Vietnam Journal of Earth Sciences, 46(1), 1-11, https://doi.org/10.15625/2615-9783/19080

Vietnam Journal of Earth Sciences
https://vjs.ac.vn/index.php/jse

Radiological risk assessment and characteristics of ^{210}Po in selected water sources in Quang Nam and Da Nang, Vietnam

Van-Hao Duong[1*], Tien Chu Trung[1], Hung Danh Tran[2], Oanh Nguyen Thi[1], Duc Do Xuan[1], Hoang Ha Nguyen Thi[3], Hung Dinh Viet[1]

[1]*VNU School of Interdisciplinary Studies, Vietnam National University, Hanoi, Vietnam*
[2]*Hanoi University of Mining and Geology (HUMG), Hanoi 100000, Vietnam*
[3]*Vietnam Japan University, Vietnam National University, Hanoi, Vietnam*

Received 05 June 2023; Received in revised form 27 August 2023; Accepted 03 October 2023

ABSTRACT

^{210}Po, one of the harmful natural isotopes with a long enough half-life, plays a significant role in environmental processes. 48 samples, including groundwater (dug wells, thermal water, and drill wells) and surface water (lakes, rivers, and streams) in the Da Nang - Quang Nam region of Vietnam were analyzed by an alpha spectrometer. Relatively low activities of ^{210}Po have been observed, whose mean values ranged from 0.15 to 4.58 and 1.34 mBq.L^{-1}. There is no significant variation in ^{210}Po activities between groundwater and surface water groups. The average ^{210}Po activity of those groups is 1.28 and 1.40 mBq.L^{-1}, respectively. The geological conditions of the study area, neutral pH values, and predominant oxidizing conditions supported the low ^{210}Po activities in the selected water sources. Average annual effective doses for adults, children, and infants due to the consumption of water containing ^{210}Po were found to be 1.15, 1.21, and 2.94 µSv.y^{-1}, respectively.

Keywords: ^{210}Po, Radiological risk assessment, drinking water, Quang Nam, Da Nang.

1. Introduction

Fresh water is an essential and necessary resource for the human diet, daily use, and productive activities (Sherif and Sturchio, 2018; Zhong et al, 2020). The occurrence of natural radioisotopes and their decay products in water is a natural phenomenon (Sekudewicz and Gąsiorowski, 2019). However, the high concentrations of natural radioisotopes can pose a significant risk to aquatic organisms (Sekudewicz and Gąsiorowski, 2019).

Polonium^{-210} (^{210}Po) is a natural radioactive isotope with a half-life of 138.4 days. It is a progeny of ^{238}U and belongs to group 1, so it is considered a carcinogen (IARC, International Agency for Research on Cancer, 2001). Several epidemiological studies have considered ^{210}Po in drinking water as a possible risk factor for cancer and other diseases in small doses (Seiler, 2016; Harrison et al., 2007).

The ^{210}Po occurrence in drinking water is widespread because of the hydrological cycle leading to its distribution in surface and groundwater environments (Carvalho et al., 2017). As a reactive element, ^{210}Po is generally considered to be adsorbed on solid surfaces in aquifer systems because it is easily removed from water by co-precipitation with Fe hydroxide, Mn oxide, colloids, and sulfides (Seiler et al., 2011; Bacon et al., 1980). For surface water, the predominant oxidizing

*Corresponding author, Email: haodv@vnu.edu.vn

conditions, heavy rainfall, the deposition of particles, and the volatility of ^{210}Po are the causes leading to the removal or dilution of ^{210}Po from the water column. That is why ^{210}Po is rarely found in near-surface drinking water sources over ~40 $mBq.L^{-1}$ (Seiler, 2011). However, several previous studies reported the ^{210}Po activity to be more than 10000 $mBq.L^{-1}$ (Burnett et al., 1987; Mullin, 1982; Lehto et al., 1999; Salonen, 1988; Seiler, 2011; Muikku et al., 2011; Seiler, 2016). Meanwhile, 100 mBq. L^{-1} is the guideline level for drinking water issued by the WHO (World Health Organization, 2011), and 200 $mBq.L^{-1}$ is Canada's maximum acceptable concentration (MAC) for ^{210}Po (Health Canada, 2007). In addition, the ^{210}Po activity in water was concerned with radiological risk when it exceeded 41 $mBq.L^{-1}$ (US Environmental Protection Agency, 2000). As an isotope emitting alpha particles, ^{210}Po is very dangerous when it enters the human body through water consumption. So, the radiological hazard assessment remains of significant concern.

Most worldwide investigations of the ^{210}Po behavior in groundwater or surface waters suggest that the controlling factor of its mobilization may be the presence of parent radioisotopes, aquifer lithology, and environmental parameters such as pH, oxidation-reduction conditions, TDS, and temperature (Zhong et al., 2020; Dickson and Herczeg, 1992; Burnett et al., 1987; Seiler, 2011; Ruberu, 2007; Outola, 2008; Ram, 2019). However, there are exceptions to previous reports, such as Upchurch et al. (1991), who concluded that there was little evidence that the reduction/oxidation reactions of ^{210}Po play a role in the mobilization of ^{210}Po in groundwater (Upchurch et al., 1991). Likewise, Seiler et al. (2011 and 2016) suggested that the pH factor and the presence of parent isotopes such as ^{226}Ra and ^{222}Rn do not seem to be essential factors in mobilizing the ^{210}Po (Seiler, 2011 and 2016). It is recognized that the ^{210}Po behavior in freshwater environments is relatively complex. A small change in environmental conditions could lead to a change in the ^{210}Po presence. Different regions have characteristics that lead to variations in the measured value of ^{210}Po activities. About this, investigating ^{210}Po in any given area provides insights and contributes to clarifying the behavior of ^{210}Po in aquatic environments. Environmental issues in Vietnam, especially the aquatic environment have been of interest to date (Nguyen et al., 2018; Quyen et al., 1995; Thi Minh Hanh et al., 2011). However, determining radionuclide contamination in the aquatic environment is still limited. The Quang Nam and Da Nang provinces are located in central Vietnam. Population growth and rapid economic development have increased the demand for groundwater and drinking water. Since this area is characterized by tectonic activity with many faults (Tran et al., 2008, 2009, 2014), the faults facilitate ^{222}Rn dispersion into the surrounding environment (Lombardi et al., 2010), and the fault system also created the aquifer host formation. That water source in the aquifer hosts dissolves ^{222}Rn, the parent of ^{210}Po. Carvalho, (2017) suggested that precursor parent decay (^{222}Rn) is the leading cause of the mobilization of ^{210}Po in water sources. In addition, uranium mines surround the study area (Cao et al., 2005; Lien et al., 2011; Nguyen, 2019), which may lead to an increase in ^{210}Po pollution on/in the surface and groundwater of this area. Therefore, the primary purposes of this study are to conduct a radiological hazard assessment of ^{210}Po due to water consumption and to provide the ^{210}Po characteristics of selected water sources in Quang Nam and Da Nang, Vietnam.

2. Geology, sampling, and analytical methods

2.1. Geological setting

The topography of the study area is characterized by hills, plateaus, medium-low mountains, and plains with lower elevations from west to east due to the substantial uplift of the Kon Tum - Da Lat massif and deep subsidence of the continental shelf. Da Nang and Quang Nam provinces are located in the central part of central Vietnam, where the Cu-De, Po-Ko, and Tra Bong faults occurred. The fault system in the study area includes sub-longitudes, longitudes of latitude northeast-southwest, and northwest-southeast. Geological formations from the ancient to the quaternary are present in most of Quang Nam - Da Nang. In the study area, there is the appearance of a series of intrusive metamorphic formations (Fig. 1). However, these formations are determined to be quite water-poor. A significant water storage formation is the Holocene diluvial formation, which occurs as deltas consisting of sand, mud, and gravel. The Pleistocene sedimentary aquifer predominates in the study regions, with the main components including fine-grained sand and quartz, which are usually known for their low radionuclide concentrations. Finally, the Neogene sedimentary formation includes siltstone, sandstone, and organic materials.

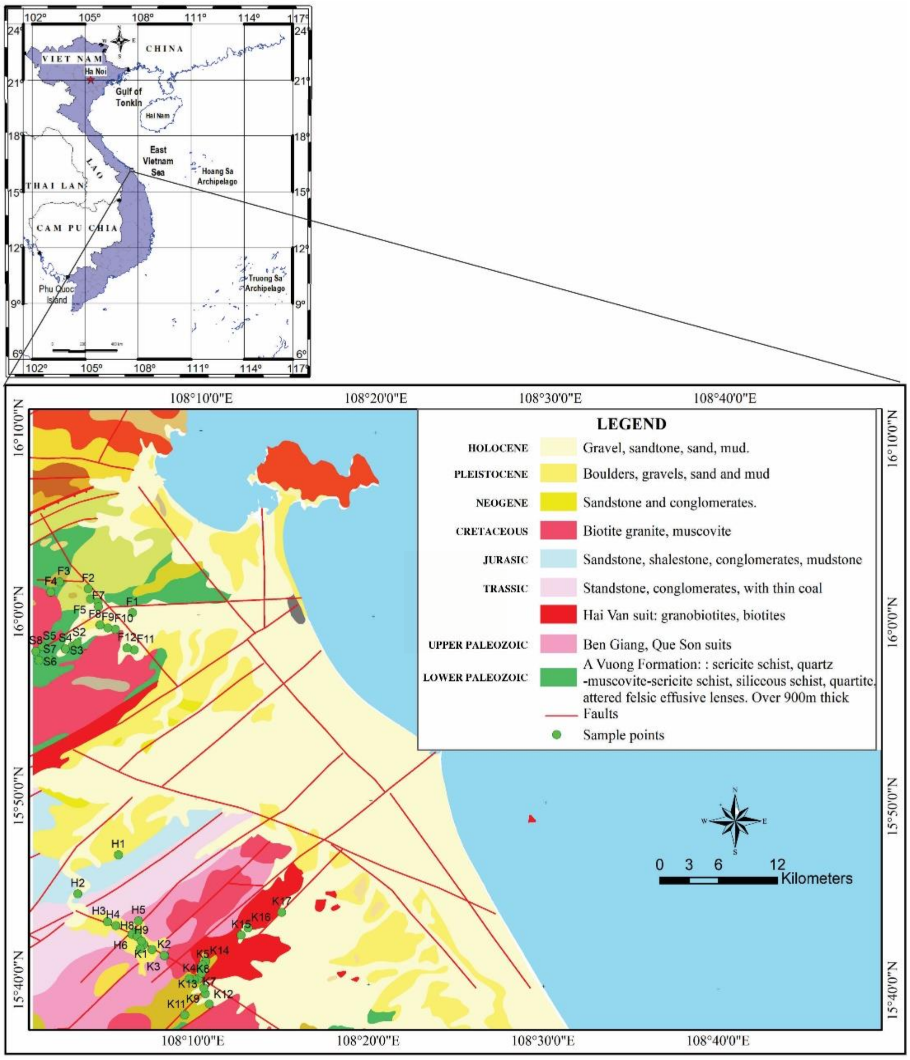

Figure 1. The geological map and sampling points of the study area

2.2. Sampling

The selected water samples represent typical locations, people use for drinking, living, and production. The sampling points are distributed within four lines of faults (Fig. 1). Groundwater (dug wells, drill wells, and thermal water) samples are collected in resident and tourist areas, and surface water (lakes, rivers, and streams) is taken next to densely populated areas, which could be a supplementary source for groundwater. 48 samples, including dug wells, drill wells, thermal water, lake, river, and spring water sources, are collected into cans of 20 liters. Acidification was carried out immediately after sampling to avoid the influence of microorganisms and the adsorption of ^{210}Po on the walls of cans. In situ, parameters such as temperature, pH, Eh, TDS, and EC of the studied water sources were measured during sampling with Hanna models HI8314 and HI2003-02.

2.3. Methods

^{210}Po determination in study samples:

Due to the complex chemical properties of polonium (Thakur et al., 2020; Ram et al., 2019), the ^{210}Po determination in water samples requires chemical separation. Alpha spectroscopy has determined ^{210}Po activity in the measured samples (IAEA, 2009).

In the laboratory, 5 liters of each water sample were prepared following the preparation procedures of IAEA (2009) and Van-Hao et al. (2021, 2022) (IAEA, 2009; Van Hao et al., 2021, 2022). A 50 mBq ^{209}Po tracer was added to the water samples initially. The ^{210}Po separation process was initiated by co-precipitation with MnO_2 by the addition of a mixture of $MnCl_2$ and $KMnO_4$ under pH conditions of ~9 (IAEA, 2009; Van Hao et al., 2021, 2022). The obtained precipitation was dissolved in 9M HCl acid solution and evaporated to dryness at <90°C. The sample was then dissolved in HCl (0.5M), and 0.5 g of ascorbic acid was added to reduce Fe^{3+} to Fe^{2+} (IAEA, 2009; Van Hao et al., 2021). The ^{209}Po and ^{210}Po were spontaneously deposited on a silver dish from the solution after ~4 h at 80°C. The ^{210}Po activity in the studied samples was determined by alpha spectroscopy (ORTEC ALPHA-DUOM1 - high-resolution PIPS detector with 450 mm^2 in area). The recovery rate of the ^{209}Po tracer was up to 90%. The time of measurement of each study sample was chosen to get less 5% of uncertainty of the counting rate at the ^{210}Po and ^{209}Po peaks.

Annual effective dose (AED):

The AED due to consumption of water containing ^{210}Po was calculated according to formula (1) (USA - EPA, 1998).

$$AED_{210Po} = A_{210Po} \times DCC \times CR \quad (1)$$

- AED_{210Po}: is the annual effective dose ($\mu Sv.y^{-1}$),
- A_{210Po} is the ^{210}Po active concentration ($Bq.L^{-1}$),
- D is the dose conversion coefficient ($Sv.Bq^{-1}$) for adults, children, and infants of 1.2×10^{-6}, $2.6 \times 10^{-6,}$ and 8.8×10^{-6} $Sv.Bq^{-1}$, respectively (UNSCEAR, 2000).
- CR is the annual consumption rate ($L.y^{-1}$) for adults, children, and infants is 730, 350, and 250 L, respectively (ICRP, 2008).

3. Results and discussions

3.1. Results

The parameters (pH, EC, TDS, Eh, and depth) of the selected water sources are shown in Table 1. Depths from surface reach to aquifer are recorded for each groundwater type up to 70 m. The pH value is expressed from 5.40 to 9.90, 7.19 on average. For temperature, except for the thermal water samples (from 38 to 55°C), the rest of the selected water has a temperature range from 23 to 32°C. The EC (µS/cm), TSD (ppm), and Eh (mV) ranged from 26 to 901 µS/cm, from 13 to 450, and from -254 to 182, with means of 159.4 µS/cm, 80.9 ppm, and 66.2 mV, respectively.

Table 1. ^{210}Po activity, environmental parameters in study water sources and annual effective dose

Sample code	Water type	Coordinates		Depth (m)	pH	EC (µS/cm)	TSD (ppm)	T0 (^{0}C)	Eh (mV)	Activity concentration of ^{210}Po (mBq.L^{-1})	Annual effective dose (µSv.y^{-1})		
		X	Y								Infants	Children	Adults
F3	Groundwater (Dig wells)	108.03396	16.02786	30	7.1	26	14	29.5	42	0.74	1.62	0.67	0.64
F10		108.08775	15.98568	10	6.3	34	17	26.5	182	1.0	2.21	0.91	0.87
S1		108.04686	15.96986	10	6.7	69	36	27.5	154	0.67	1.46	0.61	0.58
S2		108.05161	15.97275	10	6.3	85	42	28.3	116	0.33	0.73	0.3	0.29
H7		108.11053	15.71124	9	6.3	110	55	27.7	146	0.71	1.56	0.64	0.61
K7		108.17124	15.66977	9	6.6	333	164	28.8	161	0.78	1.71	0.71	0.67
K14		108.17798	15.68576	10	6.4	151	75	29.3	125	3.87	8.52	3.52	3.34
F5		108.06356	16.01283	6	5.55	60	30	30.4	130	0.42	0.92	0.38	0.36
F6	Groundwater (Drill wells)	108.07089	16.01028	25	5.4	162	81	28.3	182	0.65	1.43	0.59	0.56
F8		108.07308	15.98939	70	6.7	162	81	28.1	75	0.9	1.98	0.82	0.78
H3		108.08393	15.72051	55	7.7	640	317	28.5	-40	0.68	1.5	0.62	0.59
H4		108.09191	15.71724	50	6.1	207	103	27.4	153	0.6	1.32	0.55	0.52
H6		108.10761	15.70944	70	6.5	208	104	27.5	150	0.51	1.11	0.46	0.44
H8		108.11242	15.70764	60	9.5	400	200	29	-182	1.04	2.28	0.94	0.9
H10		108.11886	15.70039	18	6.1	235	119	30	37	1.84	4.05	1.68	1.59
H11		108.11550	15.69644	28	6.0	83	41	27.6	87	0.88	1.94	0.8	0.76
K1		108.12681	15.69578	18	6.1	112	56	28.6	135	1.5	3.3	1.36	1.3
K3		108.13883	15.69047	7	6.9	166	87	29	46	2.03	4.47	1.85	1.75
K6		108.17400	15.67975	16	5.8	66	33	30.2	166	0.7	1.55	0.64	0.61
K10		108.17803	15.65656	50	6.3	214	102	32	86	2.27	4.99	2.07	1.96
K12		108.18200	15.64731	55	7.3	275	137	28.8	79	4.1	9.02	3.73	3.54
K13		108.17443	15.67519	15	6.2	143	73	29.8	142	1.41	3.1	1.28	1.22
K17		108.24970	15.73125	30	8.2	33	16	30	44	2.99	6.57	2.72	2.58
F11	Groundwater (Thermal water)	108.10599	15.96721	50	9.2	638	318	41	-202	1.54	3.39	1.4	1.33
S5		108.01853	15.96889	65	8.4	901	450	38	-198	1.1	2.42	1.0	0.95
H9		108.11664	15.70350	NA	9.4	481	237	55	-251	0.6	1.31	0.54	0.51
K9		108.17661	15.66172	NA	9.9	474	260	48	-254	0.78	1.71	0.71	0.67
F1	Surface (Lakes)	108.10370	16.00098	0	7.6	66	71	27.8	17	1.41	3.11	1.29	1.22
F12		108.09915	15.96875	0	7.7	29	14	25	52	2.16	4.75	1.97	1.87
H1		108.09356	15.78131	0	7.5	39	20	26.8	106	1.33	2.92	1.21	1.15
H2		108.05540	15.74542	0	7.6	48	25	25.2	110	1.56	3.42	1.42	1.34
H5		108.11354	15.72177	0	7.7	86	44	30.5	102	0.7	1.54	0.64	0.61
K5		108.17522	15.68253	0	6.8	59	30	28.4	36	0.96	2.12	0.87	0.83
K8		108.16725	15.66900	0	8.9	74	38	31.9	72	0.86	1.88	0.78	0.74
K11		108.15870	15.63697	0	7.2	62	31	27.7	101	0.81	1.79	0.74	0.7
K16		108.21789	15.71654	0	7.5	60	30	29	76	0.88	1.93	0.8	0.76
F9	Surface (Rivers)	108.08053	15.98678	0	7.4	44	23	27.5	92	1.2	2.63	1.09	1.03
S3		108.04039	15.96717	0	7.6	42	21	29.3	124	1.46	3.21	1.33	1.26
F2	Surface (Streams)	108.06130	16.02202	0	7	76	38	29.3	58	0.48	1.05	0.44	0.41
F4		108.02574	16.01850	0	7	76	38	29.3	58	4.58	10.1	4.17	3.96
F7		108.07128	16.00594	0	7.2	73	36	30.2	109	0.15	0.32	0.13	0.13
S4		108.04042	15.96736	0	7.1	26	13	30	103	1.25	2.74	1.13	1.08
S6		108.01514	15.95656	0	7.6	38	19	23	85	1.47	3.24	1.34	1.27
S7		108.02565	15.95708	0	7.4	29	14	26	103	2.75	6.05	2.5	2.38
S8		108.01217	15.96464	0	8	53	27	25	99	2.84	6.26	2.59	2.46
K2		108.13825	15.69086	0	7.7	35	18	29.6	125	0.8	1.76	0.73	0.69
K4		108.16251	15.66986	0	7.6	33	17	29	90	0.95	2.1	0.87	0.82
K15		108.21140	15.71001	0	6.2	136	68	27.6	150	0.84	1.84	0.76	0.72
Average				16	7.19	159.4	80.9	29.8	66.2	1.33	2.94	1.21	1.15
Min				0	5.4	26	13	23	-254	0.15	0.32	0.13	0.13
Max				70	9.9	901	450	55	182	4.58	10.1	4.17	3.96

Table 1 shows the ^{210}Po activities in different types of water sources. The ^{210}Po activities range from 0.15 to 4.58, with a mean value of 1.34 mBq.L^{-1}. There was an insignificant difference in ^{210}Po concentration in dug wells, drill wells, thermal water, lakes, rivers, and stream water sources, with mean values of 1.06, 1.47, 1.01, 1.17, 1.33, and 4.34 mBq.L^{-1}, respectively. Based on the origin of water sources, the samples were divided into two main groups: groundwater (0.33–4.1 mBq.L^{-1}) and surface water (0.15–4.58 mBq.L^{-1}). The similarity of the ^{210}Po level was also recorded with mean values of 1.28 and 1.40 mBq.L^{-1}, respectively (Fig. 2).

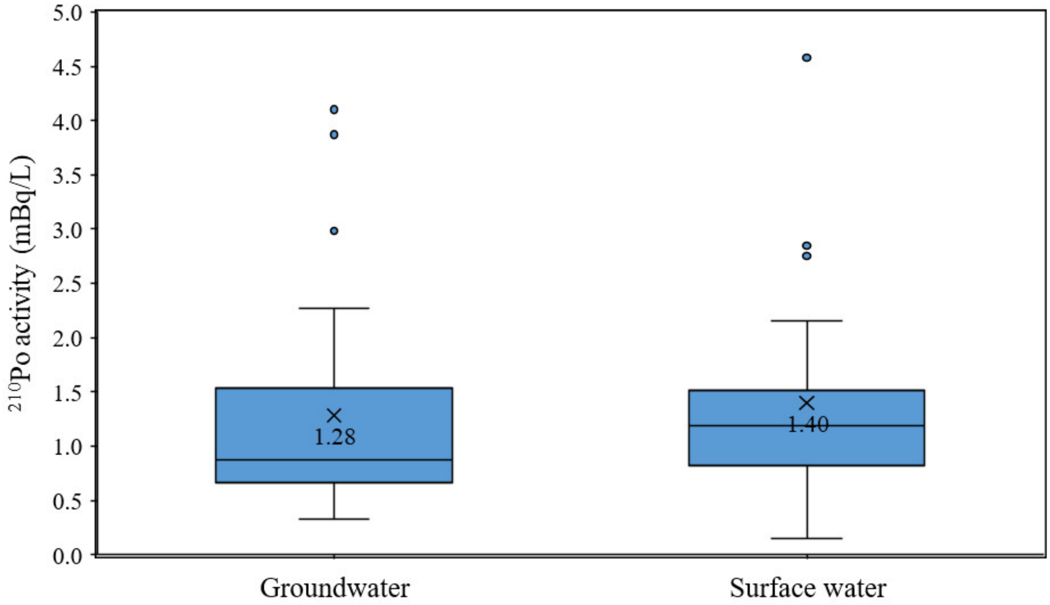

Figure 2. Distribution of ^{210}Po in surface and groundwater sources in the study area

3.1. Discussions

The ^{210}Po values in the studied water sources were relatively low compared to other sources worldwide (Table 2). For example, ^{210}Po activities in drinking water in the USA were over 555 mBq.L^{-1} due to contamination with phosphate, with a maximum level of up to 14400 mBq.L^{-1} (Burnett et al., 1987). Investigations in Finland have identified a maximum observed value of 14800 mBq.L^{-1} in several contaminated wells in granite bedrock (Muikku et al., 2011). Maximum levels exceeding 7000 mBq.L^{-1} have been found in groundwater (Vaaramaa et al., 2003) or ^{210}Po in some mineral springs up to 398 mBq.L^{-1} in Bazil (Neto et al., 1998), up to 947 mBq.L^{-1} in groundwater in Sweden (Isam Salih et al., 2002). In contrast, low ^{210}Po activity was also reported for water sources from rivers, lakes, and streams, with values typically of 0.5–10 mBq.L^{-1} in several countries such as Tajikistan, the USA, India, Poland, Malaysia, Brazil, and Croatia (Table 2). Table 2 showed that ^{210}Po activities in the present study area were higher than most selected countries, and only a few water sources were a little lower than the present study values (Benoit et al., 1990; Shaheed et al., 1997). Regarding the groundwater sources in Vietnam, the study area also observed quite similar low ^{210}Po activity with thermal water sources (groundwater) of Hai Phong, Quang Ninh, Tuyen Quang, Phu Tho, Hoa Binh, Ninh Binh, and Son La provinces (Van-Hao et al., 2022). Therein, the ^{210}Po activity was recorded as lower than in Hai Phong, Quang Ninh, Tuyen Quang, Ninh Binh, and Son La provinces, but it was higher than that in Phu Tho and Hoa Binh provinces (Van-Hao et al., 2022). Those provinces were reported to have carbonate aquifer formations, which were well-known for the low potential of radionuclides (Nguyen et al., 2021; Van-Hao et al., 2022). The variation in the content of ^{210}Po among different regions in the world further supports the view that different environments lead to a change in the mobilization-absorption capacity of ^{210}Po in water.

Table 2. Worldwide ^{210}Po activities in surface and groundwater in different locations in the world

County	Water type	^{210}Po Range (mBq.L^{-1})	Average (mBq/L)	Source
Australia	Groundwater	0–114	24.2	Walsh et al., 2014
China		0.24–6.96	2.23	Zhong et al., 2020
E. Brasil		<55–459	161	Valentim., 1997
Finland		–	14800	Muikku et al., 2011
Finland		3900–13,200	7400	Lehto et al., 1999
Finland		160–7020	1740	Vaaramaa et al., 2003
Sweden		<5–947	11	Isam Salih et al., 2002
USA		1–6590		Seiler, 2011
USA		? –14400		Burnett et al., 1987
USA		<0.1–16,600	4.57	Seiler., 2016
Republic of Palau	Lake	1–133		Kim et al., 2005
Crimean		0.5–229		Mirzoeva et al., 2020
Tajikistan		1–5.6		Skippered., 2013
USA			1.6	Talbot et al., 1984
USA			1.3	Benoit et al., 1990
India	River	0.77–1.27	1.1	Shaheed et al., 1997
India		0.86–4.49	2.67	Kavitha et al., 2017
Poland		2.15–6.03		Skwarzec et al., 2007
Poland		1.46–2.39		Skwarzec et al., 2008
Malaysia		0.63–14.98		Ahmed et al., 2018
Brazil	Spring	3–398		Neto et al., 1998
Brazil		6–1378		Nieri et al., 1996
Croatia		0.6–3		Rožmarić et al., 2012
Hai Phong -Vietnam	Groundwater		1.79	Van-Hao et al., 2022
Quang Ninh-Vietnam			2.83	
Phu Tho - Vietnam			1.19	
Tuyen Quang - Vietnam			1.39	
Ninh Binh - Vietnam			8.26	
Hoa Binh - Vietnam			1.01	
Son La - Vietnam			3.73	
Quang Nam and Da Nang - Vietnam	Groundwater		1.28	This study
	Surface water		1.34	

The ^{210}Po activities in groundwater range from 0.33 to 4.1 mBq.L^{-1} and surface water from 0.15 to 4.58 mBq.L^{-1}. These activities have been observed in previous studies because the radionuclides in groundwater are often much higher than in surface water, as it passes through soil and rock formations by dissolving many compounds and radionuclides host minerals (Akar et al., 2012; Srinivasa et al., 2018). The hydrogeological characteristics of aquifers in this area are identified as sedimentary and weathered quaternary formations, those formations of Pleistocene with the main components including fine-grained sand and quartz, which are usually known for low radionuclide concentration and little potential for supporting radionuclides into the water environment (Taylor et al., 2002). On the other hand, ^{210}Po is a reactive element and strongly binds to sediments, so it is easily removed from water through adsorption on solid surfaces in aquifer systems (Seiler et al., 2011; Bacon et al., 1980). Therefore, its activity is usually less than 5 mBq.L$^{-1,}$ reported in a previous study (Persson, 2014). Some studies found a high concentration of ^{210}Po in water under reducing conditions and pH<5 (LaRock et al., 1996; Seiler, 2016; Seiler., 2011). Accordingly, pH and oxidation-reduction conditions can be important factors affecting the mobilization of

^{210}Po in the study water environment. This study's predominant oxidizing conditions and neutral pH (5.4–9.9) could be responsible for the low ^{210}Po content in the study water sources (Table 1). The finding was approved by Seiler, (2011) when comparing data from different studies (Seiler, 2011). The mentions may explain the low activity level of ^{210}Po in this study. Interestingly, despite the existence of uranium mines in the surrounding area, it can be concluded that they do not significantly affect the ^{210}Po level in the area.

4. Annual effective dose

The AEDs for drinking water containing ^{210}Po in this study are presented in Table 1. Overall, the mean doses for adults (0.126–3.96 μSv.y^{-1}), children (0.134–4.17 μSv.y^{-1}) and Infants (0.134–4.17 μSv.y^{-1}) are all below the allowable limit of 100 μSv.y^{-1} (WHO, 20011), with mean values of 1.15, 1.21, and 2.94 μSv.y^{-1}, respectively. This result shows that consumption of water containing ^{210}Po isotope is relatively safe for residents in the study area.

5. Conclusions

^{210}Po activities have been determined in 48 water sources in Quang Nam and Da Nang, Vietnam (including groundwater (dug wells, thermal water, and drills wells) and surface water (lakes, rivers, and streams)). The ^{210}Po activities in study samples ranged from 0.15 to 4.58, with an average value of 1.34 mBq.L^{-1}. There was no significant difference in ^{210}Po activities in different water sources and in groundwater and surface water sources, with mean values of 1.28 and 1.40 mBq.L^{-1}, respectively. The low ^{210}Po activity in different types of water sources was likely related to the studied area's geological conditions, neutral pH level, and predominant oxidizing conditions that could not supply ^{210}Po to surface and groundwater sources. The low ^{210}Po content in this study was the negligible influence of uranium deposits in the region on the distribution of ^{210}Po in different water types.

The ^{210}Po activities in all water samples did not exceed the reference value guideline of 100 mBq.L^{-1}. It led to the AED due to consuming ^{210}Po in the selected water sources for adults, children, and infants within the allowable limit of 100 μSv.y^{-1}. It was relatively safe for residents in the study area regarding the ^{210}Po in drinking water.

Acknowledgments

This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 105.99-2020.02.

References

Ahmed M.F., Alam L., Mohamed C.A.R., Mokhtar M.B., Ta G.C., 2018. Health risk of Polonium^{210} ingestion via the drinking water: An experience of Malaysia international journal of environmental research and public health, 15(10), 2056.

Akar U., Gurler O., Kahraman A., Yalcin S., Kaynak G., Gundogdu O., 2012. Measurements of radium levels in bottled natural spring water of Marmara region (Turkey). Romanian Journal of Physics, 57(7-8), 1204–1210.

Alomari A.H., et al., 2019. Activity concentrations of ^{226}Ra, ^{228}Ra, ^{222}Rn and their health impact in the groundwater of Jordan. Journal of Radioanalytical and Nuclear Chemistry, 322, 305–318.

Bacon M.P., Brewer P.G., Spencer D.W., Murray J.W., Goddard J., 1980. Lead^{-210}, polonium^{-210}, manganese, and iron in the Cariaco Trench. Deep Sea Research Part A. Oceanographic Research Papers, 27(2), 119–135.

Benoit G., Hemond H.F., 1990. Polonium^{-210} and lead^{-210} remobilization from lake sediments in relation to iron and manganese cycling. Environmental Science & Technology, 24(8), 1224–1234.

Burnett W.C., Cowart J.B., Harada K., Chin P.A., 1987. Polonium in the surficial aquifer of southwest Florida. FIPR Report, 147, 105.

Canada H., 2007. Guidelines for Canadian DrinkingWater Quality Summary Table. http://www.rcan.com/download.php?file_id=525 (accessed 06.04.09).

Cao H.T., Tran V.S., Phung V.P., 2005. Study on uranium distribution in ore samples of Nong Son Basin (Viet Nam), 251–254.

Carvalho F., et al., 2017. The environmental behaviour of polonium Vienna, Austria: International Atomic Energy Agency, 484, 255.

Dickson B.L., Herczeg A.L., 1992. Naturally-occurring radionuclides in acid-Saline groundwaters around Lake Tyrrell, Victoria, Australia. Chemical Geology, 96(1-2), 95–114.

Nguyen D.C., Nowak J., 2021. Natural radioactivity in thermal waters: a case study from Poland. Energies, 14(3), 541.

Harrison J., Leggett R., Lloyd D., Phipps A., Scott B., 2007. Polonium^{-210} as a poison. Journal of Radiological Protection, 27(1), 17.

IAEA, 2009. A procedure for the determination of Po^{-210} in water samples by alpha spectrometry. IAEA Analytical Quality in Nuclear Applications No. IAEA/AQ/12.

IARC (International Agency for Research on Cancer). 2001. Monographs on the evaluation of carcinogenic risks to humans, Volume 78 ionizing radiation, Part 2: some internally deposited radionuclides.

Kavitha E., Chandrashekara M.S., Paramesh L., 2017. ^{226}Ra and ^{210}Po concentration in drinking water of Cauvery river basin south interior Karnataka State, India. Journal of Radiation Research and Applied Sciences, 10(1), 20–23.

Kim G., Kim S.J., Harada K., Schultz M.K., Burnett W.C., 2005. Enrichment of excess ^{210}Po in anoxic ponds. Environmental Science & Technology, 39(13), 4894–4899.

LaRock P., Hyun J.H., Boutelle S., Burnett W.C., Hull C.D., 1996. Bacterial mobilization of polonium. Geochimica et Cosmochimica Acta, 60(22), 4321–4328.

Lehto J., Kelokaski, P., Vaaramaa K., Jaakkola, T. 1999. Soluble and particle-bound and ^{210}Po ^{210}Pb in groundwaters. Radiochimica Acta, 85(3-4), 149–156.

Lien T.V., N.D Van, 2011. Study On The Choice Of Leaching System For Thanh My, Quang Nam Province Uranium Ores Treatment, 951–959.

Lombardi S., Voltattorni N., 2010. Rn, He and CO_2 soil gas geochemistry for the study of active and inactive faults. Applied Geochemistry, 25(8), 1206–1220.

Isam Salih M., Pettersson B.L.H., Lund E., 2002. Uranium and thorium series radionuclides in drinking water from drilled bedrock wells: correlation to geology and bedrock radioactivity and dose estimation. Radiation Protection Dosimetry, 102(3), 249–258.

Mirzoeva N.Y., Korotkov A.A., Cogan S., Trapeznikov A.V., Lazorenko G.E., 2020. ^{210}Po in Crimean salt lakes. Journal of Environmental Radioactivity, 219, 106270.

Muikku M., Heikkinen T., Solatie D., Vesterbacka P., 2011. Natural variation in ^{210}Po and ^{210}Pb activity concentrations in the urine of Finnish population groups. Radiation and Environmental Biophysics, 50, 531–538.

Mullin A., 1982. Abnormally high alpha-activity in a louisiana drinking-water supply. In Health Physics, 43(1), 91–92.

Neto A.N., Mazzilli B., 1998. Evaluation of ^{210}Po and ^{210}Pb in some mineral spring waters in Brazil. Journal of Environmental Radioactivity, 41(1), 11–18.

Nieri N., 1996. Determination of ^{210}Pb and ^{210}Po in mineral spring waters. International Atomic Energy Agency, 14(1), 32.

Nguyen B.T., 2019. Problems of managing for radioactive waste norm/tenorm in facilities of mining and processing for minerals containing radioactive elements. International Atomic Energy Agency, 27(1), 51.

Nguyen H.T., Aviso K.B., Kojima N., Tokai A., 2018. Structural analysis of the interrelationship between economic activities and water pollution in Vietnam in the period of 2000-2011. Clean Technologies and Environmental Policy, 20(3), 621–638.

Outola I., et al., 2008. Investigation of radioactivity in selected drinking water samples from Maryland. Journal of Radioanalytical and Nuclear Chemistry, 277, 155–159.

Persson B.R., 2014. ^{210}Po and ^{210}Pb in the terrestrial environment. Curr Adv Environ Sci., 2(1), 22–37.

Quyen P.B., Nhan D.D., Van San N., 1995. Environmental pollution in Vietnam: analytical estimation and environmental priorities. TrAC Trends in Analytical Chemistry, 14(8), 383–388.

Ruberu S.R., Liu Y.G., Perera S.K., 2007. Occurrence and distribution of ^{210}Pb and ^{210}Po in selected California groundwater wells. Health Physics, 92(5), 432–441.

Ram R., Vaughan J., Etschmann B., Brugger J., 2019. The aqueous chemistry of polonium (Po) in environmental and anthropogenic processes. Journal of Hazardous Materials, 380, 120725.

Ramola R., et al., 2008. "Radon occurrence in soil-gas and groundwater around an active landslide". Radiation Measurements, 43(1), 98–101.

Rožmarić M., Rogić M., Benedik L., Štrok M., 2012. Natural radionuclides in bottled drinking waters produced in Croatia and their contribution to radiation dose. Science of the Total Environment, 437, 53–60.

Salonen L., 1988. Natural radionuclides in ground water in Finland. Radiation Protection Dosimetry, 24(1-4), 163–166.

Scheib C., et al., 2013. "Geological controls on radon potential in England". Proceedings of the Geologists' Association, 124(6), 910–928.

Seiler R., 2016. ^{210}Po in drinking water, its potential health effects, and inadequacy of the gross alpha activity MCL. Science of the Total Environment, 568, 1010–1017.

Seiler R.L., 2011. ^{210}Po in Nevada groundwater and its relation to gross alpha radioactivity. Groundwater, 49(2), 160–171.

Sekudewicz I., Gąsiorowski M., 2019. Determination of the activity and the average annual dose of absorbed uranium and polonium in drinking water from Warsaw. Journal of Radioanalytical and Nuclear Chemistry, 319, 1351–1358.

Shaheed K., Somasundaram S.S.N., Hameed P.S., Iyengar M.A.R., 1997. A study of polonium^{-210} distribution aspects in the riverine ecosystem of Kaveri, Tiruchirappalli, India. Environmental Pollution, 95(3), 371–377.

Sherif M.I., Sturchio N.C., 2018. Radionuclide geochemistry of groundwater in the Eastern Desert, Egypt. Applied Geochemistry, 93, 69–80.

Skipperud L., Jørgensen A.G., Heier L.S., Salbu B., Rosseland B.O., 2013. Po^{-210} and Pb^{-210} in water and fish from Taboshar uranium mining Pit Lake, Tajikistan. Journal of environmental radioactivity, 123, 82–89.

Skwarzec B., Jahnz A., 2007. The inflow of polonium ^{210}Po from Vistula river catchments area. Journal of Environmental Science and Health, Part A, 42(14), 2117–2122.

Skwarzec B., Tuszkowska A., 2008. Inflow of ^{210}Po from the Odra River catchment area to the Baltic Sea. Chem Anal, 53, 809–820.

Skwarzec B., 1997. Radiochemical methods for the determination of polonium, radiolead, uranium and plutonium in environmental samples. Chemia Analityczna, 42, 107–115.

Srinivasa E., Rangaswamy D.R., Suresh S., Reddy K.U., Sannappa J., 2018. Measurement of ambient gamma radiation levels and radon concentration in drinking water of Koppa and Narasimharajapura taluks of Chikmagalur district, Karnataka, India. Radiation Protection and Environment, 41(1), 20.

Sukanya S., J. Noble, S. Joseph, 2021. "Factors controlling the distribution of radon (^{222}Rn) in groundwater of a tropical mountainous river basin in southwest India". Chemosphere, 263, 128096.

Talbot R.W., Andren A.W., 1984. Seasonal variations of ^{210}Pb and ^{210}Po concentrations in an oligotrophic lake. Geochimica et Cosmochimica Acta, 48(10), 2053–2063.

Taylor M.J., et al., 2002. Relationships between soil properties and high-resolution radiometrics, central eastern Wheatbelt, Western Australia. Exploration Geophysics, 33(2), 95–102. https://doi.org/10.1071/EG02095.

Thakur P., Ward A.L., 2020. ^{210}Po in the environment: insight into the naturally occurring polonium isotope. Journal of Radioanalytical and Nuclear Chemistry, 323(1), 27–49.

Thi Minh Hanh P., Sthiannopkao S., The Ba D., Kim K.W., 2011. Development of water quality indexes to identify pollutants in Vietnam's surface water. Journal of Environmental Engineering, 137(4), 273–283.

Upchurch S.B., Oural C.R., Foss D.W., Brooker H.R., 1991. Radiochemistry of uranium-series isotopes in groundwater (chemical fate of uranium-daughter radionuclides in recharge wells, Central Florida phosphate district) (revised) (No. PB-98-126253/XAB). Univ. of South Florida, Tampa, FL (United States).

United Nations Scientific Committee on the Effects of Atomic Radiation, 2000. Sources and effects of ionizing radiation, ANNEX B, Exposures from natural radiation sources. UNSCEAR 2000 REPORT, New York, 1, 97–99.

US Environmental Protection Agency, 2000. Radionuclides Notice of Data Availability Technical Support Document. http://www.epa.gov/safewater/rads/tsd.pdf (accessed 01.11.05).

USA-EPA, 1998. Limiting Values of Radionuclide Intake And Concentration and Dose Conversion Factors For Inhalation, Submersion, And Ingestion. Federal Guidance Report No. 11.

Vaaramaa K., Lehto J., Ervanne H., 2003. Soluble and particle-bound $^{234,238}U$, ^{226}Ra and ^{210}Po in ground waters. Radiochimica Acta, 91(1), 21–28.

Valentim E., Hazin C.A., Khoury H.J., Lima R.D.A., Godoy J.M., 1997. Does decorrente da ingetão de águas contendo ^{210}Pb e ^{210}Po na ragião fosfática de Pernambuco. In Proceedings of IV Encontro Brasileiro de Apliccoes Nucleares, 228–278.

Van-Hao D., Trinh Trong Phan, Bach Thao Nguyen, Duc Bang Dao, Miklós Hegedűs, Tibor Kovacs, 2022. ^{210}Po characteristic in selected thermal water sources in Northern Vietnam. Journal of Radioanalytical and Nuclear Chemistry, 331(4), 1659–1668. https://doi.org/10.1007/s10967-022-08226-z.

Van-Hao D., Chau Nguyen Dinh, Trinh Phan Trong, Trung-Tien Chu, 2021. Improvements of ^{210}Po determination method in thermal water samples. Vietnam J. Earth Sci., 44(2), 195–212. https://doi.org/10.15625/2615-9783/16851.

Van Hao D., Nguyen C.D., Nowak J., Kovacs T., Hoang Q.A., 2019. Uranium and radium isotopes in some selected thermal, surface and bottled waters in Vietnam. J. Radioanal Nucl Chem., 319(3), 1345–1349.

Walsh M., Wallner G., Jennings P., 2014. Radioactivity in drinking water supplies in Western Australia. Journal of Environmental Radioactivity, 130, 56–62.

WHO G., 2011. Guidelines for drinking-water quality. World Health Organization, 216, 303–304.

World Health Organization, 2011. World Health Organization Guidelines for Drinkingwater Quality. fourth ed.

http://www.who.int/water_sanitation_health/publications / 2011/dwq_guidelines/en/ (accessed 4.12.16).

Zhong Q., Wang X., Wang Q., Zhang F., Li L., Wang Y., Du J., 2020. ^{222}Rn, ^{210}Pb and ^{210}Po in coastal zone groundwater: Activities, geochemical behaviors, consideration of seawater intrusion effect, and the potential radiation human-health risk. Applied Radiation and Isotopes, 166, 109386.