Školski centar	29.88 1.65	52.34 2.97	684.78 25.95	84.20 3.01	152.66

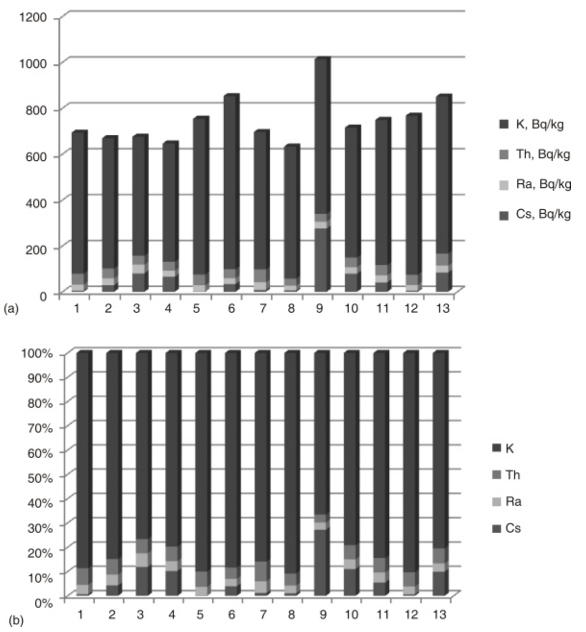

Figure 2. A cumulative activity at the locations – in Bq/kg (a), in % (b)

^{226}Ra activity concentration measured in Greek and Spanish soil, for example (25 and 32 Bq/kg, respectively [4]). At the same time, it is slightly lower than the average radium activity measured in Botswana (34.8 Bq/kg [13]) and northern Jordanian soil (42.5 Bq/kg [14]). A median of (around, 28.6 Bq/kg) is found to be lower than the global average (35 Bq/kg [4]).

Average ^{232}Th activity concentrations in the region of Southern Europe (Albania, Croatia, Greece, Portugal, Slovenia, and Spain) are found to be 24 [4-160], 45 [12-65], 21 [1-190], 51 [22-100], 35 [2-90], 33 [2-210] Bq/kg, respectively [4] (the range of individual measurements is given in brackets). In the case of soil from Mojkovac (from 31.2 to 56.3 Bq/kg), a mean value of thorium activity (43.1 Bq/kg, with a standard deviation of 6.9 Bq/kg) is found to be in accordance with the one in Croatia, but somewhat higher than in Slovenia and Spain, as well as those of above mentioned soil samples in Botswana (41.8 Bq/kg) and Jordan (26.7 Bq/kg). The median (42.9 Bq/kg) is also higher than the worldwide average median (30 Bq/kg [4]).

The minimum, maximum, mean, standard deviation and median of ^{40}K activity concentration in soil from Mojkovac have been calculated to 515.6, 753.4, 620.8, 72.7, and 614.6 Bq/kg, respectively. At all locations, ^{40}K activity was found to be higher (for 7 up to 36%) than the highest previously measured value in Montenegro (1994, using *in situ* gamma-spectrometry – 481 Bq/kg [15]). In comparison with other Southern European countries (Albania, Croatia, Cyprus, Greece, Portugal, Slovenia and Spain, with an average ^{40}K activity of 360, 490, 140, 360, 840, 370, and 470 Bq/kg, respectively [4]), an average of ^{40}K activity in soil samples from Mojkovac was found to be for the most part higher (except for Portugal). Moreover, a median of 614.6 Bq/kg is higher than the global average (400 Bq/kg).

The highest ^{137}Cs activity concentration determined in sample 9, Rudnica (276 Bq/kg), is significantly higher than, for example, that one found in the neighbouring Serbia (Lazarevac) (38.1 Bq/kg [16]), but lower than the maximum one measured in Montenegro in 1994 (740 Bq/kg [15]). As follows from data in tab. 1, the lowest ^{137}Cs level was found at location 5, Park (1.26 Bq/kg), while its average activity concentration was calculated to be about 55 Bq/kg, with a standard deviation and median of 73.5 and 33.6 Bq/kg, respectively.

At the same time, the highest contribution of ^{137}Cs to cumulative activity was found at location 9 (Rudnica) – 27% and, subsequently, at location 3 (ul.

Svetozara Drobnjaka) – 12% (fig. 2). A negligible contribution was found to exist at location 5 (Park), as well as at locations 12, 1, 8, and 7 (1%, in all four cases).

Location 8 exhibited the highest ^{40}K contribution to the total activity (91%), location 9 – the lowest being (67%). Radium-226 contributed to the total activity similarly at all locations – between 3% (locations 6, 8, 9, 12) and 6% (location 3), as well as ^{232}Th – between 3% (location 9) and 8% (location 7).

In general, the highest cumulative activity fig. 2(a) was found at location 9 – Rudnica, whilst the lowest one was at location 8 – Rudnica 1. The radium equivalent activity (tab. 1) was very similar for all measuring points in Mojkovac (ranging from 105.43 to 155.97 Bq/kg, with a mean, standard deviation and median of 133.79, 13.4, and 135.64 Bq/kg, respectively).

Absorbed and effective dose rate

Absorbed dose (D) and effective dose (E) rates due to natural radionuclides only (^{40}K, ^{226}Ra, ^{232}Th), calculated by eqs. (2) and (3), respectively, are given in tab. 2.

The absorbed dose rate eq. (2) was estimated to be in the range from 52.32 to 74.47 nGy/h, with an average of 65.18 nGy/h (standard deviation – 6.17 nGy/h), which is lower than, for example, environmental gamma dose found in northern Rechna Doab, Pakistan (the mean value of 109.1 nGy/h [17]), higher than the average previously obtained for the entire territory of Montenegro – 55 nGy/h [15], and slightly higher than the average (total) absorbed dose rate in other 7 South European countries (62 nGy/h [4]), or, for example, in Belgrade, Serbia (60.5 nGy/h [18]). Additionally, the median of absorbed dose rates (66.6 nGy/h) is also found to be higher than the global average (57 nGy/h [4]).

Table 2. Absorbed and effective dose rates due to natural radionuclides

	Location	Absorbed dose rate, D [nGyh^{-1}]	Effective dose rate, E [μSvy^{-1}]
1	Braunovići	66.63	81.72
2	ul. Dušana Tomovića	63.49	77.87
3	ul. Svetozara Drobnjaka	63.02	77.28
4	Mala škola	57.00	69.91
5	Park	69.26	84.94
6	Pumpa	67.47	82.74
7	Ilići	74.47	91.32
8	Rudnica 1	52.32	64.17
9	Rudnica	62.46	76.59
10	Hotel Sinjajevina	62.04	76.08
11	Mikronaselje	67.58	82.88
12	Juškovića potok	67.62	82.93
13	Školski centar	73.97	90.72

A relative contribution of ^{40}K, ^{226}Ra, and ^{232}Th to the highest (Ilići, location 7) and the lowest (Rudnica 1, location 8) absorbed dose rate is shown in fig. 3(a) and (b), respectively. In the case of the highest absorbed dose rate, thorium contributed with 46%, whilst in the case of the lowest one, it is potassium (46%, as well).

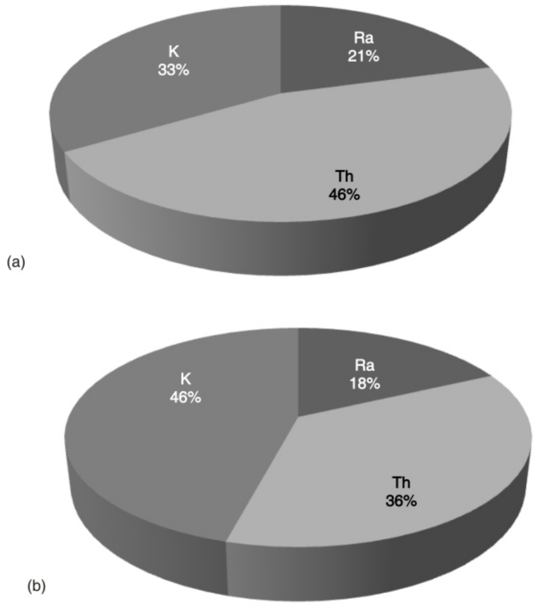

Figure 3. A relative contribution of ^{40}K, ^{226}Ra, and ^{232}Th to the highest (a), and lowest (b) determined absorbed dose rate

The corresponding mean effective dose was estimated as 79.93 μSv/y (with a standard deviation and median of 7.56 and 81.72 μSv/y, respectively) which is less than the maximum permissible dose of 1 mSv/y, as well as less than both the average annual effective dose (exposure to natural radiation sources) of 2.4 mSv and the total external terrestrial radiation of 0.48 mSv [4]. The maximum determined gamma-dose rate (91.32 μSv/y) was also found to be less than the mentioned reference values. In regard to outdoor external terrestrial radiation, a mean effective dose rate was found to be somewhat higher than the global average (0.07 mSv [4]).

Hazard indexes, gonadal dose equivalent and excess lifetime cancer risk

Hazard indexes (H_{ex} and H_{in}, calculated by eqs. (4), (5), respectively), for all the locations are presented in tab. 3.

As follows from tab. 3, the external hazard index (H_{ex}) ranged from 0.29 to 0.43. The mean value is 0.37 (as standard deviation and median – 0.04 and 0.38, re-

Table 3. Hazard index for all analyzed locations in Mojkovac

	Location	H_{ex}	H_{in}
1	Braunovići	0.38	0.45
2	ul. Dušana Tomovića	0.36	0.44
3	ul. Svetozara Drobnjaka	0.36	0.46
4	Mala škola	0.33	0.40
5	Park	0.39	0.47
6	Pumpa	0.38	0.45
7	Ilići	0.43	0.52
8	Rudnica 1	0.29	0.35
9	Rudnica	0.35	0.43
10	Hotel Sinjajevina	0.36	0.43
11	Mikronaselje	0.38	0.47
12	Juškovića potok	0.38	0.45
13	Školski centar	0.42	0.50

spectively), which is in accordance with neighboring countries, *e. g*. Serbia, where a mean value of external hazard index was found to be 0.35 [19], lower than some obtained previously for soil worldwide (*e. g*., 0.76 – soil in the Islamabad capital territory of Pakistan [20] or, 0.42 – a mean value for some areas in Haryana, India [21]).

The calculated values of the internal hazard index (H_{in}) vary from 0.35 to 0.52, with a mean, standard deviation and median of 0.45, 0.04, and 0.45, respectively. This average value is significantly lower than, for example, that of 1.02 (from 0.2 to 4.8), found at the U-mines area in India [22] or the one of 0.95, found in Islamabad [20], both of them being close to *unity*.

As mentioned, the values of H_{ex} and H_{in} for a material must be less than *unity* to keep radiation hazard negligible and allow its use as a construction material in dwellings.

For all analyzed locations in Mojkovac, H_{ex} and H_{in} are significantly lower than *unity*, and both showed a narrow range of values.

The annual gonadal dose equivalent (*G*) and excess lifetime cancer risk (*CR*) were calculated by eqs. (6) and (7), presented in figs. 4 and 5, respectively (for each measuring point). The first one (*i. e*., the annual gonadal dose equivalent (*G*) due to ^{226}Ra, ^{232}Th, and ^{40}K activity concentration in soil) ranged from about 0.37 to about 0.53 mSv/y, as shown in fig. 4. An arithmetic mean, standard deviation and median were found to be 0.46, 0.04, and 0.47 mSv/y, respectively. The values of *G* for soil samples from Mojkovac studied in this work proved to be higher than the world average (0.3 mSv/y [23]).

The excess lifetime cancer risk (*CR*) based on the ICRP 60 recommendations (fig. 5), showed a range from 0.22 to 0.32 (10^{-3}), with an arithmetic mean, standard deviation and median of about 0.28, 0.03, and 0.29 ($\cdot 10^{-3}$), respectively. This is lower than, for example, in Kirklareli, Turkey (0.43-0.61 ($\cdot 10^{-3}$) [10]), and slightly higher than the global average ($0.2 \cdot 10^{-3}$, taking into account outdoor external

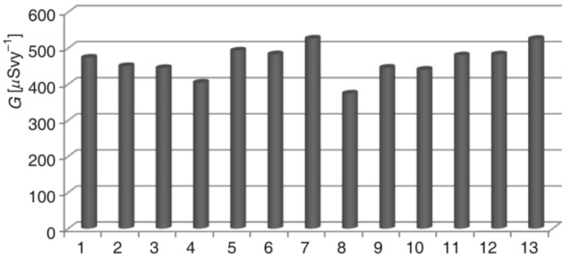

Figure 4. The annual gonadal dose equivalent for each measuring point

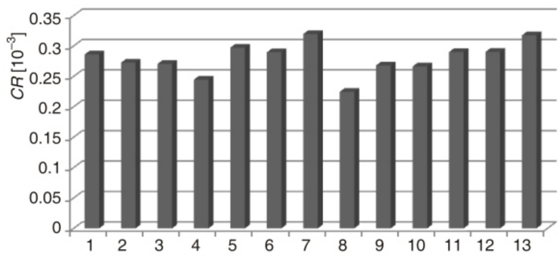

Figure 5. Excess lifetime cancer risk for 13 measuring points

terrestrial radiation, *i. e*., the average annual effective dose of 0.07 mSv [4]). At the same time, the *CR* calculated following the ICRP 103 recommendations ranged from 0.18 to 0.26 ($\cdot 10^{-3}$), with a mean, standard deviation and median of about 0.22, 0.02, and 0.23 ($\cdot 10^{-3}$), respectively.

CONCLUSIONS

None of the measuring points in the study area (Mojkovac, Montenegro) showed a radium equivalent activity higher than 370 Bq/kg. The external and internal hazard indexes were found to be significantly lower than *unity* (a mean of 0.37 and 0.45, respectively), which means that the radiation hazard is insignificant for the population living in the investigated area. However, the median of absorbed dose rates was found to be higher than 57 nGy/h. The annual gonadal dose equivalent and excess lifetime cancer risk were also found to be slightly higher than the global average values.

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РАДИОАКТИВНОСТ У ЗЕМЉИШТУ ИЗ МОЈКОВЦА – ЦРНА ГОРА И ПРОЦЕНА РАДИОЛОШКОГ РИЗИКА И РИЗИКА ОД КАНЦЕРА

Узорци земљишта из Мојковца – Црна Гора, анализирани су стандардном гама-спектрометријом и одређене су активности ^{226}Ra, ^{232}Th, ^{40}K и ^{137}Cs. Средње концентрације активности биле су 28,6, 43,1, 620,8 и 55 Bq/kg, респективно. Да би се проценио ризик од зрачења анализирани су радијум еквивалентна активност, јачина апсорбоване дозе, годишња ефективна доза, индекс радијационог ризика (услед спољашњег и унутрашњег излагања) и годишња гонадална доза, са средњим вредностима – 133,79 Bq/kg, 65,18 nGy/h, 79,93 μSv/y, 0,37, 0,45 и 0,46 mSv/y, респективно. За време живота од 70 година, средња целоживотна доза гама зрачења износи 5,6 mSv, а са овим повезани ризик од канцера је 2,8 10^{-4}.

Кључне речи: радиоактивност земљишта, радиолошка опасност, ризик од канцера