



Radiological risk assessment to the public due to the presence of radon in water of Barnala district, Punjab, India

Supriya Rani · Sandeep Kansal · Amit Kumar Singla · Rohit Mehra

Received: 24 November 2020 / Accepted: 14 June 2021 / Published online: 26 June 2021
© The Author(s), under exclusive licence to Springer Nature B.V. 2021

Abstract Various research studies have shown that exposure to radon gas is a cause of concern for health effects to the public. The present work has been carried out for the radiological risk assessment to the public due to the presence of radon isotopes in drinking water of Barnala district of Punjab, India, for the first time using scintillation-based radiation detector. A total of 100 samples were collected from different sources of water (canal and underground water) from 25 villages on grid pattern of $6 \times 6 \text{ km}^2$ in the study area for uniform mapping. In situ measurements were carried out to find out Rn-222 concentration in water samples. The measured values have been found to vary from 0.17 ± 0.01 to $9.84 \pm 0.59 \text{ BqL}^{-1}$ with an average value of $3.37 \pm 0.29 \text{ BqL}^{-1}$, which is well below the recommended limit of 100 BqL^{-1} (WHO 2004). The annual effective dose due to ingestion and inhalation of radon has also been calculated for various age groups like infants, children and adults to understand the age-wise dose distribution. The calculated values suggest that there is no significant health risk to the general public from radon in water.

Keywords Radon · Smart RnDuo · Radiological risk · Age-wise ingestion and inhalation dose

Introduction

Exposure of humans to radon gas is a cause of concern and many pooled as well as individual studies have been carried out to find the radiation levels and so the radiological health risk to the general public. About 90% of radiation exposure to humans is from natural sources like cosmic, terrestrial and internal (S Kansal et al. 2015). Among the various sources of natural ionizing radiations present on the earth, Rn-222 alone contributes to more than 50% of the total dose received by the general public (UNSCEAR, 2000; Parminder Singh et al., 2015) and is known to be the second largest cause of lung cancer after smoking (WHO, 2009; H. Al-Zabadi et al. 2015). Radon, a progeny of uranium, is an inert, colourless and odourless gas found in numerous kinds of rocks like granites, metamorphic rocks and sedimentary rocks containing phosphate (Errol Lowerence et al. 1991; Linda C.S. Gunderson et al. 1992; Fernando P. Carvalho et al., 2007). Radon gas is fifteen times more soluble than other noble gases like helium and neon in water and is dissolved and transported with the water when underground water moves through radium-rich soil and rocks. The existence of natural radioactivity in water is

S. Rani · S. Kansal (✉) · A. K. Singla
Department of Physics, Maharaja Ranjit Singh Punjab
Technical University, Bathinda 151001, India
e-mail: skansal2k1@gmail.com

R. Mehra
Department of Physics, Dr. B.R. Ambedkar, National
Institute of Technology, Jalandhar 144011, India

based on the local geological conditions of the source, soil or rocks (Fatima et al., 2007). Dissolved radon in water may enter into indoor air through de-emanation when water is used for showering, laundry (UNSCEAR, 2000).

A report by the National Research Council of the United States attributed 3,000 to 32,000 lung cancer deaths per year (with a mean of about 19,000 deaths annually) to Rn-222 and its short-lived progeny in indoor air (NCBI, 1999). Furthermore, there is a plethora of the literature suggesting that there is no safe level for stochastic (probabilistic) effects to occur (Tsoulfanidis et al. 2015). Several studies on radon and its correlation with geology have been attempted in different parts of the world (Choubey & Ramola, 1997; Ramola et al., 1989; Tanner, 1986). From various epidemiological combined investigation of seven North American case–control studies, it was established that radon in homes increases the risk of lung cancer to the local population (Lubin et al. 1995, 1997; D Krewski et al., 2005; Singla et al., 2021a). In a study by Henshaw, it was revealed that indoor radon concentration is related to leukaemia and certain different malignancies (Henshaw et al. 1990). According to USEPA, 1991, consumption of water causes 168 cancer deaths every year, 89% of lung cancer deaths were caused by breathing in radon released to the indoor air from water and 11% of stomach cancer deaths were caused by consuming water containing radon (USEPA, 1991; Rohit Mehra et al., 2015; Singla et al., 2021b). Radioactive contamination can lead to various life-threatening diseases like cancer and renal failures (Paivi Kurttio et al., 2006; K Skeppstorm et al. 2007; S Kansal et al., 2011). Radon progenies can also stick to aerosol particles thereby exposing indoor occupants to elevated radon exposure (Mishra et al. 2008). These progenies deliver most of the dose to tissues, thereby damaging the genetic material and leading to mutations. ICRP recommends a threshold exposure limit of 1 mSv per year for general public and 20 mSv per year for radiation workers for the total dose received for all sources (ICRP 2010). However, as per the United States Nuclear Regulatory Commission (US-NRC), exposure levels to individuals must be kept ‘as low as reasonably achievable’ (principle of ALARA). Besides acting as an indicator for uranium deposits, Rn-222 has some unique properties due to which it finds its use as a geophysical tracer for locating faults and geological structures (Tanner, 1986; Nazir et al., 2020a). However,

the most important aspect of studying radon is the radiological hazard it poses to general public (Bajwa et al., 2005; Nazir et al., 2020b, c).

Water, being a basic component of all life forms, is essential for the survival of all living beings. It is therefore imperative to test water for such toxic and radiological components. Keeping in view the significance of the adverse health effects of radon, many studies have been carried out worldwide for quantifying radon in water. The present study in Barnala district of Punjab, India, has been carried out for the first time using Smart RnDuo to find the radiological risk assessment to the public. The ingestion and inhalation doses for various age groups like infants (1–2 year), children (8–12 year) and adults (above 17 year) have also been calculated. The data obtained in this study will add to the relevant scientific data pool for the radon mapping of the country.

Study area

Figure 1 shows the study area with latitude of 30°22′28.24″ North and longitude of 75°32′55.32″ East. The total geographical area of this district is 1410 km². According to the Central Ground Water Board (2013) the hydrogeology of the area, is occupied by Indo Gangetic alluvial plain of quaternary age and falls in Ghaggar sub basin. The groundwater occurs in alluvium formations comprising fine to coarse sand which form potential aquifer. The rocks of the Aravalli-Delhi subgroup and the Malani igneous suite comprise grey-wacke, ortho-quartzites, carbonate-sediments, calcareous shale and slates and the high-heat-producing granites and felsites from the basement in region. There is no drainage system in the area except the Dhuala drain which intersects its territory. This drain carries flood water when heavy rainfall occurs in the catchment area. Abohar branch of Sirhind canal system passes in south-eastern part of the district. The groundwater is alkaline in nature (H.S. Virk, 2019). The main sources for drinking water in the study area comes from the canal and groundwater.

Methodology

The study area is divided into grid pattern of 6 × 6 km² for uniform mapping. A total of 100 water

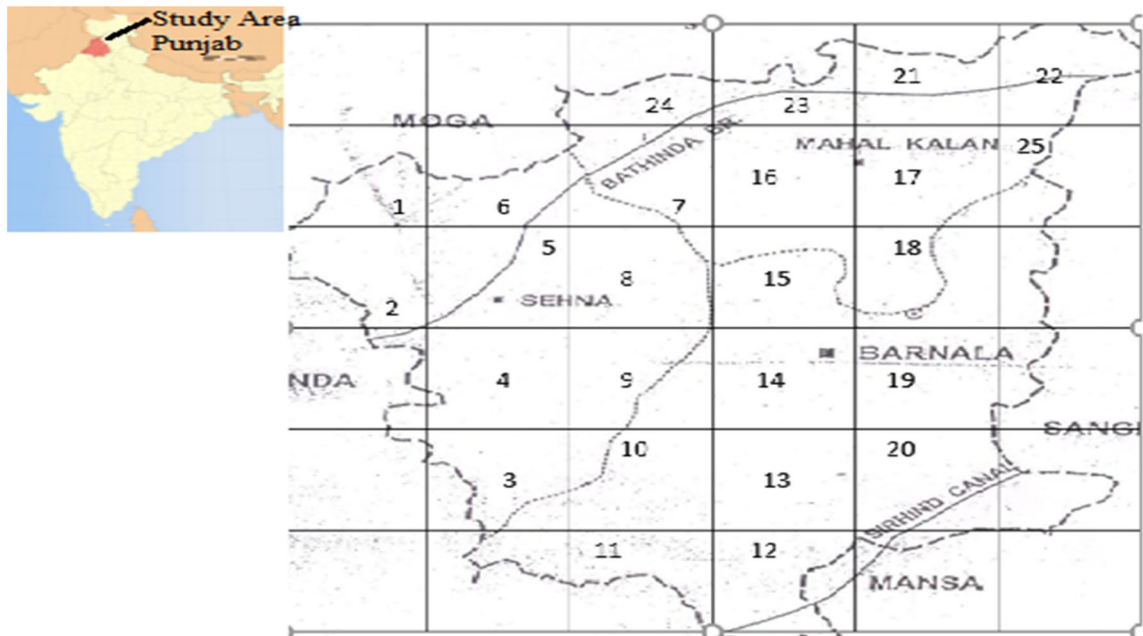


Fig. 1 Map of study area (grid pattern), Barnala district, Punjab

samples were procured from 25 different villages with four samples (2 canal water, 2 underground water) from each village in each grid. The samples were collected in 60 mL airtight cleaned glass bottles. The samples were collected underwater by putting the sampling water bottles in the water container/ bucket (Fig. 2) so that radon could not escape during the sample collection. All sampling bottles were fully filled up to the top ensuring no bubble formation in the sample. The glass bottles have been preferred over other materials as it has more radon retention

ability than other materials (P. Vesterbacka et al., 2010).

To measure Rn-222 concentration in the collected water samples in real time, a scintillation-based radon monitor, Smart RnDuo developed by Radiation Protection & Advisory Division (RP&AD) at Bhabha Atomic Research Centre (BARC), Mumbai, India (J.J. Gaware et al., 2011), has been used. A complete set up for radon monitoring is shown in Fig. 3. Prior to radon estimation, the inbuilt pump was turned on for 5 min to flush the air inside the detector in an open loop, and

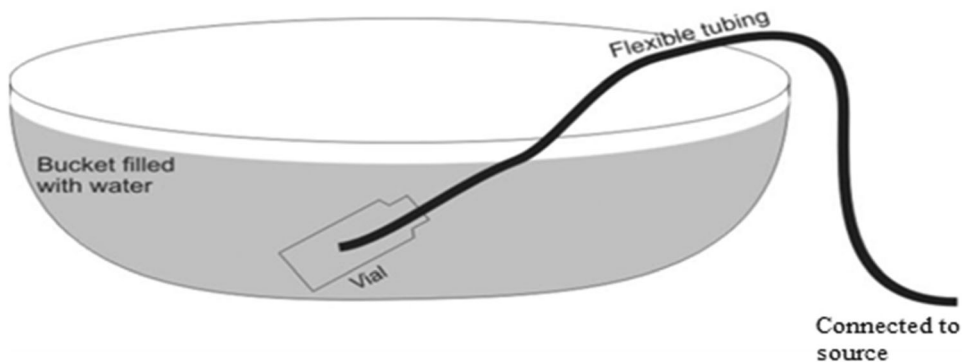


Fig. 2 A schematic set up for water collection from source

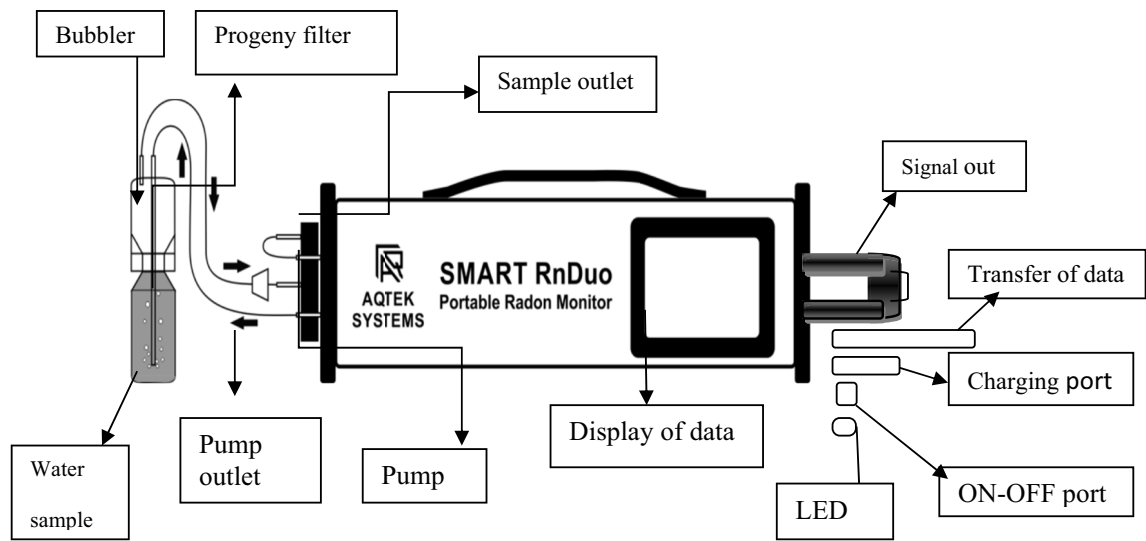


Fig. 3 A setup for measuring radon in water samples

afterwards, sample bottle was connected with bubbler using rubber tubing. The pump was turned on in the closed loop for 5 min for extraction of radon from water. It has been done with the help of bubbler which is fixed on the top of sampling bottle. One end of the tube is connected with air inside the detector, and other end is put inside water bottle through the bubbler in such a way that when pump is in “ON” mode then air moves from detector to the water sample and bubbles are produced in it. The pump was turned off after 5 min and was given 5 min delay for thoron decay and to avoid the impact of the thoron on the radon estimation. The extracted radon (C_{air}) further flows towards detector volume and gathered in scintillation cell by passing through “progeny filters” and “thoron discriminator” eliminating radon/thoron progenies and thoron. The radon measurements in Smart RnDuo are based on the detection of alpha particles emitted from radon, and its decay products formed inside a cell volume which are continuously counted by the PMT and the associated counting electronics. The alpha counts obtained are processed by a microprocessor unit as per the developed algorithm the display the concentration of radon. The sample was analysed in continuous mode for 1 h of 15 min cycle each at constant temperature. Smart RnDuo attains an efficiency of 95% for radon within running time of 15 min. The instrument has minimum detection limit of 8 Bqm^{-3} at 1 sigma and 1 h counting cycle for

radon, whereas the maximum detection limit is 10 MBqm^{-3} (Radon Hand Book developed by BARC, Mumbai, India; Nazir et al., 2020b). The device was calibrated using standard radon-thoron sources (Model RN-1025 & TH-1025) procured from Pylon Electronics Inc. Ottawa, Canada in a 0.5 m^3 calibration chamber at laboratory facility of Bhabha Atomic Research Centre (BARC), Mumbai, India (B.K. Sahoo et al., 2013; Singh et al., 2020). The scintillation detector has two advantages, one is the least effect of humidity and another is that the counting error is less than the allowed limit of 10% (Jobbagy V et al. 2017).

For statistical analysis of the data, OriginLab 8.5, IBM-SPSS and Microsoft Excel 2010 were used (Nazir, 2020).

Calculations

(i) Calculation for radon in water

The following formula is used to estimate the radon concentration in liquid (C_{liq}) from the measured concentration of radon in air (C_{air}) in water samples is given by Smart RnDuo (J.J.Gaware et al., 2011):

$$C_{\text{liq}} = C_{\text{air}} \left(k + \frac{V_{\text{air}}}{V_{\text{w}}} \right) \quad (1)$$

where C_{air} is concentration of radon in air (Bqm^{-3}), C_{liq} is concentration of radon in water (Bqm^{-3}),

V_{air} and V_w are the air and water volumes, and k ($= 0.25$) is partition coefficient between air and water.

(ii) Estimation of annual effective dose due to ingestion and inhalation

The dose exposure due to ingestion and inhalation from the Radon in water has been calculated by the parameters given in UNSCEAR report (2000).

(a) The ingestion dose due to radon concentration in water is given by UNSCEAR, 2000:

$$I_D = C_{liq} \times A_{DWI} \times 365 \times DF \tag{2}$$

where I_D is the ingestion dose per year ($\mu Sv y^{-1}$), C_{liq} is the radon concentration in water, A_{DWI} is the age-wise daily water intake (for infants (0–2 year)(0.8 L), for children (8–12 year)(2.5 L) and for adult (above 17 years) (3L) (WHO, 2004).

and DF is the dose conversion factor for radon ($3.5 nSv Bq^{-1}$) for adults, ($5.9 nSv Bq^{-1}$) for children and ($23 nSv Bq^{-1}$) for infants (UNSCEAR, 2000).

(b) The inhalation dose due to consumption of radon in drinking water is given by UNSCEAR, 2000:

$$Inh_D = C_{liq} \times R_w^a \times \phi_{Rn222} \times o \times DF \tag{3}$$

where Inh_D is the inhalation dose per year ($\mu Sv y^{-1}$), C_{liq} is the radon concentration in water,

R_w^a is the ratio of radon in air and water/ transfer coefficient (10^{-4}), ϕ_{Rn222} is the equilibrium factor between radon and its progeny (0.4), (equilibrium factor is when radon is secular equilibrium with its progeny). o is the time of individual average indoor occupancy ($7000 hy^{-1}$), (ICRP assumes 80% annual indoor occupancy (ICRP 1993) and DF is the dose conversion factor for inhalation of radon ($33 nSv (Bq h m^{-3})^{-1}$) for infants, ($31.4 nSv (Bq h m^{-3})^{-1}$) for children and ($28.3 nSv (Bq h m^{-3})^{-1}$) for adults (Brudecki et al., 2014).

Results and discussion

Table 1 shows the measured radon concentration in all 100 water samples. The concentration varies from a minimum value of $0.17 \pm 0.01 BqL^{-1}$ (Sehra, canal water) to maximum value of $9.84 \pm 0.59 BqL^{-1}$

(Dhanula, canal water) with a mean value of $3.01 \pm 0.29 BqL^{-1}$. These values are lower than the safe limit of $11 BqL^{-1}$ as recommended by USEPA (1991), $100 BqL^{-1}$ by WHO (2004) and $4–40 BqL^{-1}$ by UNSCEAR (2008). The average value in the studied area is slightly more than the $2.72 BqL^{-1}$ in Bathinda district, India (Mehra et al., 2015) but less than $3.63 BqL^{-1}$ in Faridkot district, $4.7 BqL^{-1}$ in Mansa and Muktsar district (Mehra et al., 2015). Figure 4 shows a frequency distribution graph for radon concentration. It has been observed that concentration in 31% of the samples lies between 0–2 BqL^{-1} , in 32% samples it lies between 2–4 BqL^{-1} , and in 37% samples, it lies between 4–10 BqL^{-1} .

Table 1 also shows the annual effective dose due to ingestion and inhalation of radon in drinking water for various age groups. The annual effective dose due to ingestion for infants (0–2 year) lies in the range of 1.54 ± 0.09 to $90.89 \pm 5.41 \mu Sv y^{-1}$ with a mean value of $31.13 \pm 2.68 \mu Sv y^{-1}$, for children (8–12 year) it lies in the range of 1.47 ± 0.09 to $86.48 \pm 5.15 \mu Sv y^{-1}$ with a mean value of $29.62 \pm 2.53 \mu Sv y^{-1}$, and for adults (above 17 years), it lies in the range of 1.32 ± 0.08 to $77.94 \pm 4.64 \mu Sv y^{-1}$ with a mean value of $26.69 \pm 2.3 \mu Sv y^{-1}$. The annual inhalation dose varies from 1.12 ± 0.07 to $66.17 \pm 3.93 \mu Sv y^{-1}$ with a mean value of $22.66 \pm 1.95 \mu Sv y^{-1}$ for infants, 0.9 ± 0.05 to $52.95 \pm 3.15 \mu Sv y^{-1}$ with a mean value of $18.14 \pm 1.56 \mu Sv y^{-1}$ for children and 0.64 ± 0.04 to $37.7 \pm 2.24 \mu Sv y^{-1}$ with a mean value of $12.91 \pm 1.11 \mu Sv y^{-1}$ for adults. The calculated dose values are well below the annual effective dose of $100 \mu Sv y^{-1}$ recommended by WHO (2004, 2008).

From the measured values, a weak correlation ($R^2 = 0.06$) has been found for the radon concentration in groundwater samples with the depth of well (24–153 m) as shown in Fig. 5. Table 2 shows the descriptive statistics using SPSS, from which it has been found that the underground water sources have higher levels for Rn-222 than canal water sources and the same is shown in Fig. 6. This may be because of the reason that underground water directly encounters U-238 rich rocks that release Rn-222 in water and cannot escape to atmosphere (Skeppstorm et al. 2007; A.N. Voronov et al. 2004). Also, radon levels are generally higher in underground water as compared to canal water because of the presence of granite, sand and gravel in the bedrock (Stojkovic et al. 2015). In

Table 1 Radon concentration and annual effective dose due to ingestion and inhalation for various age groups

S. No	Place (Grid no.)	Source	Rn-222 (BqL ⁻¹)	Annual effective dose due to inhalation ($\mu\text{Sv yr}^{-1}$)			Annual effective dose due to ingestion ($\mu\text{Sv yr}^{-1}$)		
				Infants (0–2 yr)	Children (8–12 yr)	Adults (above 17 yr)	Infants (0–2 yr)	Children (8–12 yr)	Adults (above 17 yr)
1	Dhanula (20)	CW	2.94 ± 0.31	27.19 ± 2.84	25.87 ± 2.7	23.32 ± 2.43	19.8 ± 2.06	15.84 ± 1.65	11.28 ± 1.18
2		UG	8.17 ± 0.21	75.49 ± 1.94	71.82 ± 1.72	64.74 ± 1.66	54.96 ± 1.41	43.99 ± 1.13	31.13 ± 0.8
3		UG	4.39 ± 0.37	40.59 ± 3.38	38.62 ± 3.22	34.81 ± 2.9	29.55 ± 2.46	23.65 ± 1.97	16.83 ± 1.4
4		CW	9.84 ± 0.56	90.89 ± 5.14	86.48 ± 4.89	77.94 ± 4.41	66.17 ± 3.74	52.95 ± 2.99	37.7 ± 2.13
5	Bhaduar (2)	UG	9.54 ± 0.55	88.16 ± 5.1	83.89 ± 4.85	75.6 ± 4.37	64.19 ± 3.71	51.37 ± 2.97	36.57 ± 2.11
6		UG	9.27 ± 0.47	85.65 ± 4.34	81.5 ± 4.13	73.46 ± 3.72	62.36 ± 3.16	49.91 ± 2.53	35.53 ± 1.8
7		CW	5.65 ± 0.44	52.19 ± 4.02	49.66 ± 3.82	44.76 ± 3.45	38 ± 2.92	30.41 ± 2.34	21.65 ± 1.67
8		CW	4.09 ± 0.37	37.81 ± 3.42	35.98 ± 3.26	32.42 ± 2.94	27.53 ± 2.49	22.03 ± 1.99	15.68 ± 1.42
9	Jangiana (6)	UG	6.05 ± 0.43	55.9 ± 4	53.19 ± 3.81	47.94 ± 3.43	40.7 ± 2.91	32.57 ± 2.33	23.19 ± 1.66
10		UG	5.45 ± 0.34	50.36 ± 3.14	47.92 ± 2.99	43.19 ± 2.69	36.66 ± 2.28	29.34 ± 1.83	20.89 ± 1.3
11		CW	7.47 ± 0.49	69.05 ± 4.5	65.7 ± 4.28	59.22 ± 3.86	50.27 ± 3.27	40.23 ± 2.62	28.64 ± 1.87
12		CW	1.63 ± 0.22	15.07 ± 2.07	14.34 ± 1.97	12.92 ± 1.77	10.97 ± 1.5	8.78 ± 1.2	6.25 ± 0.86
13	Channa (4)	UG	7.17 ± 0.48	66.28 ± 4.44	63.06 ± 4.23	56.84 ± 3.81	48.25 ± 3.23	38.62 ± 2.59	27.49 ± 1.84
14		UG	6.14 ± 0.39	56.73 ± 3.6	53.98 ± 3.43	48.65 ± 3.09	41.31 ± 2.62	33.06 ± 2.1	23.53 ± 1.49
15		CW	4.98 ± 0.42	46.04 ± 3.89	43.81 ± 3.7	39.49 ± 3.33	33.52 ± 2.82	26.83 ± 2.26	19.1 ± 1.61
16		CW	2.39 ± 0.41	22.06 ± 3.82	20.99 ± 3.64	18.92 ± 3.28	16.06 ± 2.78	12.85 ± 2.23	9.15 ± 1.59
17	Nainewal (1)	CW	2.75 ± 0.3	25.42 ± 2.77	24.19 ± 2.63	21.8 ± 2.37	18.51 ± 2.01	14.81 ± 1.61	10.54 ± 1.15
18		UG	7.25 ± 0.47	66.98 ± 4.36	63.74 ± 4.15	57.44 ± 3.74	48.77 ± 3.17	39.03 ± 2.54	27.78 ± 1.81
19		UG	7.11 ± 0.42	65.7 ± 3.88	62.51 ± 3.69	56.34 ± 3.33	47.83 ± 2.82	38.26 ± 2.26	27.25 ± 1.61
20		CW	1.41 ± 0.35	13.05 ± 3.21	12.41 ± 3.05	11.19 ± 2.75	9.5 ± 2.33	7.6 ± 1.87	5.41 ± 1.33
21	Saina (5)	UG	7.66 ± 0.49	70.74 ± 4.49	67.31 ± 4.27	60.66 ± 3.85	51.5 ± 3.27	41.22 ± 2.62	29.34 ± 1.86
22		UG	7.38 ± 0.37	68.19 ± 3.42	64.88 ± 3.25	54.48 ± 2.93	49.65 ± 2.48	39.73 ± 1.99	28.28 ± 1.42
23		CW	5.85 ± 0.45	54.08 ± 4.17	51.46 ± 3.97	46.38 ± 3.58	39.38 ± 3.03	31.51 ± 2.43	22.43 ± 1.73
24		CW	2.22 ± 0.32	20.49 ± 2.96	19.49 ± 2.82	17.57 ± 2.54	14.92 ± 2.15	11.94 ± 1.73	8.5 ± 1.23
25	Tapa (3)	UG	2.48 ± 0.28	22.93 ± 2.59	21.82 ± 2.46	19.67 ± 2.22	16.7 ± 1.88	13.36 ± 1.51	9.51 ± 1.07
26		UG	2.37 ± 0.31	21.9 ± 2.86	20.84 ± 2.73	18.78 ± 2.46	15.94 ± 2.08	12.76 ± 1.67	9.08 ± 1.19
27		CW	1.29 ± 0.21	11.94 ± 1.9	11.36 ± 1.81	10.24 ± 1.63	8.69 ± 1.38	6.95 ± 1.11	4.95 ± 0.79
28		CW	0.92 ± 0.16	8.54 ± 1.48	8.13 ± 1.41	7.33 ± 1.27	6.22 ± 1.08	4.98 ± 0.86	3.54 ± 0.61

Table 1 continued

S. No	Place (Grid no.)	Source	Rn-222 (BqL ⁻¹)	Annual effective dose due to inhalation (μSvyr ⁻¹)			Annual effective dose due to ingestion (μSvyr ⁻¹)		
				Infants (0–2 yr)	Children (8–12 yr)	Adults (above 17 yr)	Infants (0–2 yr)	Children (8–12 yr)	Adults (above 17 yr)
29	Draj (11)	UG	3.8 ± 0.34	35.12 ± 3.18	33.41 ± 3.02	30.11 ± 2.72	25.57 ± 2.31	20.46 ± 1.85	14.57 ± 1.32
30		UG	4.12 ± 0.48	38.07 ± 4.44	36.22 ± 4.22	32.65 ± 3.8	27.72 ± 3.22	22.18 ± 2.58	15.79 ± 1.84
31		CW	1.44 ± 0.25	13.26 ± 2.3	12.62 ± 2.19	11.37 ± 1.97	9.66 ± 1.67	7.73 ± 1.34	5.5 ± 0.96
32		CW	1.07 ± 0.23	9.89 ± 2.12	9.41 ± 2.01	8.48 ± 1.82	7.2 ± 1.54	5.76 ± 1.23	4.1 ± 0.88
33	Mehta (10)	UG	1.88 ± 0.22	17.36 ± 2.07	16.52 ± 1.97	14.89 ± 1.77	12.64 ± 1.5	10.12 ± 1.2	7.2 ± 0.86
34		UG	1.74 ± 0.17	16.08 ± 1.57	15.3 ± 1.49	13.79 ± 1.35	11.71 ± 1.14	9.37 ± 0.92	6.67 ± 0.65
35		CW	3.19 ± 0.3	29.46 ± 2.79	28.03 ± 2.65	25.27 ± 2.39	21.45 ± 2.02	17.17 ± 1.62	12.22 ± 1.16
36		CW	0.97 ± 0.11	8.97 ± 1.06	8.54 ± 1.01	7.7 ± 0.91	6.53 ± 0.77	5.23 ± 0.62	3.72 ± 0.44
37	Dhurkot (12)	UG	1.41 ± 0.2	13.07 ± 1.81	12.43 ± 1.72	11.2 ± 1.55	9.51 ± 1.32	7.61 ± 1.05	5.42 ± 0.75
38		UG	1.57 ± 0.36	14.51 ± 3.33	13.8 ± 3.17	12.44 ± 2.85	10.56 ± 2.42	8.45 ± 1.94	6.02 ± 1.38
39		CW	0.25 ± 0.08	2.28 ± 0.73	2.17 ± 0.69	1.96 ± 0.63	1.66 ± 0.53	1.33 ± 0.43	0.95 ± 0.3
40		CW	0.34 ± 0.1	3.14 ± 0.93	2.98 ± 0.88	2.69 ± 0.79	2.28 ± 0.67	1.83 ± 0.54	1.3 ± 0.38
41	Sanghere (18)	CW	0.24 ± 0.07	2.2 ± 0.69	2.09 ± 0.66	1.89 ± 0.59	1.6 ± 0.5	1.28 ± 0.4	0.91 ± 0.29
42		CW	3.15 ± 0.32	29.14 ± 2.94	27.73 ± 2.8	24.99 ± 2.52	21.22 ± 2.14	16.98 ± 1.71	12.09 ± 1.22
43		UG	4.98 ± 0.46	46.02 ± 4.25	43.78 ± 4.04	39.46 ± 3.65	33.5 ± 3.09	26.81 ± 2.48	19.09 ± 1.76
44		UG	5.57 ± 0.59	51.44 ± 5.41	48.95 ± 5.15	44.11 ± 4.64	37.45 ± 3.93	29.97 ± 3.15	21.34 ± 2.24
45	Wajidke (15)	CW	0.28 ± 0.08	2.56 ± 0.78	2.44 ± 0.74	2.2 ± 0.67	1.86 ± 0.57	1.49 ± 0.46	1.06 ± 0.32
46		UG	5.23 ± 0.49	48.33 ± 4.53	45.98 ± 4.31	41.44 ± 3.88	35.18 ± 3.29	28.16 ± 2.64	20.04 ± 1.88
47		UG	4.34 ± 0.37	40.07 ± 3.41	38.13 ± 3.25	34.36 ± 2.93	29.18 ± 2.48	23.35 ± 1.99	16.62 ± 1.42
48		CW	4.73 ± 0.38	43.7 ± 3.54	41.58 ± 3.36	37.48 ± 3.03	31.82 ± 2.57	25.46 ± 2.06	18.13 ± 1.47
49	Sehra (9)	UG	1.46 ± 0.23	13.45 ± 2.1	12.79 ± 2	11.53 ± 1.8	9.79 ± 1.52	7.83 ± 1.22	5.58 ± 0.87
50		UG	1.4 ± 0.21	13.94 ± 1.94	12.31 ± 1.85	11.09 ± 1.66	9.42 ± 1.41	7.54 ± 1.13	5.37 ± 0.8
51		CW	0.32 ± 0.07	2.95 ± 0.68	2.81 ± 0.65	2.53 ± 0.58	2.15 ± 0.49	1.72 ± 0.4	1.22 ± 0.28
52		CW	0.17 ± 0.08	1.54 ± 0.71	1.47 ± 0.67	1.32 ± 0.61	1.12 ± 0.52	0.9 ± 0.41	0.64 ± 0.29
53	Chuhanke (16)	CW	3.39 ± 0.32	31.29 ± 2.97	29.78 ± 2.83	26.84 ± 2.55	22.78 ± 2.16	18.23 ± 1.73	12.98 ± 1.23
54		UG	2.35 ± 0.29	21.71 ± 2.68	20.66 ± 2.55	18.62 ± 2.3	15.81 ± 1.95	12.65 ± 1.56	9.01 ± 1.11
55		UG	2.15 ± 0.26	19.87 ± 2.38	18.91 ± 2.27	17.04 ± 2.05	14.47 ± 1.73	11.58 ± 1.39	8.24 ± 0.99
56		CW	0.75 ± 0.07	6.96 ± 0.66	6.62 ± 0.63	5.97 ± 0.56	5.07 ± 0.48	4.06 ± 0.38	2.89 ± 0.27

Table 1 continued

S. No	Place (Grid no.)	Source	Rn-222 (BqL ⁻¹)	Annual effective dose due to inhalation (μSvyr^{-1})			Annual effective dose due to ingestion (μSvyr^{-1})		
				Infants (0–2 yr)	Children (8–12 yr)	Adults (above 17 yr)	Infants (0–2 yr)	Children (8–12 yr)	Adults (above 17 yr)
57	Barmala (19)	CW	1.34 ± 0.18	12.36 ± 1.68	11.76 ± 1.59	10.6 ± 1.44	9 ± 1.22	7.2 ± 0.98	5.13 ± 0.7
58		UG	1.82 ± 0.22	16.8 ± 2.05	15.98 ± 1.95	14.41 ± 1.75	12.23 ± 1.49	9.79 ± 1.19	6.97 ± 0.85
59		UG	2.2 ± 0.26	20.33 ± 2.4	19.34 ± 2.29	17.43 ± 2.06	14.8 ± 1.75	11.84 ± 1.4	8.43 ± 1
60		CW	2.35 ± 0.21	21.71 ± 1.97	20.66 ± 1.88	18.62 ± 1.69	15.81 ± 1.43	12.65 ± 1.15	9.01 ± 0.82
61	Kurar (22)	CW	0.23 ± 0.1	2.16 ± 0.97	2.05 ± 0.92	1.85 ± 0.83	1.57 ± 0.7	1.26 ± 0.56	
62		CW	0.27 ± 0.1	2.54 ± 0.88	2.42 ± 0.84	2.18 ± 0.76	1.85 ± 0.64	1.48 ± 0.52	1.05 ± 0.37
63		UG	2.36 ± 0.38	21.81 ± 3.51	20.75 ± 3.34	18.7 ± 3.01	15.88 ± 2.55	12.71 ± 2.05	9.04 ± 1.46
64		UG	2.42 ± 0.26	22.4 ± 2.38	21.31 ± 2.27	19.21 ± 2.05	16.31 ± 1.73	13.05 ± 1.39	9.29 ± 0.99
65	Mehal Kalan (17)	CW	0.2 ± 0.08	1.87 ± 0.77	1.78 ± 0.73	1.6 ± 0.66	1.36 ± 0.56	1.09 ± 0.45	0.78 ± 0.32
66		CW	4.02 ± 0.16	37.15 ± 1.48	35.35 ± 1.41	31.86 ± 1.27	27.05 ± 1.08	21.65 ± 0.86	15.41 ± 0.61
67		UG	5.56 ± 0.42	51.37 ± 3.88	48.88 ± 3.69	44.06 ± 3.33	37.4 ± 2.82	29.93 ± 2.26	21.31 ± 1.61
68		UG	5.41 ± 0.38	50 ± 3.55	47.58 ± 3.37	42.88 ± 3.04	36.41 ± 2.58	29.13 ± 2.07	20.74 ± 1.47
69	BhemiDesa (21)	UG	3.58 ± 0.33	33.09 ± 3.09	31.49 ± 2.94	28.38 ± 2.65	24.09 ± 2.25	19.28 ± 1.8	13.73 ± 1.28
70		UG	3.89 ± 0.42	35.94 ± 3.88	34.2 ± 3.69	30.82 ± 3.33	26.17 ± 2.82	20.94 ± 2.26	14.91 ± 1.61
71		CW	2.15 ± 0.22	19.87 ± 1.99	18.91 ± 1.9	17.04 ± 1.71	14.47 ± 1.45	11.58 ± 1.16	8.24 ± 0.83
72		CW	0.55 ± 0.11	5.09 ± 1.04	4.84 ± 0.99	4.36 ± 0.89	3.7 ± 0.75	2.96 ± 0.6	2.11 ± 0.43
73	Dangarh (23)	UG	3.3 ± 0.32	30.45 ± 2.98	28.97 ± 2.84	26.11 ± 2.56	22.17 ± 2.17	17.74 ± 1.74	12.63 ± 1.24
74		UG	3.52 ± 0.36	32.52 ± 3.33	30.95 ± 3.17	27.89 ± 2.85	23.68 ± 2.42	18.95 ± 1.94	13.49 ± 1.38
75		CW	2.25 ± 0.19	20.81 ± 1.79	19.8 ± 1.7	17.84 ± 1.53	15.15 ± 1.3	12.12 ± 1.04	8.63 ± 0.74
76		CW	0.56 ± 0.06	5.2 ± 0.59	4.95 ± 0.56	4.46 ± 0.5	3.79 ± 0.43	3.03 ± 0.34	2.16 ± 0.24
77	Aspalkalan (24)	UG	4.08 ± 0.35	37.69 ± 3.26	35.86 ± 3.1	32.32 ± 2.79	27.44 ± 2.37	21.96 ± 1.9	15.63 ± 1.35
78		UG	4.01 ± 0.32	37.05 ± 2.96	35.26 ± 2.81	31.78 ± 2.54	26.98 ± 2.15	21.59 ± 1.72	15.37 ± 1.23
79		CW	1.13 ± 0.23	10.47 ± 2.17	9.96 ± 2.06	8.97 ± 1.86	7.62 ± 1.58	6.1 ± 1.26	4.34 ± 0.9
80		CW	2.91 ± 0.16	26.91 ± 1.51	25.61 ± 1.44	23.08 ± 1.3	19.59 ± 1.1	15.68 ± 0.88	11.16 ± 0.63
81	Attar Singh Wala	UG	3.88 ± 0.23	35.81 ± 2.13	34.07 ± 2.02	30.71 ± 1.82	26.07 ± 1.54	20.86 ± 1.24	14.85 ± 0.88
82	(7)	UG	3.96 ± 0.25	36.59 ± 2.31	34.82 ± 2.2	31.38 ± 1.98	26.64 ± 1.68	21.32 ± 1.35	15.18 ± 0.96
83		CW	2.59 ± 0.32	23.9 ± 2.93	22.74 ± 2.79	20.5 ± 2.51	17.4 ± 2.13	13.93 ± 1.71	9.91 ± 1.22
84		CW	1.58 ± 0.47	14.58 ± 4.37	13.87 ± 4.16	12.5 ± 3.75	10.61 ± 3.18	8.49 ± 2.55	6.05 ± 1.81

Table 1 continued

S. No	Place (Grid no.)	Source	Rn-222 (BqL ⁻¹)	Annual effective dose due to inhalation (μSvyr ⁻¹)			Annual effective dose due to ingestion (μSvyr ⁻¹)		
				Infants (0–2 yr)	Children (8–12 yr)	Adults (above 17 yr)	Infants (0–2 yr)	Children (8–12 yr)	Adults (above 17 yr)
85	Handiaya (13)	UG	4.35 ± 0.37	40.18 ± 3.42	38.24 ± 3.26	34.46 ± 2.94	29.26 ± 2.49	23.41 ± 1.99	16.67 ± 1.42
86		UG	4.42 ± 0.39	40.84 ± 3.6	38.86 ± 3.43	35.02 ± 3.09	29.74 ± 2.62	23.8 ± 2.1	16.94 ± 1.49
87		CW	2.75 ± 0.5	25.44 ± 4.6	24.21 ± 4.37	21.82 ± 3.94	18.52 ± 3.34	14.82 ± 2.68	10.55 ± 1.91
88		CW	1.37 ± 0.3	12.66 ± 2.81	12.05 ± 2.67	10.86 ± 2.41	9.22 ± 2.04	7.38 ± 1.64	5.25 ± 1.16
89	Hariagarh (8)	CW	4.12 ± 0.36	38.07 ± 3.31	36.22 ± 3.15	32.65 ± 2.84	27.72 ± 2.41	22.18 ± 1.93	15.79 ± 1.37
90		UG	4.66 ± 0.38	43.08 ± 3.54	40.99 ± 3.36	36.95 ± 3.03	31.37 ± 2.57	25.1 ± 2.06	17.87 ± 1.47
91		UG	4.75 ± 0.4	43.89 ± 3.7	41.76 ± 3.52	37.64 ± 3.17	31.96 ± 2.69	25.57 ± 2.15	18.2 ± 1.53
92		CW	2.01 ± 0.28	18.59 ± 2.58	17.69 ± 2.46	15.94 ± 2.21	13.53 ± 1.88	10.83 ± 1.5	7.71 ± 1.07
93	Kattu (25)	UG	4.39 ± 0.1	40.54 ± 0.04	38.58 ± 0.04	34.77 ± 0.03	29.52 ± 0.03	23.62 ± 0.02	16.82 ± 0.02
94		UG	4.32 ± 0.01	39.92 ± 0.09	37.98 ± 0.09	34.23 ± 0.08	29.06 ± 0.07	23.26 ± 0.05	16.56 ± 0.04
95		CW	3.67 ± 0.01	33.9 ± 0.03	32.26 ± 0.03	29.07 ± 0.03	24.68 ± 0.02	19.75 ± 0.02	14.06 ± 0.01
96		CW	2.17 ± 0.01	20.02 ± 0.02	19.04 ± 0.02	17.16 ± 0.02	14.57 ± 0.01	11.66 ± 0.01	8.3 ± 0.01
97	Diwana (14)	UG	4.96 ± 0.01	45.86 ± 0.05	43.64 ± 0.04	39.33 ± 0.04	33.39 ± 0.03	26.72 ± 0.03	19.02 ± 0.02
98		UG	5.05 ± 0.31	46.66 ± 2.86	44.4 ± 2.73	40.02 ± 2.46	33.97 ± 2.08	27.19 ± 1.67	19.35 ± 1.19
99		CW	3.63 ± 0.01	33.58 ± 0.03	31.96 ± 0.03	28.8 ± 0.03	24.45 ± 0.02	19.57 ± 0.02	13.93 ± 0.01
100		CW	1.97 ± 0.01	18.24 ± 0.02	17.35 ± 0.02	15.64 ± 0.02	13.28 ± 0.01	10.63 ± 0.01	7.56 ± 0.01
Minimum			0.17 ± 0.01	1.54 ± 0.09	1.47 ± 0.09	1.32 ± 0.08	1.12 ± 0.07	0.9 ± 0.05	0.64 ± 0.04
Maximum			9.84 ± 0.59	90.89 ± 5.41	86.48 ± 5.15	77.94 ± 4.64	66.17 ± 3.93	52.95 ± 3.15	37.7 ± 2.24
Average			3.37 ± 0.29	31.13 ± 2.68	29.62 ± 2.53	26.69 ± 2.3	22.66 ± 1.95	18.14 ± 1.56	12.91 ± 1.11
Kurtosis			0.22 ± -0.82	0.22 ± -0.82	0.22 ± -0.82	0.22 ± -0.82	0.22 ± -0.82	0.22 ± -0.82	0.22 ± -0.82
Skewness			0.75 ± -0.04	0.75 ± -0.04	0.75 ± -0.01	0.75 ± -0.04	0.75 ± -0.04	0.75 ± -0.04	0.75 ± -0.04
1 st Quartile			1.57 ± 0.19	14.52 ± 1.79	13.82 ± 1.62	12.46 ± 1.54	10.57 ± 1.3	8.46 ± 1.05	6.02 ± 0.74
2 nd Quartile			3.05 ± 0.31	28.17 ± 2.82	26.8 ± 2.66	24.16 ± 2.42	20.51 ± 2.05	16.41 ± 1.64	11.68 ± 1.17
3 rd Quartile			4.71 ± 0.38	43.55 ± 3.54	41.43 ± 3.37	37.34 ± 3.04	31.71 ± 2.58	25.37 ± 2.06	18.06 ± 1.47

CW- Canal water, UG- Underground water

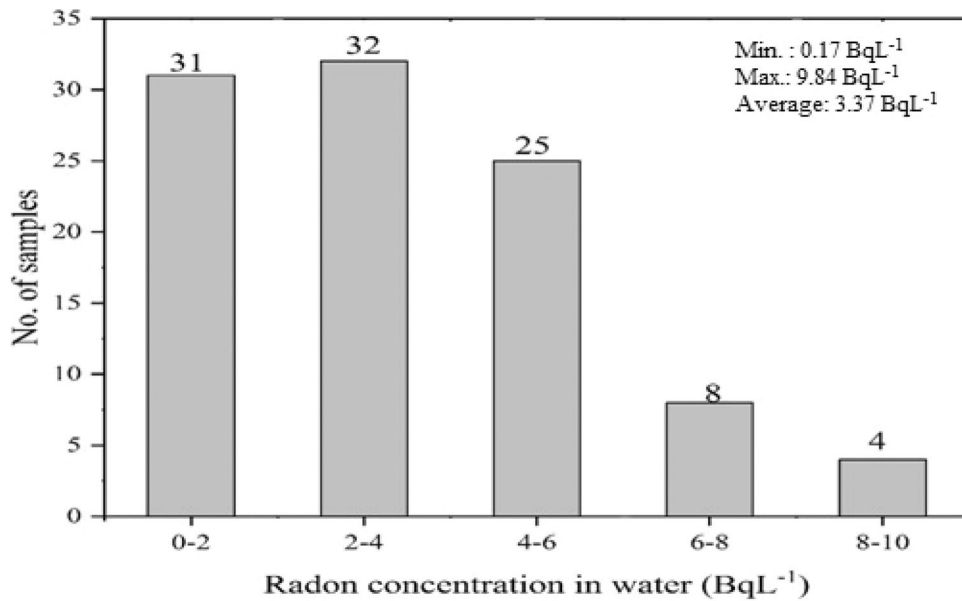


Fig. 4 Frequency distribution of radon concentration in all 100 water samples

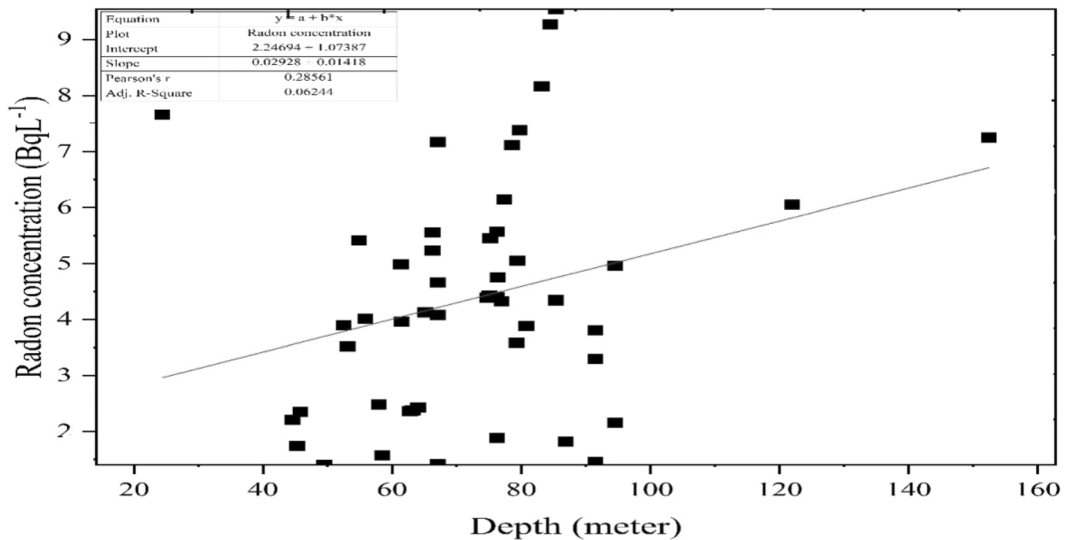


Fig. 5 Correlation between depth and radon concentration in underground water samples

contrast, Rn-222 in canal water samples can easily escape to atmosphere due to aeration and agitation in water. The variation in Rn-222 concentration in canal water and underground water depends upon geological factors and topography (Fonollosa E et al. 2016). The results show that the average Rn-222 concentration in underground water samples is $4.39 \pm 0.33 \text{ BqL}^{-1}$ which is higher than the average concentration of Rn-222 in canal water sources is $2.29 \pm 0.26 \text{ BqL}^{-1}$.

Using data from table no.1, the whisker plot has been drawn as shown in Fig. 7, in which minimum and maximum value of radon concentration are represented by lower and upper whiskers, respectively, while solid part in the box shows the mean concentration. The upper and lower lines in the whisker box plot represent the third and first quartile, whereas the line in the middle in the box shows second quartile or median.

Table 2 Descriptive statistics using SPSS for samples collected from canal water and underground water

Radon concentration (BqL ⁻¹)											
Sources of water	N (no. of samples)	Minimum	Maximum	Mean with std. error	Std. Deviation	Variance	Skewness with std. error	Kurtosis with std. error			
Canal water	50	.17	9.84	2.29 .27	1.94	3.77	1.66 .33	4.03 .66			
Underground water	50	1.40	9.54	4.39 .29	2.06	4.25	.57 .33	−.08 .66			

Fig. 6 Intercomparison between canal and underground water samples

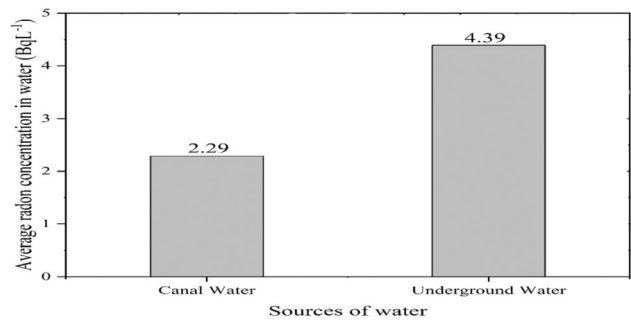
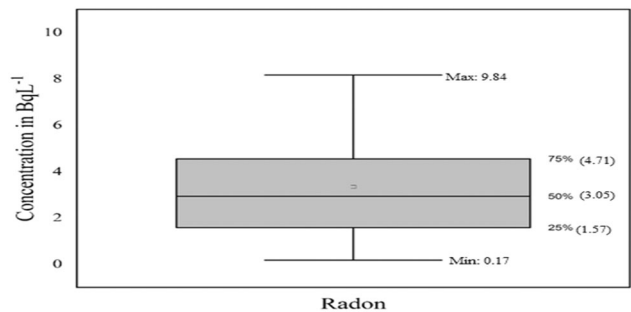


Fig. 7 Box whisker plot for radon concentration



A normality test using Origin Lab 8.5, at a significance level of 0.01, revealed that the canal water data were not significantly drawn from a normally distributed population, while the groundwater data were significantly drawn from a normally distributed population. Table 2 shows a comparative descriptive statistical analysis of drinking water from canal and underground water (50 samples each) using IBM-SPSS. The minimum and maximum radon-222 concentration in canal and groundwater ranged from 0.17 – 9.84 Bqm⁻³ and 1.40 – 9.54 Bqm⁻³, respectively, with a standard deviation of 1.94 Bqm⁻³ and 2.06 Bqm⁻³, respectively. The mean (± SE) for canal and groundwater was found to be 2.29 ± 0.27 Bqm⁻³

and 4.39 ± 0.29 Bqm⁻³, respectively. For canal water, a positive value of 1.66 for skewness shows that the distribution is highly skewed and a high kurtosis value of 4.03 shows that the distribution is leptokurtic. Compared to a normal distribution, its tails are longer and fatter and often its central peak is higher and sharper. Similarly, for groundwater, a value of 0.57 for skewness shows that the data are moderately skewed, while as a negative value of kurtosis indicates that a distribution is platykurtic, that is, the distribution is flat and has thin tails.

Table 3 shows the comparison of measured Rn-222 concentration in water samples in the studied area with

Table 3 Worldwide comparison of radon (Rn-222) concentration in water samples

S. No	Area	Radon (BqL ⁻¹)		Reference
		range	Mean value	
1	Iran	0.064 – 49.1	16.2	A. Banish et al., (2011)
2	Cyprus	0.3- 20	5.9	Dimitriou Nikolopoulos et al. (2008)
3	Greece	0.8- 24	5.4	Dimitriou Nikolopoulos et al. (2008)
4	Brazil	0.95- 36	36	Adilson Lima Marques et al., (2004)
5	Turkey	1.46–53.64	–	U AkarTarim et al. (2012)
6	South Korea	0–300	–	Cho et al., (2004)
7	China	0.71– 3735	–	Zhuo et al., (2001)
8	Sweden	5–3470	–	Salih et al., (2004)
9	Saudi Arabia	0.04–67.44	–	Alabudula'aly et al. (2014)
10	Barnala District Punjab, India	0.17–9.84	3.01	Present study

worldwide values and has been found to be lesser than these values.

Conclusion

- The measured values of Rn-222 concentration have been found to be below the recommended limit of 100 BqL⁻¹ by WHO (2004), 11 BqL⁻¹ by USEPA, 1991 and 4–40 BqL⁻¹ by UNSCEAR, 2008.
- The annual effective dose due to ingestion and inhalation for infants has been found to be higher than the dose received by children and adults. While overall dose is far well below the safe limit of 100 μ Svy⁻¹ recommended by WHO (2008).
- The underground water samples have slightly higher values of radon concentration than in canal water because the radon easily escapes from canals, while underground water retains.
- A weak positive correlation of radon in underground water with depth has been found.
- As the measured values in the studied area are below the recommended safe limits, so it can be concluded that radon in water may not pose any significant radiological risk to the public.

Acknowledgements We appreciate the residents of the study area for their support during field work.

Author's contribution Research plan has been designed by Supriya Rani and Sandeep Kansal and the manuscript has been

prepared with the contribution of Amit Kumar Singla and Rohit Mehra. The sample collection was carried out by Supriya Rani.

Funding Self-Financed.

Declarations

Conflict of interest The Authors declare that there is no conflict of interest.

References

- Abdulrahman, I., & Alabudula'aly, . (2014). Occurrence of radon in groundwater of Saudi Arabia. *Journal of Environmental Radioactivity*, 138, 186–191.
- Akar Tarim, U., Gurler, O., Akkaya, N., Kilic, S., Yalein, G. K., & Gundogdu, O. (2012). Evaluation of radon concentration in well and tap waters in Bursa Turkey. *Radiation Protection Dosimetry*, 150(2), 207–212.
- Al Zabadi, H., Mallah, K., & Saffarini, G. (2015). Indoor exposure assessment of radon in the elementary schools Palestine. *International Journal of Radiation Research*, 13(3), 221–228.
- Bajwa, B. S., Mahajan, S., Singh, H., Singh, J., Singh, S., Walia, V., & Virk, H. S. (2005). A study of groundwater radon concentration in Punjab and Himachal Pradesh States India. *Indoor and Inbuilt Environment*, 14(6), 481–486.
- Banish, A., Arabshahi, H., & Pourhabib, Z. (2011). Radioactivity and dose assessment of heavy radioactive pollution, radon and radium from water sources of 3 northern regions in Iran. *International Journal of Physical Science*, 6(35), 7969–7977.
- Brudecki, K., Li, W. B., Meisenberg, O., Tschiersch, J., Hoeschen, C., & Oech, U. (2014). Age dependent inhalation dose to members of the public from indoor short-lived radon progeny. *Radiation and Environmental Biophysics*, 53(3), 535–549.

- Carvalho, F. P., Oliveira, J. M., Lopes, I., & Batista, A. (2007). Radionuclides from past uranium mining in rivers of Portugal. *Journal of Environmental Radioactivity*, 98, 298–314.
- Cho, J. S., Ahn, J. K., Kim, H.-C., & Lee, D. W. (2004). Radon concentrations in groundwater in Busan measured with a liquid scintillation counter method. *Journal of Environmental Radioactivity*, 75, 105–112.
- Choubey, V. M., & Ramola, R. C. (1997). Correlation between geology and radon levels in groundwater, soil and indoor air in Bhilangana Valley, Garhwal Himalaya, India. *Environmental Geology*, 32, 258–262.
- Dimitrios Nikolopoulos & Annal Louizi. (2008). Study of indoor radon and radon in drinking water in Greece and Cyprus: Implications to exposure and dose. *Radiation Measurements*, 43, 1305–1314.
- Fatima, I., Zaidi, M. A., & Tahir, S. N. A. (2007). Measurement of natural radioactivity in bottled drinking water in Pakistan and consequent dose estimates. *Radiation Protection Dosimetry*, 123, 234–240.
- Fonollosa, E., Peñalver, A., Borrull, F., & Aguilar, C. (2016). Radon in spring waters in the south of Catalonia. *Journal of Environmental Radioactivity*, 151, 275–281.
- Gaware, J. J., Sahoo, B. K., Sapra, B. K., & Mayya, Y. S. (2011). Indigenous development and networking of online radon monitors in the underground uranium mine. *Radiation Protection and Environment*, 34, 37–40.
- Gundersen, L. C. S., Randall Schumann, R., Otton, J. K., Dubiel, R. F., Douglass, E., & Owen & Kendell A. Dickinson, . (1992). Geology of radon in the United States. *Geological Society of America Special Papers*, 271, 1–16.
- Henshaw, D. E. (1990). Radon as a causative factor in induction of myeloid leukemia and other cancers. *Lancet*, 355, 1008–1015.
- ICRP International Commission Radiation Protection. (2010). Radiological protection against radon exposure. ICRP Publication 126. *Annals of the ICRP*, 43, 3–37.
- Jobbágy, V., Altzitzoglou, T., Malu, P., Tanner, V., & Hult, M. (2017). A brief overview on radon measurements in drinking water. *Journal of Environmental Radioactivity*, 173, 18–24.
- Kansal, S., Mehra, R., & Singh, N. P. (2011). Uranium concentration in groundwater samples belonging to some areas of Western Haryana, India using Fission track registration technique. *Journal of Public Health and Epidemiology*, 3(8), 352–357.
- Krewski, D., Lubin, J. H., Zeilinski, J. M., Micheal Alavanja, V. S., Catalan, , et al. (2005). Residential radon and risk of lung cancer: A analysis of 7 North American case control studies. *Epidemiology*, 16(2), 137–145.
- Kurttio, P., Harmoinen, A., Saha, H., Saha, L., & Zeev karpas, Hannu Komulainen & Anssi Auvinen, . (2006). Kidney toxicity of ingested uranium from drinking water. *American Journal of Kidney Diseases*, 47(6), 972–982.
- Lawrence, E., Poeter, E., & Wanty, R. (1991). Geohydrologic, geochemical, and geologic controls on the occurrence of radon in ground water near Conifer, Colorado, USA. *Journal of Hydrology*, 127, 367–386.
- Lubin, J. H., Boice, J. D., & Jr. . (1997). Lung cancer risk for residential radon: Meta-analysis of eight epidemiologic studies. *Journal of National Council Institute*, 89(1), 49–57.
- Lubin, J. H., & J. D. . (1995). Lung cancer in radon-exposed miners and estimation of risk from indoor exposure. *Journal of the National Cancer Institute*, 87(11), 817–827.
- Marques, A. L., dos Santos, W., & Geraldo, L. P. (2004). Direct measurements of radon activity in water from various natural sources using nuclear track detectors. *Applied Radiation and Isotopes*, 60, 801–804.
- Mehra, R., Bhagotra, P., & Kaur, K. (2015). Radon and thoron levels of Mansa and Muktsar district of Punjab India. *Frontiers in Environmental Science*, 3, 37.
- Mehra, R., Kaur, K., & Bhagotra, P. (2015). Annual effective dose of radon due to exposure in indoor air and groundwater in Bathinda district of Punjab. *Indoor and Built Environment*, 25(5), 848–856.
- Mishra, R., & Mayya, Y. S. (2008). Study of a deposition-based direct thoron progeny sensor (DTPS) technique for estimating equilibrium equivalent thoron concentration (EETC) in indoor environment. *Radiation Measurements*, 43, 1408–1416.
- Nazir, S. (2020). Continuous radon measurements at high altitude physics observatory, Gulmarg, Kashmir valley, J&K. *Mendeley Data*. <https://doi.org/10.17632/vdzpw2hsbb.4>.
- Nazir, S., Shakeel Simnani, B. K., Sahoo, I. R., & Sajad Masood, (2020a). Monitoring geothermal springs and groundwater of Pir Panjal, Jammu and Kashmir for radon contamination. *Journal of Radioanalytical and Nuclear Chemistry*, 326(3), 1915–1923. <https://doi.org/10.1007/s10967-020-07451-8>
- Nazir, S., Simnani, S., Sahoo, B. K., et al. (2020b). Dose estimation of radioactivity in groundwater of Srinagar City, Northwest Himalaya, employing fluorimetric and scintillation techniques. *Environmental Geochemistry Health*, 43, 837–854. <https://doi.org/10.1007/s10653-020-00576-5>.
- Nazir, S., Simnani, S., Mishra, R., et al. (2020c). Simultaneous measurements of radon, thoron and their progeny for inhalation dose assessment in indoors of Srinagar, J&K, India. *Journal of Radioanalytical and Nuclear Chemistry*, 325, 315–328. <https://doi.org/10.1007/s10967-020-07233-2>.
- NCBI. (1999). *National Research Council committee on Risk Assessment of exposure to radon in drinking water*. National Academic Press.
- Ramola, R. C., Sandhu, A. S., Singh, M., & Virk, H. (1989). Geochemical exploration of uranium using radon measurement techniques. *Nucl Geophy*, 3, 57–69.
- Sahoo, B. K., Sapra, B. K., Kanse, S. D., Gware, J. J., & Mayya, Y. S. (2013). A new pinhole discriminated $^{222}\text{Rn}/^{220}\text{Rn}$ passive measurement device with single entry face. *Radiation Measurement*, 58, 52–60.
- Salih, I., Backstrom, M., Karlsson, S., Lund, E., Pettersson, H., & B.L. . (2004). Impact of fluoride and other aquatic parameters on radon concentration in natural waters. *Applied Radiation and Isotopes*, 60(1), 99–104. <https://doi.org/10.1016/j.apradiso.2003.10.007>
- Sandeep Kansal & Rohit Mehra. (2015). Evaluation and analysis of ^{226}Ra , ^{232}Th and ^{40}K and radon exhalation rate in the soil samples for health risk assessment. *International Journal of Low Radiation*, 10(1), 352–357.

- Singh, B., Kant, K., ManeeshaGarg, A. S., Sahoo, B. K., & Sapra, B. K. (2020). Quantification of radon/thoron exhalation rates of soil samples collected from district Faridabad of Southern Haryana, India. *Journal of Radioanalytical and Nuclear Chemistry*, 326(1), 831–843.
- Singh, P., Probhjot Singh, B. K., & Sahoo & B.S. Bajwa, . (2015). A study on uranium and radon levels in drinking water sources of a mineralized zone of Himachal Pradesh, India. *Journal of Radioanalytical and Nuclear Chemistry*, 309, 541–549.
- Singla, A. K., Kansal, S., & Mehra, R. (2021a). Quantification of radon contamination in drinking water of Rajasthan, India. *Journal of Radioanalytical and Nuclear Chemistry*, 327(3), 1149–1157.
- Singla, A. K., Kansal, S., & Mehra, R. (2021b). Dose distribution to individual tissues and organs due to exposure of alpha energies from radon and thoron to local population of Hanumangarh, Rajasthan, India. *Journal of Radioanalytical and Nuclear Chemistry*, 327(3), 1073–1085.
- Skeppström, K., & Olofsson, B. (2007). Uranium and radon in groundwater. *European Water*, 17, 51–62.
- Stojkovic, Z. S., Svare-bGajic, J. V., Dorevic, M. Z., Grahvac, N. L., Vasin, J. R., Duorvic, A. D., & Kravic, S. Z. (2015). Study on the quality of ground, spring and river waters in South-East Serbia. *Hemijaska Industrija*, 69, 185–192.
- Tanner AB (1986). Geological factors that influence radon availability, indoor radon levels, Publ. SP-54, Air Pollution control Assoc. Pittsburg, PA, 1–2.
- Tsoufanidis, N., & Landsberger, S. (2015). *Measurement detection of radiation* (4th ed.). CRC Press.
- UNSCEAR (2000). Report, Volume 1, Annex B: Exposure from Natural Radiations Sources.
- UNSCEAR (2008). Report, Volume 1, Annex B: Exposure from Natural Radiations Sources.
- USEPA (1991). Federal Register 40 parts 141 and 142; National primary Drinking Water regulations; Radionuclides; proposed Rule (U.S. Environmental Protection Agency). U.S. Government Printing Office.
- Vesterbacka, P., Petterson, H., Hanste, U.-M., Jakobson, E., Kolstad, T., Roos, P., & Ostergren, I. (2010). Intercomparison of Rn-222 determination from groundwater. *Applied Radiation and Isotopes*, 68, 214–218.
- Virk, H. S. (2019). Uranium content anomalies in groundwater of Barnala district of Malwa belt of Punjab (India) for health risk assessment. *Journal of Oncology and Hematology*, 8(1), 19–26.
- Voronov, A. N. (2004). Radon-rich waters in Russia. *Environmental Geology*, 46, 630–634.
- WHO. (2004). *Guidelines for drinking-water quality. Recommendations*.
- WHO. (2008). *WHO Guidelines for drinking-water quality. World Heal Organ Press*.
- WHO (2009). WHO handbook on indoor radon, A health Public perspective.
- Zhuo, W., Iida, T., & Yang, X. (2001). Occurrence of Rn-222, Ra-226, Ra-228 and U in groundwater in Fujian Province, China. *Journal of Environmental Radioactivity*, 53, 111–120.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.