Radiological impact of an active quarry in the Papuk Nature Park, Croatia

Branko Petrinec, Davor Rašeta, and Dinko Babić

Institute for Medical Research and Occupational Health, Zagreb, Croatia

[Received in December 2021; Similarity Check in December 2021; Accepted in February 2022]

Papuk Nature Park, unlike most similar parks and preserves in the world, contains active quarries. Quarries dig stone from the ground, creating dust and exposing deeper, potentially more radioactive layers. Since the forest trails in the Park lead right up to the quarries, we believed it was important to determine the radiological impact of the quarries on the Park environment. We measured ambient dose rate equivalent \( H^{*}(10) \) and sampled moss at 26 Park locations along two of four quarries, along the road between them, and near Lake Orahovac, a very popular tourist destination close to the quarries. Moss is a standard bioindicator of exposure to heavy metals, including radionuclides. Using-gamma ray spectrometry we determined the activity concentration of \(^{137}\text{Cs}\) and of representative naturally occurring radionuclides \(-\ ^{238}\text{U},\ ^{226}\text{Ra},\ ^{210}\text{Po},\ ^{228}\text{Th},\ \text{and}\ ^{40}\text{K} -\) in sampled moss. \( H^{*}(10) \) at selected locations was similar to the background \( H^{*}(10) \) measured continuously all over Croatia. The ranges of measured activity concentrations of \(^{137}\text{Cs}\) and naturally occurring radionuclides in moss did not differ significantly from other parts of Croatia and nearby countries.

KEY WORDS: \(^{137}\text{Cs};\ \text{ambient dose rate equivalent } H^{*}(10);\ \text{gamma ray spectrometry; moss; naturally occurring radionuclides}

Papuk is the highest mountain of eastern Croatia. In 1999, an area of Papuk was designated a nature park (1), and in 2007, Papuk Nature Park (PNP) was designated a Global Geopark by the United Nations Educational, Scientific and Cultural Organization (UNESCO) (2). In the eastern part of the PNP, there is the Radlovac Quarry complex consisting of four quarries close together: Hercegovac, Oršulica, Brenzberg-Točak, and Žervanjska. Hercegovac and Oršulica are sources of dolomite (sediment rock), while Brenzberg-Točak and Žervanjska provide diabase (volcanic rock) (Figure 1). While the quarries are not attractive to PNP visitors, they are very close to Lake Orahovac, a very popular tourist destination on the edge of the PNP. In addition, popular hiking trails lead through the forest right up to and around the quarries.

Quarries are considered a potential source of increased radioactivity, as stone digging can bring material containing increased radioactive content to the surface (3, 4). Research into potentially negative radiological impact of quarries has been focused on the exposure of quarry workers to ionising radiation (5–7) and on radioactive content analysis of quarry products (8–24). However, research of radiological effects of a quarry on its surroundings is not common. Quarries are often situated in solitary areas, even though some become tourist destinations and nature preserves as part of the remediation process, such as the Quarry Nature Park in Canada (25), Park Hall Country Park and Humie Quarry (26), Helsby Quarry Woodland Park (27), Quarry Park & Nature Preserve Stearns County, Minnesota (28), and Portland Quarries Nature Park (29, 30).

Considering that the Radlovac Quarry is part of the PNP and very close to major tourist and hiking routes, we wanted to ascertain that there was no adverse radiological effect on the close environment. To do that, we measured ambient dose rate equivalent \( H^{*}(10) \) at 24 locations around and between two quarries and at two locations near Lake Orahovac. We also measured radionuclide content in moss collected from these locations using gamma ray spectrometry.

MATERIALS AND METHODS

We selected 24 locations along the Brenzberg-Točak and Žervanjska quarries and the road between them and two additional locations by Lake Orahovac, a couple of kilometres away (Figure 2). The locations were selected based on the availability of moss. All the locations except the two by Lake Orahovac were on forest trails.

Sampling and \( H^{*}(10) \) measurements took place in April and May of 2018. At each location we registered the coordinates, measured ambient dose rate equivalent \( H^{*}(10) \) and sampled moss in order to determine radionuclide content using gamma ray spectrometry. We did not consider investigating the closest quarry to Lake Orahovac, Hercegovac, as it was in the process of
16

remediation. Instead, we selected the next two closest ones connected by a road.

\( H^*(10) \) measurements were taken with the RDS-31 S/R Multipurpose Survey Meter (San Ramon, CA, USA) (31) at each location at the height of 1 m above the ground in no less than five three-minute gamma dose rate measurements within a radius of five meters from the central location to cover the whole area where moss was sampled. The survey meter was calibrated by the manufacturer ahead of measurements using the reference \( ^{137}\text{Cs} \) source and reference dose rate of 3 mSv/h.

While \( H^*(10) \) values are a solid indicator of radiological impact on the environment and people, true radiological exposure can only be assessed with a full characterisation of gamma-emitting radionuclides in the area.

Mosses are organisms that efficiently accumulate different elements from the environment and are often used as bioindicators of pollution (or its absence) with metals (32–36), including radioactive uranium, thorium, and caesium (37–40) or with potassium (37). Without a developed root system to absorb nutrients from the ground, mosses predominantly absorb nutrients and pollutants from the air (40–42). A recent research (42) suggests that under certain conditions, which include high availability of dust in the area and relatively low precipitation, the main source of nutrients and pollutants is not deposition from the atmosphere, but deposition of local dust.

Moss was collected, cleaned from dead leaves, soil, and other detritus, and packed into 5 L plastic bags for transport. Depending on the quantity available at each location, moss was collected within the radius of up to 5 m from the registered coordinates to ensure at least 1 L of moss for each sample after drying. Moss was dried to a constant mass in the laboratory and then packed and sealed in standard 1 L Marinelli beakers and left undisturbed for 30 days to establish secular equilibrium in the \( ^{238}\text{U} \) decay chain. We measured activity concentrations of selected radionuclides (naturally occurring radionuclides and \( ^{137}\text{Cs} \)) using the ORTEC gamma-ray spectrometry system (Advanced Measurement Technology, Inc., Oak Ridge, TN, USA), which uses a high purity Ge (HPGe) coaxial GMX-type detector (relative efficiency of 74.2 % and peak full width at half maximum of 2.24 keV, all at 1.33 MeV \( ^{60}\text{Co} \)). Energy and efficiency were calibrated using certified calibration sources manufactured by the Czech Metrology Institute (Jihlava, Czech Republic), and corrections for true coincidence made using the EFFTRAN program (43). Calibration source was a known mixture of radionuclides dissolved in \( \text{H}_2\text{O} \) packed into the same geometry (Marinelli beaker) that was used for sample measurements.

Each sample was measured for 80,000 seconds. The following peaks were analysed: 46.5 keV (\( ^{208}\text{Pb} \)), 63.3 keV and the double peak at 92.4 and 92.8 keV (\( ^{238}\text{U} \)), 351 keV and 609 keV (\( ^{226}\text{Ra} \) calculated as \( ^{214}\text{Pb} \) and \( ^{214}\text{Bi} \) average), 662 keV (\( ^{137}\text{Cs} \)), 911 keV (\( ^{232}\text{Th} \)), and 1461 keV (\( ^{40}\text{K} \)).

---

**Figure 1** Location of the PNP within Croatia and locations of quarries Hercegovač, Oršulica, Brenzberg-Točak, and Žervanjska, as well as Lake Orahovac in the PNP (Source: Google Maps)
RESULTS AND DISCUSSION

Ambient dose rate equivalents $H^*(10)$ ranged between 0.05 µSv/h and 0.14 µSv/h, which is within the background range measured in Croatia (44, 45).

Moss radionuclide measurements are presented in Table 2. Table 3 shows the averages for the locations grouped as follows: along the Žervanjska quarry (locations 1, 2, 9; group 1), along the Brenzberg-Točak quarry (locations 7, 8, 19–22, 25–26; group 2), along the road between these two quarries (3–6, 10–18; group 3), and by Lake Orahovac (23, 24; group 4) (Figure 2). Moss samples collected by Lake Orahovac showed, on average, lower activity concentrations of naturally occurring radionuclides than samples collected along and between the quarries, save for $^{137}$Cs. Samples collected along the road showed higher $^{40}$K and lower $^{40}$K activity concentrations than samples collected along the quarries. Samples collected along the Žervanjska quarry had higher $^{40}$K, $^{232}$Th, and $^{238}$U activity concentrations than samples collected at other locations.

Table 1 $H^*(10)$ measurements at 26 PNP locations around the Radiovac Quarry

| Location | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|----------|---|---|---|---|---|---|---|
| Latitude | 45°30'12" | 45°30'13" | 45°30'15" | 45°30'19" | 45°30'27" | 45°30'37" | 45°30'45" |
| Longitude| 17°48'09" | 17°48'19" | 17°48'58" | 17°49'10" | 17°49'16" | 17°49'27" | 17°49'38" |
| $H^*(10)$ (µSv/h)| 0.10±0.03 | 0.12±0.05 | 0.10±0.03 | 0.10±0.05 | 0.10±0.04 | 0.05±0.02 | 0.10±0.04 |

Figure 2 Locations of measurements near Žervanjska quarry (1, 2, 9), near Brenzberg-Točak quarry (7, 8, 19–22, 25–26), near the road between those quarries (3–6, 10–18) and near Lake Orahovac (23–24) (Source: Google Maps)
Table 2 Activity concentration measurements in moss collected at 26 PNP locations around the Radlovac Quarry

| Location | Activity concentration (Bq/kg) |
|----------|------------------------------|
|          | $^{40}$K | $^{137}$Cs | $^{232}$Th | $^{238}$U | $^{226}$Ra | $^{210}$Pb |
| 1        | 409±20  | 2.50±1.5  | 29.2±5  | 35.8±10 | 15.5±1  | 241±35  |
| 2        | 222±10  | 12.1±0.9  | 13.8±2  | 24.8±6  | 20.4±1  | 303±20  |
| 3        | 357±20  | 35.0±2    | 12.9±3  | 18.5±8  | 18.5±1  | 607±50  |
| 4        | 379±10  | 2.47±0.7  | 24.6±3  | 39.1±10 | 37.3±2  | 233±30  |
| 5        | 178±10  | 25.9±1    | 12.5±2  | 17.8±6  | 19.2±2  | 778±40  |
| 6        | 170±10  | 8.17±1    | 9.99±3  | 17.0±13 | 5.54±0.4 | 363±30  |
| 7        | 150±9   | 24.1±1    | 9.57±2  | 12.6±5  | 11.6±0.9 | 654±30  |
| 8        | 300±10  | 5.56±0.6  | 5.92±1  | 8.50±4  | 6.18±0.7 | 672±30  |
| 9        | 203±10  | 25.4±2    | 15.1±3  | 21.6±11 | 4.72±0.6 | 903±60  |
| 10       | 247±20  | 11.8±1    | 15.9±3.5 | 37.8±10 | 18.2±2  | 996±80  |
| 11       | 167±9   | 7.11±1    | 8.98±2  | 12.0±5  | 13.2±0.9 | 800±30  |
| 12       | 173±10  | 11.2±1    | 10.7±2  | 11.0±6  | 8.04±0.6 | 897±40  |
| 13       | 213±10  | 20.9±2    | 13.5±3  | 14.2±7  | 30.0±2  | 289±45  |
| 14       | 144±10  | 22.4±2    | 10.2±3  | <20     | 3±0.3   | 603±70  |
| 15       | 153±10  | 13.8±1    | 11.0±2  | <5      | 4±0.5   | 779±70  |
| 16       | 178±10  | 16.1±2    | 10.7±3  | 11.5±8  | 27.8±3  | 498±50  |
| 17       | 222±20  | 24.6±2    | 14.3±4  | 17.4±6  | 21.8±2  | 405±60  |
| 18       | 199±10  | 25.8±2    | 13.3±3  | 17.6±10 | 11.5±1.5 | 620±40  |
| 19       | 189±10  | 24.5±2    | 8.71±3  | 24.0±20 | 12.2±1  | 625±60  |
| 20       | 184±10  | 12.6±1    | 10.1±2  | 18.0±7  | 19.2±2  | 754±40  |
| 21       | 213±10  | 15.3±1    | 9.07±3  | 12.6±6  | 4.15±0.4 | 564±40  |
| 22       | 332±10  | 7.65±1    | 11.5±2  | 16.3±12 | 29.9±2  | 418±60  |
| 23       | 232±10  | 25.7±2    | 6.49±3  | <10     | 2±0.2   | 303±50  |
| 24       | 198±10  | 35.0±2    | 7.84±3  | <10     | <2      | 571±50  |
| 25       | 437±20  | 4.40±1    | 22.1±5  | 26.2±10 | 6.37±0.5 | 536±70  |
| 26       | 301±10  | 0.53±0.5  | 17.39±3 | 24.6±7  | 26.5±1.5 | 310±30  |
| Range    | 150–437 | 0.53–35.0  | 5.92–29.2 | <DL–39.1 | <DL–37.3 | 233–996 |
| Average  | 236     | 16.2      | 12.9    | 19.9    | 15.1    | 566     |

DL – detection limit, the lowest quantifiable value

To put these numbers in a context, Table 4 shows a comparison with findings from other studies in the same geographic area where possible.

Activity concentrations of $^{137}$Cs vary greatly, depending on the actual Chernobyl fallout. The values for $^{137}$Cs activity concentration in Table 4 were measured over the last 15 years. According to Betsou et al. (48) and Cevik & Celik (49), the ecological half-life of $^{137}$Cs in moss is between 2.1 and 22 years, depending on the species. Our findings indicate that the investigated area was not a hot spot during the Chernobyl fallout.

Compared to other reports (Table 4), our measurements show no indication that $^{40}$K present in moss is the result of anything else but K present in in all living organisms.

Normally, $^{232}$Th, $^{238}$U, and $^{226}$Ra are not present in the air in Croatia (45) in measurable quantities, which points to a local source – more specifically dust – in a similar fashion as described for Pb in moss in a park (42) – and explains high values, among the highest reported (53). As activity concentrations of $^{232}$Th and $^{238}$U are normally independent of each other, the weak correlation (correlation coefficient of 0.78) we found suggests the same origin.

While $^{226}$Ra and $^{238}$U are part of the same decay chain, their chemical properties are different enough that their concentrations routinely
differ both in soil and in living organisms (58–60). Therefore, it is no surprise that the correlation between 226Ra and 238U values was marginal (correlation coefficient of 0.54).

Measured 210Pb activities are high in view of recent literature, even higher than around some coal-fired power plants (56, 57), but not as high as reported for some locations in Bosnia and Herzegovina (55) and Greece (47). 210Pb in the atmosphere is the result of the leakage of 222Rn from soil and 210Pb indicates the presence of 222Rn in the air. Without a detailed long-term study of local weather patterns, we cannot be positive if the 210Pb detected in moss is the result of local 222Rn release or of 222Rn transport from afar. While 222Rn is considered dangerous to humans, the danger is real in closed spaces, where it can accumulate in the air. Out in the open, 222Rn is not considered dangerous, especially not for short exposure times (hours or days) (61).

| Area                        | Activity concentration (Bq/kg) |
|-----------------------------|---------------------------------|
|                            | 137Cs  | 40K   | 232Th | 238U  | 226Ra | 210Pb |
| Plitvice, Croatia (40)      | 14.7–510.9 | 84.9–194 | 2.03–8.92 | <DL–12.3 | 5.9–23.6 | 67.9–369 |
| Beograd area, Serbia (46)   | 9–221   | 110–490 | <DL–45 | <DL–80 | <DL–75 |
| Northern Greece (47)        | 0–425   | 120–750 | 147–1920 |
| Salzburg area, Austria (48) | 1145–14092 | 51–319 |
| Odur province, Turkey (49)  | 31–469  | 350–1440 |
| Bosnia and Herzegovina (50) | 4–1612  |
| Eastern Serbia (39)         | 64–484  | 1.4–28  | 1.1–50  | 1.1–41 |
| Eastern Serbia (51)         | 25–427  | 1.0–37  | 0.4–28  | 0.3–36 |
| Palong area, Malaysia (52)  | 2.8–14.0 | 1.44–7.68 |
| Serbia (53)                 | <DL–17  | 2.2–36  | 526–881 |
| Thailand (53)               | 2.5–327  | <DL–300 | 199–660 |
| Sobieswo island, Poland (54)| 1.36–3.87 | 133–501 |
| Bosnia and Herzegovina (55) | <DL–2000 |
| Thrace region, Turkey (41)  | 178–852 |
| Western Turkey (56)         | 200–650 |
| North-western Turkey (57)   | 219–724 |
| Papuk, Croatia               | 0.53–35.0 | 150–437 | 5.92–29.2 | <DL–39.1 | <DL–37.3 | 233–996 |

DL – detection limit, the lowest quantifiable value

**CONCLUSION**

Our measurements of \(H'(10)\) along the Brenzberg-Točak and Žervanijska quarry fields and at two locations by Lake Orahovac show that the Radiocav Quarry complex does not present a radiological threat to Park visitors and environment, as they kept within the typical range of values of background \(H'(10)\) in Croatia.

Activity concentrations of naturally occurring radionuclides \(^{232}\)Th, \(^{238}\)U, \(^{226}\)Ra, \(^{40}\)K, and of anthropogenic isotope \(^{137}\)Cs in moss support these findings and do not stand out in respect to activity concentrations in moss reported in the rest of Croatia or neighbouring countries.

**Conflict of interests**

None to declare.

**Acknowledgements**

We would like to thank Igor Puharić and Stjepan Bošković for their valuable help in field work.

**REFERENCES**

1. Zakon o proglašenju Parka prirode “Papuk” [Act on promulgation of Papuk Nature Park, in Croatian]. Narodne novine 45/1999.
2. Papuk UNESCO Global Geopark [displayed 8 December 2021]. Available at https://en.unesco.org/global-geoparks/papuk

3. Nwankwo CU, Ogundare FO, Folley DE. Radioactivity concentration variation with depth and assessment of workers' doses in selected mining sites. J Radiat Res Appl Sci 2015;8:216–20. doi: 10.1016/j.jrras.2015.01.004

4. Rangrong J, Zhaolun L, Ming Z. Depth profiling of radioactive nuclides in soil. Nucl Sci Techn 1995;2:121–5.

5. Marchetti E, Tonnarini S, Orlando C, Bruno M, Amici M, PaOLELLI C, Antonelli BM, Palotti L, Mazzini G, Tonnarini S. Natural radioactivity exposure: risk assessment of workers in Italian quarries. In: 11th International Congress of the International Radiation Protection Association; 23–28 May 2004. Madrid: IRPA; 2004.

6. Nwankwo LI, Akiokihle CO, Alabi AB, Ojo OO, Ayodele TA. Environmental ionizing radiation survey of quarry sites in Ilorin industrial area, Nigeria. Nig J Basic Appl Sci 2014;22:1–4. doi: 10.4314/njab.v22i1.1

7. Bent KM, Warturere PN, Nyamari J, Arika J. Levels of ionizing radiations in selected quarries in Nyamira County, Kenya. Heliyon 2020;6:e04363. doi: 10.1016/j.heliyon.2020.e04363

8. Shonita AM, Draz WM, Ali FA, Yassien MA. Natural radioactivity levels and evaluation of radiological hazards in some Egyptian ornamental stones. J Radiat Res Appl Sci 2018;11:323–7. doi: 10.1016/j.jrras.2018.06.002

9. Dentoni V, Da Pe0 S, Aghdam MM, Randaccio P, Lai D, Carrednù N, Bernardini A. Natural radioactivity and radon exhalation rate of Sardinian dimension stones. Constr Build Mater 2020;247:118337. doi: 10.1016/j.conbuildmat.2020.118377

10. Alnour IA, WagarH, Ibrahim N, Laili Z, Omar M, Hamzah S, Idi BY. Natural radioactivity measurements in the granite rock of quarry sites, Johor, Malaysia. Radiat Phys Chem 2012;81:1842–7. doi: 10.1016/j.radphyschem.2012.08.005

11. Del Claro F, Paschuk SA, Córteza JN, Denny V, Kappke J, Perna AFN, Martins MR, Santos TO, Rocha Z, Schelin HR. Radioisotopes present in building materials of workplaces. Radiat Phys Chem 2017;140:141–5. doi: 10.1016/j.radphyschem.2017.02.037

12. Al-Zahrani JH. Estimation of natural radioactivity in local and imported polished granite used as building materials in Saudi Arabia. J Radiat Res Appl Sci 2017;10:241–5. doi: org:10.1016/j.jrras.2017.05.001

13. Ali KK, Awadh SM, Al-Auweidey MR. Assessment natural radioactivity of marble raw material at Kufa Cement Quarry in Najaf Governorate, Iraq. J Sci 2015;55:454–62.

14. Kumara PARP, Mahakumara P. Estimating natural radiation exposure from building materials used in Sri Lanka. J Radiat Res Appl Sci 2018;11:350–4. doi: 10.1016/j.jrras.2018.07.001

15. Samuel OO. Radiation exposure level in some granite quarry sites within Ohimini and Gwer-East Local Government Areas of Benue State Nigeria. Insights Med Phys 2018;2(3):12.

16. Long S, Sdruligh S, Tate B, Martin P. A Survey of Naturally Occurring Radiative Material Associated with Mining. Technical Report Series No. 161, 2012 [displayed 10 March 2022]. Available at https://www.arpansa.gov.au/sites/default/files/legacy/pubs/technicalreports/ tr161.pdf

17. Smeters RCGM, Tomas JM. A practical approach to limit the radiation dose from building materials applied in dwellings, in compliance with the Euratom Basic Safety Standards. J Environ Radioact 2019;196:40–9. doi: 10.1016/j.jenvrad.2018.10.007

18. Elnobi S, Harb S, Ahmed NK. Influence of grain size on radionuclide activity concentrations and radiological hazard of building material samples. Appl Radiat Isot 2017;130:43–8. doi: 10.1016/j.apradiso.2017.09.021

19. Leonardi F, Bonczyk M, Nuccetelli C, Wysocka M, Michalik B, Ampollini M, Tonnarini S, Rubin J, Niedbalska K, Trevisi R. A study on natural radioactivity and radon exhalation rate in building materials containing norm residues: preliminary results. Constr Build Mater 2018;173:172–9. doi: 10.1016/j.conbuildmat.2018.03.254

20. Turhan Ş, Demir K, Karataş M. Radiological evaluation of the use of clay brick and pavement brick as a structural building material. Appl Radiat Isot 2018;141:95–100. doi: 10.1016/j.apradiso.2018.08.022

21. Ghenu ST, Oladejo OF, Alayande O, Olukoru SF, Fasasi MK, Balogun FA. Assessment of radiological hazard of quarry products from southwestern Nigeria. J Radiat Res Appl Sci 2016;9:20–5. doi: 10.1016/j.jrras.2015.08.004

22. Kayakökü H, Karatepe Ş, Doğru M. Measurements of radioactivity and dose assessments in some building materials in Bilecik, Turkey. Appl Radiat Isot 2016;115:172–9. doi: 10.1016/j.apradiso.2016.06.020

23. Nuccetelli C, Trevisi R, Leonardi F, Ampollini M, Cardellini F, Tonnarini S, Kovler K, Vargas Trassiera C. Radiological characterization of the ancient Roman tuff-pozzolana underground quarry in Orvieto (Italy): A natural laboratory to revisit the interactions between radionuclides and aerosols. J Environ Radioact 2017;168:54–60. doi: 10.1016/j.jenvrad.2016.07.003

24. Abdulah A, Jaikol E, Arshad N, Saat A. Radiological assessments of quarry dust from quarries in Kelantan, Malaysia. AIP Conference Proceedings 2009;206(020022. Available at 10.1063/1.3089321

25. Quarry Nature Park, Canada [displayed 8 December 2021]. Available at https://www.ccnv.ca/157/Quarry-Nature-Park

26. Park Hall Country Park & Hulme Quarry Nature National Reserve, UK [displayed 8 December 2021]. Available at http://webapps.stoke.gov.uk/uploadedfiles/Waymarked_Walks_Park_Hall_Country_Park.pdf

27. Helsby Quarry Woodland Park, UK [displayed 8 December 2021]. Available at https://www.merseyforest.org.uk/things-to-do/walks-bike-rides-and-more/walks/helsby-quarry-woodland-park/

28. Quarry Park & Nature Preserve, USA [displayed 8 December 2021]. Available at https://www.stearnscountymn.gov/396/Quarry-Park-Nature-Preserve

29. Portland Quarries Nature Park, UK [displayed 8 December 2021]. Available at https://www.dorsetwildlifetrust.org.uk/portland-quarries-nature-park

30. Portland Quarries Nature Park - Green Infrastructure Case Study (NE386) [displayed 8 December 2021]. Available at http://publications.naturalengland.org.uk/publication/5260232

31. Mirion Technologies (RADOS) Health Physics Division. RDS-31 S/R Multi-Purpose Survey Meter User's Manual, Doc No: 2096 6082. Ver: 2.1 [displayed 21 October 2021]. Available at https://www.laurussystems.com/wp-content/uploads/RDS_31_MANUAL.pdf

32. Tyler G. Bryophytes and heavy metals: a literature review. Bot J Linn Soc 1990;104:231–53. doi: 10.1111/j.1095-8339.1990.tb02220.x

33. Pesch R, Schroeder W. Mosses as bioindicators for metal accumulation: Statistical aggregation of measurement data to exposure indices. Ecol Ind 2006;6:137–52. doi: 10.1016/j.ecolind.2005.08.018

34. Galsoumis I, Letrouit MA, Deschamps C, Savanne D, Avnaim M. Atmospheric metal deposition in France: initial results on moss
calibration from the 1996 biomonitoring. Sci Total Environ 1999;232:39–47. doi: 10.1016/S0048-9697(99)00108-4
35. Grodziska K, Szarek-Lukaszewska G. Response of mosses to the heavy metal deposition in Poland - an overview. Environ Pollut 2001;114:443–51. doi: 10.1016/S0269-7491(00)00227-X
36. Mazzoni AC, Lanzer R, Bordin J, Schaefer A, Wasmu R. Mosses as indicators of atmospheric metal deposition in an industrial area of southern Brazil. Acta Bot Bras 2012;26:553–8. doi: 10.1590/S0102-33062012000300005
37. Marović G, Franic Z, Senčar J, Bithu T, Vugrinec O. Mosses and some mushroom species as bioindicators of radioaerosol contamination and risk assessment. Coll Antropol 2008;32(Suppl 2):109–14.
38. Marović G, Lokobauer N, Bauman A. Risk estimation of radioactive contamination after the Chernobyl accident using bioindicators. Health Phys 1992;62:332–7. doi: 10.1097/00004032-199204000-00005
39. Ćučulović A, Ćučulović R, Saboljević M, Radenkovic MB, Veselinović G. Natural radionuclide uptake by mosses in eastern Serbia in 2008–2013. Arh Hig Rada Toksikol 2016;67:31–7. doi: 10.1515/aiht-2016-06721-4
40. Babić D, Skoko B, Franic Z, Senčar J, Šoštarić M, Petroić Lj, Avdić M, Kovačić G, Branica G, Petrinec B, Bithu T, Franić Z, Marović G. Baseline radioecological data for the soil and selected bioindicator organisms in the temperate forest of Plitvice Lakes National Park, Croatia. Environ Sci Pollut Res Int 2020;27:21040–56. doi: 10.1007/s11356-020-08369-0
41. Kılıç Ö, Belivermiş M, Siddokur E, Sezer N, Erentürk SA, Hacıyakupoglu S, Madadzada A, Frontasyeva M. Assessment of $^{210}$Po and $^{210}$Pb by moss biomonitoring technique in Thrace region of Turkey. Haciyakupoglu S, Madadzada A, Frontasyeva M. Assessment of $^{210}$Po and $^{210}$Pb by moss biomonitoring technique in Thrace region of Turkey. J Radioanal Nucl Chem 2019;322:699–706. doi: 10.1007/s10967-019-08721-4
42. Yang H, Appelby PG. Use of lead-210 as a novel tracer for lead (Pb) sources in plants. Sci Rep 2016;6:21707. doi: 10.1038/srep21707
43. Vidmar T. EFFTRAN-A Monte Carlo efficiency transfer code for gamma-ray spectrometry. Nucl Instrum Meth Phys Res A 2005;550:603–8. doi: 10.1016/j.nima.2005.05.055
44. EURDEP. Gamma Dose Rate, Simple Map [displayed 8 December 2021]. Available at https://remap.jrc.ec.europa.eu/Simple.aspx
45. Institute for Medical Research and Occupational Health. Praćenje stanja radioaktivnosti u Republici Hrvatskoj. Izvještaj za 2021. Available at https://civilna-zastita.gov.hr/UserDocsImages/dokumenti/Radioloska_i_nuklearna_sigurnost/Nacionalna_izjava_fiskcionalu_2021.pdf
46. Grodžiska K, Szarek-Lukaszewska G. Response of mosses to the heavy metal deposition in Poland - an overview. Environ Pollut 2001;114:443–51. doi: 10.1016/S0269-7491(00)00227-X
47. Betsou Ch, Tsakini E, Kazakis N, Hansman J, Krmr M, Frontasyeva M, Ioannidou A. Heavy metals and radioactive nuclide concentrations in mosses of Greece. Radiat Eff Defects Solids 2018;173:851–6. doi: 10.1080/10420150.2018.1528611
48. Iurian AR, Hofmann W, Lettner H, Türk R, Cosma C. Long term study of Cs-137 concentrations in lichens and mosses. Romanian J Phys 2011;56:983–92.
49. Ćučulović A, Saboljević M, Veselinović G. The activity concentrations of $^9$K, $^{226}$Ra, $^{228}$Th, $^{232}$U and $^{210}$Pb in moss from spas in eastern Serbia in the period 2000–2012. Arch Biol Sci 2014;66:691–700. doi: 10.2298/ABS1402691C
50. Termiti Raml A, Wahab A, Hussein MA, Khalik Wood A. Environmental $^{226}$Ra and $^{232}$Th concentration measurements in an area of high level natural background radiation at Palong, Johor, Malaysia. J Environ Radioact 2005;89:287–304. doi: 10.1016/j.jenvrad.2004.06.008
51. Krmr M, Warranavee K, Radnović D, Svlka J, Bhongsuwan T, Frontasyeva MV, Pavlov SS. Airborne radionuclides in mosses collected at different latitudes. J Environ Radioact 2013;117:45–8. doi: 10.1016/j.jenvrad.2011.08.009
52. Adrović F, Adrović J, Kamberović J, Hrdljević D, Djurković D, Kamberović J. Determination of the concentration activity of radioactive $^{210}$Pb in mosses of Bosnia and Herzegovina. J Environ Radioact 2013;117:45–8. doi: 10.1016/j.jenvrad.2011.08.009
53. Boryło A, Romanczyk G, Skwarzec B. Lichens and mosses as polonium and uranium biomonitorers on Sobieszewo Island. J Radioanal Nucl Chem 2017;311:859–69. doi: 10.1007/s10967-016-5079-8
54. Adrović F, Adrović J, Kamberović J. Determination of the concentration activity of radioactive $^{210}$Pb in mosses of Bosnia and Herzegovina. J Environ Radioact 2013;117:45–8. doi: 10.1016/j.jenvrad.2012.08.001
55. Uğur A, Özden B, Sac MM, Yener G. Biomonitoring of $^{210}$Po and $^{210}$Pb using lichens and mosses around a uranium-coal fired power plant in western Turkey. Atmosph Environ 2003;37:2237–45. doi: 10.1016/S1352-2310(03)00147-X
56. Belivermiş M, Kılıç Ö, Cayır A, Coskun M, Coskun M. Assessment of $^{210}$Po and $^{210}$Pb in lichen, moss and soil around Can coal-fired power plant, Turkey. J Radioanal Nucl Chem 2016;360:753–31. doi: 10.1007/s10967-015-4169-3
57. Adrović F, Adrović J, Kamberović J, Hrdljević D, Djurković D, Kamberović J. Determination of the concentration activity of radioactive $^{210}$Pb in mosses of Bosnia and Herzegovina. Int J Mod Biol Res 2020;8:1–11. doi: 10.33500/ijmbr.2020.8.001
58. Petrinec B, Šoštarić M, Babić D. The role of physics in radioecology and radiotoxicology. Arh Hig Rada Toksikol 2019;70:3–13. doi: 10.2478/ahrt-2019-00322
59. Šoštarić M, Petrinec B, Avdić M, Petroić Lj, Kovačić G, Frančić Z, Franić Z, Marović G, Rašeta D, Bešlić I, Babić D. Radioactivity of soil in Croatia I naturally occurring decay chains. Arh Hig Rada Toksikol 2021;72:6–14. doi: 10.2478/ahrt-2021-72-3439
60. Šćavničar S, Bermanec V, Kniewald G, Barišić D, Oreščanin V. Uranium minerals in the Radlovac series metamesciments at Mt. Papuk, Croatia. Geol Croat 2007;60:165–71. doi: 10.4154/GC.2007.05
61. WHO. Radon and Health, 2021 [displayed 10 March 2022]. Available at https://www.who.int/news-room/fact-sheets/detail/radon-and-health
Radiološki utjecaj aktivnoga kamenoloma u Parku prirode Papuk

Za razliku od većine sličnih parkova i rezervata prirode u svijetu, u Parku prirode Papuk nalaze se aktivni kamenolomi. U kamenolomima se izvlači kamen iz tla, pri čemu se stvara prašina te se otkrivaju dublji, potencijalno radioaktivniji slojevi. Budući da šumski putovi u Parku prirode Papuk vode do samih kamenoloma, važno je odrediti njihov radiološki učinak na taj park prirode. Mjerili smo ekvivalent ambijentalne brzine doze $H^{*}(10)$ i uzorkovali smo mahovinu na 26 lokacija oko dvaju od četiriju kamenoloma, oko ceste između njih te uz Orahovacko jezero, popularno turističko odredište u blizini kamenoloma. Mahovina je standardni bioindikator za teške metale, uključujući i radionuklide. Gamaspektrometrijskom smo metodom u uzorkovanim mahovinama odredili koncentracije aktivnosti $^{137}$Cs i reprezentativnih prirodnih radionuklida: $^{226}$Ra, $^{228}$Ra, $^{210}$Pb, $^{232}$Th, i $^{40}$K. Na odabranim je lokacijama $H^{*}(10)$ sličan onom koji se kontinuirano mjeri drugdje u Republici Hrvatskoj. Rasponi izmjerenih vrijednosti koncentracija aktivnosti $^{137}$Cs i odabranih prirodnih radionuklida u mahovinama značajno se ne razlikuju od raspona izmjerenih vrijednosti koncentracija aktivnosti navedenih radionuklida u mahovinama uzorkovanim drugdje u Hrvatskoj i u susjednim zemljama.

KIJUČNE RIJEČI: $^{137}$Cs; ekvivalent ambijentalne brzine doze $H^{*}(10)$; gamaspektrometrija; mahovina; prirodni radionuklidi