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Measurement of Natural Radionuclides in Drinking Water and Risk Assessment in a Volcanic Region of Italy, Campania

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Abstract: The physical–chemical properties of water are closely linked to the geological nature of the site where they are located. This aspect becomes even more interesting when analyzing the natural radionuclides in the drinking water of a volcanic territory such as Campania in southern Italy. This study concerned the measurement of activity concentration of gross alpha and beta, radon, and tritium to evaluate their biological impact. The measurements were carried out using alpha spectrometry for alpha emitters, proportional counter for beta emitters, the electret system for radon in water, and finally liquid scintillation for the measurement of tritium concentration. The biological impact was assessed considering the indicative dose, if applicable, and the effective annual dose of radon. Although the results show that the values are below international and national references, the radiological characterization of drinking water is of fundamental importance to optimize the radiation protection of the population.

Keywords: drinking water; natural radionuclides; gross alpha; gross beta; radon; tritium; radiological impact; internal exposure

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1. Introduction

Drinking water is one of the limited but necessary resources for life. It presents a matrix in which substances harmful to human health are often dissolved and, among these, there are radionuclides. Even if the contamination can be both natural and artificial, it is known that, while it is possible to contain and limit its diffusion for artificial sources, for natural ones, the same approach cannot be applied since they are the most widespread and abundant.

Natural radionuclides are commonly found in drinking water since they are released from the filtration of water in rocks through the process of both erosion and dissolution [1]. The most copious element present in rocks is ^{238}U and its progeny, among which radon (^{222}Rn) is worth mentioning. ^{222}Rn is an imperceptible and ubiquitous noble gas with a half-life of 3.8 days, whose biological effects are best known for internal exposure and for inhalation. In fact, ^{222}Rn and its daughters (^{218}Po, ^{214}Po), once inhaled, can reach the cells of the bronchioles where the emitted alpha particles can cause DNA damages, which could probably lead to cancer [2–6]. According to epidemiologic studies, in 2009, the World Health Organization (WHO) recognized gas radon as the second cause of lung cancer after smoking [7] and, before that in 1998, the International Agency for Research on Cancer (IARC) identified radon as carcinogens of group 1 [8]. Another scenario of internal exposure to radon gas is ingestion. Although radon is the most commonly present

radionuclide in water, it is relatively insoluble in water, and its solubility is inversely proportional to temperature [9,10]. Furthermore, the use of water releases radon into the indoor air, thus, 90% of the dose of ^{222}Rn in drinking water is due to inhalation rather than digestion [11]. For these considerations, also reported by ICRP n. 103 [12], the World Health Organization (WHO) in the Guidelines for Drinking-Water Quality reports that "the setting of screening levels and guidance levels to limit the dose from ingestion of radon contained in drinking-water is not usually necessary" [13]. However, ingesting radon through water can also pose a direct health risk since radon remains in the stomach and could irradiate sensitive intestinal tract cells before passing through the small intestine to the blood and rapidly being expelled from the body [14,15]. Therefore, radon in drinking water could potentially produce adverse health effects in addition to lung cancer, even though there are no studies that show the connection between radon and stomach tumor [16]. Additionally, the biological impact of other radionuclides is considered relevant given the accumulation of ^{228}Ra, ^{226}Ra, ^{210}Po in bones and teeth [17] or the potential correlation between ^{40}K and the development of tumors [18].

The radiation exposure due to the alpha emitters is commonly higher than the beta ones since alpha particles have a high LET and, therefore, they can deliver high amounts of energy in a small distance [19,20]. In fact, another screening parameter for approaching radiological risk management in drinking water is measurements of the gross α and β activity concentration. This kind of measurement is frequently adopted due to its simplicity and low cost [21,22], even if it does not take into consideration the specific radionuclides for the alpha emitters [13,21,23,24]. Conversely, the technique used for the evaluation of the gross beta activity can detect most of the beta particles emitters that can be found in water in non-emergency situations. Nevertheless, some radionuclides, such as ^{3}H, ^{14}C, and ^{35}S, cannot be revealed because of their lack of emissions or their low emission energy [13,25]. This evaluation includes Potassium-40 (^{40}K), a very widespread radionuclide beta-gamma emitter of primordial origin. Another element present in the water is tritium, a cosmogenic radioactive isotope of hydrogen that decays in helium-3 (^{3}He) through the emission of electrons (β-). Tritium forms in the atmosphere and falls such as rain, and its activity concentration in drinking waters is of the order of a few Bq/L [26]. It could also be produced by anthropogenic activities (research and nuclear power plants) but represents a very small fraction. Generally, an adult human being ingests approximately 500 Bq/year drinking 730 L of water per year, absorbing an average annual dose of 0.01 µSv [27]. Tritium can occur in three different forms: as tritium water (HTO), tritium gas (HT), and bound to organic molecules (OBT) [28]. While the majority of tissue irradiation is due to the absorption or internal formation of HTO, since it is distributed throughout the body, the inhalation of tritiated water vapor is almost completely absorbed by the lungs and the skin through the exchange process of perspiration [29–31]. Unfortunately, there are not many epidemiological studies that evaluate the effects of tritium exposure alone [32], and the few available do not contain enough details necessary to the assessment of the risks correlated to the exposure to this element [33,34].

From the analysis of this scenario, it is clear how important it is to monitor the activity concentration of radionuclides in drinking water and that this must be regulated.

Globally, WHO does not provide guidance for the monitoring of radon gas in water and the management of risk from ingestion, assuming that it is instead necessary to monitor the concentration of radon activity in the air for the management of internal exposure by inhalation. Screening levels are 0.5 Bq/L for gross alpha activity and 1 Bq/L for gross beta activity. If none of these values is exceeded, the Individual Dose Criterion (IDC) of 0.1 mSv/year will not be exceeded either. In the case that the gross beta activity is higher than the screening levels, the contribution of ^{40}K must be subtracted, and the residual beta activity is calculated. Finally, for radionuclides that emit low-energy beta activity, such as tritium, routine analysis is not necessary. However, specific measurement techniques can be used [13].

Therefore, if a country wants to establish a national screening level for radon in drinking water, it should be based on the national reference level for radon in indoor air. This is the case of European Member States [35], which must also set a parameter value (screening level) of 100 Bq/L, above which it is necessary to assess the risk and the corrective actions to be taken. Each Member State can based on the data of its territory, define a value for the parameter value between 100 and 1000 Bq/L and the indicative dose (ID), which is the effective dose for 1 year of ingestion resulting from both artificial and natural radionuclides except for tritium, potassium-40, radon, and its short-lived decay products.

The Italian legislation regulates the radioactivity levels in waters intended for human consumption through the Decree-Law n. 28/2016 [36], which implemented the European Directive 51/2013/EURATOM.

This decree manages the activity of natural radionuclides found in drinking waters of the distribution network, contained in tanks, bottles, or other vessels, and the ones used in the food business. The regulatory decree does not include natural mineral waters nor medical waters since their control is destined to regions and autonomous provinces through the implementation of several control programs evaluated and examined by the Ministry of Health [36].

Last but not least, an important aspect is the geological and hydrogeological contextualization of the area, the radioactivity of the rock, the soil, and the well.

This study reports, for the first time, the analysis of natural radionuclides activity concentration in drinking water inside the wells, in a volcanic territory, Campania region (southern Italy), subject of radiological characterization investigations also conducted by our team due to the great radiological interest it represents [37–57]. In addition, the annual effective dose due to radon ingestion was evaluated, questioning the hypothesis that in a volcanic region, the exposure to natural ionizing radiation is higher than in other territories.

2. Materials and Methods

2.1. Area of Sampling and Characterization

The samples analyzed in this study were collected by operators with specialized training of the Gori S.p.A., the company that deals with water management in the western area of the Campania region, during a timeframe of 3 years (May 2017–May 2019). The study area involved 32 municipalities (Figure 1) with 95 sampling points (wells), totaling 207 samples. The sites of sampling can be grouped into 3 water subsystems: Monti Lattari, Ausino, and Vesuviano.

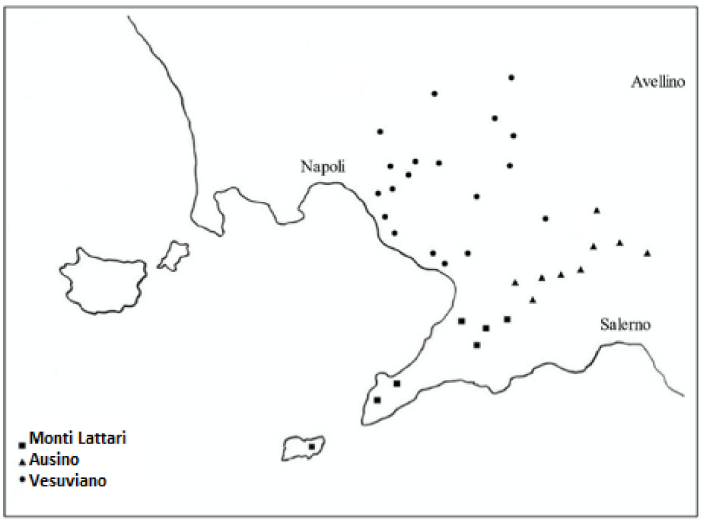


Figure 1. Schematic distribution of the water sources in Campania region for sample collection.

The analyses of the samples were carried out by the Radioactivity Laboratory (LaRa) of the Department of Physics of the University of Naples "Federico II," according to UNI EN ISO 9001:2015.

2.2. Sample Preparation for α and β Measurements

The measurement of the gross alpha and beta activity was carried out according to the technique described by EPA 900 [58]. The samples were prepared with the following procedure:

- Take 50 mL of stabilized sample;
- Let the sample evaporate almost completely on a plate at 250 °C;
- Add 5 mL of HNO_3 16N and reduce the volume of the sample (twice);
- Add 10 mL of 1N HNO_3;
- Cool the sample.

Once this procedure was completed, the sample needed to be moved on a plate according to the following procedure:

- Add small amounts of the sample on the plate at 150 °C until reaching the complete transfer of the sample;
- Wait for the complete evaporation of the sample;
- Dry the sample at 250 °C for 2 h;
- Make sure that the plate is completely free of moisture and that the layer of the sample is as homogeneous as possible.

2.3. Sample Preparation for Tritium Measurements

The method used to gauge the tritium concentration in the samples is the one defined in the UNI EN ISO 9698 [59], which provides the necessary procedure to measure the activity concentration of tritium in drinking waters through liquid scintillation counting. This technique involves the distillation of the sample to eliminate any chemical or radiometric interference according to the following procedure:

- Take 140 mL of sample;
- Add 150 mg of sodium thiosulfate;
- Add 300 mg of sodium carbonate;
- Discard the first 40 mL of the distilled sample;
- Collect 50 mL of the sample from its intermediate portion.

Afterwards, the aliquot of the sample was transferred into a polyethylene vial to perform the liquid scintillation counting. The procedure used for the preparation of the vial is listed below:

- Put 10 mL of scintillating liquid Ultima Gold PerkinElmer® (Waltham, MA, USA) into the vial;
- Add 10 mL of the distilled sample into the vial, making sure to take an aliquot of the sample at all depths;
- Mix the emulsion;
- Clean the vial on the outside;
- Cover the vial with tinfoil to minimize both the photoluminescence and chemiluminescence interferences, and wait for 2 h.

2.4. Sample Preparation for ^{222}Rn Activity Concentration Measurements

The standard procedure used for the sampling, packaging, and transportation of water samples was ISO 13164-1:2013, then, the sample was put in a 140 mL glass sample bottle with a screw cap and measured as it was without any type of treatment.

2.5. Minimum Detectable Activity

The Minimum Detectable Activity (MDA) is the lowest value of radioactivity that the measurement equipment can register, and it depends on many factors, such as the number of radioactive events, the efficiency of the instrument, or the environmental

background. The detection limits for the different radionuclides are listed in the Decree-Law n. 28/2016 [36], Annex III, and are listed in Table 1.

Table 1. Minimum Detectable Activity (MDA) for each parameter, reference norm, and technique reported in reference [36].

Parameter	Standard Procedure	Used Technique	Calculated Detection Limit (Bq/L)	Detection Limit Required by the Decree-LAW (Bq/L)
Radon	ISO 13164-1	Electret	1	10
Tritium	ISO 9698	Liquid Scintillation	3	10
Gross Alpha	EPA 900	Alpha Spectrometry	0.02	0.04
Gross Beta	EPA 900	Proportional Chamber	0.2	0.2

2.6. Evaluation of Gross Alpha and Beta Activity Concentration

The method used to determine the gross alpha activity concentration involves silicon solid-state detectors. In this study, the Ortec® Alpha Duo spectrometer (Peschiera Borromeo, Milano, IT) and the detectors ULTRA-AS were used, this last characterized by an area of 900 mm^2 that ensures very high efficiency for ultra-low background application [60]. For beta emitters, a proportional counter, the Berthold Technologies Umo LB 123 monitor with the LB 123 probe and LB 7411 lead chamber [61], was used to allow the counting of radiations and their differentiation.

The gross alpha and beta activity was calculated using the following equation:

$$C = \frac{CPS_{net}}{Efficiency} \cdot \frac{1}{V} \; [Bq/L] \tag{1}$$

where CPS_{net} indicates the counts per second, obtained through the subtraction of the background value from that of the sample; V is the sample volume equal to 0.05 L; and the efficiency is equal to 0.0332 for the alpha spectrometry and 0.105 for the beta spectrometry.

The values of the efficiencies were obtained using sources of known activity, such as Am-241 (Emax = 5.48 MeV) for the alpha spectrometry, and H-3 (Emax = 18.6 keV), and C-14 (Emax = 156 keV), respectively, for low and high energies, for the beta spectrometry. The background activity was measured using a distilled water sample.

2.7. Determination of Tritium Activity Concentration

Tritium activity concentration was measured through liquid scintillation counting with the PerkinElmer® Wallac 1220 Quantulus (Ultra Low-Level Liquid Scintillation Spectrometer). This spectrometer was equipped with 3 trays, each of which can contain 20 samples for a total of 60 vials. Using the Tritium Configuration [62], provided by the instrument itself, the samples were analyzed for 5 h. The background activity, which must be measured every time the type and/or batch of the scintillating liquid is changed, was analyzed in the same timeframe. Tritium activity concentration was determined through the following equation:

$$C_{net} = C_T - C_{BKG} \left[\frac{Bq}{L}\right] \tag{2}$$

where C_{net} is the final concentration; C_T is the tritium concentration in the sample; and C_{BKG} is the background concentration, which was determined as the average of several measurements.

The error on those measurements was calculated through the following equation:

$$\sigma = \sqrt{(err_T)^2 + (err_{BKG})^2} \tag{3}$$

2.8. Measurements of Radon Activity Concentration

The system used to measure the radon activity concentration was the Electret Ion Chamber (EIC) E-Perm® system [63]. As reported by Kotrappa et al. [64], the equipment including:

- Electrometer (Rad. Elec. Inc. Mod. 6383-01, Frederick, MD, USA);
- 140 mL glass bottle with screw cap used to collect the water sample;
- 4 L glass jar with hermetically sealed ring cap;
- E-Perm® chamber in Short-Short Term (SST) configuration.

Once transported to the LaRa laboratory, each bottle containing the water sample was opened and immediately placed in the glass jar with the E-Perm® chamber suspended in the SST configuration. The jar holding both the electret and the sample was airtight sealed for 94 h to allow radon to reach equilibrium with its offspring. Radon activity concentration was calculated using the formula provided by the manufacturer of the used equipment [65,66]:

$$CRn(water) = CRn \cdot B1 \cdot B2 \cdot B3; \quad (4)$$

$$CRn = \left[\frac{\left(V_i - V_f\right)}{(CF \cdot T)} - G_\gamma C1 \right] \cdot 37 \quad (5)$$

$$CF = C2 + C3 \cdot \frac{\left(V_i + V_f\right)}{2} \quad (6)$$

where CRn indicates the radon concentration in the air inside the jar; $B1$ takes into account the delay period between the collection of the sample and the start of the measurement; $B2$ is a constant based on analysis period; $B3$ indicates the ratio between the volume of the jar and the one of the water sample; V_i and V_f indicate, respectively, the electret voltage before and after the exposure; T is the exposure time; G_γ indicates the gamma radiation background; and $C1$, $C2$ and $C3$ are constants provided by the E-Perm® chamber manufacturer and are, respectively, equal to 0.097, 1.670, and 5.742×10^{-4}.

CF is the calibration factor in Volts Bq m^{-3} d.

The error was calculated through the following equations:

$$\sigma = \frac{CRn(water)}{\sigma_{\%}} \cdot 100; \quad (7)$$

$$\sigma_{\%} = \sqrt{\left(\sigma_{fix}\right)^2 + (\sigma_{elect})^2 + (\sigma_{BKG})^2} \quad (8)$$

where $\sigma_{fix} = 5$, $\sigma_{elec} = (1.4 \times 100)/(V_i - V_f)$ and $\sigma_{BKG} = 0.01 \times (C_{BKG}/CRn)$.

2.9. Indicative Dose (ID)

If the gross alpha and beta activity concentrations were a result greater than, respectively, 0.1 Bq/L and 0.5 Bq/L, it was necessary to determine the concentration of specific radionuclides, to determine whether exceeding screening levels leads to exceeding 0.1 mSv for DI. For the gross beta activity concentration, the exceedance of the reference value may be due to the presence of ^{40}K. Therefore, it was preferable to replace the gross activity with the residual one obtained through the evaluation and subtraction of ^{40}K. The ID was calculated based on the activity concentrations of radionuclides and using the reported dose coefficients Directive 96/29/Euratom [35]. Based on these dose coefficients and assuming an annual water intake of 730 L, the derived activity concentrations were calculated for the individual radionuclides, which corresponded to an effective dose of 0.1 mSv/year (Table 2). The ID was calculated according to the following formula:

$$\sum_1^n \frac{C_i(obs)}{C_i(der)} \times 0.1 \quad (9)$$

where $C_i(obs)$ is the observed concentration of the i-th radionuclide, and $C_i(der)$ is the derived concentration of the i-th radionuclide.

Table 2. Derived activity concentration of radionuclides in drinking water ([36], Annex 3).

Origin	Radionuclide	Derived Activity Concentration (Bq/L)
Natural	^{238}U	3.0
	^{234}U	2.8
	^{226}Ra	0.5
	^{228}Ra	0.2
	^{210}Pb	0.2
	^{210}Po	0.1
Artificial	^{14}C	240
	^{90}Sr	4.9
	$^{239}Pu/^{240}Pu$	0.6
	^{241}Am	0.7
	^{60}Co	40
	^{134}Cs	7.2
	^{137}Cs	11
	^{131}I	6.2

2.10. Estimation of ^{222}Rn Effective Annual Dose (EAD)

The assessment of radon radiological effects was provided by EAD received by the population.

For EAD calculation, the yearly consumption of water must be taken into consideration. The average water consumption rates [67], listed in Table 3, were divided into 3 different categories (infants, children, and adults) distributed through 6 groups (G1–G6).

Table 3. The average consumption rate of water for each age category, as reported in reference [67].

Age Category	Age Group	Age Range (Years)	Average Consumption Rate (L/year)
Infants	G1	0–1	200
Children	G2	1–2	260
	G3	2–7	300
	G4	7–12	350
	G5	12–17	600
Adults	G6	>17	730

The EAD was given by the following Equation (10):

$$EAD = A \times C \times DCF \quad (10)$$

where A indicates radon activity concentration in water (Bq/L); C is the average consumption rate (L/year); and DCF is the dose coefficient factor, which is equal to 3.5×10^{-9} (Sv/Bq).

3. Results and Discussion

As previously mentioned, the Decree-Law n. 28/2016 [36] regulates the activity concentration of the radioactive elements found in drinking water and indicates the reference levels listed in Table 4. The exceedance of these levels, which are not to be confused with limit values, entails the assessment of the risks for human health to require the adoption of measures that actively improve the quality of the water.

Table 4. Reference levels for activity concentration of radiological parameters evaluated in drinking water [36].

Parameter	Reference Level (Bq/L)
Gross Alpha Activity	0.1
Gross Beta Activity	0.5
Radon Activity Concentration	100
Tritium Activity Concentration	100

3.1. α and β Activity Concentration

The results revealed that the gross alpha activity concentration values fell within the regulatory reference value of 0.1 Bq/L. The estimated values for each water subsystem, 46% of which resulted lower than the MDA level, are listed in Table 5, while the variability of the gross alpha activity concentration values with the water subsystem is shown in Figure 2.

Table 5. Mean values of gross alpha activity concentration for each water subsystem analyzed.

Water Subsystem	Mean Value (Bq/L)	Minimum Value (Bq/L)	Maximum Value (Bq/L)
Monti Lattari	0.05 ± 0.03	0.005 ± 0.002	0.08 ± 0.04
Ausino	0.04 ± 0.02	0.0006 ± 0.0002	0.09 ± 0.06
Vesuviano	0.04 ± 0.02	0.0010 ± 0.0003	0.09 ± 0.04

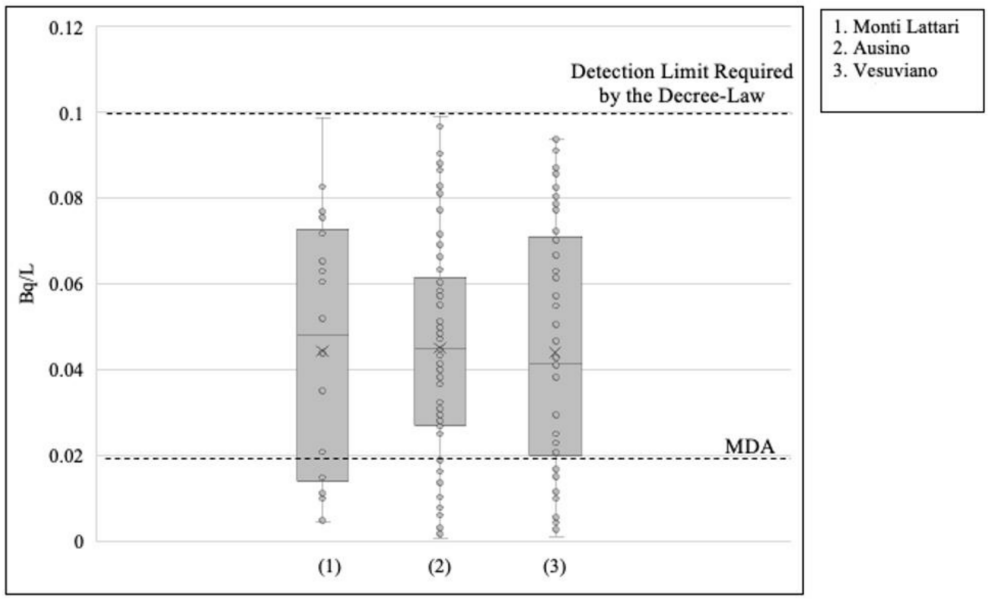


Figure 2. Variability of alpha activity concentration of the water subsystems. The graph reports median, 25th, and 75th percentile. Additionally, two horizontal lines represent the value of the MDA equal to 0.02 Bq/L and the detection limit required by the Decree-Law equal to 0.10 Bq/L.

Regarding the gross beta activity concentration values, only 16 samples did not fall within the reference value of 0.5 Bq/L (Table 6). However, after calculating the residual activity concentration, all values resulted lower than the MDA.

Table 6. Gross beta activity concentration of 16 samples and the calculated residual beta activity concentration.

Sample ID	Gross Beta Activity Concentration (Bq/L)	Residual Beta Activity Concentration (Bq/L)
17_017	1.03 ± 0.15	<0.2
17_041	2.11 ± 0.30	<0.2
17_042	0.77 ± 0.11	<0.2
17_044	0.77 ± 0.11	<0.2
17_045	0.51 ± 0.07	<0.2
17_054	1.01 ± 0.14	<0.2
17_056	1.22 ± 0.17	<0.2
17_057	1.01 ± 0.14	<0.2
17_058	1.25 ± 0.18	<0.2
17_075	0.94 ± 0.13	<0.2
17_078	1.22 ± 0.17	<0.2

Table 6. *Cont.*

Sample ID	Gross Beta Activity Concentration (Bq/L)	Residual Beta Activity Concentration (Bq/L)
17_120	0.86 ± 0.12	<0.2
17_127	1.15 ± 0.16	<0.2
17_137	1.67 ± 0.24	<0.2
17_138	1.79 ± 0.25	<0.2
17_139	3.29 ± 0.47	<0.2

The values calculated for the different water subsystems are listed in Table 7, and the variability of the activity concentration values with the water subsystem is shown in Figure 3.

Table 7. Mean values of gross beta activity concentration for each water subsystem analyzed.

Water Subsystem	Mean Value (Bq/L)	Minimum Value (Bq/L)	Maximum Value (Bq/L)
Monti Lattari	0.33 ± 0.09	0.030 ± 0.004	0.43 ± 0.03
Ausino	0.26 ± 0.15	0.0032 ± 0.0004	0.48 ± 0.08
Vesuviano	0.3 ± 0.1	0.10 ± 0.01	0.48 ± 0.07

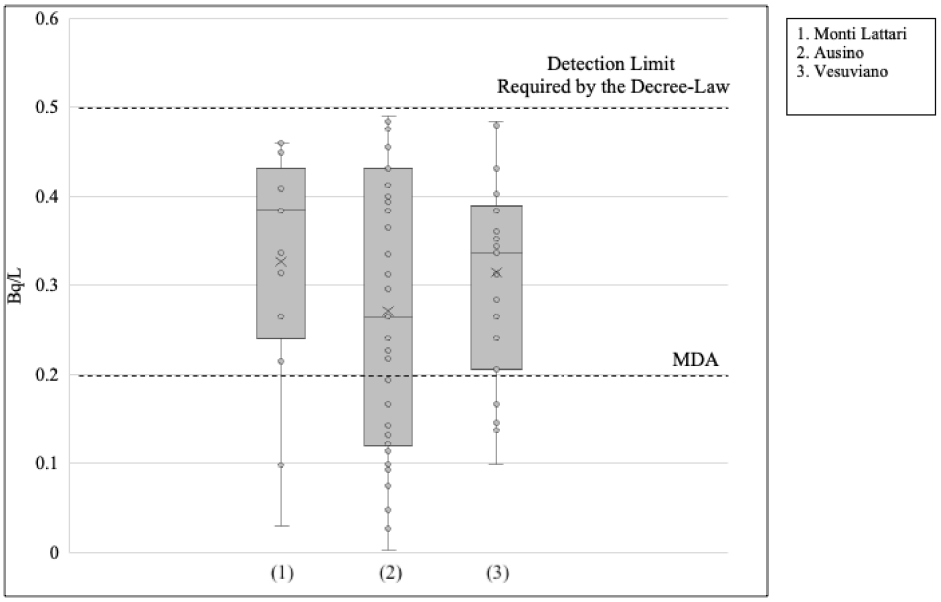


Figure 3. Variability of alpha activity concentration of the water subsystems. The graph reports median, 25th, and 75th percentile. Additionally, two horizontal lines represent the value of the MDA equal to 0.2 Bq/L and to the detection limit required by the Decree-Law equal to 0.5 Bq/L.

From the results obtained in this study, it was evident that all the values of the gross alpha and beta activity concentration were below the limit established by the decree. Nevertheless, there were several points for which a more in-depth investigation would be necessary. To identify those points, a critical value, defined as 90% of the reference value established by the Decree-Law n. 28/2016 [36], was identified. In particular, the critical value for the gross alpha activity concentration was equal to 0.09 Bq/L, while it was 0.45 Bq/L for the other parameter. Subsequently, samples with activity concentration above this critical value were selected, and multiple measurements were carried out in a timeframe of three years. During this period, while some samples showed a decrease in the gross alpha and beta activity concentration, sometimes even below the MDA, others did not follow this trend. Therefore, further investigations of this site were deemed fundamental.

3.2. Tritium Concentration

The tritium activity concentration values of all the samples analyzed in this study resulted in lower than the reference level of 100 Bq/L. Furthermore, 17% of these values fell within the MDA level, while the remaining 83% resulted higher. The variability of the activity concentration values with the water subsystem is shown in Figure 4, and the values for each water subsystem are reported in Table 8.

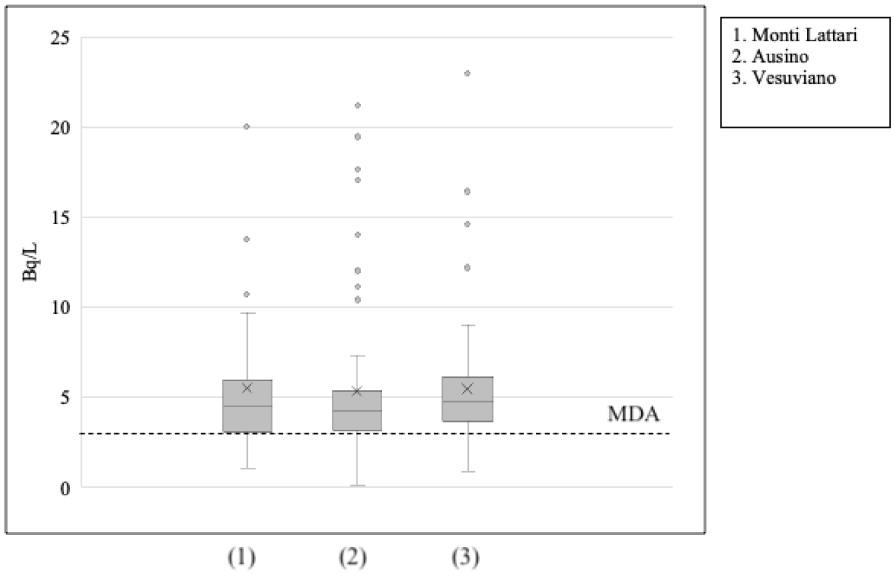


Figure 4. Variability of tritium concentration of the water subsystems. The graph report median, 25th, and 75th percentile. The graph reports a horizontal line in correspondence to the value of the MDA equal to 3 Bq/L.

Table 8. Values of tritium concentration for each water subsystem analyzed.

Water Subsystem	Mean Value (Bq/L)	Minimum Value (Bq/L)	Maximum Value (Bq/L)
Monti Lattari	8.49 ± 5.50	1.06 ± 1.35	20.00 ± 2.84
Ausino	5.80 ± 4.10	0.13 ± 1.47	21.20 ± 3.04
Vesuviano	5.11 ± 2.19	0.83 ± 1.52	12.19 ± 2.80

Since the tritium activity concentration values are lower than the reference level set by the decree, further investigations are not necessary. This result highlights that the tritium found in drinking water has natural origins and, therefore, it is not a residue of the nuclear period or a pollutant from illegal contaminations.

3.3. Radon Activity Concentration

Radon activity concentration values resulted lower than the reference level of 100 Bq/L. The assessed values are listed in Table 9, while the variability of the activity concentration with the water subsystem is shown in Figure 5.

Table 9. Mean values of radon activity concentration for each water subsystem analyzed.

Water Subsystem	Mean Value (Bq/L)	Minimum Value (Bq/L)	Maximum Value (Bq/L)
Monti Lattari	8.31 ± 0.09	3.4 ± 0.5	16.7 ± 0.9
Ausino	9.38 ± 0.07	3.2 ± 0.3	48.1 ± 1.4
Vesuviano	6.11 ± 0.06	1.3 ± 0.3	27.3 ± 1.4

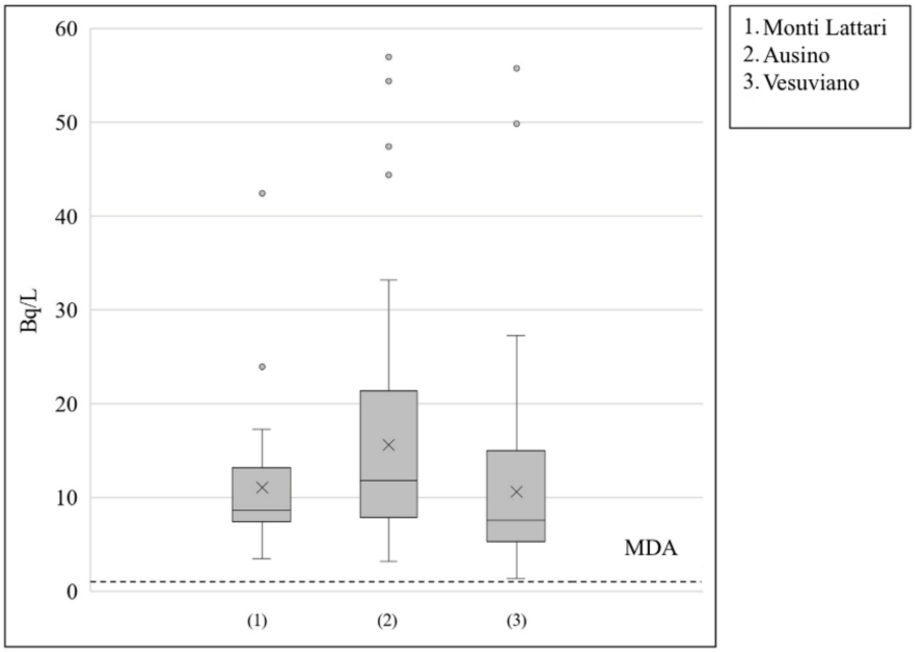


Figure 5. Variability of radon concentration of the water subsystems. The graph report median, 25th, and 75th percentile. Additionally, two horizontal lines represent the value of the MDA equal to 1 Bq/L.

These data do not differ significantly among the analyzed water subsystems, therefore, we do not believe that further investigation on the activity concentration of radon in water and the nature of the soil is necessary.

3.4. ^{222}Rn Effective Annual Dose (EAD)

The EAD to assess the radon exposure to the population was calculated with the method described in the previous paragraph. The dose was calculated for both the mean and the maximum value of radon activity measured in water, and the results are listed in Table 10.

Table 10. Mean and maximum effective annual dose calculated for each water subsystem. The calculated doses are divided into three different categories (infants, children, and adults) distributed through six groups (G1–G6).

Water Subsystem	Age Group (years)	Mean Effective Annual Dose (mSv/year)	Max Effective Annual Dose (mSv/year)
Monti Lattari	G1 (0–1)	0.0058 ± 0.0001	0.0117 ± 0.0006
	G2 (1–2)	0.0076 ± 0.0001	0.0152 ± 0.0008
	G3 (2–7)	0.0087 ± 0.0001	0.0176 ± 0.0009
	G4 (7–12)	0.0102 ± 0.0001	0.0205 ± 0.0011
	G5 (12–17)	0.0175 ± 0.0002	0.0352 ± 0.0018
	G6 (>17)	0.0212 ± 0.0003	0.0428 ± 0.0022
Ausino	G1 (0–1)	0.0066 ± 0.0001	0.0337 ± 0.0010
	G2 (1–2)	0.0085 ± 0.0001	0.0438 ± 0.0013
	G3 (2–7)	0.0098 ± 0.0001	0.0505 ± 0.0015
	G4 (7–12)	0.0115 ± 0.0001	0.0589 ± 0.0017
	G5 (12–17)	0.0197 ± 0.0001	0.1010 ± 0.0030
	G6 (>17)	0.0240 ± 0.0002	0.1228 ± 0.0036
Vesuviano	G1 (0–1)	0.0043 ± 0.0001	0.0191 ± 0.0010
	G2 (1–2)	0.0056 ± 0.0001	0.0248 ± 0.0013
	G3 (2–7)	0.0064 ± 0.0001	0.0287 ± 0.0015
	G4 (7–12)	0.0075 ± 0.0001	0.0334 ± 0.0017
	G5 (12–17)	0.0128 ± 0.0001	0.0573 ± 0.0029
	G6 (>17)	0.0156 ± 0.0001	0.0697 ± 0.0035

As it is possible to see from the data recorded in Table 10, the Ausino subsystem is characterized by a dose higher than the others. In particular, the Group 6 of the Adults (>17 years) presents a maximum dose of 0.1228 ± 0.0036 mSv/year. Conversely, the Vesuviano subsystem presents a minimum dose of 0.0043 ± 0.0001 mSv/year for the Group 1 of the Infants (0–1 years). These results are probably due to the peculiar geology of the Region and its volcanic origins.

4. Conclusions

This study investigates the radiological aspect of the quality of drinking water in a large area of the Campania region, which is divided into three different water subsystems and the distribution company identifies with: Monti Lattari, Ausino, and Vesuviano. The gross alpha and beta, tritium, and radon activity concentrations were assessed. All the obtained results fall within the reference values of 0.1 and 0.5 Bq/L, respectively, for gross alpha and beta provided by the Decree-Law n. 28/2016 [36]. Therefore, the analyzed waters do not present a risk to human health. Additionally, the values of both tritium and radon activity concentration are well below the reference level set by the legislation of 100 Bq/L, thus additional investigations are not considered necessary.

Nevertheless, the ^{222}Rn EAD was calculated to indicate the mean and maximum dose to the population due to ingestion of radon found in drinking water. In order to illustrate a more likely scenario, we adopted the consumption rates indicated in the IAEA report [67], as shown in Table 3, instead of 60 L/year considered by UNSCEAR report [11]. Our results show that radon found in drinking water in the western area of the Campania region does not represent a health risk for the population. Nevertheless, ^{222}Rn EAD calculated for the Ausino subsystem are slightly higher than the ones of the other sampling areas. In particular, ^{222}Rn EAD for the Adults (Group 6) is equal to 0.1228 mSv/year, probably because of the geological settings of the territory in question.

Such a thorough and capillary investigation, which uses an approach that goes beyond the indications contained in Legislative Decree 28/2016, allows to optimize the monitoring activity and improve the assessment of the radiological risk of drinking water.

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