# SPATIAL DISTRIBUTION OF GAMMA – EMITTING RADIONUCLIDES IN SOILS IN BANSKO – RAZLOG REGION

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**Abstract**

*Radiological investigations have been performed in Bansko-Razlog region, Bulgaria by means of high-resolution gamma-spectrometry of soil samples. The activity concentrations of the natural radionuclides $^{238}U$, $^{232}Th$ and $^{40}K$ as well as of the fission product $^{137}Cs$ have been determined. The spatial distributions of the activity concentrations of the radionuclides are mapped and discussed. The comparison between spatial distributions of the activity concentrations of the $^{40}K$ and $^{137}Cs$ shows good negative correlation between activity concentrations of the two radionuclides. The high-resolution map of spatial distribution of the ratio of the activity concentrations of $^{238}U$ and $^{232}Th$ shows a clearly visible increase in activity of $^{238}U$ in east, adjacent to the former uranium mines. It has been shown that the continuous spatial distributions of the activity concentrations obtained by using the kriging interpolation allows us to obtain a more detailed picture of activity concentrations of the radionuclides compared with other statistical methods such as linear regression, etc.*

**Key words:** *radioactivity, gamma-spectrometry, U-238, Th-232, K-40, Cs-137, activity concentration*

## 1. INTRODUCTION

The development in the modern life styles due to the industrial developments drastically increased the risks of soil contamination, especially external contaminants, such as radionuclides, entering a soil body through wet or dry precipitation (IAEA 2004). It is important to identify the concentration of radioactive isotopes in soil because it constitutes a path for radioactivity to humans, animals and plants, and is an indicator of radioactive accumulation in the environment. Detection and quantification of environmental radiations and radioactivity may be performed for a number of reasons. One general purpose is to gain knowledge and improved understanding of the world. Another reason may be to assess the impact of human activities involving the using of radioactive isotopes on the environment.

Gamma-rays are strong penetrating radiation from natural and man-made sources, and therefore gamma-ray spectrometry is a powerful tool for the monitoring and assessment of the environmental radioactivity (IAEA 2003). The widespread and ever-increasing use of nuclear power and other contaminating technologies as well as the potential risk of terrorist attack involving radioactive or nuclear devices, make it necessary to evaluate the natural background radioactivity in order to detect all man-made contamination, assess its impact and implement appropriate countermeasures to protect the population and the environment (UNSCEAR 1988). Different studies concerning the determination of radionuclide concentrations in soil have been performed, s. for example (Kam & Bozkurt 2007; Al-Hamarneh & Awadallah 2009; Almayahi et al. 2012). They often result in maps of terrestrial radiation (Anagnostakis et al. 1996; Licinio et al. 2013; Kovacs et al. 2013). Measurements of the environmental radioactivity may be used to estimate the terrestrial radiation dose to the human population and to indentify areas of high natural radiation hazard (Iacob 1996; Taskin et al. 2009; Sinani & Dollani 2015). Extensive investigations in radionuclide concentrations in soil are regularly carried out in the radiation risk zones like nuclear power plant, areas close to uranium mines and other facilities where radioactive materials are used or produced (Carvalho et al. 2009; Momcilovic et al. 2010).

The aim of the present study is to determine the activity concentrations of $^{238}U$, $^{232}Th$, $^{40}K$ and $^{137}Cs$ in surface soil samples in the region of Razlog-Bansko and to calculate and draw their spatial distribution maps.

## 2. MATERIALS AND METHODS

### *2.1. Investigated area*

The geographical name of the Bansko-Razlog region is Razlog hollow, which is located between $41.7^0$ to $41.9^0$N and $23.4^0$ to $23.6^0$E, between Pirin Mountain, Rila Mountain and the Rhodope Mountain. Razlog hollow is the highest hollow in South Bulgaria, with average altitude 865 meters above see level. In the central part of the hollow the relief is almost flat with a slight declination to the East towards the Rhodope Mountain. The investigated area was selected for several reasons: 1) Town Bansko is a big tourist center of international importance. A large number of Bulgarian and foreign tourists practicing skiing come here during the winter season. Bansko is also hosting a round of FIS Alpine Ski World Cup. During the summer season, Bansko and the surrounding villages are a base camps for attacking the highest peak of the Pirin Mountain – Vihren, and other attractive sites in Pirin and Rila mountains. 2) Razlog municipality covers a large part of the National Park "Pirin" and the National Park "Rila". The National Park "Pirin" is included in the UNESCO Convention for the preservation of the world's natural and cultural monuments; 3) Several sites of the former uranium mining and milling industry are located in Razlog hollow, only about twenty kilometers east of Bansko (Figure 1). This proximity requires a special study of the environmental impact of uranium mining and possible exposure risk to the population.

### *2.2. Soil samples collection and preparation*

A total of forty surface soil samples were collected from flat and undisturbed by man or nature soil's surface. Square shaped soil samples (0.25 m × 0.25 m) with a thickness of 0.1 m were extracted from the surface. A number of soil samples were covered by some type of grasses, other were not. Each soil sample was labeled according to the geographical coordinates and those coordinates were later used to indicate the position on the simplified map by filled squares (Figure 1). One additional soil sample was collected from sand quarry containing material used for construction of buildings and roads in the study area. Soil samples were placed in plastic bags and dried at room temperature. Then samples were passed through a sieve with mesh size of 2 mm to eliminate organic materials, small stones and other foreign materials and dried at $120^0$C in a drying oven in a few hours. The dried samples were ground in a glass mortar and passed through a sieve with mesh size of 0.5 mm. In order to maintain radioactive equilibrium between $^{238}U$ and its daughters, the homogenized samples were transferred to 500 $cm^3$ Marinelli bakers and kept for a few weeks (IAEA 1989).

The sampling points were located approximately in a grid 1 km × 1 km. In this way a total area of about 40 $km^2$ was investigated – virtually the whole accessible area along the railway between Banya, Razlog and Dobrinishte. Sampling points are selected near the most frequently visited infrastructures and objects: roads Razlog-Bansko (*Road 19*), Razlog-Bania (*Road 84*), Bansko-Bania (*Road 1901*), Bansko-Dobrinishte (*Road 19*), railway stations Razlog, Bansko and Dobrinishte, lift to the ski slopes, closed to hotels, lodges and other tourist sites. About 25% of the sampling points were situated in the villages. Soil samples were taken also from several additional points located away from main roads and infrastructures to apply more conservative selection approach.

### *2.3. Gamma-ray detection system*

Gamma-spectrometric measurements were performed on a Canberra Packard gamma-spectrometer equipped with HPGe-detector. The HPGe-detector has an efficiency of 25% and energy resolution of 1.9 keV for 1.33 MeV gamma-transition from $^{60}Co$ and 1.1 keV for 122 keV gamma-transition from $^{57}Co$. The detector is surrounded with lead shields and is adapted for low level gamma-radiation

measurements. The background gamma-ray spectrum was measured and subtracted to get the net count rate for each sample.

The activity concentration of $^{40}K$ was estimated from the area of the 1460.8 keV gamma peak. The activity concentration of $^{232}Th$ was calculated using the peaks at 338.3 keV ($^{228}Ac$) and 911.2 keV ($^{228}Ac$). The activity concentration of $^{238}U$ was estimated using the peak 1001.03 ($^{234m}Pa$). The activity concentration of $^{137}Cs$ was determined from the gamma peak of 661.66 keV.

## 3. RESULTS AND DISCUSSION

Activity concentrations of $^{238}U$, $^{232}Th$, $^{40}K$ and $^{137}Cs$ radionuclides in soils, collected from the study area, with their counting errors are listed in Table 1. The table also shows the geographical coordinates of sampling points, minimum, maximum, mean and standard deviation of activity concentrations. All values are reported as $Bq.kg^{-1}$ dry weight.

The activity concentrations of $^{137}Cs$ vary from < 0.45 to 124.0 $Bq.kg^{-1}$ with a mean value of 27.7 $Bq.kg^{-1}$ and a standard deviation of 23.6 $Bq.kg^{-1}$. Preliminary results were published in Kostov et al. (2005). The most extensive investigations of the $^{137}Cs$ content in soils in Bulgaria after the Chernobyl accident have been performed by Bulgarian Nuclear Society (BNS) (1996). The authors determined the activity concentration of $^{137}Cs$ in many soil samples taken from about 40 different places in North-East Bulgaria between 1993 and 1995. They concluded that the residual soil contamination in the region to this time does not exceed 100 $Bq.kg^{-1}$. Kostov et al. (2005) reported mean value of 27.7 $Bq.kg^{-1}$ of the activity concentration of $^{137}Cs$ in Bansko-Razlog region. In order to make direct comparison with the data from BNS (1996) they performed a decay correction and obtained a value of 38.4 $Bq.kg^{-1}$. In this way Kostov et al. (2005) concluded that the residual $^{137}Cs$ contamination in Razlog hollow was of the same order and lower than the $^{137}Cs$ contamination in North-East Bulgaria and the contribution of the Chernobyl accident to the radiation exposure on the population in Bansko – Razlog region was “insignificant”.

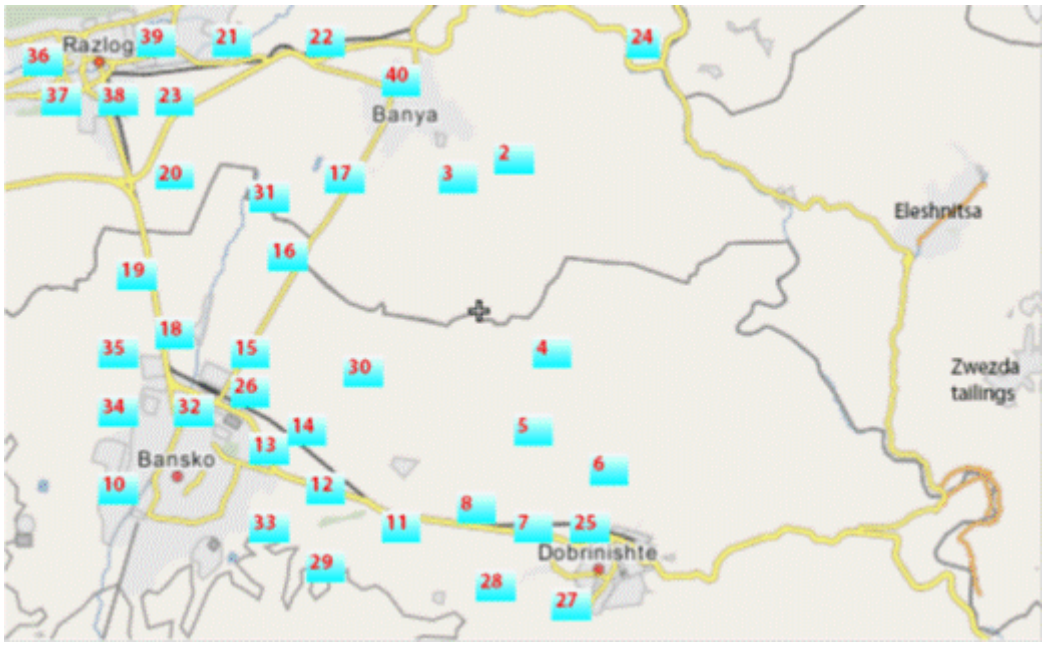



**Figure 1.** Simplified map of the investigated region. The sampling points are marked with the filled squares and the corresponding number.

In this work we present the high-resolution spatial map of the distribution of the activity concentration of $^{137}$Cs in Bansko-Razlog region (Figure 2). It is the first detailed map of the spatial distribution of the activity concentration of $^{137}$Cs of an area in Bulgaria after the Chernobyl accident in 1986. All the high-resolution spatial maps presented in this work were obtained by statistical analysis and kriging interpolation of the experimental data (Kobilarov 2014). Raykov (1978) attributed value of the activity concentrations of $^{137}$Cs less than 40 Bq.kg$^{-1}$ as a result of atmospheric testing of nuclear weapons during the 1950s and early 1960s for the entire Bansko-Razlog region. In order to make direct comparison with the data from Raykov (1978) we perform a decay correction, taking into account the half life of $^{137}$Cs. For the time of sampling in this study we calculate a value of the activity concentrations of 137Cs less than 20 Bq.kg$^{-1}$. This condition is satisfied for almost 50% from Bansko-Razlog region (Figure 2). For the rest of the region the activity concentrations of $^{137}$Cs are approximately equal or higher than 20 Bq.kg-1 reaching a maximum value of 124 Bq.kg$^{-1}$. The detailed map confirms the initial conclusions of Kostov et al. (2005) that the Chernobyl accident did not cause considerably contamination in Bansko-Razlog region.

The activity concentrations of $^{40}$K vary from 467.0 to 1114.0 Bq.kg$^{-1}$ with a mean value 829.9 Bq.kg$^{-1}$ and a standard deviation 154.6 Bq.kg$^{-1}$. All samples analyzed in this work show the activity concentration of $^{40}$K higher than the world average value of 400 Bq.kg$^{-1}$ reported by UNSCEAR (2000) and the average value for Bulgaria – 400 Bq.kg$^{-1}$ (Vasilev 2002).

The activity concentrations of $^{232}$Th vary from 32.0 to 94.0 Bq.kg$^{-1}$ with a mean value 56.3 Bq.kg$^{-1}$ and s standard deviation 13.9 Bq.kg$^{-1}$. All samples show activity concentration of $^{232}$Th higher than the world average value and the average value for Bulgaria – 30 Bq.kg$^{-1}$ (UNSCEAR 2000; Vasilev 2002).

The activity concentrations of $^{238}$U vary from 30.0 to 87.0 Bq.kg$^{-1}$ with a mean value 48.8 Bq.kg$^{-1}$ and a standard deviation 14.2 Bq.kg$^{-1}$. The spatial distribution of the activity concentration of $^{238}$U is shown of Figure 5. From the figure it is seen that nearly 20% of the area has values close to the average in Bulgaria and in the world (40 Bq.kg$^{-1}$ and 35 Bq.kg$^{-1}$, respectively) (UNSCEAR 2000; Vasilev 2002).

**Table 1.** Activity concentrations of $^{238}$U, $^{232}$Th, $^{40}$K and $^{137}$Cs in Bq.kg$^{-1}$ in collected soil samples.

| № | *Geographical Coordinates of sampling points* | $^{238}$U | $^{232}$Th | $^{40}$K | $^{137}$Cs |
|---|---|---|---|---|---|
| 1 | 41.980566 N, 23.332155 E | 51±2 | 71±3 | 717±21 | 14.0±0.5 |
| 2 | 41.875609 N, 23.539969 E | 54±2 | 68±2 | 953±19 | <0.45 |
| 3 | 41.873206 N, 23.533788 E | 55±1 | 63±2 | 797±16 | 35.0±1.0 |
| 4 | 41.853760 N, 23.545705 E | 30±1 | 62±2 | 969±19 | 3.0±0.4 |
| 5 | 41.840796 N, 23.545082 E | 53±2 | 94±2 | 1050±21 | 3.±0.4 |
| 6 | 41.833062 N, 23.553928 E | 48±1 | 78±2 | 866±17 | 1.±0.1 |
| 7 | 41.826455 N, 23.547271 E | 55±2 | 78±3 | 1114±22 | 10.±0.5 |
| 8 | 41.827456 N, 23.535402 E | 42±1 | 33±2 | 572±11 | 124.±1 |
| 9 | 41.758931 N, 23.546353 E | 78±2 | 75±5 | 838±17 | 41.0±0.4 |
| 10 | 41.826732 N, 23.476566 E | 45±1 | 58±1 | 847±17 | 8.0±0.2 |
| 11 | 41.828150 N, 23.522305 E | 39±1 | 36±1 | 512±10 | 39.0±0.4 |
| 12 | 41.831391 N, 23.510439 E | 61±2 | 57±2 | 914±18 | 37.0±0.7 |
| 13 | 41.836459 N, 23.499835 E | 39±2 | 48±1 | 805±24 | 7.0±0.5 |

| | | | | | |
|---|---|---|---|---|---|
| 14 | 41.841517 N, 23.505331 E | 44±2 | 52±2 | 817±24 | 18.0±0.5 |
| 15 | 41.853056 N, 23.500289 E | 61±2 | 50±4 | 778±15 | 58.0±1.0 |
| 16 | 41.862035 N, 23.506891 E | 55±1 | 63±1 | 891±17 | 12.0±0.2 |
| 17 | 41.869442 N, 23.514494 E | 51±2 | 50±2 | 742±22 | 43.0±0.8 |
| 18 | 41.854048 N, 23.481126 E | 63±2 | 59±2 | 730±14 | 19.0±0.4 |
| 19 | 41.863514 N, 23.478613 E | 37±1 | 32±1 | 751±15 | 29.0±0.9 |
| 20 | 41.871950 N, 23.475794 E | 51±2 | 38±2 | 710±21 | 6.0±0.2 |
| 21 | 41.886338 N, 23.497561 E | 34±1 | 60±2 | 660±13 | 11.0±0.3 |
| 22 | 41.887035 N, 23.508556 E | 47±1 | 53±1 | 877±17 | 4.0±0.1 |
| 23 | 41.879655 N, 23.488901 E | 32±1 | 46±3 | 740±14 | 41.0±0.4 |
| 24 | 41.887179 N, 23.570835 E | 87±2 | 33±1 | 467±9 | 14.0±0.5 |
| 25 | 41.825559 N, 23.561251 E | 86±2 | 74±5 | 862±17 | 58.0±0.5 |
| 26 | 41.842918 N, 23.492703 E | 53±2 | 64±4 | 943±18 | 24.0±0.7 |
| 27 | 41.812062 N, 23.549770 E | 49±2 | 42±2 | 745±14 | 52.0±0.5 |
| 28 | 41.814441 N, 23.541185 E | 35±1 | 54±1 | 1042±20 | 22.0±0.4 |
| 29 | 41.825523 N, 23.507813 E | 34±1 | 54±1 | 1052±21 | 26.0±0.2 |
| 30 | 41.850795 N, 23.510644 E | 70±2 | 74±3 | 794±15 | 55.0±1.0 |
| 31 | 41.866898 N, 23.496551 E | 45±2 | 66±3 | 967±19 | 7.0±0.5 |
| 32 | 41.835550 N, 23.486938 E | 47±2 | 54±3 | 899±18 | 35.0±0.4 |
| 33 | 41.825790 N, 23.493495 E | 32±1 | 59±2 | 1060±21 | 25.0±0.2 |
| 34 | 41.838017 N, 23.476978 E | 58±2 | 61±2 | 834±16 | 29.0±0.6 |
| 35 | 41.838275 N, 23.477120 E | 45±2 | 59±1 | 958±19 | 20.0±0.2 |
| 36 | 41.889531 N, 23.458729 E | 37±1 | 42±1 | 722±14 | 34.0±0.3 |
| 37 | 41.886799 N, 23.458986 E | 30±1 | 41±1 | 634±12 | 67.0±0.7 |
| 38 | 41.887758 N, 23.465724 E | 36±1 | 48±1 | 708±14 | 27.0±0.3 |
| 39 | 41.890585 N, 23.466604 E | 33±2 | 50±2 | 1114±22 | 14.0±0.5 |
| 40 | 41.882327 N, 23.526533 E | 49±2 | 54±2 | 744±15 | 35.0±0.7 |
| Min | | 30.0 | 32.0 | 467.0 | 0.45 |
| Max | | 87.0 | 94.0 | 1114.0 | 124.0 |
| Mean | | 48.8 | 56.3 | 829.9 | 27.7 |
| Stand. dev. | | 14.2 | 13.9 | 154.6 | 23.6 |

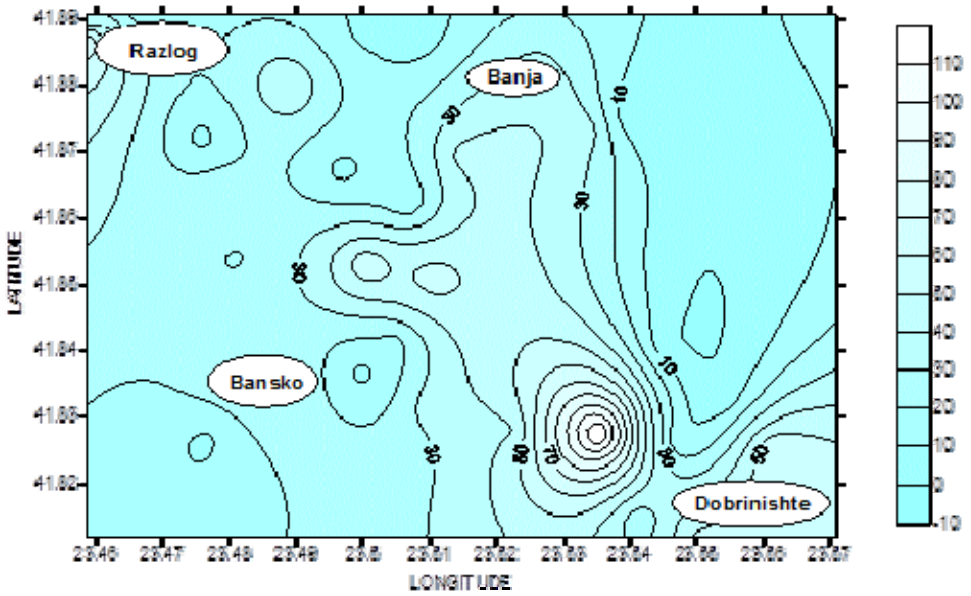



**Figure 2.** Spatial distribution of the activity concentration of $^{137}Cs$ in $Bq.kg^{-1}$.

The spatial distributions of the activity concentrations of $^{40}K$ and $^{232}Th$ are shown of Fig. 3 and Fig. 4, respectively. In general, the spatial distributions of the activity concentrations of $^{40}K$ and $^{232}Th$ are similar. In the distribution of $^{40}K$ there are three areas of the activity concentration of $^{40}K$ with values higher than the mean value (829.9 $Bq.kg^{-1}$). First of them is located north of Dobrinishte and has two local maxima (sampling points 5 and 7) with activities 1050 $Bq.kg^{-1}$ and 1114 $Bq.kg^{-1}$, respectively. The second is located south of Bansko and has a maximum value of activity 1060 $Bq.kg^{-1}$ (sampling point 33) and the third area with a maximum of 967 $Bq.kg^{-1}$ (sampling point 31) is located north of Bansko. In the spatial distribution of $^{232}Th$ there are two areas of the activity concentration of $^{232}Th$ with values higher than the mean value (56.3 $Bq.kg^{-1}$). One of them is located north of Dobrinishte with maximum value 94 $Bq.kg^{-1}$ (sampling point 5) and second is located north of Bansko with maximum value 74 $Bq.kg^{-1}$ (sampling point 30). Lower values of the activity concentrations of $^{40}K$ and $^{232}Th$ were observed in the region of Razlog and west of Dobrinishte. The areas with minimum values 512 $Bq.kg^{-1}$ (sampling point 11) and 36 $Bq.kg^{-1}$ (sampling point 11) about the spatial distributions of $^{40}K$ and $^{232}Th$, respectively, are located west of Dobrinishte. The other areas with minimum values 634 $Bq.kg^{-1}$ (sampling point 37) and 32 $Bq.kg^{-1}$ (sampling point 19) about the spatial distributions of $^{40}K$ and $^{232}Th$, respectively, are located in the region of Razlog.

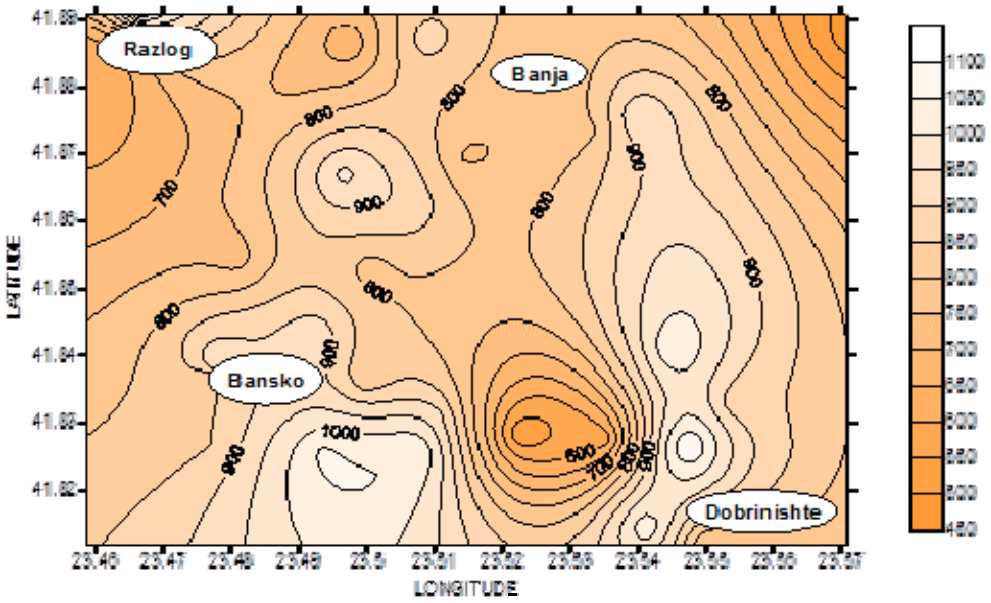



**Figure 3.** Spatial distribution of the activity concentration of $^{40}K$ in $Bq.kg^{-1}$.

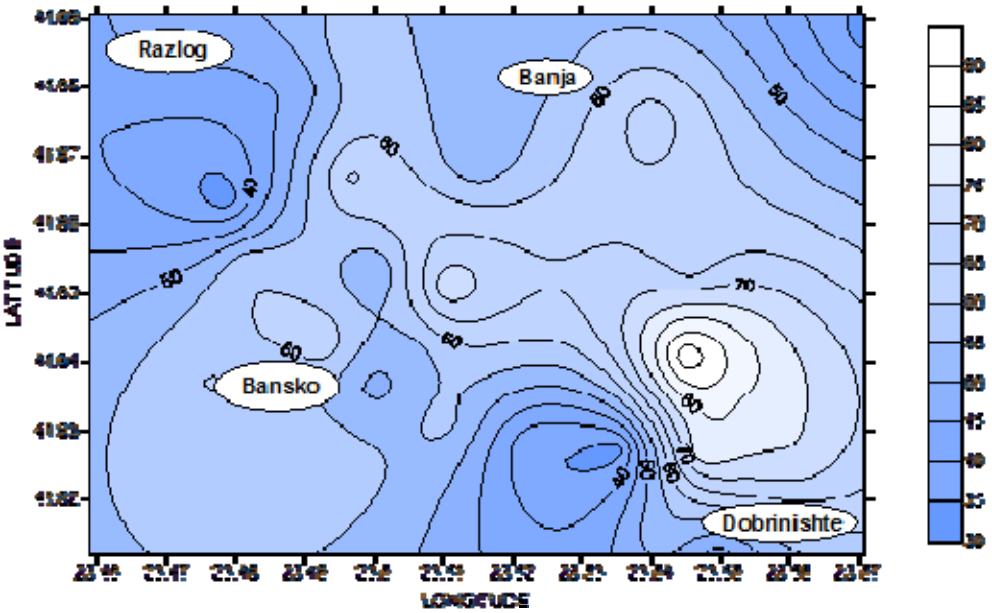



**Figure 4.** Spatial distribution of the activity concentration of $^{232}Th$ in $Bq.kg^{-1}$.

$^{40}K$ and $^{137}Cs$ have different origin in the environment. $^{40}K$ is a natural radionuclide while $^{137}Cs$ is an artificial radionuclide, but they are isotopes of elements which belong to the lithium group (Group IA, alkali metals). Because of that they have similar physical and chemical properties and competitive-sorption behavior in the soil (Kubica et al. 2007). In this report we use two statistical methods for finding a relationship between the activities of $^{40}K$ and $^{137}Cs$ – correlation analysis and ordinary kriging interpolation for mapping the spatial distributions of $^{137}Cs$ and $^{40}K$. Correlation coefficient between the activities of $^{137}Cs$ and $^{40}K$ is R = 0.42. Coefficient of determination $R^2$ = 0.18 which means that only 18% of the total variation of the values of activity concentration of $^{137}Cs$ is accounted by a linear relationship with values of the activity concentration of $^{40}K$ (Walpole & Myers, 1989).

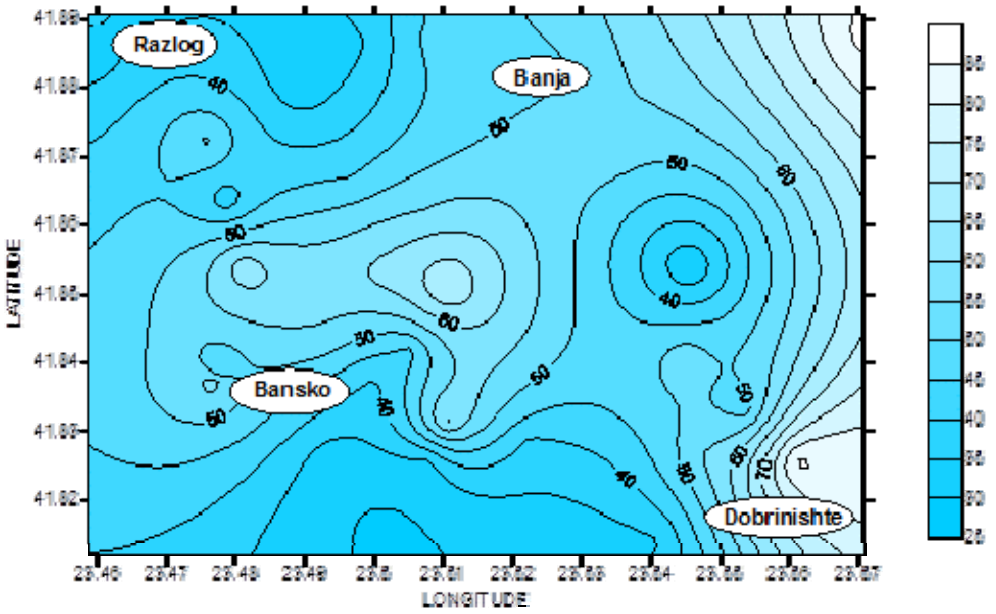



**Figure 5.** Spatial distribution of the activity concentration of $^{238}U$ in Bq.kg$^{-1}$.

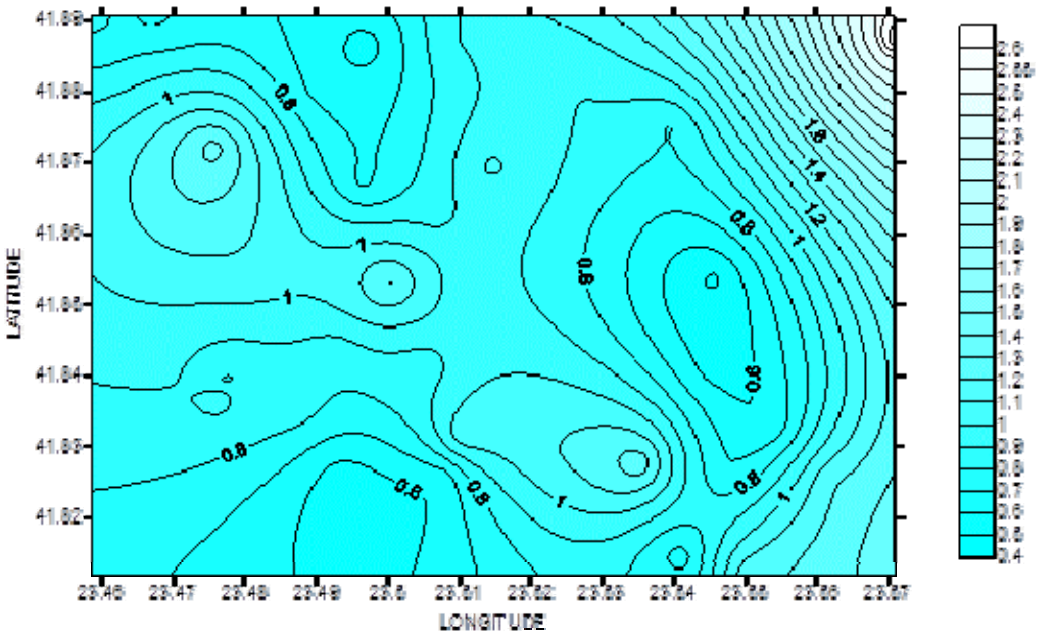



**Figure 6.** Spatial distribution of the ratio of the activity concentration of $^{238}U$ and $^{232}Th$.

Although the P-value for the F-test (P = 0.007) is less than the accepted significance level α = 0.05, this is a low level of correlation between activity concentrations of $^{137}Cs$ and $^{40}K$. On the other hand the comparison of Fig. 2 and Fig. 3 shows that areas of increasing activity concentration of $^{137}Cs$ correspond to areas of decreasing of the activity concentration of $^{40}K$. In the central area between meridians $23.51^0$ and $23.54^0$ E is clearly seen that the area of the activity of $^{137}Cs$ higher than the mean value (27.7 Bq.kg$^{-1}$) coincide with the area of the activity of $^{40}K$ lower than the mean value (829.9 Bq.kg$^{-1}$). It is obvious the coincidence of the area with coordinates $23.52^0$ – $23.54^0$ E and $41.82^0$ – $41.84^0$ N, where it has seen a sharp increase in the activity concentration of $^{137}Cs$ to the maximum value of 124.0 Bq.kg$^{-1}$ coinciding with a sharply decreasing in the activity concentration of 40K to the minimum value of 467.0 Bq.kg$^{-1}$. East of the meridian $23.54^0$ E is seen an area of activity of $^{137}Cs$

lower than the mean value, which coincides with an area of activity of $^{40}$K higher than the mean value. In this way the spatial distributions of the activities of $^{137}$Cs and $^{40}$K confirm competitive-sorption behavior of the two radionuclides.

West of the meridian 23.50$^0$ E this coincidence is not so clear. This can be explained by intensive urbanization of this area in recent years associated with construction of large numbers of hotels and service infrastructures. Urbanization can affect the activity levels of the radionuclides (Licinio et al. 2013).

The mean value of the activity concentration of $^{232}$Th is higher than that of $^{238}$U due to the low geochemical mobility and insoluble nature in water of thorium. But in 12 soil samples activity concentration of $^{238}$U is higher than that of $^{232}$Th. Tsai et al. (2011) reported a good correlation between the activities of $^{238}$U and $^{232}$Th with correlation coefficients $R \geq 0.9$. In our study the correlation coefficient between the activities of the two radionuclides is $R = 0.43$. Coefficient of determination $R^2 = 0.18$ which means that 18% of the total variation of the values of the activity concentration of $^{238}$U is accounted by a linear relationship with values of the activity concentration of $^{232}$Th. P-value for the F-test ($P = 0.002$) is less than the accepted significance level $\alpha = 0.05$ which means that there is weak correlation between activity concentrations of $^{232}$Th and $^{238}$U. This weak correlation is due to the proximity of the former uranium mines. Figure 6 shows the spatial distribution of the ratio of the activity concentrations of $^{238}$U and $^{232}$Th. An area with elevated activity of $^{238}$U is clearly visible on Fig. 6. The ratio is $\leq 1$ for almost the entire area and becomes $> 1$ in the eastern part of the studied region and increases with the longitude in east, adjacent to the former uranium mines.

## 4. CONCLUSIONS

The activity concentrations of the natural radionuclides $^{238}$U, $^{232}$Th and $^{40}$K, as well as of the fission product $^{137}$Cs have been measured in the Bansko-Razlog region. The activity concentrations of $^{137}$Cs vary from < 0.45 to 124.0 Bq.kg$^{-1}$ (mean value 27.7 Bq.kg$^{-1}$). These values are mainly due to the atmospheric testing of nuclear weapons during the 1950s and early 1960s. The contribution of the Chernobyl accident to the radioactive contamination of the investigated region is negligible.

The measured activity concentrations of $^{238}$U, $^{232}$Th and $^{40}$K vary in the range 30.0-87.0 Bq.kg$^{-1}$ (mean value 48.8 Bq.kg$^{-1}$), 32.0-94.0 Bq.kg$^{-1}$ (mean value 56.3 Bq.kg$^{-1}$) and 467.0-1114.0 Bq.kg$^{-1}$ (mean value 829.9 Bq.kg$^{-1}$), respectively. The activity concentrations of $^{40}$K and $^{232}$Th are almost two times higher than the mean values for Bulgaria. The activity concentration of $^{238}$U is higher than the mean value for Bulgaria.

The high-resolution spatial distribution maps of the activity concentrations of $^{137}$Cs and $^{40}$K show an inverse correlation between the activity concentrations of these radionuclides. This result confirmed competitive-sorption behavior of $^{137}$Cs and $^{40}$K in the soil.

The high-resolution map of spatial distribution of the ratio of the activity concentrations of $^{238}$U and $^{232}$Th shows a clearly visible increase in activity of $^{238}$U in east, adjacent to the former uranium mines.

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