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^{222}Rn in selected waters sources from Quang Nam - Da Nang region - Central part of Vietnam

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ABSTRACT

This paper presents the radon concentrations of forty-eight samples collected from lakes, streams and rivers as surface water, from dug well as ground water and from boreholes and thermal waters as underground waters in the Da Nang – Quang Nam, central part of Vietnam. The measured radon concentrations varied from 0.265 (in lake water) to 107 Bq L^{-1} (in underground water) with the following trend from the lowest to the highest: ^{222}Rn in lakes<^{222}Rn in rivers<^{222}Rn in stream<^{222}Rn in dug wells<^{222}Rn in thermal waters<^{222}Rn in drilled wells. Overall, the average ^{222}Rn concentration in groundwater is twelve times higher than that in the surface water.

Assuming that each person drinks 2.10^{-3} m^3 d^{-1} and uses six cubic meters for washing purposes per month, the estimated total annual effective dose due to ingestion and inhalation of radon from the studied water samples ranges from 1.3 to 541 μSv y^{-1} for adults; from 1.2 to 479 μSv y^{-1} for children; and from 2.1 to 838 μSv y^{-1} for infants.

1. Introduction

Water pollution is one of the most pressing issues today, with various pollutants encompassing nutrient overload, micro-plastics, organic compounds, heavy metals, run off from industrial outputs, and radionuclides in water (Lu et al., 2020). Radionuclide contamination in water has emerged as one of the serious concerns for ecosystems and human health due to its toxicity and potential mutagenesis. There are three natural radon isotopes ^{222}Rn, ^{220}Rn and ^{219}Rn with half-life ($T_{1/2}$) of 3.825 days, 54.5 s and 3.92 s respectively. All of them are alpha emitters, but due to the longest decay period, the ^{222}Rn and its progeny are considered the most hazardous (Iná et al., 2017). Therefore, in this paper the word "radon" refers only to the ^{222}Rn isotope.

Radon is a natural radionuclide and colorless, odorless gas and is easily soluble in water (Iná et al., 2017; Jean et al., 2018; Ramola, Choubey, Negi, Prasad, & Prasad, 2008; Sanjon et al., 2019). Previous studies have demonstrated ^{222}Rn activity to be the highest in groundwater among all progenies of the ^{238}U decay chain (Baskaran, 2016; Carvalho et al., 2014; Hess, Michel, Horton, Prichard, & Conglio, 1985; Loomis, Watson, & Crawford-Brown, 1988). Its concentration depends on various factors such as aquifer characteristics, water-rock interactions, residence time of water in aquifers, geology, quantity of radium and so on (Choubey, Sharma, & Ramola, 1997; Moore, 1999; Nikolopoulos, Vogiannis, & Louizi, 2009). On the other hand, surface water, such as lakes or rivers, are also of particular interest due to the hydrological processes and direct influence on ^{222}Rn (Al- et al., 1999;

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Fonollosa, Penalver, Borrull, & Aguilar, 2016; Hammond, Simpson, & Mathieu, 1977; Oner, Yalim, Akkurt, & Orbay, 2009; Schubert, Schmidt, Paschke, Lopez, & Balcázar, 2008). Exposure to high radon content in drinking water can cause undesirable side effects for public health, over a long period of time (Duggal, Sharma, & Mehra, 2020). Consumption of water with radon could lead to potential risks such as cancer or damage to the gastric mucosa (Duggal et al., 2020; Loomis et al., 1988; World Health Organization, 2009). The maximum allowable activity concentration of radon (^{222}Rn) in drinking water recommended by WHO is 100 Bq L^{-1} (World Health Organization, 2022). In recent times, as an effort to identify and minimize the radon impact on public health, many studies concerning the presence and behavior of ^{222}Rn in various water sources have been published (Duggal et al., 2013, 2020; Fonollosa et al., 2016; Moreno et al., 2014, 2018; Qadir, Asaad, Qadir, Ahmad, & Abdullah, 2021; Ró et al., 2008; Seminsky et al., 2019; Telahigue, Agoubi, Souid, & Kharroubi, 2018; Tsunomori, Shimodate, Ide, & Tanaka, 2017). Regarding to the radiological safety, the radionuclides in each kind of drinking water resource should be analyzed, including paying specific attention to radon. In Vietnam, studies dealing with environmental pollution or water contamination is alluring interest to the scientific community (Nagy et al., 2001; Owada et al., 2007; Tran et al., 2014). However, studies on radioactive contamination in aquatic bodies are scarce.

Due to the uncontrolled exploitation as well as improper usage of water by humans, pollution can be often observed in drinking water resources, especially in surface water bodies, and rapidly refreshing aquifers.

Apart from this, the population growth and rapid economic development had led to an increased demand for groundwater and drinking water sources. The provinces of Quang Nam–Da Nang, located in the central part of Vietnam, are considered as the country's engines of growth. This area is characterized by tectonic activity, the presence of many faults, and geothermal masses (Nagy et al., 2001; Owada et al., 2007; Tran et al., 2014). In consequence, there is emergence of groundwater and thermal water can be heated by geothermal masses. Radon in water is related principally to the host rock formation (Duggal et al., 2020; Kawabata et al., 2020; Moreno et al., 2018; Sukanya, Noble, & Joseph, 2021; Telahigue et al., 2018). In addition to this, the Quang Nam province gives home to some uranium and rare earth mines with a relatively large area (Cao, Tran, & Phung, 2005; Lien & Van, 2011; Nguyen, 2019). This could release a large amount of radionuclides into the aquatic environment. Therefore, the aims of the present study are as follows: (1) provide a database of ^{222}Rn concentration in selected water resources in the area, (2) identify the relationship between ^{222}Rn characteristics and underlying geological factors (3) estimate the annual effective dose to inhabitants using the water from the studied water bodies in the area.

2. Description of the study area, sampling, and measurements

2.1. Geology setting

Quang Nam and Da Nang provinces belong to the Central part of Vietnam (Fig. 1). In the region, there is Truong Son belt in the West, the upland area in the middle and a lowland in the East. The Central part of Vietnam is characterized by the strong uplift of the Kon Tum-Da Lat block and the deep sinking of the continental shelf (Hả et al., 2020). There are many faults and the area belongs principally into four extension systems: sub-longitude, meridian, northeast-southwest, and northwest-southeast. There are two main fault systems in the study areas, which have directions NW-SE and SW-NE (Fig. 1).

In the Quang Nam–Da Nang provinces, there is a presence of formations from the Archaic up to the Quaternary epoch. Based on the objectives set for the present study, our discussion is limited only to the water hosting formation or the suits especially related to water and radon. The principal water hosting bodies are as follows: The Holocene formation diluvia occurs as the river deltas with sand, mud and gravel. The main ions in the Holocene water are HCO_3^-, Cl^-, Ca^{2+} and Na^+ with mineralization from a few tens mg to several hundred mg per liter (Nguyen, 1992). Water in the Holocene extrusive basalt formations occurs in the fractures and its mineralization ranges from 0.2 to 0.4 g L^{-1} (Nguyen, 1992). The Pleistocene water hosting formation is distributed in all the regions. The main components of the sediment formation include tiny grain sands with quartz. The mineralization of the water in

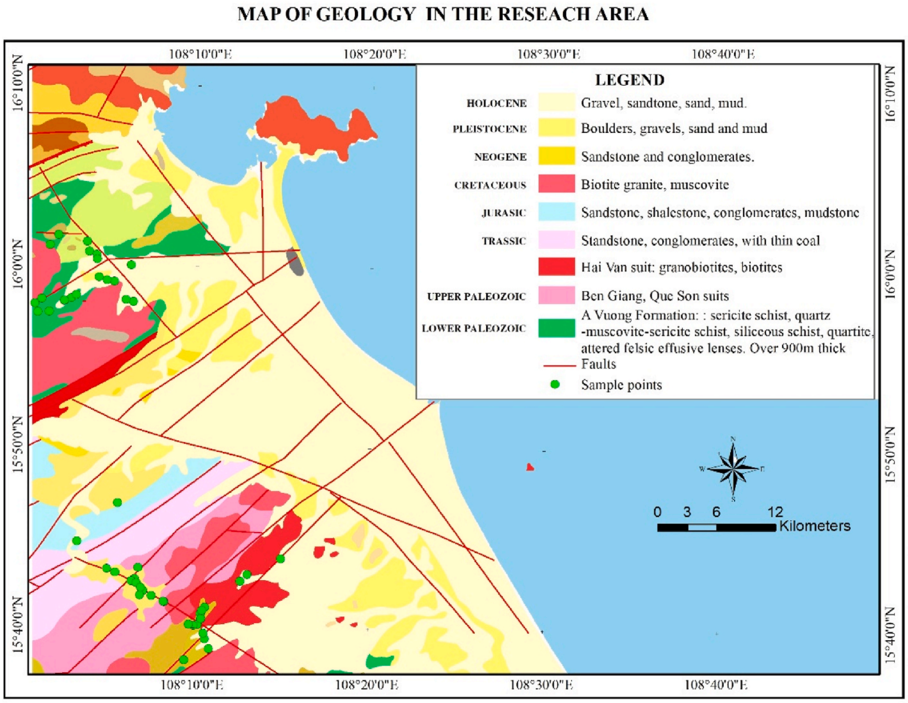

Fig. 1. The geological sketch of the studied area modified from (Hải et al., 2020, Doung et al. 2023).

the Pleistocene sediments range from a few tenths of a gram to above 2 g per liter, where the ions HCO_3^-, Cl^-, Ca^{2+} and Na^+ are prevailing (Nguyen, 1992). Similar to the Holocene formations, the water occurs in the fractures of the Pleistocene extrusive basalts, and mineralization is lower than 0.5 g L^{-1} (Nguyen, 1992). The water hosting Neogene sedimentary formation in the Quang Nam province consists of mudstone and sandstone with gravel and organic material. The water in this formation is often brackish indicating the immigration of the sea water. The Mesozoic and Paleozoic formations occur in the depth of a few hundred meters below the surface and consist of dense sandstone, conglomerates and some extrusive rocks as andesite, tuff and rhyolite. The formations are regarded as limited water hosting beds. The lithology of the potential water hosting formation in the study region is shown in Fig. 2.

In the Quang Nam – Da Nang region there are some intrusive metamorphic suits. The first is the metamorphic suit with two mica gneiss granite, gneiss biotite with muscovite. The second is the Paleogene biotite granite, two mica granite and aplite granite. The intrusive formations are rather poor in water.

2.2. Sampling and measurement

The sampling profiles were selected based on four major fault zones including F, S, H and K (Fig. 3). In these zones water occurs in the underground fractures and pores of the formation. The profiles F and S are located mainly in the Hoa Vang district, Da Nang, while profiles H and K are in two adjacent districts, Que Son and Nong Son in Quang Nam province. The 48 sampling points are located in the four mentioned profiles. The water samples were collected from rivers, lakes, streams, dug wells, drilled wells and thermal water sources. All the water sources from where the samples were taken, are currently consumed as drinking water. The temperature (T), acidity-basicity indicator (pH), redox potential (Eh), total dissolved solids (TDS), and electrical conductivity (EC) of the studied waters were measured in situ during sampling using Hanna instruments model HI8314 and HI2003-02®.

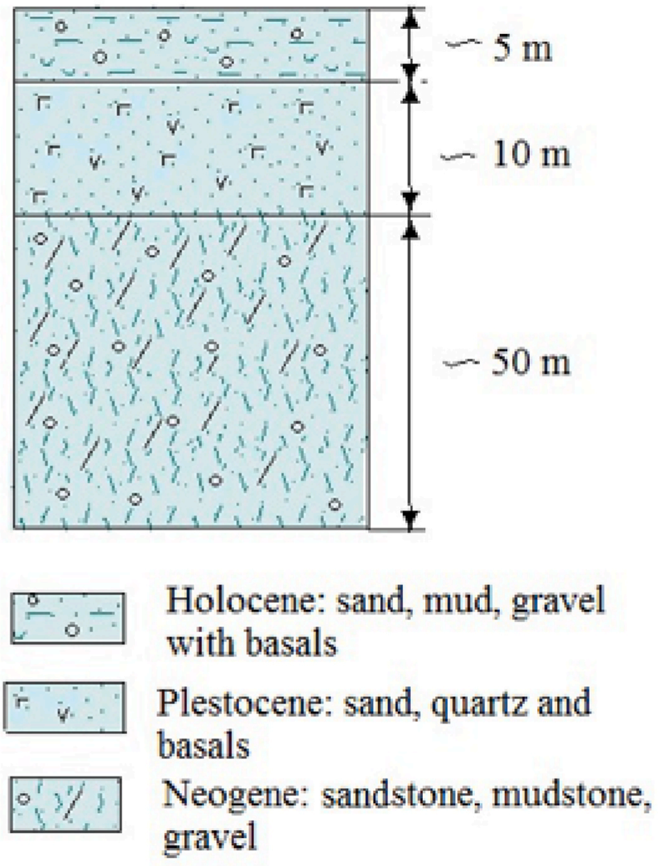

Fig. 2. The lithology of the main water bearing formations.

The sampling procedure for determining of the ^{222}Rn concentration in water was performed following previously well described procedures (Abdallah, Habib, Nuwayhid, Chatila, & Katul, 2007; Duggal et al., 2020; Moreno et al., 2018; Qadir et al., 2021). The ^{222}Rn activity concentration was measured directly by a RAD 7 radon meter manufactured by Durridge Company Inc® (USA). For the measurement of ^{222}Rn concentration in water, the needed volume of water sample was 250 mL for ^{222}Rn concentration below 100 Bq L^{-1} and 40 mL samples were used for higher ^{222}Rn activity. The RAD 7 has a measuring range from 0.1 to 200000 pCi/L and accuracy of 0.1 pCi L^{-1}. The energy range is from 6 to 9 MeV which will only be conducted for ^{222}Rn progenies. To get an accurate performance, the experimental procedure was conducted according to the manufacturer's instructions (DURRIDGERAD, 2018). This procedure includes the calibration technique, checking and making sure that the optimize humidity throughout the measurement chamber. The temperature needs to be controlled to avoid affecting the solubility of the gas. The calibration was performed by the manufacturer for the new driver.

2.3. Annual effective dose

The effective annual doses to humans upon exposure to Rn following ingestion and inhalation was calculated using the measured Rn concentrations and the UNSCEAR formulas assessing the two pathways of exposure from water borne radon (Duggal et al., 2020; UNSCEAR, 2000).

$$AED_{total} = AED_{ing} + AED_{inh} = (C_{Rn} \times D_{f1} \times A_i) + (C_{Rn} \times R \times F \times D_{f2} \times T) \quad (1)$$

where AED_{total}-the total effective annual dose due to absorption of Rn through drinking water consumption and inhalation of radon gas released from the water; AED_{ing} - the annual effective dose due to absorption of Rn by drinking water; AED_{inh} - the annual effective dose due to inhalation of radon released from the water; C_{Rn} - average activity concentration of ^{222}Rn in water (Bq L^{-1}); D_{f1}- ^{222}Rn dose conversion factor (UNSCEAR, 2000), for adults (≥17 years) is 3.5×10^{-6} mSv Bq^{-1}; for children (from 7 to 12 years) - 5.9×10^{-6} mSv Bq^{-1} and for infants between 1 and 2 years - 23×10^{-6} mSv Bq^{-1}; A_i is the annual water consumption with assumption, for adults - 730 L; for children - 330 L and for infants- 230 L. R is the coefficient expressing the ^{222}Rn released from the water into the air and equals to 10^{-4}; F is the equilibrium coefficient between ^{222}Rn and its progeny equal to 0.4 for indoor air; D_{f2}: ^{222}Rn dose conversion factor 9×10^{-6} mSv Bq^{-1} h^{-1} m^3, and T is the annual average time of each person spent indoors 7000 h per year (UNSCEAR, 2000).

3. Result and discussions

3.1. Activity concentration

The measured ^{222}Rn activity and physical parameters (pH, EC, TDS, Eh and depth) of the studied waters are shown in Table 1 and Appendix I respectively. Most of the surface waters were near neutral, excluding the waters from K8 and S8 with pH = 8.9 and 8, while mildly acidic to neutral water was found in dug well waters (4.97–7.09) and mildly acidic to slightly alkaline water was observed in borehole water (5.11–9.52) and alkaline thermal water (8.41–9.87). Surface water (rivers, lakes, and streams) had lower mean EC and TDS values (56.38 μS cm^{-1} and 30 ppm) than groundwater (239 μS cm^{-1} and 120 ppm). The Eh in surface water is higher than that in groundwater, with values of 88.9 and 44.7 mV, respectively. Most of the groundwater samples were taken from depths less than 70 m below the surface.

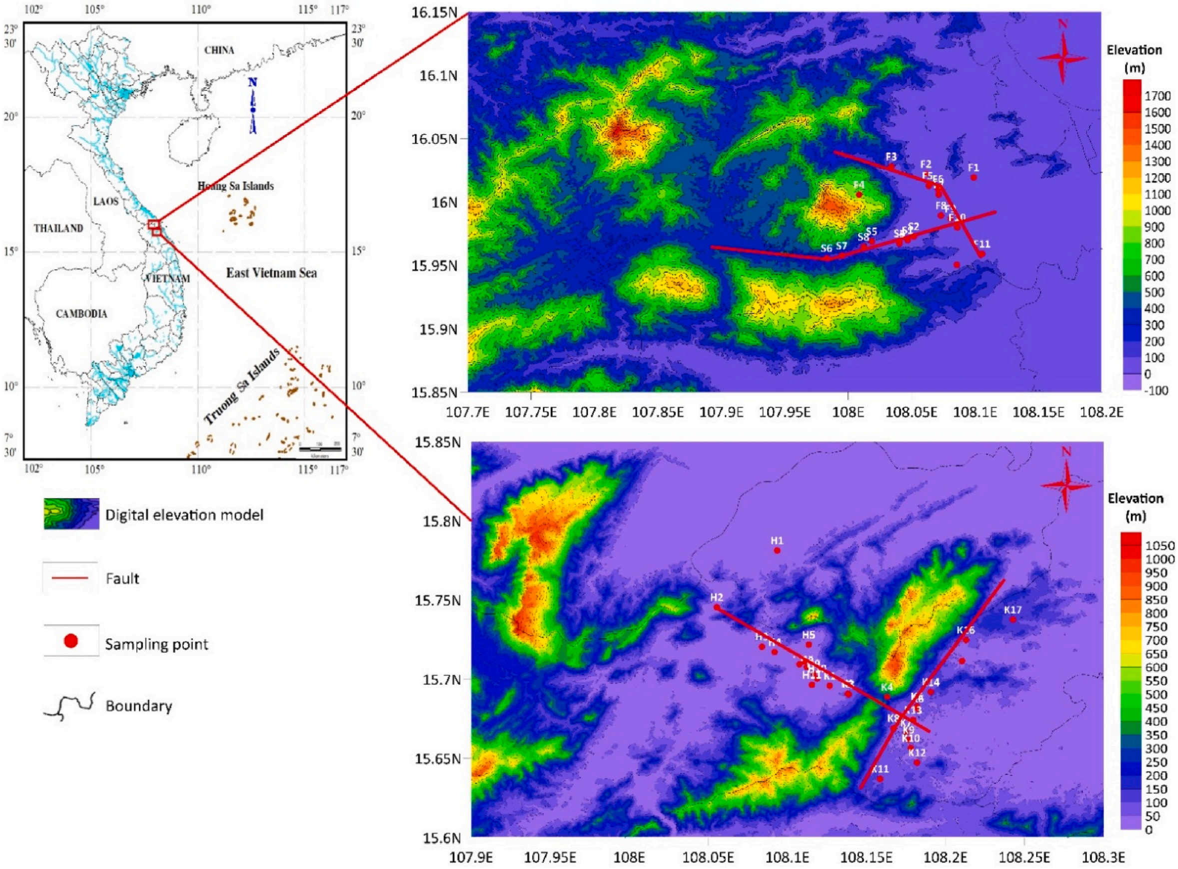

Fig. 3. The location of Quang Nam and Da Nang provinces in Vietnam (a) and the sampling points on a morphology map with the main faults in the studied region.

The data in Table 1 shows that, except for the K10 point, where the Rn content is 107 Bq L^{-1}, the ^{222}Rn concentrations were lower than the WHO recommended upper reference level for drinking water - 100 Bq L^{-1} (World Health Organization, 2022). The average ^{222}Rn activity in drill well water (46.9 Bq L^{-1}) and thermal water (24.7 Bq L^{-1}] is eight and fourteen times higher than that in surface waters – lake and stream (3.1 Bq L^{-1}) respectively (Table 1). There are broad ranges of ^{222}Rn activity variation in both mentioned types of water, from 0.3 to 19.6 Bq L^{-1} for surface and from 1.2 to 107 Bq L^{-1} for underground water. Such high ^{222}Rn in K10 can be related to the tectonic trap of radon. The results of our study were consistent with the findings of studies of other scientists (Moreno et al., 2018; Abu-et al., 2018; Shu'aibu, Khandaker, Baballe, Tata, & Adamu, 2021). The contents of radon in groundwater are often higher than that in surface water, since ^{222}Rn released from the rocks into the water during its migration in the underground environment (Akar et al., 2012; Srinivasa, Rangaswamy, Suresh, Reddy, & Sannappa, 2018).

The average ^{222}Rn activities in the studied waters follows the order as: $^{222}\text{Rn}_{\text{lakes}} < {}^{222}\text{Rn}_{\text{rivers}} < {}^{222}\text{Rn}_{\text{streams}} < {}^{222}\text{Rn}_{\text{dug wells}} < {}^{222}\text{Rn}_{\text{thermal waters}} < {}^{222}\text{Rn}_{\text{drilled wells}}$. Radon in groundwater and thermal water are mainly related to the geology of the host formation and the tectonics of the region (Kawabata et al., 2020; Moreno et al., 2018; Sukanya et al., 2021; Telahigue et al., 2018; Vinson, Vengosh, Hirschfeld, & Dwyer, 2009). The lowest ^{222}Rn content is recorded in lake water (surface water), followed by rivers and stream water. A similar trend was observed in relation to ^{222}Rn's contact with the soil and rock. An assumption could be made that the limited contact of water in case of stagnant bodies of lake with soil or rock led to the lowest ^{222}Rn content. In the case of groundwater, the highest ^{222}Rn activity was found in well water and the least in thermal water. Water temperature is one of the factors governing ^{222}Rn release from water. Radon in water releases rapidly at higher temperatures (Sukanya et al., 2021; UNSCEAR, 2000; Wilhelm, Battino, & Wilcock, 1977). The coefficients of the linear correlation between the measured parameters of the studied waters are shown in Table 2. Since the study waters are from different kinds of sources, there is no correlation excluding water mineralization (TDS) and electrical conductivity (EC). The correlation coefficient between EC and TDS is equal almost to one, which shows the correlation between the electricity conduction and the water mineralization. This may also reflect the operating principles of the HI2003-02 device, however it must be noted that the correlation between TDS and EC is not always linear, and the relationship depends on water salinity and material contents (Rusydi, 2018).

The data in Table 2 show that excluding depth there is no correlation between ^{222}Rn and the other physical and chemical parameters of water. This fact can be explained, since Rn is gas, which is not related to the mineralization, Eh and pH of water. The Rn content in water is related mostly to the rock formation and the discussion present in the below section. The correlation coefficient between ^{222}Rn and depth is highest (0.61). This relation is related to the direct interaction between water and rock formation.

3.2. Influence of geological factors

^{222}Rn activity in groundwater is variable from place to place (Sukanya et al., 2021). Numerous studies suggest that geology is the most important factor controlling ^{222}Rn concentration in groundwater (Friedmann et al., 2017; Scheib, Appleton, Miles, & Hodgkinson, 2013; Sukanya et al., 2021). In this study, the highest level of ^{222}Rn in groundwater was found at point K10, the point in Que Son district, Quang Nam, where there are Late Paleozoic - Early Mesozoic gneiss intrusive blocks. This intrusive rock is usually rich in natural

Table 1

Measured activity concentrations of ^{222}Rn and calculated annual effective doses for people resulted by consumption and inhalation of Rn released from the waters.

Reservoir	sample	^{222}Rn [BqL^{-1}]	AEDing [μSv y^{-1}]			AEDinh	Total annual effective dose [μSv y^{-1}]		
			adults	child	infant		adults	child	infants
Lake	F1	3.6	9.15	7.07	19.2	9.15	18.3	16.2	28.4
Lake	F12	0.7	1.80	1.39	3.78	1.80	3.60	3.19	5.58
Lake	H1	0.3	0.86	0.67	1.81	0.86	1.72	1.53	2.67
Lake	H2	1.7	4.30	3.33	9.03	4.30	8.61	7.63	13.3
Lake	H5	0.7	1.75	1.35	3.67	1.75	3.50	3.10	5.42
Lake	K5	0.8	2.12	1.64	4.46	2.12	4.24	3.76	6.58
Lake	K8	0.3	0.67	0.52	1.40	0.67	1.33	1.18	2.07
Lake	K11	0.5	1.35	1.05	2.84	1.35	2.71	2.40	4.20
Lake	K16	6.5	16.3	12.6	34.2	16.3	32.6	28.9	50.5
Min		0.3	0.7	0.5	1.4	0.7	1.3	1.2	2.1
Max		6.5	16.3	12.6	34.2	16.3	32.6	28.9	50.5
Aver.		1.7	4.3	3.3	8.9	4.3	8.5	7.5	13.2
Stream	F2	3.1	7.79	6.02	16.3	7.79	15.5	13.8	24.1
Stream	F4	19.6	49.5	38.2	104	49.5	99.0	87.7	153
Stream	F7	5.6	14.0	10.8	29.4	14.0	28.0	24.8	43.4
Stream	S4	1.1	2.89	2.23	6.06	2.89	5.77	5.12	8.95
Stream	S6	1.0	2.43	1.88	5.11	2.43	4.87	4.32	7.54
Stream	S7	3.1	7.90	6.11	16.6	7.90	15.8	14.0	24.5
Stream	S8	2.1	5.26	4.07	11.0	5.26	10.5	9.33	16.3
Stream	K2	6.1	15.3	11.8	32.1	15.3	30.6	27.1	47.4
Stream	K4	0.3	0.79	0.61	1.66	0.79	1.58	1.40	2.45
Stream	K15	1.4	3.64	2.82	7.65	3.64	7.29	6.46	11.3
Min		0.3	0.79	0.61	1.66	0.79	1.58	1.4	2.45
Max		19.6	49.5	38.2	104	49.5	99	87.7	153
Average		4.8	10.9	8.5	23.0	10.9	21.9	19.4	33.9
River	F9	4,0	10.2	7.88	21.4	10.2	20.4	18.8	31.6
River	S3	2.0	5.07	3.91	10.64	5.07	10.1	8.98	15.7
Dig well	F3	1.2	3.04	2.35	6.37	3.04	6.07	5.38	9.41
Dig well	F10	12.5	31.5	24.3	66.1	31.5	63.0	55.8	97.6
Dig well	S1	39.2	98.7	76.2	207	98.7	197	175	306
Dig well	S2	17.0	42.8	33.1	89.9	42.8	85.6	75.9	133
Dig well	H7	41.1	104	80.1	217	104	207	184	321
Dig well	K7	30.4	76.6	59.2	161	76.6	153	136	238
Dig well	K14	9.9	25.0	19.3	52.5	25.0	50.0	44.3	77.5
Min		1.2	3.0	2.3	6.4	3.0	6.10	5.40	9.40
Max		41.1	104	80.1	218	104	207	184	321
average		21.6	54.5	42.1	114	54.5	109	96.6	169
Drilling well	F6	18.9	47.5	36.7	99.8	47.5	95.1	84.2	147
Drilling well	F8	47.9	121	93.3	254	121	242	214	374
Drilling well	H3	18.6	46.8	36.2	98.3	46.8	93.7	83.0	145
Drilling well	H4	49.9	126	97.2	264	126	252	223	390
Drilling well	H6	31.5	79.3	61.2	166	79.3	158	140	245
Drilling well	H8	35.5	89.4	69.1	188	89.4	179	158	277
Drilling well	H10	50.3	126	97.9	266	126	253	224	392
Drilling well	H11	35.7	90.1	69.6	189	90.1	180	159	279
Drilling well	K1	48.9	123	95.3	258	123	246	218	382
Drilling well	K3	26.2	66.1	51.1	138	66.1	132	117	204
Drilling well	K6	38.5	97.0	74.9	204	97.0	194	172	300
Drilling well	K10	107	270	209	567	270	540	479	838
Drilling Wells	K12	56.1	141	109	297	141	283	251	438
Drilling Wells	K13	69.8	176	136	369	176	352	312	545
Drilling Wells	K17	68.9	174	134	364	174	347	308	538
Min		18.6	46.8	36.2	98.3	46.8	93.7	83	145
Max		107	270	209	567	270	541	479	838
average		42.4	118	91,4	248	118	237	210	367
Thermal water	F11	70.5	177	137	373	178	355	314	550
Thermal water	S5	1.3	3.15	2.43	6.61	3.15	6.30	5.58	9.76
Thermal water	H9	9,7	24.4	18.9	51.3	24.4	48.9	43.3	75.8
Thermal water	K9	17.3	43.6	33.7	91.6	43.6	87.2	77.3	135
Min		1.3	3.2	2.4	6.6	3.2	6.3	5.6	9.8
Max		70.5	178	137	373	178	355	315	550
average		24.7	62	48.0	131	62.3	124	110	193
Total	Min	0.26	0.67	0.52	1.4	0.67	1.3	1.2	2.1
	Max	107	270	209	567	270	541	479	838
	Average	21.7	54.6	42.2	115	54.6	109	96.8	169

radionuclides, such as uranium and thorium, and favorably releases ^{222}Rn through a high density of faults and fractures (Ramola et al., 2008; Scheib et al., 2013; Sukanya et al., 2021). In addition, this area is close to the uranium mines in Nong Son district, so naturally high radium concentration ores might be also partially responsible (Cao et al., 2005; Lien & Van, 2011; Nguyen, 2019). The geological structure of studied aquifers has marshy or coastal coal-bearing coarse grain sediments, including aggregate, sandstone, and silt, combined with faults in the northwest-southeast direction. It is favorable for transporting radionuclides in groundwater from the Nong Son to Que Son area. Radon can travel considerable distances through connected porous media such as weathered soil or rubble (Moreno et al., 2018). For surface water, ^{222}Rn

Table 2

The correlation between the ^{222}Rn activity and water parameters.

	Depth (m)	pH	EC (µS cm^{-1})	TDS (ppm)	Temp (^{o}C)	Eh (mV)	^{222}Rn (Bq L^{-1})
Depth (m)	1						
pH	−0.03	1					
EC	0.54	0.42	1				
TDS (ppm)	0.52	0.43	0.99	1			
Temp (^{o}C)	0.05	0.55	0.62	0.62	1		
Eh (mV)	−0.09	−0.74	−0.50	−0.51	−0.68	1	
^{222}Rn (Bq L^{-1})	0.61	−0.22	0.23	0.22	0.11	−0.02	1

is strongly related to climatic factors, geology of the surface soil and rocks, and ^{222}Rn gets exhaled due to open water (Abu-et al., 2018; Shu'aibu et al., 2021). Among the surface water, higher ^{222}Rn activity concentration was recorded in stream water, located at point F4. This point is located on Ba Na Mountain, where granite intrusion, gabbro with porphyry biotite granite, two-mica porphyry granite, and gneiss structures are dominating. This area has a large number of faults, and activity concentrations may vary due to variations in climatic conditions.

3.3. Assessment of the total effective annual dose

The annual effective dose calculated due to consumption of drinking water containing ^{222}Rn in this study is presented in Table 1. Overall, the average total effective annual dose for adults, children and infants are near the reference dose level of 100 µSv y^{-1} (World Health Organization, 2004), with values ranging from 1.3 to 541 and 109 µSv y^{-1} on average for adults; from 1.2 to 479 and 97 µSv y^{-1} on average for children and 2.1 to 838 and 169 µSv y^{-1} on average for infants. Despite consuming less water, infants are found to have significantly higher effective doses than adults. This difference is due to a more vigorous metabolism and intensively growing organs in comparison with adults with already developed physiques (Duggal et al., 2020). On the other hand, if water is boiled for infants, it will lose at least some of its radon content to the air, so the calculated value might overestimate exposure. Differences in mean effective dose for different types of water are noted in Table 1 with the highest values for groundwater from drilled wells and the lowest for surface water from lake water. Assuming that an adult consumes 2.10^{-3} m^{3} per day and uses six cubic meters for washing purposes per month, the annual effective dose due to ingestion and inhalation of radon from the studied water samples is below the maximum reference level recommended (Council Directive 2013).

4. Conclusion

The following conclusions are drawn from the obtained results:

Except for groundwater taken from location K10, the ^{222}Rn activity level in the studied waters are below the EU recommended upper limit - 100 Bq L^{-1} (Council Directive 2013). The average ^{222}Rn content in groundwater is twelve times higher than that observed in surface water with values of 36.7 and 3.1 Bq L^{-1}, respectively. The highest and lowest activities are recorded for a drilled well (K10) and lake water (H1), respectively. The trend of ^{222}Rn concentration was observed as follows: $^{222}\mathrm{Rn}_{\mathrm{lakes}} < {}^{222}\mathrm{Rn}_{\mathrm{rivers}} < {}^{222}\mathrm{Rn}_{\mathrm{streams}} < {}^{222}\mathrm{Rn}_{\mathrm{dug\ wells}} < {}^{222}\mathrm{Rn}_{\mathrm{thermal}} < {}^{222}\mathrm{Rn}_{\mathrm{drilled\ wells}}$. ^{222}Rn content in surface water is significantly lower than that in the underground water, where probably the geology, temperature and depth acted as the main controlling factors on ^{222}Rn occurrence. The principal factors controlling the ^{222}Rn in water are the geological information and tectonics. Higher ^{222}Rn levels tend to be related to the granite formations and faults or could be related to uranium mines close to the study area.

The annual effective dose for local residents due to usage of the surface water sources is below the maximum reference level recommended by WHO and the European Union (100 µSv y^{1}). In the case of underground waters, the calculated annual effective doses are higher than 100 µSv y^{-1}, so these waters should be processed to decrease the ^{222}Rn in water before using as tab water.

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Appendix I

The parameter of studied water sources (Duong et al., 2023) and activity concentrations of ^{222}Rn

Sample code	Water type	Depth (m)	pH	EC (µS cm^{-1})	TSD (ppm)	T (^{0}C)	Eh(mV)	^{222}Rn (Bq L^{-1})
F1	Lake	ND	7.56	66.0	71.0	27.8	17.0	3.63
F12	Lake	ND	7.72	29.0	14.0	25.2	52.0	0.71
H1	Lake	ND	7.51	39.0	20.0	26.8	106	0.34
H2	Lake	ND	7.57	48.0	25.0	25.2	110	1.71
H5	Lake	ND	7.66	86.0	44.0	30.5	102	0.69
K5	Lake	ND	6.81	59.0	30.0	28.4	36.0	0.84
K8	Lake	ND	8.86	74.0	38.0	31.9	72.0	0.26
K11	Lake	ND	7.15	62.0	31.0	27.7	101	0.54
K16	Lake	ND	7.48	60.0	30.0	29.1	76.0	6.47
F4	Stream	ND	7.01	76.0	38.0	29.3	58.0	19.6
F2	Stream	ND	7.02	76.0	38.0	29.3	58.0	3.09
F7	Stream	ND	7.21	73.0	36.0	30.2	109	5.55
S4	Stream	ND	7.13	26.0	13.0	30.3	103	1.15
S6	Stream	ND	7.56	38.0	19.0	23.0	85.0	0.97
S7	Stream	ND	7.41	29.0	14.0	26.2	103	3.14
S8	Stream	ND	7.95	53.0	27.0	25.4	99.0	2.09
K2	Stream	ND	7.71	35.0	18.0	29.6	125	6.07

(*continued on next page*)

(*continued*)

Sample code	Water type	Depth (m)	pH	EC (μS cm^{-1})	TSD (ppm)	T (^{0}C)	Eh(mV)	^{222}Rn (Bq L^{-1})
K4	Stream	ND	7.61	33.0	17.0	29.2	90.0	0.31
K15	Stream	ND	6.24	136	68.0	27.6	150	1.45
F9	River	ND	7.36	44.0	23.0	27.5	92.0	4.05
S3	River	ND	7.64	42.0	21.0	29.3	124	2.01
F3	Dug well	30	7.09	26.0	14.0	29.5	42.0	1.20
F10	Dug well	10	4.97	34.0	17.0	26.5	182	12.5
S1	Dug well	10	5.6	69.0	36.0	27.5	154	39.2
S2	Dug well	10	6.31	85.0	42.0	28.3	116	17.0
K7	Dug well	9.0	6.63	333	164	28.8	161	30.4
K14	Dug well	10	6.38	151	75.0	29.3	125	9.93
F6	Drill well	25	5.11	162	81.0	28.3	182	18.9
F8	Drill well	70	6.71	162	81.0	28.1	75.0	47.9
H3	Drill well	55	7.71	640	317	28.5	-40.0	18.6
H4	Drill well	50	6.11	207	103	27.4	153	49.9
H6	Drill well	70	6.47	208	104	27.5	150	31.5
H8	Drill well	60	9.52	400	200	29.1	-182	35.5
H10	Drill well	18	6.11	235	119	30.2	37.0	50.3
H11	Drill well	28	5.98	83.0	41.0	27.6	87.0	35.7
K1	Drill well	18	6.06	112	56.0	28.6	135	48.9
K3	Drill well	7.0	6.91	166	87.0	29.3	46.0	26.2
K10	Drill well	50	6.32	214	102	32.1	86.0	107
K6	Drill well	16	5.79	66.0	33.0	30.2	166	38.5
K12	Drill well	55	7.26	275	137	28.8	79.0	56.1
K13	Drill well	15	6.17	143	73.0	29.8	142	69.8
K17	Drill well	30	8.24	33	16.0	30.1	44.0	68.9
H9	Thermal water	ND	9.42	481	237	55.0	-251	9.70
K9	Thermal water	ND	9.87	474	260	48.3	-254	17.3
F11	Thermal water	50	9.16	638	318	41.1	-202	70.5
S5	Thermal water	50	8.41	901	450	38.4	-198	1.25
Average		16	7.18	163	82.6	29.9	63.1	21.3
Min		ND	4.97	26.0	13.0	23.0	-254	0.26
Max		70	9.87	901	450	55.0	182	107

ND: Not determined

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