Nuclear Engineering and Technology 55 (2023) 3046–3053

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

The presence of carcinogenic radon in the Padma River water, adjacent to the Rooppur Nuclear Power Plant

M.M. Mahfuz Siraz [a, *], M.S. Alam [b], Jubair A.M.[b], S.C. Das [c], J. Ferdous [a], Z. Hossain [a], S. Das [d], Mayeen Uddin Khandaker [e, f], D.A. Bradley [f, g], Shinji Tokonami [h], S. Yeasmin [a]

[a] *Health Physics Division, Atomic Energy Centre, Dhaka, 1000, Bangladesh*
[b] *Department of Nuclear Engineering, University of Dhaka, Dhaka, 1000, Bangladesh*
[c] *Institute of Nuclear Minerals, Bangladesh Atomic Energy Commission, Savar, Dhaka, 1207, Bangladesh*
[d] *Atomic Energy Centre, East Nasirabad, Chattogram, Bangladesh*
[e] *Department of General Educational Development, Faculty of Science and Information Technology, Daffodil International University, DIU Rd, Dhaka, 1341, Bangladesh*
[f] *Centre for Applied Physics and Radiation Technologies, School of Engineering and Technology, Sunway University, 47500, Bandar Sunway, Selangor, Malaysia*
[g] *Centre for Nuclear and Radiation Physics, Department of Physics, University of Surrey, Guildford, Surrey, GU2 7XH, UK*
[h] *Institute of Radiation Emergency Medicine, Hirosaki University, 66-1 Honcho, Hirosaki, 036-8564, Japan*

ARTICLE INFO

Article history:
Received 24 July 2022
Received in revised form
2 October 2022
Accepted 25 April 2023
Available online 9 May 2023

Keywords:
Radon
RAD H_2O
Rooppur Nuclear Power Plant
Effective doses

ABSTRACT

Radon is a naturally occurring carcinogenic agent, poses a serious health hazard when inhaled or ingested in significant amounts. The water of the Padma river will be used as a tertiary coolant for the soon-to-be-commissioned ‘Rooppur Nuclear Power Plant’. Hence, it is important to assess the radiological status of the river prior to the commission of this power plant. Therefore, for the first time, 25 samples of water were collected from various locations of the Padma River and analyzed for radon concentration using the RAD H_2O (DURRIDGE) radon monitoring device. The radon concentrations were found in the range from 0.077 ± 0.036 to 0.494 ± 0.211 Bq/L with a mean of 0.250 ± 0.093 Bq/L. All the concentrations were found to be below the recommended limits of WHO (100 Bq/L) and USEPA (11.1 Bq/L). The mean annual effective dose due to the radon exposure via inhalation and ingestion pathways were 0.638 μSv/y and 0.629 μSv/y, respectively, which were all well below the annual effective dose recommended by WHO (0.1 mSv/y). Since Bangladesh lacks a national safety limit of radon in water, this pioneering study provides baseline data on radon levels for the environment around Rooppur Nuclear Power Plant.

1. Introduction

Radon (^{222}Rn), a progeny of uranium (^{238}U) decay series with a half-life of 3.82 days, is a colorless and odorless noble gas found in higher amounts in rocks such as granites, metamorphic rocks, sedimentary rocks containing phosphate, and soils of the earth's crust [1–3]. According to United Nations Environment Programme (UNEP), ^{222}Rn alone contributes to more than (50%) of the natural radiological dosage to the general public [4,5]. Because of its capacity to generate a variety of biological consequences, radon gas is considered a hazardous agent for human health. Radon may enter the human body via two processes, inhalation through the respiratory system and ingestion (drinking water) through the gastrointestinal tract. Radium behaves chemically like calcium and is deposited on bone surfaces. Radon being inert gas does not deposit. Only small proportion of it gets absorbed in the inner lining of respiratory tract. It is the decay products of radon that deposit on the surfaces of respiratory tract and give dose, so studies on radon concentration are essential from the radiological point of view [6,7]. Being a noble gas with a short half-life, ^{222}Rn does not react with the environment and do not accumulate for long. The health risk from radon inhalation is caused by its short-lived progenies ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po, rather than the radon gas itself. Once inhaled, decay products of radon being particulates will deposit in the respiratory tract and irradiate the lung tissues, contributing

---

[*] Corresponding author.
E-mail address: mahfuzsiraz1985@yahoo.com (M.M.M. Siraz).

https://doi.org/10.1016/j.net.2023.04.038

significantly to the internal radiation dose [8,9]. Meanwhile, some progeny are moved to bodily fluids and carried to organs other than the respiratory organs, causing harm to those organs via radiation exposure. High amounts of radon in drinking water can cause cancer in the stomach, digestive system, and respiratory system [10]. The International Agency for Research on Cancer (IARC), a branch of the World Health Organization (WHO), has classified radon as a group 1 carcinogen [4,5], and the WHO has named radon as the second leading cause of lung cancer after tobacco smoke, as well as a severe risk to non-smokers [11,12]. Recent epidemiological studies in the United States estimate that radon exposure kills roughly 20,000 people yearly [13].

The occurrences of natural radionuclides are influenced by various parameters, including lithology and the presence or absence of faults and fractures [14–16]; hence the concentration of natural radionuclides varies significantly over the earth's surface. Radon may be present in the soil, air, and water in the lakes, rivers, springs, groundwater, and even precipitation [11,17]. The unique properties of naturally occurring radioactive radon gas have led to its use as a geophysical tracer for identifying the geological structure and hidden faults, measuring and monitoring groundwater movement into the lake and sea water along the shore, in earthquake prediction and uranium deposit exploration, and as a tracer in the study of atmospheric transfer processes [18–22]. However, in the absence of aeration, ^{222}Rn may quickly diffuse from solid objects into the water when various natural water resources come into contact with soil and rocks [23–25]. It is highly volatile and easily dissolved and released from water.

Water from the Padma River will be used as the tertiary coolant for the Rooppur Nuclear Power Plant during its operation, which is scheduled to commission in 2023. In addition, the Padma River water is used by thousands of people residing on the river banks for drinking, washing, cooking, bathing, etc. The world's two largest drinking water sources are surface water and groundwater [14]. Chemical, microbiological, and radioactive pollution should be avoided in drinking water [26,27]. Due to the enormous volume of radioactivity-bearing excavation debris that remains after minerals are extracted from their ores in mining sites, ^{222}Rn is one of the principal pollutants in surface and groundwater resources in mining locations [28–30]. When these fluids are used in showering, washing clothes, cleaning dishes, humidifiers, flushing toilets, cooking, etc, the radon in the water becomes accessible for breathing via degassing [31,32]. According to the USEPA, radon in drinking water causes approximately 168 cancer deaths per year, with 89% of these deaths due to lung cancer caused by breathing radon released into the indoor air from water and 11% due to stomach cancer caused by consuming radon-contaminated water [4,33].

The primary goals of this study are a) to measure the radon in the Padma river water for the first time and evaluate the associated radiological hazards, and b) to provide factual baseline data for safe guideline limits for radon in water at the national level. It is expected that the obtained data of radon in the Padma river water may help to assess the scenario of radon in water in both regular operations and any accidental case of the Rooppur Nuclear Power Plant.

2. Study area

The current study concentrates on the Padma River, one of the major rivers in Bangladesh. The Ganges River originates from Himalaya flows through India, and enters Bangladesh as the Padma River, which then meets with Jamuna and Meghna River in its course to the final destination the Bay of Bengal, and carries enormous terrestrial sediments. The annual sediment load is about 16 million metric tons. The average annual discharge of the river is about 35,000 m^3s^{-1} and the width varies from 4 to 8 km. The average current velocity fluctuates from 4 to 5 ms^{-1} and depth varies from 20 to 21 m [34]. The mean annual rainfall received by its catchment is about 12,00 mm, of which about 70% happens during the monsoon period. The temperature range varies from 8 °C (winter) to 39°C (summer), with an annual average temperature from 23.5 °C to 25 °C. The annual average evaporation varies from 18 to 140.2 mm, and the humidity fluctuates from 62.3 to 87.8% [35].

The study area lies between the latitude 23°50' - 24°10′N and longitude 88°45' - 89°25′E. It passes through the Kumarkhali, Kushtia sadar, Mirpur, and Daulatpur Upazilas of Kushtia district, Pabna sadar, Bheramara, and Ishwardi Upazilas of Pabna district, Lalpur Upazila of Natore district and Bagha Upazila of Rajshahi district (Fig. 1). Geologically, the Padma River in the study area consists of mainly riverine alluvial clay, silt, very fine to coarse sand and gravels of Holocene age (Fig. 2) [36,37]. Except for some intermixing, the grain size increases from clay to gravel with depth. The subsurface strata were more consolidated with depth from dense sand to very dense sand with gravel at the base from about 60 to 100 m depth, probably due to high energy compaction from lithification and seismic activity. Moreover, the less dense materials above the dense layer can occur a liquefaction effect during seismic phenomena. The basal gravel layer may be related to the past glacial period [37]. The present geomorphological setting of Padma River is favourable for transportation and deposition of fine sediments of alluvium clay, silt and fine sand. The erosion and deposition of the Padma river bank are influenced by the unstable water flow during the monsoon and dry season and also by the yearly flood. Due to the

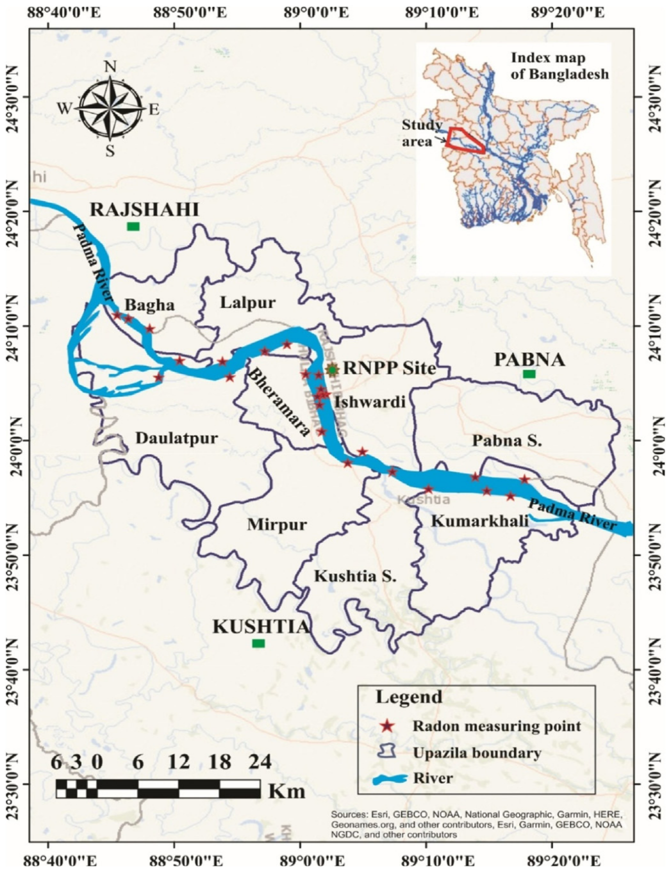

Fig. 1. Location map showing the study area and the radon measuring points.

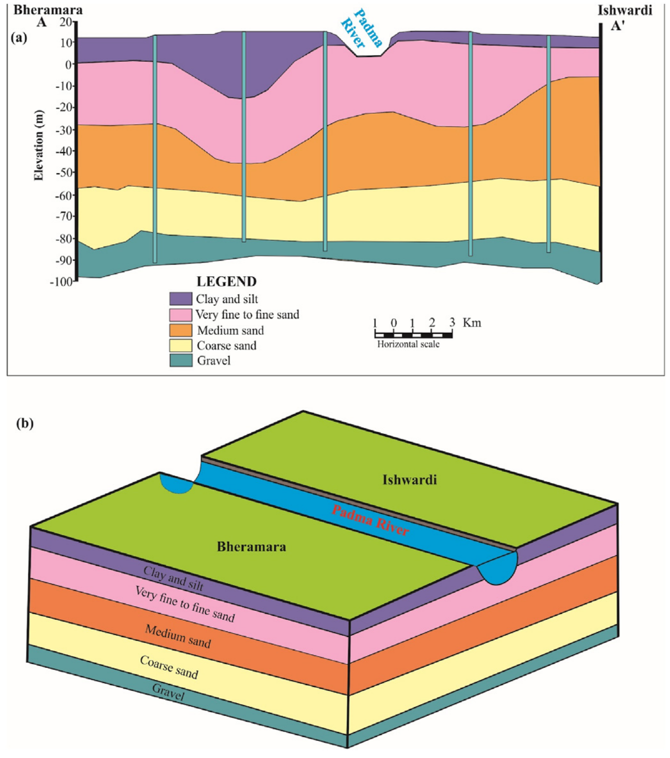

Fig. 2. (a) Geological cross section along the A-A' (Bheramara-Ishwardi) line [41]. (b) 3-D view of subsurface geology along the cross-section line at Bheramara to Ishwardi [36].

erosion and depositional phenomenon, numerous bars and islands (locally called chars) formed in their course [38]. The mineralogical study of the sediments of Padma River includes quartz, feldspar, mica, ilmenite, magnetite, garnet, rutile, hornblende, and corundum [39]. The geochemical study of Padma River sediments in the Rajshahi district suggests that the sediments were derived from the source area containing mostly felsic to intermediate igneous rock, possibly from the Himalayan belt and catchment areas of the Ganges [40].

3. Sampling strategy

An environmental monitoring program's primary goal is quickly identifying a radioactive threat to safeguard the population and the environment [42]. The primary goal of sampling is to ascertain background levels or the type of contamination at a given location. The sampling approach must also guarantee that the samples represent the region under inquiry. Simple random sampling, two-stage sampling, stratified sampling, systematic grid sampling, systematic random sampling, cluster sampling, double sampling, search sampling, and transect sampling are several sampling methodologies [38–40]. Depending on the kind and location of pollutants, a representative sample strategy may incorporate two or more of these sampling methodologies.

We adopted a stratified systematic sampling strategy in our research, which divides the population into groups (strata). Stratified sampling is more complicated than random sampling and needs more previous knowledge. The benefit of stratified sampling is that it divides the population into smaller groups, each of which is predicted to be more homogeneous than the total population. According to prior information or analytical data, the individual strata are chosen based on features that set them apart from other strata and are known to have an impact on the measured parameter of interest (such as sampling depth, soil horizon, contaminant concentration, and source. Because the Hardinge Bridge is so close to the RNPP, we have considered its location and obtained different samples near it (Fig. 1). Another two sub-divisions ran along with Rajshahi and Kustia, which are upstream and downstream side of the Padma river, respectively, and in these areas, we have performed systematic sampling by regularly obtaining samples on both sides of the river during the study period.

4. Measurement technique

Several techniques such as Gamma Spectroscopy (GS), Lucas Cell (LC), and Liquid Scintillation (LS) can be used for measuring radon in water. Gamma spectroscopy detects gamma rays emitted from radon decay products in a sealed container of radon-bearing water. The LC technique is labor-intensive, requiring a sophisticated glassware system and a vacuum pump to empty a Lucas (scintillation) cell, followed by the bubble of gas through the water sample until the cell fills. The Liquid Scintillation technique was developed in the 1970s. In a 25 mL glass vial, a liquid scintillation cocktail is introduced to the sample. The cocktail sucks the radon out of the water, causing the alpha particles to scintillate as it decays. However, it is difficult to transport the scintillation cocktail (organic solvent) used in the LS method, which limits its applications in various areas. Compared to the LS, the RAD H_2O provides technology as precise as the LS, and RAD7 is more portable, less labor-intensive, and less costly. It also gets rid of the necessity for harmful chemicals [43].

The RAD H_2O is an attachment for the RAD7 that allows measuring radon in water at concentrations above the minimum detectable activity (MDA). The MDA concentration of this instrument is 0.004 BqL^{-1} [24,43]. The RAD7 with printer, the water vial with aerator cap, and the desiccant tube attached to the aerator cap and held by a clamp on the retort stand make up the setup. The term “background” in a radon detector describes erroneous counts that take place even when there is no radon present. Background can be caused by an instrument's characteristics or its parts, or presence of other types of radiation in the area around the instrument, or their interference with the instrument. The radon that was measured will remain in the RAD7's internal sample cell after making a water or air measurement. This radon will incorrectly affect the subsequent measurement if it is still present when begin a new measurement. This is especially concerning when the previous measurement's radon concentration was high in comparison to the subsequent measurement. In such a situation it is a must to fully remove the radon from the RAD7 and its air-conducting accessories, such as the aerator head, tubes, and desiccant, in order to get ready for the subsequent water measurement. This procedure is known as “purging the system.” For this reason, the RAD7 detector must be put into purge mode for at least 10 min to eliminate excessive humidity and radon from the system. The intrinsic background of the RAD7 is less than 1 count per hour, which corresponds to a concentration of less than 2 pCi/L in a 40 mL water sample (even lower for the 250 mL sample). So the background of RAD7 is low enough and negligible, especially, after the device has been purged from radon for 10 min. The desiccant ($CaSO_4$, Drierite, WA Hammond, USA) must be used to dry the air stream before it reaches the RAD7 in the RAD H_2O. The RAD7 may report inaccurate radon concentrations or become damaged owing to condensation on sensitive internal components if the desiccant is not used correctly. The relative humidity has a significant influence on the measurement. The relative humidity within the RAD7 will remain below 10% for the measurement duration if it is thoroughly dried off before use [44]. If not, the humidity will grow while the RAD7 is in counting mode, and the pump is turned off and may climb by more than 10% before the measurement period ends. Very low relative humidity (6–8%) was recorded during the current investigation measurement.

A solid-state alpha detector is used in the DURRIDGE RAD7 [45]. Using a semiconductor material, a solid-state detector converts alpha radiation directly into an electrical signal. A solid-state, Ion-implanted, Planar, Silicon alpha detector is at the hemisphere's core. Concerning the detector, the high voltage power circuit charges the inner conductor to a potential of 2000–2500 V, generating an electric field across the cell volume. Care and experience are required to obtain a quality sample. When assessing the radon content of water, sampling technique-or lack thereof-is typically the main source of mistake. The water sampled needs to be both a) an accurate representation of the water being tested, and b) such that it has never been in contact with air. The water sample in the current experiment was taken with extreme care so that it didn't come into contact with the outside air. On the RAD7, two protocols (Wat-40 and Wat-250) are available for radon assessment of water samples, depending on the vial size (40 or 250 mL). Before radon measurement, it is critical to choose the proper methodology since it regulates the pumping and counting cycle and the calculation based on the sample vial size. Since larger sample size or bulk sampling offers more counts per minute above the background, therefore to increase the sensitivity and accuracy at low radon concentrations, the RAD7 radon detector was operated according to the Wat 250 procedure.

The RAD H_2O approach uses a closed-loop aeration strategy in which the air and water volumes are constant and independent of flow rate. The radon is constantly extracted as the air cycles through the water until a state of equilibrium is reached. After around 5 min, the RAD H_2O system has reached equilibrium, and no additional radon can be extracted from the water. The extraction efficiency, or the proportion of radon extracted from the water to the air loop as a percentage of the equilibrium value, is generally 99% for a 40 mL sample and 94% for a 250 mL sample. By multiplying the air loop concentration by a predetermined conversion coefficient that depends on the sample size, the RAD7 estimates the sample water concentration. The volume of the air loop, the volume of the sample, and the equilibrium radon partition coefficient at room temperature were used to calculate this conversion coefficient. In a nutshell, this device works on the following principles: (1) radon is expelled from a water sample using a bubbling kit, (2) expelled radon enters a hemisphere chamber via air circulation, (3) polonium decayed from radon is collected onto a silicon solid-state detector via an electric field, and (4) radon concentration is estimated from the polonium count rate [7,46]. The schematic diagram of RAD H_2O is shown in Fig. 3.

The results of the sample were adjusted from the time of the sample when it was collected to the time when it was counted. Although analytical accuracy will decrease as the sample gets weaker and weaker, decay correction can be employed for samples counted up to 10 days after sampling. Decay correction is the exponential function with a time constant of ^{222}Rn, which is 132.4 h, and the formula for decay correction factor (DCF) [43] is

$$DCF = e^{T/132.4} \qquad (1)$$

5. Dosimetry calculation

Internal radon exposure comes primarily from inhalation and ingestion, which is harmful to the respiratory organs. When water is collected and used, radon is inhaled, and radon is ingested when radon-contaminated water is consumed. Therefore, by using Equations (1) and (2), the annual effective dose due to radon inhalation and ingestion is calculated from the experimentally measured values of the radon concentration for adult population [6–9].

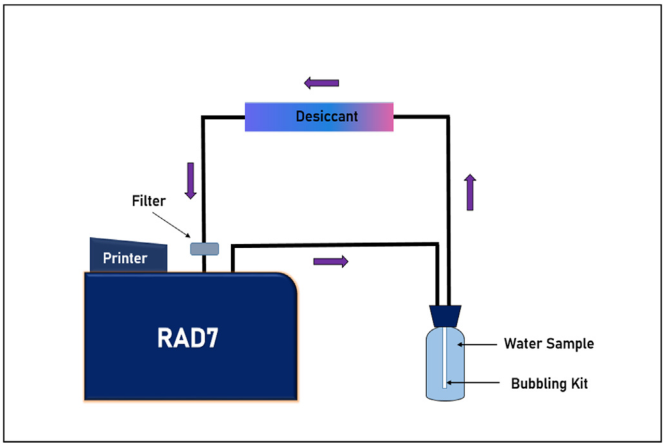

Fig. 3. The schematic diagram of RAD H_2O.

$$W_{ig}\ (\mu Sv/y) = C_{RnW} \times C_W \times EDC \times 10^{-3} \qquad (2)$$

$$W_{in}\ (\mu Sv/y) = C_{RnW} \times R_{AW} \times F \times O \times DCF \times 10^{-3} \qquad (3)$$

Where, W_{ig} and W_{in} represents effective doses due to ingestion and inhalation (μSv/y), respectively, C_{RnW} = measured radon concentration (Bq/L), C_W = daily water consumption for adult people (2 L/day) [6], EDC (Effective Dose Coefficient for adult people) = 3.5nSv/Bq for radon ingestion [47], 10^{-3} is used for the conversion of nano-to-micro unit, R_{AW} = ratio of radon in the air to water (10^{-4}) [47], F (equilibrium factor between radon and its progeny) = 0.4 [47], O (mean indoor occupancy factor) = 7000 h/y [47], DCF (dose conversion factor) = 9 nSv/h per Bq/m3 [47], here T is the duration between sample collection and sample measurement.

6. Results and discussion

Table 1 represents geographical coordinates, ^{222}Rn concentration (Bq/L), the annual effective dose due to ingestion and inhalation of radon of the twenty-five surface water samples collected from the Padma river. Sample no. RNPP-01 to RNPP-07, RAJ-08 to RAJ-16, and KUS-17 to KUS-25 were collected near the Hardinge Bridge & Lalon Shah bridge (close to RNPP), along with Rajshahi and Kushtia respectively. The radon concentration in river water samples ranged from 0.077 ± 0.036 to 0.494 ± 0.211 Bq/L with an average of 0.250 ± 0.093 Bq/L. The maximum concentration of radon (0.494 ± 0.211 Bq/L) was found in RNPP-02, and the minimum concentration of radon (0.077 ± 0.036 Bq/L) was found in RAJ-10. These values are lower than the maximum concentration level of 11 Bq/L as recommended by USEPA, 100 Bq/L by WHO [1,4,33,45]. Some natural and anthropogenic activities, such as radium concentration in aquifer rock, temperature, pressure, geological structure, inputs from streams, degree of water turbulence, bottom sediments, and human activities such as mining, milling, air effluent, industrial solid and liquid wastes, fertilizer leaching, mineral mining, etc., influence radon concentration in groundwater and surface water [30,31,47–50]. Because Rn-222 in surface water samples can quickly escape to the atmosphere due to aeration and movement in the water, as well as the lack of significant interaction

Table 1
Radon concentration in and the annual effective dose (Ingestion and inhalation) in surface river water samples from the studied area.

Sample ID	Latitude (N)	Longitude (E)	Mean Radon Concentration (Bq/L)	Annual Effective Dose of Ingestion (μSv/y)	Annual Effective Dose of Inhalation (μSv/y)	Total Annual Effective Dose (μSv/y)
RNPP01	24° 4′ 3.5″ N	89° 2′ 4.3″ E	0.359 ± 0.153	0.917	0.904	1.821
RNPP02	24° 3′ 59.1″ N	89° 1′ 47.5″ E	0.494 ± 0.211	1.262	1.244	2.506
RNPP03	24° 03′ 90.9″	89° 01′ 39.0″ E	0.448 ± 0.212	1.144	1.128	2.272
RNPP04	24° 3′ 51.9″ N	89° 1′ 22.8″ E	0.300 ± 0.071	0.767	0.757	1.524
RNPP05	24° 03′ 07.3″N	89° 01′ 33.0″ E	0.322 ± 0.124	0.822	0.811	1.632
RNPP06	24° 5′ 35.7″ N	89° 1′ 19.3″ E	0.204 ± 0.000	0.522	0.515	1.037
RNPP07	24° 5′ 45.9″ N	89° 0′ 25.9″ E	0.209 ± 0.098	0.394	0.389	0.783
RAJ08	24° 07′ 49″ N	88° 56′ 71.4″ E	0.408 ± 0.165	1.042	1.027	2.069
RAJ09	24° 5′ 33.2″ N	88° 54′ 24.3″ E	0.188 ± 0.030	0.481	0.474	0.955
RAJ10	24° 5′ 31.9″ N	88° 48′ 46.6″ E	0.077 ± 0.036	0.196	0.194	0.390
RAJ11	24° 8′ 33.68″ N	88° 45′ 32.2″ E	0.159 ± 0.150	0.406	0.401	0.807
RAJ12	24° 9′ 46.2″ N	88° 48′ 3.3″ E	0.179 ± 0.036	0.458	0.452	0.910
RAJ13	24° 10′ 39.3″ N	88° 46′ 20.8″ E	0.206 ± 0.072	0.526	0.519	1.044
RAJ14	24° 6′ 58.9″ N	88° 50′ 26.1″ E	0.106 ± 0.000	0.270	0.266	0.537
RAJ15	24° 7′ 29.1″ N	88° 59′ 2.9″ E	0.103 ± 0.049	0.264	0.261	0.525
RAJ16	24°06′ 54.4″ N	88°53′ 50.5″ E	0.154 ± 0.073	0.268	0.526	0.269
KUS17	24°00′48.1″ N	89°01′43.9″ E	0.128 ± 0.036	0.328	0.323	0.651
KUS18	23°58′03.5″ N	89°03′46.8″ E	0.256 ± 0.146	0.654	0.645	1.298
KUS19	23°56′77.7″ N	89°07′19.7″ E	0.284 ± 0.109	0.727	0.717	1.443
KUS20	23° 55′ 46.4″ N	89° 10′ 12.1″ E	0.233 ± 0.036	0.594	0.586	1.180
KUS21	23°55′37.5″ N	89°14′49.4″ E	0.104 ± 0.074	0.266	0.262	0.529
KUS22	23°55′10.4″ N	89°16′41.7″ E	0.367 ± 0.148	0.938	0.925	1.862
KUS23	23° 56′ 36.5″ N	89° 17′ 49.1″ E	0.319 ± 0.076	0.815	0.804	1.619
KUS24	23° 56′ 49.5″ N	89° 13′ 53.7″ E	0.319 ± 0.075	0.815	0.804	1.619
KUS25	23°59′21.6″ N	89°05′03.7″ E	0.314 ± 0.148	0.803	0.792	1.595
AVERAGE			0.250 ± 0.093	0.638	0.629	1.267
MIN			0.077 ± 0.036	0.196	0.194	0.390
MAX			0.494 ± 0.211	1.262	1.244	2.506

with radon emitting mineral elements, lower radon concentration values in surface water are predicted [24,51]. The total annual effective dose for river water ranged from 0.390 μSv/y to 2.506 μSv/y with an average of 1.267 μSv/y. The calculated dose values are well below the annual effective dose of 100 μSv/y recommended by WHO [1,4,18,45]. The spatial variation of radon concentration in the study area is shown in Fig. 4.

A comparative analysis of the activity concentration of ^{222}Rn in this study with similar literature across the world is given in Table 2. The radon level was found very high in some river water, such as in Sharavathi River [32] located in Karnataka, India (Maximum radon level 9.92 Bq/L), in Balakot and Mansehra Cities [52], Northern Pakistan (Maximum radon level 11.79 Bq/L) and in Gold and Bismuth mining area [28], Kwara State, Nigeria (Maximum radon level 24.71 Bq/L). K.M. Rajashekara [32] explained that the reason for higher radon concentration in Sharavathi river in Karnataka, India, may be attributed to the geology of the region, which consists of gneisses complex, which forms the basement full of relicts of high-grade metamorphic rocks, Archean granitic gneisses which contain higher concentrations of ^{226}Ra and other radionuclides belonging to the uranium and thorium series. High radon concentration was found in the earthquake-affected areas of northern Pakistan [52], and surface water samples were collected from the fault zone of the Balakot and Mansehra regions. From the geology of the studied area, it was clear that the area was rich with metamorphic and sedimentary rocks, which consist of gneiss, gneissose schist, and granitoid schist; shales and some limestone also occur occasionally in the pine zone of the study areas. These rocks contain uranium-bearing minerals, a source of radon emanation. The Gold and Bismuth mining sites situated in

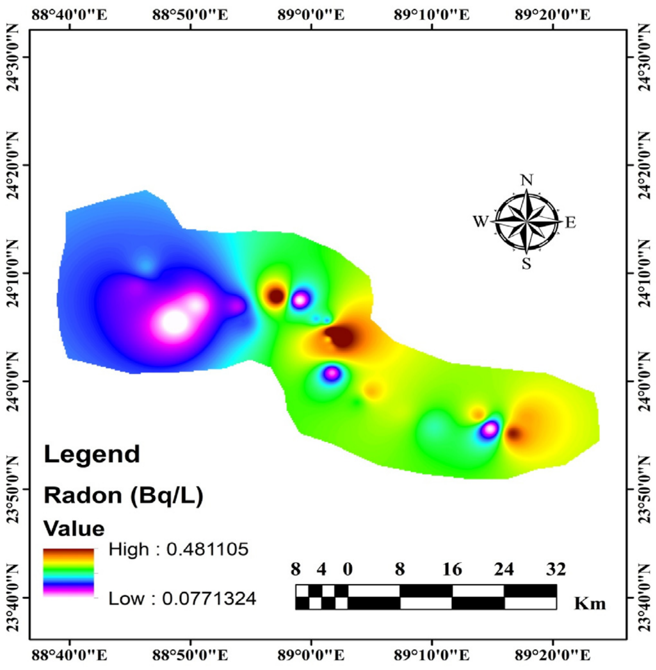

Fig. 4. Spatial variation of radon concentration in the study area.

Kwara state, Nigeria are underlain by basement complex rocks represented by phyllites, gneisses, granodiorites, granites, schists and pegmatite [28], which was the main reason for the high radon level. Nevertheless, the geological map of the Padma river shows that there are no volcanic areas or mountains around this river, and neither any mining site nor the study area was rich with metamorphic and sedimentary rocks. Geologically, the Padma River in the study area consists of mainly riverine alluvial clay, silt, very fine to coarse sand, and gravels of Holocene age. These were the significant reasons for the low radon level in this Padma river water. Additionally, because of the close geological coherence, the result of this study is in close agreement with the previous research carried out in the different river surface waters of the world, such as in Hemavathi river (average radon level 0.67 Bq/L), Kali river (average radon level 0.63 Bq/L) located in Karnataka, India [32,53]; Khasa river (average radon level 0.1575 Bq/L) in Kirkuk City, NE Iraq [54]; Yesihrmak river (average radon level 0.52 Bq/L) in Amasya city, Turkey [53]; Cubatao river (average radon level 0.5 Bq/L) in Santos region, Brazil [55].

7. Conclusion

The present study determined, for the first time, the concentrations of radon in the Padma River water samples collected from the nearby region of the Rooppur Nuclear Power Plant, and then evaluated the associated effective doses via ingestion and inhalation pathways. Radon in all water samples was below the recommended limits of USEPA and WHO, and the associated effective doses were also below the recommended limit by WHO. Although the radiological hazard due to radon in the Padma River water is within safety limits, it cannot be neglected because according to Linear No Threshold Model (LNT) model, there is no threshold for cancer occurrence-even for low doses, there is risk of cancer.

Table 2
Worldwide comparison of radon (Rn-222) concentration in river surface water samples.

Sl.	Region of study		Radon Concentration (Bq/l)		Methodology	Characteristics of the studied area	Ref
			Range	Mean			
1	Karnataka, India	Hemavathi River	0.20–1.60	0.67	$RADH_2O$	Granitic gneisses and schists.	[56]
		Kali River	0.16 to 1.79	0.63	Alpha Guard	Pre-Cambrian gneisses, granites, granite, gneisses, schists, and charnockite.	[32]
		Sharavathi River	1.19 to 9.92	5.11	Alpha Guard	Greywacke, dolomite, quartzite, metavolcanics, laterites, tonalitic gneisses and local ferruginous cherts	[32]
2	Khasa River in Kirkuk city, NE Iraq		0.035–0.359	0.1575	$RADH_2O$	Khasa River mixed with the sewage that comes from Kirkuk City- the richest city with crude oil in the world.	[54]
3	Yesihrmak River, Amasya city, Turkey		0.28 to 1.08	0.52	Vacuum Water Degassing System and Radiation Monitor	Yesihrmak River water (surface) in the center of the city of Amasya in Turkey	[53]
4	Santos region, Brazil	Cubatao river	0.43 to 0.56	0.50	Nuclear track detectors	The Santos region hosts the largest fertilizer plants in Brazil.	[55]
		Jurubatuba river	–	2.4			
		Quilombola river	–	1.48			
5	NorthTransylvania, Romania		0.9–4.5	2.0	LUK-VR (Lucas cell)	North Transylvania mainly corresponds to a post-tectonic depression surrounded by the Alpine chain of the Carpathians.	[57]
6	The western part of Egypt		0.13–3.90	1.74	nuclear track detectors	Desert	[58]
7	The north-eastern region of Poland		Max-9.968	3.39	Liquid scintillation counter	Low-Triassic, low-Jurassic, and middle Devonian levels.	[59]
8	Southwest Coastal Region of Peninsular Malaysia		1.2–9.63	5.04	$RADH_2O$	Triassic, dominated by sedimentary rocks.	[24]
9	Balakot and Mansehra Cities, Northern Pakistan		4.99–11.79	8.31	LUK-WG- 1001 system (Lucas cell)	Metamorphic and sedimentary rocks consist of gneiss, schist and granitoid schist.	[52]
10	Gold and Bismuth Mining area, Kwara State, Nigeria		16.23 ± 3.45 –24.71 ± 4.51	19.14 ± 3.98	$RAD\text{-}H_2O$	Basement complex rocks are represented by phyllites, gneisses, granodiorites, granites, schists and pegmatites	[28]
11	Padma river, Bangladesh (Current Study)		0.077 ± .036 –0.494 ± .211	0.25 ± 0.093	$RAD\text{-}H_2O$	Riverine alluvial clay, silt, very fine to coarse sand and gravels of the Holocene age	

Besides this, Bangladesh has no national safety limit for the radon in water. Therefore, the measured data is useful for future perspective, especially in the post-commissioning era of the RNPP.

A few recommendations are proposed to mitigate the health hazards arising from radon.

- The river water should be treated before consumption. The easiest, economical, and most effective method is to simply agitate the water from one container to another, removing most of the radon in the water.
- Storing water in standard lidless containers before consumption releases radon gas into the air by natural decay.
- Frequent radon monitoring should be carried out after the Rooppur Nuclear Power Plant starts its operation to ensure radiological protection of the nearby population.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors like to thank Albert Joydhar, Senior Scientific Assistant, Health Physics Division, Atomic Energy Centre Dhaka for helping in collection of water sample.

References

[1] S. Rani, S. Kansal, A.K. Singla, R. Mehra, Radiological risk assessment to the public due to the presence of radon in water of Barnala district, Punjab, India, Environ. Geochem. Health 43 (12) (2021) 5011–5024, https://doi.org/10.1007/s10653-021-01012-y.

[2] Y. Narayana, H.M. Somashekarappa, N. Karunakara, D.N. Avadhani, H.M. Mahesh, K. Siddappa, Natural radioactivity in the soil samples of Coastal Karnataka of South India, Health Phys. 80 (1) (2001) 24–33, https://doi.org/10.1097/00004032-200101000-00006.

[3] D.M. Bonotto, L. Caprioglio, Radon in groundwaters from Guarany aquifer, South America: environmental and exploration implications, Appl. Radiat. Isot. 57 (6) (2002) 931–940, https://doi.org/10.1016/S0969-8043(02)00230-0.

[4] T. Thumvijit, et al., Identifying indoor radon sources in Pa miang, chiang mai, Thailand, Sci. Rep. 10 (1) (2020) 1–14, https://doi.org/10.1038/s41598-020-74721-6.

[5] UNEP, United Nations Scientific Committee on the Effects of Atomic Radiation - Radiation Effects and Sources, 2016.

[6] R.D. Evans, Radium in man, Health Phys. 27 (5) (1974) 497–510, https://doi.org/10.1097/00004032-197411000-00010.

[7] N.F. Salih, Determine the contaminations of radon in the drinking water using NTDs (CR-39) and RAD7 detectors, Arabian J. Sci. Eng. 46 (6) (2021) 6061–6074, https://doi.org/10.1007/s13369-020-05267-y.

[8] H.L. Kusnetz, Radon Daughters in Mine Atmospheres —a field method for determining concentrations, Am. Ind. Hyg. Assoc. Q 17 (1) (1956) 85–88, https://doi.org/10.1080/00968205609344380.

[9] S.S. Althoyaib, A. El-Taher, Natural radioactivity measurements in groundwater from Al-Jawa, Saudi Arabia, J. Radioanal. Nucl. Chem. 304 (2) (2015) 547–552, https://doi.org/10.1007/s10967-014-3874-7.

[10] S. Sharma, V. Duggal, R. Mehra, A. Rani, Radon concentration in groudwater and associated effective radon concentration in groudwater and associated effective dose assessment in, Int. J. Innov. Res. Sci. Eng. (May) (2017) 69–78.

[11] M. Shamsaddini, A. Negarestani, M. Malakootian, N. Javid, Study of radon concentration of drinking water sources in adjacent areas of Sabzevaran fault, J. Radioanal. Nucl. Chem. 326 (2) (2020) 1437–1446, https://doi.org/10.1007/s10967-020-07426-9.

[12] WHO, Indoor Radon a Public Health Perspective 110 (2007).

[13] L. Martins, A. Pereira, A. Oliveira, L.F.S. Fernandes, F.A.L. Pacheco, A new framework for the management and radiological protection of groundwater resources: the implementation of a Portuguese Action Plan for Radon in drinking water and impacts on human health, Water (Switzerland) 11 (4) (2019), https://doi.org/10.3390/w11040760.

[14] S. Nazir, S. Simnani, B.K. Sahoo, R. Mishra, T. Sharma, S. Masood, Monitoring geothermal springs and groundwater of Pir Panjal, Jammu and Kashmir, for radon contamination, J. Radioanal. Nucl. Chem. 326 (3) (2020) 1915–1923, https://doi.org/10.1007/s10967-020-07451-8.

[15] S.M. Abdallah, R.R. Habib, R.Y. Nuwayhid, M. Chatila, G. Katul, Radon measurements in well and spring water in Lebanon, Radiat. Meas. 42 (2) (2007) 298–303, https://doi.org/10.1016/j.radmeas.2006.11.004.

[16] N. Ali, E.U. Khan, P. Akhter, F. Khan, A. Waheed, Estimation of mean annual effective dose through radon concentration in the water and indoor air of Islamabad and Murree, Radiat. Protect. Dosim. 141 (2) (2010) 183–191, https://doi.org/10.1093/rpd/ncq160.

[17] C. Tansi, A. Tallarico, G. Iovine, M. Folino Gallo, G. Falcone, Interpretation of radon anomalies in seismotectonic and tectonic-gravitational settings: the south-eastern Crati graben (Northern Calabria, Italy), Tectonophysics 396 (3–4) (2005) 181–193, https://doi.org/10.1016/j.tecto.2004.11.008.

[18] N. Ahmad, J. Rehman, J. ur Rehman, G. Nasar, Assessments of 226Ra and 222Rn concentration in well and tap water from Sik, Malaysia, and consequent dose estimates, Hum. Ecol. Risk Assess. 25 (7) (2019) 1697–1706, https://doi.org/10.1080/10807039.2018.1559034.

[19] A.B. Tanner, Radon Migration in the Ground: a Supplementary Review, U.S. Department of Energy, 1980.

[20] I.R. Ajayi, O.O. Kuforiji, Natural radioactivity measurements in rock samples of Ondo and Ekiti states in Nigeria, Radiat. Meas. 33 (1) (2001) 13–16, https://doi.org/10.1016/S1350-4487(00)00092-5.

[21] J. Yong, et al., Radon concentration measurement and effective dose assessment in different brands of commercial bottled water produced in China, Water Sci. Technol. Water Supply 20 (5) (2020) 1581–1591, https://doi.org/10.2166/ws.2020.061.

[22] G. Krishan, M.S. Rao, C.P. Kumar, P. Semwal, Radon concentration in groundwater of east coast of West Bengal, India, J. Radioanal. Nucl. Chem. 303 (3) (2015) 2221–2225, https://doi.org/10.1007/s10967-014-3808-4.

[23] J. Yong, Q. Liu, B. Wu, Y. Hu, G. Feng, Assessment of radiation dose hazards caused by radon and its progenies in tap water by the human dosimetric model, J. Water Health 19 (6) (2021) 933–945, https://doi.org/10.2166/wh.2021.113.

[24] N.F. Ismail, S. Hashim, M.S. Mohd Sanusi, A.T. Abdul Rahman, D.A. Bradley, Radon levels of water sources in the southwest coastal region of Peninsular Malaysia, Appl. Sci. 11 (15) (2021), https://doi.org/10.3390/app11156842.

[25] W. Zhuo, T. Iida, X. Yang, Occurrence of 222Rn, 226Ra, 228Ra and U in groundwater in fujian province, China, J. Environ. Radioact. 53 (1) (2001) 111–120, https://doi.org/10.1016/S0265-931X(00)00108-9.

[26] B.C. Shivakumara, M.S. Chandrashekara, E. Kavitha, L. Paramesh, Studies on 226Ra and 222Rn concentration in drinking water of Mandya region, Karnataka State, India, J. Radiat. Res. Appl. Sci. 7 (4) (2014) 491–498, https://doi.org/10.1016/j.jrras.2014.08.005.

[27] UNSCEAR, *Sources and Effects of Ionizing Radiation*, United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes, I, 2000.

[28] M.M. Orosun, T.B. Ajibola, F.C. Akinyose, O. Osanyinlusi, O.D. Afolayan, M.O. Mahmud, Assessment of ambient gamma radiation dose and annual effective dose associated with radon in drinking water from gold and lead mining area of Moro, North-Central Nigeria, J. Radioanal. Nucl. Chem. 328 (1) (2021) 129–136, https://doi.org/10.1007/s10967-021-07644-9.

[29] M.M. Orosun, M.R. Usikalu, K.J. Oyewumi, T.A. Adagunodo, Natural radionuclides and radiological risk assessment of granite mining field in Asa, North-central Nigeria, MethodsX 6 (2019) 2504–2514, https://doi.org/10.1016/j.mex.2019.10.032.

[30] S. Bello, R. Nasiru, N.N. Garba, D.J. Adeyemo, Annual effective dose associated with radon, gross alpha and gross beta radioactivity in drinking water from gold mining areas of Shanno and Bagwai, Kano state, Nigeria, Microchem. J. 154 (2020), 104551, https://doi.org/10.1016/j.microc.2019.104551. October 2019.

[31] E.B. Faweya, O.A. Agbetuyi, A.O. Talabi, T. Adewumi, O. Faweya, Radiological implication of 222Rn concentrations in waters from quarries environs, correlation with 226Ra concentrations and rocks geochemistry, Arabian J. Geosci. 14 (11) (2021), https://doi.org/10.1007/s12517-021-07385-9.

[32] K.M. Rajashekara, Y. Narayana, K. Siddappa, 222Rn concentration in ground water and river water of coastal Karnataka, Radiat. Meas. 42 (3) (2007) 472–478, https://doi.org/10.1016/j.radmeas.2006.12.010.

[33] US EPA, Radon in Drinking Water Regulations, 2012.

[34] M.M. Billah, Mapping and monitoring erosion-accretion in an alluvial river using satellite imagery - the river bank changes of the Padma river in Bangladesh, Quaest. Geogr. 37 (3) (2018) 87–95, https://doi.org/10.2478/quageo-2018-0027.

[35] S. Hassan, a F.M. Akhtaruzzaman, Environmental change detection of the Padma river in the north-western part of Bangladesh using multi-date landsat data, Proc. Int. Conf. Environ. Asp. Bangladesh (October) (2010) 193–195.

[36] A. Islam, Z. Sein, V. Ongoma, M. Islam, M. Alam, F. Ahmed, Geomorphological and land use mapping: a case study of Ishwardi under Pabna district, Bangladesh, Adv. Res. 4 (6) (2015) 378–387, https://doi.org/10.9734/air/2015/14149.

[37] S. De Silva, E. Nigel, R. Wightman, Geotechnical ground investigation for the Padma main bridge, in: IABSE-JSCE Joint Conference on Advances in Bridge Engineering-II, 2010, pp. 427–436.

[38] M.T. Islam, River Channel Migration : a Remote Sensing and Gis Analysis, 2010, ESA Living Planet Symp, 2010. July.

[39] M. A, , et al.Rahman, RIVER SANDS OF BANGLADESH, LAP LAMBERT ACADEMIC PUBL, 2014.

[40] S. Ali, E.M. Limited, S.S. Ahmed, Geochemical Characteristics of Recent Sediments of Channel Bar of the Ganges (Padma) River, Bangladesh, 2019.

December 2021.

[41] J.I.C.A. Jica, Groundwater Modelling of the Proposed Site of Bheramara Power Station and Surrounding Areas, Eng. Assoc. Limited, Dhaka., 2008. Feasibility report.

[42] International Atomic Energy Agency, Guidelines on soil and vegetation sampling for radiological monitoring, Tech. Reports Ser. No. 486 (486) (2019).

[43] DURRIDGE Company Inc., RAD H 2 0 User Manual (2011) 1–29, 978.

[44] H. Yakut, E. Tabar, Z. Zenginerler, N. Demirci, F. Ertugral, Measurement of 222Rn concentration in drinking water in Sakarya, Turkey, Radiat. Protect. Dosim. 157 (3) (2013) 397–406, https://doi.org/10.1093/rpd/nct157.

[45] K.M. Opondo, K. Sims, Electronic radon detector user manual [Online]. Available: https://durridge.com/documentation/RAD7.Manual.pdf, 2012.

[46] U. EPA, Superfund program representative sampling guidance, Program 4 (1995) 1–58. December.

[47] UNSCEAR, SOURCES AND EFFECTS OF IONIZING RADIATION, United Nations Scientific Committee on the Effects of Atomic Radiation, I, c, 2010.

[48] I. Opoku-Ntim, O. Gyampo, A.B. Andam, Risk assessment of radon in some bottled water on the ghanaian market, Environ. Res. Commun. 1 (10) (2019), 105001, https://doi.org/10.1088/2515-7620/ab4568.

[49] WHO, Guidelines for Drinking-Water Quality, fourth ed., incorporating the 1st addendum, 2017.

[50] S. Şahin Bal, E. Tanrıverdi, S. Yalçın, M. Doğru, F. Özbey, The radon concentrations of some waters in Bitlis (Turkey) and their dose estimates, Environ. Dev. Sustain. 23 (12) (2021) 17650–17667, https://doi.org/10.1007/s10668-021-01404-1.

[51] G.M. Shilpa, B.N. Anandaram, T.L. Mohankumari, Measurement of 222Rn concentration in drinking water in the environs of Thirthahalli taluk, Karnataka, India, J. Radiat. Res. Appl. Sci. 10 (3) (2017) 262–268, https://doi.org/10.1016/j.jrras.2017.05.007.

[52] F. Khan, N. Ali, E.U. Khan, N.U. Khattak, K. Khan, Radon monitoring in water sources of Balakot and Mansehra cities lying on a geological fault line, Radiat. Protect. Dosim. 138 (2) (2009) 174–179, https://doi.org/10.1093/rpd/ncp214.

[53] F. Oner, H.A. Yalim, A. Akkurt, M. Orbay, The measurements of radon concentrations in drinking water and the Yeşilirmak River water in the area of Amasya in Turkey, Radiat. Protect. Dosim. 133 (4) (2009) 223–226, https://doi.org/10.1093/rpd/ncp049.

[54] D.O. Kareem, A.A. Ibrahim, O.S. Ibrahiem, Heavy metal and radon gas concentration levels in Khasa River in Kirkuk City (NE Iraq) and the associated health effects, Arabian J. Geosci. 13 (19) (2020), https://doi.org/10.1007/s12517-020-06037-8.

[55] A.L. Marques, W. Dos Santos, L.P. Geraldo, Direct measurements of radon activity in water from various natural sources using nuclear track detectors, Appl. Radiat. Isot. 60 (6) (2004) 801–804, https://doi.org/10.1016/j.apradiso.2004.01.015.

[56] K.C. Shivanandappa, N. Yerol, Radon concentration in water, soil and sediment of Hemavathi River environments, Indoor Built Environ. 27 (5) (2018) 587–596, https://doi.org/10.1177/1420326X16688522.

[57] D.C. Nita, M. Moldovan, T. Sferle, V.D. Ona, B.D. Burghele, Radon concentrations in water and indoor air in North - west regions of Romania, Rom. Rep. Phys. 58 (SUPPL) (2013) 2016–2020.

[58] A. Hussein, Evaluation of the radiation dose from radon ingestion from different types of drinking water samples in Egypt using nuclear track detectors (LR-115 Type II), Radiat. Protect. Environ. 42 (4) (2019) 168, https://doi.org/10.4103/rpe.rpe_21_19.

[59] M. Zalewski, M. Karpiñska, Z. Mnich, J. Kapała, P. Zalewski, Study of 222Rn concentrations in drinking water in the north-eastern hydroregions of Poland, J. Environ. Radioact. 53 (2) (2001) 167–173, https://doi.org/10.1016/S0265-931X(00)00122-3.