ASSESSMENT OF RADIATION EXPOSURE AROUND ABANDONED URANIUM MINING AREA OF STARA PLANINA MT., SERBIA

by

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The aim of this work was to estimate the health and radiation hazard due to external irradiation from terrestrial radionuclides in the Stara planina Mt. region, which is important because of past uranium mining activities on the mountain. Soil samples were collected inside the flotation processing facilities, their surroundings and more distant locations, *i. e.* from areas considered certainly affected, potentially affected, and unaffected by former mining and uranium ore processing activities. The radiological and health risk assessments were done by calculating the six main parameters, based on the activity concentration of ^{238}U, ^{232}Th, and ^{40}K in soil samples as determined by gamma-ray spectrometry. Increased values of the risk parameters were observed only for sites where uranium ore was processed, while the location surrounding these compounds showed values that are usual for this mountain or slightly above them. Calculations of the risk parameters for the background area showed no radiation risk for the local and seasonal population. The presence of U and Th was detected in all water samples from creeks surrounding the facilities, but only in the water from the facility drainage pipe did their concentration exceed the limits given for the uranium content in drinking water. In conclusion, the results obtained in this study fall within the range of values in similar studies conducted worldwide and are below the values which can cause a significant radiation hazard.

Key words: radiological assessment, uranium, thorium, soil, water

INTRODUCTION

Irradiation of the human body from external sources originates mainly from gamma radiation of terrestrial radionuclides of the ^{238}U and ^{232}Th series and from ^{40}K, these elements are always present, but at different levels [1]. Extensive studies of the distribution of primordial radionuclides performed worldwide [1] including Serbia [2] showed wide variations of the natural concentration of these radionuclides depending mostly on geological conditions. However, it is generally considered that external irradiation from these radionuclides, except in a few cases [3-6], does not represent a serious risk to human health.

The situation, however, can be quite different in areas surrounding uranium mines, since materials with higher uranium content can be spread by weathering. Even when mining activities have ceased, installations at uranium mines can still have a significant impact on the environment. Consequently, investigations of terrestrial natural radiation near abandoned uranium mines have received particular attention worldwide and led to extensive surveys in many countries [7-9]. These results are important for estimating population exposure and serve as reference information to assess any changes in the radioactivity level.

Geologically, the territory of Serbia includes a great number of different rock complexes, but the largest uranium mineralized area in Serbia is located on Stara Planina Mt. In addition, uranium mining activities have been conducted on this location for several years. From the environmental and health hazard point of view, the increased uranium concentration within the sites of the abandoned mines and processing facilities is expected and not of much concern in itself. The more important issue is whether this local contamina-

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tion had spread over wider populated areas. The wider area around former uranium mines on Stara Planina Mt. is scarcely inhabited today, but the development of a ski resort on the mountain is slowly inducing the repopulation of some of its regions. We have recently performed an extensive study of the distribution of natural radionuclides in surface soils on Stara Planina Mt. including the vicinity of abandoned mines [10]. An increased concentration of radionuclides has been found in the vicinity of mines as compared to the rest of the mountain indicating the spread of radionuclides from mining and processing sites. However, the knowledge of the concentration of radionuclides in the soil does not show *per se* whether this poses a health hazard for the population. We therefore used these results and some new measurements to calculate all relevant parameters for assessment of the potential risks from environmental irradiation [1, 10-12]. Some preliminary results have been published in our earlier publication [13], but in this work we present a comprehensive work on a large number of sites where potential health hazards are analysed according to specific regions around uranium mines (affected, potentially affected, background). In addition, we included analysis of radionuclide content in water in the vicinity of mines to complete the assessment of potential health hazards in the area.

EXPERIMENTAL

Study area and sampling

Stara Planina, the largest mountain in Serbia, is located in the east of the country and forms a part of the Carpathian-Balkan mountain range, *i. e*. the western portion of the wider Stara Planina (Balkan Mt.) massif. There were two centrally situated uranium mines on Stara Planina Mt. The mines were operational from 1960 until 1966. The maximum production of uranium ore was 200 and 60 tonnes per day in the Gabrovnica and Mezdreja plant, respectively. After the mining activities ceased, the local population intensified using the land around the mines for grazing and some agricultural production.

Samples of undisturbed soil (up to the depth of 10 cm, three subsamples per location) were taken from 19 locations (affected, A1-A19) in the central part of Stara Planina Mt. where the abandoned uranium mines are situated (including a few samples from within the processing facilities in Gabrovnica) and from 11 locations (potentially affected, P1-P11) in the area between these mines which we considered as potentially affected according to their position relative to mining installations, the hydrography of the terrain and its geochemical characteristics (fig. 1). For comparison, 25 samples (B1-B25) were taken in parts of Stara Planina Mt. where mining activities have never been conducted (including the ski resort areas). The exact geographical co-ordinates of all sampling locations were obtained *via* the Global Positioning System (Garmin eTrex Vista) and the majority of them can be found in our previous publication [10].

The water samples (fig. 1) were taken from the drainage pipe of the Gabrovnica mine, by the main gate of the facility (A1w) and from two creeks that flow immediately by the processing facilities in Gabrovnica (A2w) and Mezdreja (A3w).

Sample preparation was performed according to recommended procedures [14]. In brief, all soil samples were weighed and air-dried until constant weight was reached. The samples were then pulverised, homogenised, and sieved to pass through a 2 mm mesh. Water was sampled in the amount of 6 dm^3, and after sampling the water was acidified, pre-concentrated to a tenth part of its initial volume, and transferred to Marinelli beakers (total volume 500 cm^3). The beakers with soil and water samples were kept hermetically sealed for one month prior to radioactivity measurements, to ensure equilibrium between ^{226}Rn and its daughters before gamma spectrometric analysis.

Radioactivity measurements

The specific activities were measured using an HPGe gamma-ray spectrometer (ORTEC AMETEK, 34% relative efficiency and 1.65 keV FWHM for ^{60}Co at 1.33 MeV). The quality assurance check on calibration was performed using standard reference material through the International Atomic Energy Agency (IAEA) proficiency for the determination of gamma emitting radionuclides [15]. The total uncertainty of the activity measurements was typically in the range of 3% to 10%. Additional details concerning measurements of specific radioactivity can be found in our previous papers [10, 16].

Calculation of quantities for determining radiation risks

Absorbed gamma dose rate, $\dot{D}$ [$nGyh^{-1}$], in the air at 1 m above ground level was calculated from the measured specific activities of the soil samples taking into account factors of 0.462, 0.604, and 0,042 for converting specific activities to the absorbed dose as given below

$$\dot{D} \quad 0.462A_{\mathrm{U}} \quad 0.604A_{\mathrm{Th}} \quad 0.042A_{\mathrm{K}} \qquad (1)$$

where A_{U}, A_{Th}, and A_{K} are the specific activities [$Bqkg^{-1}$] of ^{238}U, ^{232}Th, and ^{40}K, respectively [1]. Other radionuclides such as ^{137}Cs, ^{90}Sr, and the ^{235}U series can be neglected as they contribute very little to the total dose from the environmental background

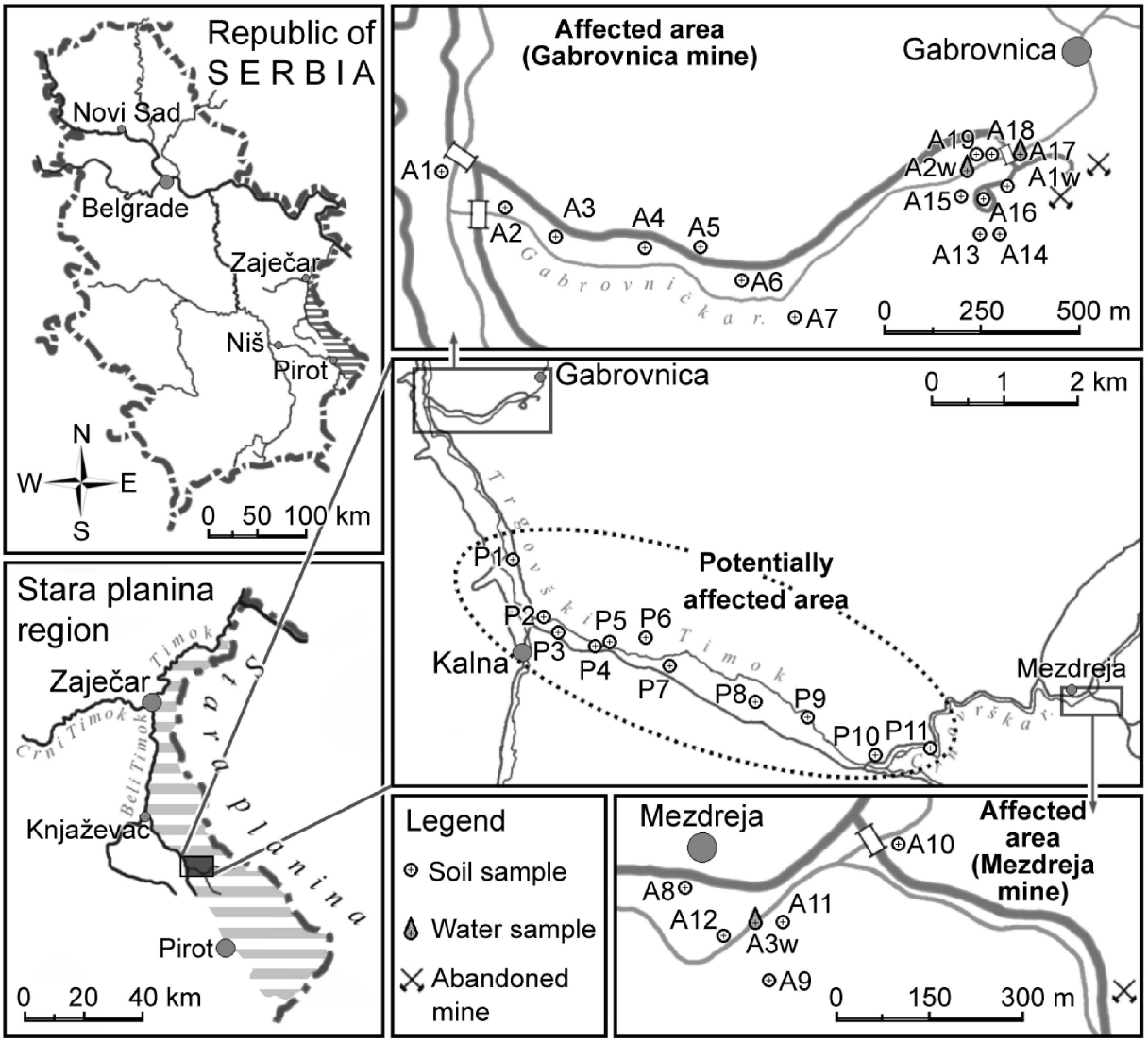

Figure 1. Simplified map of Stara Planina Mt. with sampling points in the affected (A) and potentially affected (P) area

[17-20]. Conversion factors for the calculation of from the activities per unit area or mass were published by several authors [17-25].

Radium equivalent activity, A_{Ra}^{eq} [Bqkg^{-1}], is an index that has been introduced to represent the specific activities of ^{238}U, ^{232}Th, and ^{40}K by a single quantity which takes into account the radiation hazards associated with them. It was calculated using the equation [12]

$$A_{Ra}^{eq} \quad A_{\mathrm{U}} \quad 1.43A_{\mathrm{Th}} \quad 0.07A_{\mathrm{K}} \qquad (2)$$

External hazard index. This is a useful guideline for regulating the safety standards of radiation protection for the general public. The annual effective dose for radium equivalent activity of 370 Bq/kg corresponds to the dose limit of 1 mSv for the general population [10]. This index is calculated as [12]

$$H_{\mathrm{ex}} \quad \frac{A_{\mathrm{U}}}{370} \quad \frac{A_{\mathrm{Th}}}{259} \quad \frac{A_{\mathrm{K}}}{481} \qquad (3)$$

Annual gonadal dose. The gonads, the active bone marrow, and the bone surface cells are considered the organs of interest [26]. Therefore, the annual gonadal dose, *AGD* [μSv], for both indoors and outdoors due the specific activities of radionuclides in the soil was calculated using the following equation [27]

$$AGD \quad 3.09A_{\mathrm{U}} \quad 4.18A_{\mathrm{Th}} \quad 0.314A_{\mathrm{K}} \qquad (4)$$

Annual outdoor effective dose, AED_{out} [μSv], was calculated from the absorbed gamma dose rate using the factor to convert the effective dose rate to the absorbed dose rate in air for adults of 0.7 Sv/Gy for environmental exposures to gamma rays and the outdoor occupancy factor (the fraction of time spent outdoors) of 0.2, both proposed by UNSCEAR [1]

$$AED_{out} \quad 0.7 \quad 0.2\dot{D}N_{\mathrm{h}} \qquad (5)$$

where $\dot{D}$ [nGyh^{-1}] is the absorbed gamma dose rate in air, and N_{h} is the number of hours in 1 year (8760 h) [1].

Excess lifetime cancer risk outdoors ($ELCR_{out}$) was calculated as follows

$$ELCR_{out} \quad AED_{out}\, PC\, DL \qquad (6)$$

where *PC* is the nominal probability coefficient for detriment-adjusted cancer risk of 5.5 10^{-2} Sv^{-1} for the whole population and *DL* is the lifespan (70 years) [1].

RESULTS AND DISCUSSION

Descriptive statistics for specific activities of ^{238}U, ^{232}Th, and ^{40}K in soil samples taken from the background, potentially affected and affected area of Stara Planina Mt. are presented in tab. 1. The mean specific activities of radionuclides of interest (^{238}U and ^{232}Th) in the potentially affected area are slightly higher than in the background area which could be associated with mining and processing activities. However, specific activities for both nuclides are increased, which also could be explained on the basis of a variety of lithological components. Also, the range of activities, *i. e*. the difference between maximum and minimum activity is roughly the same for both areas and such variations are within the variations found worldwide. The situation in the affected area is completely different. The specific activities of ^{238}U and ^{232}Th are around 2.4 and 1.8 higher than the worldwide average values [1] and significantly higher than in the background area. Also, values of specific activities for ^{238}U differ by a factor of 8 in the affected area which is a clear indication for the existence of hot-spots as a consequence of mining activities, since the affected areas are relatively small (see fig. 1) and no significant variations in lithological components can be expected.

The mean value for soils in the background area is near the worldwide average value (58 nGy/h) [1]. Mean values for both potentially affected and affected areas are higher. The reported values of $\dot{D}$ for Serbian regions without mining and milling activities fell in the interval from 16.9 nGy/h to 125 nGy/h [28, 29]. All of the calculated $\dot{D}$ in the study areas are in that range, except values for sample points A3 (164 7 nGy/h), A9 (214 ± 9 nGy/h), and A13 (206 ± 16 nGy/h). The soil for sample A13 was taken inside the fence of the processing facility in Gabrovnica, while sample points for A3 and A9 are located just nearby the local roads used for ore transportation.

The relative contribution to the total gamma dose rate due to radionuclides from ^{238}U series for all areas studied is presented in fig. 2. It is clearly evident that radionuclides from the uranium series contribute most to the total absorbed gamma dose rate in the affected area which is obviously a direct consequence of mining activities, ore processing and transportation.

The obtained range and mean values of the total absorbed gamma dose rate due to ^{238}U, ^{232}Th, and ^{40}K are compared with values reported for mining areas worldwide (tab. 2). The values obtained in this study are similar to those reported for uranium mining and milling sites in Australia, Hungary, and Spain [30-32]. Higher absorbed gamma dose rates have been reported for uranium mining areas in Kyrgyzstan and Namibia [8, 33].

The mean values of A_{Ra}^{eq} in affected (200 Bq/kg), potentially affected (175 Bq/kg) and background (110 Bq/kg) areas (tab. 3) are well below the value 370 Bq/kg, which corresponds to the dose limit of 1 mSv acceptable for the general public. However, in two locations (A9 and A13) the values of A_{Ra}^{eq} exceed that limit.

Previous parameters represent dosimetric quantities based on activity concentrations of radionuclides of interest. These parameters cannot provide useful infor-

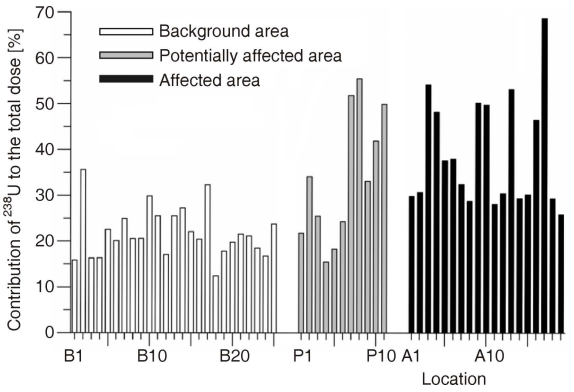

Figure 2. Contribution of radionuclides of ^{238}U series to the total absorbed dose in the air in the background (B), potentially affected (P), and affected (A) area

Table 1. Descriptive statistics of the total absorbed gamma dose rate and specific activity of ^{238}U, ^{232}Th, and ^{40}K in soil from background (B), potentially affected (P), and affected (A) areas

Parameter	Total absorbed gamma dose rate [nGyh^{-1}]			Specific activity of ^{238}U [Bqkg^{-1}]			Specific activity of ^{232}Th [Bqkg^{-1}]			Specific activity of ^{40}K [Bqkg^{-1}]		
Area	B	P	A	B	P	A	B	P	A	B	P	A
Range	46	74	194	36	96	206	32	70	103	522	337	913
Mean	55	83	95	26	63	85	31	51	53	567	564	560
Median	52	78	89	24	63	54	30	44	51	550	595	555
Mode	34	46	21	13	22	31	19	44	65	355	394	525
St. deviation	11	23	51	9	34	66	8	21	24	152	122	189
Minimum	34	46	21	13	22	31	19	30	6	334	394	64
Maximum	80	120	215	49	118	237	51	99	109	855	731	977

Table 2. Gamma dose rates from different mining regions worldwide

Country	Mine region	Gama dose rate [nGyh^{-1}]
Kyrgyzstan [8]	Mailuu Suu	148
Australia [30]	Naberlek	125-300
Spain [31]	Albala	46-126
	La Haba Don Benito	13-114
	Alburquerque	25-117
	Juzbado – Vitigudino	32-180
	Andujar – Cardena	12-117
	Cabril – Penarroya	20-126
Hungary [32]	Kovagoszolos	95-252
	Cserkut	78-123
Namibia [33]	Arandis	99 to 1305

mation about risk for people who live (or could live) on the location where the soil samples were collected. That kind of information can be obtained through calculations of H_{ex} and *AGD*. The value of H_{ex} must be less than unity to keep the radiation hazard insignificant, *i. e.* to keep the radium equivalent activity and annual dose under permissible limits (370 Bq/kg and 1 mSv, respectively). Although the mean value of H_{ex} for the affected area (0.55) does not exceed unity, values at two locations (A9 and A13) do exceed unity (tab. 3). This indicates a potential radiation risk for the population. The mean *AGD* value for sampling points in the potentially affected area is slightly lower than for sampling points in the affected area, but in the background area this value is 1.7 times lower (tab. 3). The results obtained for studied locations in affected and potentially affected areas are higher than doses reported for example in Belgrade (Serbia) with a mean of 428 μSv (min. 177 μSv, max. 630 μSv) [34]. On the other hand, all of the *AGD* calculations for the background area are within the Belgrade range of *AGD* values. Also, the results for all three investigated areas are comparable with *AGD* values reported for Montenegro ranging from 0.199 mSv to 1.270 mSv [35]. The highest values were recorded for points A3, A9, and A13, and they are equal to 1.13 mSv, 1.48 mSv, and 1.42 mSv, respectively, which can be considered as potentially hazardous.

The parameters H_{ex} and *AGD* do not take into account the amount of time that people actually spend in the affected areas over one year. The assessment of potential radiation risk should include the fraction of time during which people are exposed to an increased level of radiation. This extra risk can be expressed by the AED_{out} which takes into account the outdoor occupancy factor. Based on the assumption that people do not stay outdoors in the investigated location more than 20% of the whole daytime (approximately 5 h per day), the outdoor occupancy factor was set at 0.2. Investigated areas are almost uninhabited after mining activities have ceased, so the setup of this coefficient at this level seems to be appropriate. As shown in tab. 3 the AED_{out} values for all locations among the investigated area are far below the maximum permissible value of 1 mSv recommended by the ICPR for members of the general public [10], even at locations with the highest activity (A3, A9, and A13).

The mean values of $ELCR_{out}$ for the affected ($4.47\ 10^{-4}$) and potentially affected ($3.94\ 10^{-4}$) area were found to be higher than the world $ELCR_{out}$ value ($2.90\ 10^{-4}$), while the mean $ELCR_{out}$ for the background area ($2.57\ 10^{-4}$) suits the world average [1], and also the mean values for Belgrade (Serbia) ($2.78\ 10^{-4}$) [34], and Montenegro ($2.70\ 10^{-4}$) [35]. All calculated $ELCR_{out}$ values are in the range of results which were reported for the Kirklareli valley and Bursa in Turkey, regions without uranium mining activities, with the exception of $ELCR_{out}$ for sampling points A9 and A13 that are slightly above the maximum calculated value for the Bursa region ($8.38\ 10^{-4}$) [36, 37]. Obtained $ELCR_{out}$ values for all sampling areas covered by our study are well below the mean value for the Mazandaran province in Iran ($26\ 10^{-4}$) which is an area with a high population density [38].

Based on results obtained in this study, the only locations where the measured and calculated parameters significantly exceed the values expected for this part of Serbia are locations marked A3, A9, and A13. The site A13 is of no concern since it is located within the fence of the processing facility in Gabrovnica. Sites A3 and A9 could become potentially hazardous if houses were to be built there. Also, our study did not systematically cover the area around mines and there is a possibility that more "hot-spots" exist.

Results of radioactivity measurements and radiometric determination of U, Th, and K in water samples are given in tab. 4. The concentration of U and Th in water coming from the drainage pipe in Gabrovnica (A1w) by far exceeds values found in the creeks. However, the concentration of U and Th in water in the Gabrovnica creek downstream is rather low. Also, soil samples from the creek bed did not show increased concentrations of U and Th, so there is neither U and Th precipitation, nor absorption of these elements by river sediments. According to domestic regulations, the maximum allowable concentration of U in bottled natural drinking water is 50 g/dm^3 [39]. The provi-

Table 3. Radium equivalent activity, external hazard index, annual gonadal dose, annual outdoor effective dose, and excess lifetime cancer risk outdoors at different locations in studied areas; data for background area are presented only as the mean value without specifying sampling spots since none of values exceeded normal value for activity

Location	Radium equivalent activity [Bqkg^{-1}]	External hazard index	Annual gonadal dose [μSv]	Annual outdoor effective dose [μSv]	Excess lifetime cancer risk outdoors [$^{-4}$]
Background area					
Mean	110	0.31	387	67	2.6
Min	70 7	0.19 0.02	242 24	42 4	1.6 0.2
Max	163 50	0.46 0.14	571 176	99 30	3.8 1.2
Potentially affected aea					
P1	95 4	0.26 0.01	325 14	56 2	2.2 0.1
P2	218 12	0.60 0.03	713 37	125 7	4.8 0.3
P3	162 12	0.45 0.04	546 50	95 8	3.7 0.3
P4	156 8	0.43 0.02	530 25	92 4	3.5 0.2
P5	140 7	0.39 0.02	482 25	83 4	3.2 0.2
P6	256 8	0.71 0.02	840 26	147 5	5.7 0.2
P7	195 15	0.54 0.04	638 46	113 8	4.4 0.3
P8	164 7	0.45 0.02	537 23	95 4	3.7 0.2
P9	115 5	0.32 0.01	390 16	68 3	2.6 0.1
P10	196 12	0.54 0.03	660 39	116 7	4.5 0.3
P11	228 10	0.63 0.03	759 31	134 6	5.2 0.2
Mean	175	0.48	584	102	3.9
Min	95 4	0.26 0.01	325 14	56 2	2.2 0.1
Max	256 8	0.71 0.02	840 26	147 5	5.7 0.2
Affected area					
A1	160 13	0.44 0.04	533 49	93 8	3.6 0.3
A2	149 11	0.41 0.03	501 41	87 7	3.4 0.3
A3	350 15	0.96 0.04	1132 48	201 9	7.7 0.3
A4	219 12	0.60 0.03	722 38	127 7	4.9 0.3
A5	207 9	0.57 0.03	693 30	122 5	4.7 0.2
A6	194 15	0.53 0.04	639 48	112 9	4.3 0.3
A7	198 13	0.54 0.04	649 43	114 8	4.4 0.3
A8	160 8	0.44 0.02	538 27	94 5	3.6 0.2
A9	458 20	1.26 0.06	1484 67	263 12	10.1 0.4
A10	239 11	0.65 0.03	775 36	138 6	5.3 0.2
A11	188 8	0.52 0.02	622 26	109 5	4.2 0.2
A12	105 4	0.29 0.01	368 13	64 2	2.5 0.1
A13	439 34	1.20 0.09	1421 106	253 19	9.7 0.7
A14	172 6	0.47 0.02	566 20	99 4	3.8 0.1
A15	97 3	0.27 0.01	333 12	58 2	2.2 0.1
A16	190 6	0.52 0.02	619 20	110 4	4.2 0.1
A17	45 2	0.12 0.01	142 6	26 1	1.0 0.1
A18	105 4	0.29 0.01	360 13	63 2	2.4 0.1
A19	119 4	0.33 0.01	416 14	72 3	2.8 0.1
Mean	200	0.55	659	116	4.5
Min	45 2	0.12 0.01	142 6	26 1	1.0 0.1
Max	458 20	1.26 0.06	1484 67	263 12	10.1 0.4

sional guideline value for uranium in drinking-water is 30 g/dm^3 based on its chemical toxicity for kidneys as set by the World Health Organisation (WHO) [40]. The same concentration of uranium is set as the maximum contaminant level for uranium in drinking water by the Environmental Protection Agency, USA [41]. WHO guidance levels for radionuclides in drinking water are 10 Bq/dm^3 for ^{238}U and 10 Bq/dm^3 for ^{232}Th. Comparing specific activities for these radionuclides from tab. 4, it can be seen that all values meet WHO guidance levels, but such results do not themselves imply that the water is suitable for consumption. It seems that the analysed waters do not represent a health hazard, except of course the water from the drainage pipe which is certainly not used for any purpose. Moreover, the water from these creeks is not generally used as

Table 4. Specific activity of ^{238}U, ^{232}Th, and ^{40}K and massic elemental concentrations of U, Th, and K in sampled waters

Sample	Specific activity [Bqdm^{-3}]		
	^{238}U	^{232}Th	^{40}K
A1w	0.991 0.090	0.472 0.037	0.225 0.022
A2w	0.023 0.008	0.023 0.003	0.013 0.002
A3w	0.007 0.006	0.021 0.001	0.131 0.011
Sample	Massic elemental concentration [μgdm^{-3}]		
	Uranium	Thorium	Potassium
A1w	80.91 7.29	116.32 9.12	(7.42 0.73) 10^3
A2w	1.86 0.65	5.67 0.74	(0.43 0.07) 10^3
A3w	0.57 0.49	5.18 0.28	(4.32 0.36) 10^3

drinking water, but values from tab. 4 are useful as a starting point for a broader analysis, since these creeks are tributaries of the river Trgoviški Timok whose waters are used both for drinking and watering of plants.

CONCLUSION

The results of radiological characterization of the abandoned uranium mining area showed that potential radiation risk exists only for the population of areas located in the immediate vicinity of mines and processing facilities. A region assigned as potentially affected is an area where several populated places including Kalna, a former administrative centre and headquarters of the uranium mines, are settled. Radiation hazard indices for this area fall between or slightly above the limits reported for Serbia and also worldwide. Though the radiation hazard associated with external irradiation from natural gamma emitters in a potentially affected area is of no immediate concern, the remediation measures are needed, especially having in mind the tremendous disrepair of the processing facilities.

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AUTHOR CONTRIBUTIONS

Sample collection and experimental work was carried out by M. N. Tanić and M. Z. Momčilović, geological data were provided by J. R. Kovačević, while M. N. Tanić, S. D. Dragović, and G. G. Bačić wrote the manuscript.

REFERENCES

[1] ***, UNSCEAR 2008, United Nations Scientific Committee on the Effects of Atomic Radiation, Sources and Effects of Ionising Radiation, United Nations, New York, 2010
[2] Dragović, S., *et al*., Distribution of Primordial Radionuclides in Surface Soils from Serbia and Montenegro, *Radiat. Meas., 41* (2006), 5, pp. 611-616
[3] Radhakrishna, A. P., *et al*., A New Natural Background Radiation Area on the Southwest Coast of India, *Health Phys., 65* (1993), 4, pp. 390 395
[4] Sohrabi, M., Environments with Elevated Natural Radiation, *Proceedings*, International Conference on Restoration of Environment with Radioactive Residues, Arlington, Via., USA, November 29 to December 3, 1999, IAEA Publication STI/PUB/1092, IAEA-SM-SM-359/1.7, 2000, pp. 113-134
[5] Veiga, R., *et al.*, Measurement of Natural Radioactivity in Brazilian Beach Sands, *Radiat. Meas., 41* (2006), 2, pp. 189-196
[6] Heikal, M. Th. S., *et al*., Natural Radioactivity in Basement Rocks and Stream Sediments, Sharm El Sheikh Area, South Sinai, Egypt: Radiometric Levels and Their Significant Contributions, *Arab. J. Geosci., 6* (2013), 9, pp 3229-3239
[7] Fernandes, H. M., *et al.*, Management of Uranium Mill Tailing: Geochemical Processes and Radiological Risk Assessment, *J. Environ. Radioact., 30* (1996), 1, pp. 69 95
[8] Vandenhove, H., *et al*., Assessment of Radiation Exposure in the Uranium Mining and Milling Area of Mailuu Suu, Kyrgyzstan, *J. Environ. Radioact., 88* (2006), 2, pp. 118-139
[9] Carvalho, F. P., *et al*., Radioactivity in the Environment Around Past Radium and Uranium Mining Sites of Portugal, *J. Environ. Radioact., 96* (2007), 1-3, pp. 39-46
[10] Momčilović, M., *et al*., Distribution of Natural Radionuclides in Surface Soils in The Vicinity of Abandoned Uranium Mines in Serbia, *Environ. Monit. Assess., 185* (2013), 2, pp. 1319-1329
[11] ***, ICRP, The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103, *Ann. ICRP, 37* (2007), pp. 2-4
[12] Beretka, J., Matthew, P. J., Natural Radioactivity of Australian Building Materials, Industrial Wastes and By-Products, *Health Phys., 48* (1985), 1, pp. 87-95
[13] Momčilović, M., *et al*., Population Doses from Terrestrial Exposure in the Vicinity of Abandoned Uranium Mines in Serbia, *Radiat. Meas., 45* (2010) 2, pp. 225-230
[14] ***, IAEA, Measurement of Radionuclides in Food end the Environment – A Guidebook, International Atomic Energy Agency, Vienna, Austria, 1989
[15] ***, IAEA, Report on the IAEA-CU-2006-03 World-Wide open Proficiency Test on the Determina-

tion of Gamma Emitting Radionuclides, Seibersdorf, Austria, 2007
[16] Dragović, S., *et al*., Artificial Neural Network Modelling of Uncertainty in Gamma-Ray Spectrometry, *Nucl. Instrum. Meth. Phys. Res. A, 540* (2005), 2-3, pp. 455-463
[17] Beck, H. L., *et al*., *In situ* Ge(Li) and NaI(Tl) Gamma-Ray Spectrometry, Report HASL-258, US-DOE, Environmental Measurement Lab, New York, USA, 1972
[18] Kocher, D. C., Sjoreen, A. L., Dose-Rate Conversion Factors for External Exposure to Photon Emitters in Soil, *Health Phys., 48* (1985), 2, pp. 193-205
[19] Jacob, P., *et al*., Effective Dose Equivalents for Photon Exposures from Plane Sources on the Ground, *Radiat. Prot. Dosim., 14* (1986), 4, pp. 299-310
[20] Leung, K. C., *et al*., Gamma Radiation Dose from Radionuclides in Hong Kong Soil, *J. Environ. Radioact., 11* (1990), 3, pp. 279-290
[21] Chen, S. Y., Calculation of Effective Dose-Equivalent Responses for External Exposure from Residual Photon Emitters In Soil, *Health Phys., 60* (1991), 3, pp. 441-426
[22] ***, US EPA, EPA-402-R-93-081, External Exposure to Radionuclides in Air, Water and Soil, Federal Guidance Report No. 12, United States Environmental Protection Agency, Washington DC, USA, 1993
[23] Saito, K., Jakob, P., Gamma Ray Fields in the Air Due to Sources in the Ground, *Radiat. Prot. Dosim., 58* (1995), 1, pp. 29-45
[24] Likar, A., *et al.*, Monte Carlo Determination of Gamma-Ray Dose Rate with the Geant System., *Health Phys., 75* (1998), 2, pp. 165 169
[25] Clouvas, A., *et al*., Derivation of Indoor Gamma Dose Rate from High Resolution *in situ* Gamma Ray Spectra, *Health Phys., 78* (2000), 3, pp. 274-281
[26] ***, UNSCEAR 1988, United Nations Scientific Committee on the Effects of Atomic Radiation, Sources, Effects and Risks of Ionising Radiation, United Nations, New York, 1988
[27] Mamont-Ciesla, K., *et al*, Radioactivity of Building Materials in Poland, *Proceedings*, Second Special Symposium on Natural Radiation Environment, Bombay, India, January 19 to January 23, 1981, G. Vorha, K. C. *et al*., Ed(s)., Halsted Press, New York, USA, 1982, p. 551-556
[28] Dragović, S., *et al*., Population Doses from Terrestrial Gamma Exposure in Serbia, *Arch. Oncol., 15* (2007), 3-4, pp. 78-80
[29] Dragović, S., *et al*., Assessment of Gamma Dose Rates from Terrestrial Exposure in Serbia and Montenegro, *Radiat. Prot. Dosim., 121* (2006), 3, pp. 297 302
[30] Waggit, P., Restoration of the Nabarlek Uranium Mine and Mill Site, *Proceedings*, International Conference on Restoration of Environments with Radioactive Residues, Arlington, Via., USA, November 29 to December 3, 1999, IAEA Publication STI/PUB/1092, IAEA-SM-SM-359/1.7, 2000, pp. 429-444
[31] Quindos Poncela, L. S., *et al*., Population Dose in the Vicinity of Old Spanish Uranium Mines, *Sci. Total Environ., 329* (2004), 1-3, pp. 283-288
[32] Gorjancz, Z., *et al.*, Population Dose in the Vicinity of Closed Hungarian Uranium Mine, *Radiat. Prot. Dosim., 118* (2006), 4, pp. 448-452
[33] Oyedele, J. A., *et al*., Assessment of Natural Radioactivity in the Soils of Rossing Uranium Mine and Its Satellite Town in Western Namibia, Southern Africa, *Nucl. Instr. Meth. Phys. Res. A, 619* (2010), 1-3, pp. 467-469
[34] Janković-Mandi, L. J., Dragović, S., Assessment of Terrestrial Gamma Exposure to the Population of Belgrade (Serbia), *Radiat. Prot. Dosim., 140* (2010), 4, pp. 369-377
[35] Antović, N. M. *et al*., Radioactivity in Soil from Mojkovac, Montenegro, and Assessment of Raiological and Cancer Risk, *Nucl Technol Radiat, 27* (2012), 1, pp. 57-63
[36] Taskin, H., *et al*., Radionuclide Concentrations in Soil and Lifetime Cancer Risk Due to Gamma Radioactivity in Kirklareli, Turkey, *J. Environ. Radioact., 100* (2009), 1, pp. 49-53
[37] Karahan G., Risk Assessment of Baseline Outdoor Gamma Dose Rate Levels Study of Natural Radiation Sources in Bursa, Turkey, *Radiat. Prot. Dosim., 142* (2010), 2-4, pp. 324-331
[38] Abbaspour, M., *et al.*, Relationship of Soil Terrestrial Radionuclide Concentrations and the Excess of Lifetime Cancer Risk in Western Mazandaran Province, Iran, *Radiat. Prot. Dosim., 142* (2010), 2-4, pp. 265-272
[39] ***, Regulations on Sanitary Correctness of Drinking Water, Official Gazette of the Federal Republic of Yugoslavia, No. 42/98 and 44/99, 1999
[40] ***, WHO, Guidelines for Drinking-Water Quality 4th ed., World Health Organisation, Geneva, Switzerland, 2011
[41] ***, US EPA, EPA-820-R-11-002, Edition of the Drinking Water Standards and Health Advisories, United States Environmental Protection Agency, Washington DC, USA, 2011

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ПРОЦЕНА РАДИЈАЦИОНОГ ИЗЛАГАЊА У ОКОЛИНИ НАПУШТЕНИХ РУДНИКА УРАНИЈУМА НА СТАРОЈ ПЛАНИНИ

Циљ рада је био процена здравственог и радијационог ризика за људе услед спољњег озрачивања гама зрачењем терестријалних радионуклида у региону Старе планине, што је важно због ранијих активности рудника уранијума на планини. Узорци земљишта су прикупљени унутар самих флотационих постројења, њихове околине и локација на већем растојању од њих, тј. са простора за које је сматрано да су сигурни, потенцијално или уопште нису угрожени експлоатацијом руде уранијума и њеном прерадом. Радијациони и здравствени ризик су процењени израчунавањем шест главних параметара на основу специфичних активности ^{238}U, ^{232}Th и ^{40}K у узорцима земљишта које су одређене гама-спектрометријском методом. Повишена вредност параметара ризика је уочена једино на локацијама на којима је вршена прерада уранијумске руде, док су вредности ових параметара за локације из околине постројења сличне или незнатно више од уобичајених за Стару планину. Прорачуни за простор сматран неугроженим показују да је радијациони ризик за локално становништво и туристе незнатан. Присуство уранијума и торијума је установљено у свим узорцима воде узетим из водотокова који протичу у непосредној околини флотационих постројења, али је само у води која је узоркована из дренажне цеви флотационог постројења у Габровници садржај уранијума већи од дозвољених концентрација овог елемента у пијаћој води. Закључак је да су резултати добијени овим истраживањем у опсегу вредности добијених у сличним студијама спроведеним широм света, и да се налазе испод вредности које могу довести до значајног радијационог ризика.

Кључне речи: процена радијационог излагања, уранијум, торијум, земљиште, вода