Distribution of natural radionuclides and radon concentration in the riverine environs of Cauvery, South India

C. S. Kaliprasad and Y. Narayana

ABSTRACT

Systematic studies were carried out to understand the distribution of natural radionuclides in sediments and radon in water in the riverine environs of Cauvery, one of the major rivers of South India. The activity of radionuclides in the sediment was measured by gamma ray spectrometry. The radon emanation from the sediment was measured by the sealed 'can technique' and the radon in the water was measured using the RAD-7 instrument. The mean values of ^{40}K, ^{226}Ra, and ^{232}Th in the sediment samples were found to be 297.3 ± 4.16 Bq kg^{-1}, 75.1 ± 2.64 Bq kg^{-1}, and 85.5 ± 2.62 Bq kg^{-1}, respectively. The mean activity of radon, radon exhalation rate, and radium content were found to be 135.68 Bq m^{-3}, 327.1 mBq m^{-1} h^{-1}, and 133.03 mBq kg^{-1}, respectively. The radon in the water ranged from 0.19 kBq m^{-3} to 1.40 kBq m^{-3}. The hyper pure germanium gamma spectroscopy measured via ^{226}Ra activity and the radon activity measured by the passive can technique showed good correlation. The mean value of radon in the water was within the internationally recommended level. The sediment was considered safe for the purpose of construction, except for some extreme values, and the water was deemed safe for drinking.

Key words | can technique, RAD-7, radionuclides, radon, river, sediment

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INTRODUCTION

The aquatic environment plays a key role in the transfer of contaminants to the geographic area through water and sediment. When compared to all other aquatic environments, the riverine environ is vital for study of natural radionuclide concentration. The river sediment is used as a construction material and the river water is used for agriculture, in industries, and for household purposes. River sediments contain natural radionuclides accumulated from the soil due to erosion, weathering of rocks, and the river bed itself. Monitoring the release of radiation from gamma sources is important to assess the radiation dose to the human population. The natural radionuclide mainly arises from radioactive series ^{238}U and ^{232}Th and singly occurring radionuclide ^{40}K. The external gamma radiation exposure to the population changes due to the geology and geographical conditions of the area and its associated radioactivity level in the soil (Linsalata 1994).

^{222}Rn is a colorless and odorless chemically inert radioactive gas. It is a daughter product of ^{226}Ra, which decays to ^{222}Rn emitting alpha particles. Therefore, the important discharge of radon is ^{222}Rn. The exposure of radon and its progenies over time causes considerable biological damage to the human body; through the function of respiratory changes, it causes cancer of the lungs (Saad 2008). Also, natural water sources like bore wells, rivers, and lakes used for drinking purposes, contain the dissolved form of radon, which comes from the Radium-226 present in the rocks, soil, and sediment. Since the water used for drinking and household purposes includes the dissolved form of radon, it delivers a radiation dose to the body, from radon

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and its progeny, that causes health effects, like lung cancer, to the population. Therefore, the estimation of the health risk associated with radon is important. In view of this, in the present investigation, an attempt was made to measure radionuclide concentration and radon exhalation rate in the sediment and radon activity concentration in the water of the Cauvery River, in order to assess the radiation dose delivered to the public.

MATERIALS AND METHODS

Study area

The river Cauvery originates in the region of Brahmmagiri hills, at Talakaveri situated in the Western Ghats of Karnataka. The total length of the river is about 800 km from its origin to its outfall in the Bay of Bengal; of this about 320 km of the river flows through Karnataka. The river basin comes under latitude 10° 05′ N and 13° 30′ N and longitude 75° 30′ E and 79° 45′ E. It covers almost 24.7% of the total area of India (Kaliprasad & Narayana 2016a). The area under the river basin of Cauvery experiences a tropical monsoon climate with bimodal rainfall pattern. The temperature varies from 13.5°C to 41°C from the winter to summer season (Narayana *et al.* 2016). The river is the major source for the hydro-electric project, irrigation, and drinking water.

Sample collection and preparation

Sampling stations were identified along the river with a detailed study of the geology and accessibility of sampling locations. The sampling locations were recorded using global positioning system and all the recorded locations are shown in Figure 1. The field work was carried out during August 2014 for collecting of the sediment and water samples. As per the Environment Measurement Laboratory (EML) standard procedure (EML 1983), the water samples from the river, which the people used for drinking purposes, and the sediment samples from the river drainage were collected. The sediment samples were cleaned to remove impurities like pebbles and organic materials. About 1 litre of the water and 4 kg of the sediment were collected and stored in polyvinyl chloride (PVC) containers and polythene bags, respectively (Kaliprasad & Narayana 2016b). The samples were taken to the laboratory for further processing. The sediment sample was dried and sieved through a 250-micron mesh. The sieved sample was stored and sealed in a 250 ml PVC container for secular equilibrium between ^{226}Ra and its daughter products (Narayana *et al.* 2007; Narayana *et al.* 2016).

Activity measurement

In the present investigation, the gamma ray spectrometry technique was used to determine the activity concentration of the radionuclides in the sediment sample using the high-resolution n-type hyper pure germanium (HPGe) detector (NGC 3019, DSG). The detector has good relative efficiency of about 34% and the resolution was 1.9 keV at 1.33 MeV energy. It was shielded using thick lead blocks on all four sides to reduce background radiation. The output of the detector was analyzed using a 16 K multi-channel analyzer (MCA-3 series/P7882, FAST com tec.) (Narayana *et al.* 2016). The activity concentration of individual samples was determined by using the spectra obtained from the counting. The ^{40}K activity was calculated using the peak 1.46 MeV, and the ^{232}Th activity was calculated using energy 0.911 MeV of ^{223}Ac. The ^{226}Ra activity was calculated using the peak 0.609 MeV of ^{214}Bi.

The minimum detectable limit (MDL) for each radionuclide was calculated: for ^{40}K it is 12.43 Bq kg^{-1}, for ^{232}Th it is 1.162 Bq kg^{-1}, and for ^{226}Ra it is 1.259 Bq kg^{-1}. The MDL was calculated using the equation,

$$\mathrm{MDL} = CL\frac{B^{(1/2)}}{T}\times\frac{100}{E}\times\frac{100}{a}\times\frac{1000}{W}\ \mathrm{Bq\ kg^{-1}} \tag{1}$$

where

CL is the confidence level (%),
B is the background count in the peak region,
T is the counting time in sec,
E is the efficiency of the detector for a particular energy,
W is the weight of the sample, and
a is the abundance of the radionuclide (%).

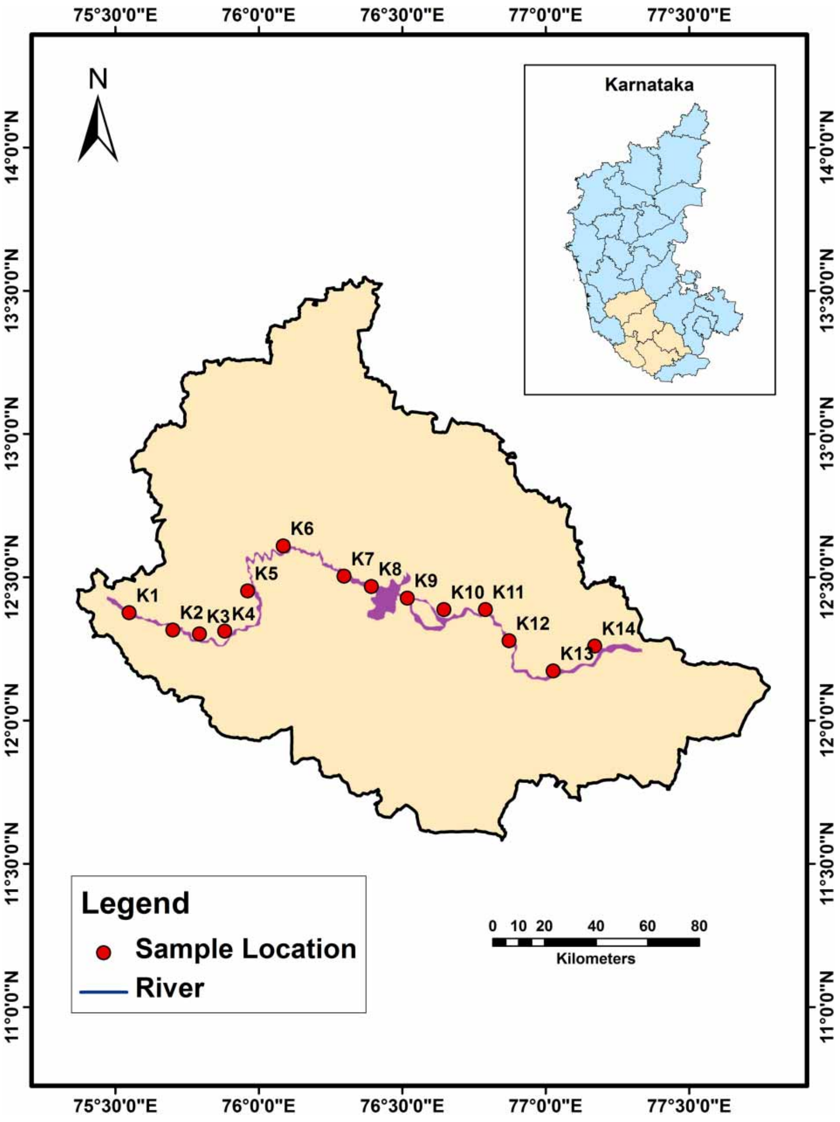

Figure 1 | Cauvery River basin map.

The activity of the sample was calculated using the equation,

$$A = S \times \frac{100}{E} \times \frac{100}{a} \times \frac{1000}{W}\ \mathrm{Bq\ kg^{-1}} \tag{2}$$

where

S is net count per second,
E is the efficiency of the detector for particular energy,
W is the weight of the sample, and
a is the abundance of the radionuclide (%).

Radon exhalation rate

The radon exhalation rate in the sediment samples of the Cauvery River was determined by the 'sealed can technique' using solid state nuclear track (SSNT) detectors. About 100 g of the dried and sieved (250 μ) sediment sample was taken in each 'can' (diameter 7.0 cm and height 10.5 cm) and an LR-115 Type II SSNT detector (3 cm × 3 cm) was fixed on the top inside of each 'can'. Each 'can' was kept airtight to reach equilibrium (about 4 hours) between the radon and its progeny, and hence, the geometry of the 'can' and the time of exposure determines the equilibrium activity of the emergent radon. The 'cans' were kept for 90 days for exposure of radon, then the removed films (detectors) were etched in 2.5 N NaOH at 60 ± 1°C for a period of 60 mins in a water bath at constant temperature to enlarge the tracks produced from the alpha particles from the decay of radon (Qureshi *et al.* 2000). The background track density of the detector was measured using unexposed detectors under the same etching condition. The alpha particle tracks produced in the films were counted using a spark counter made by the Baba Atomic Research Centre, Mumbai.

Effective radium concentration (C_R) can be calculated using Equation (3) below (Singh *et al.* 1997; Nagaraju *et al.* 2013; Kaliprasad & Narayana 2016a, 2016b):

$$C_{Ra} = \frac{\rho h A}{M K T_e} \tag{3}$$

where

ρ is the track density cm^{-2} (0.056 track cm^{-2} d^{-1} (Bq m^{-1})),
T_e is the effective exposure time in an hour,
h is the distance between the detector films and the surface of the specimen sample,
M is the mass of the sample,
A is the area of cross-section of the cylindrical can, and
K is the sensitivity factor and its value is $K = 0.0312$ tracks m^{-2} d^{-1} Bq^{-1} m^{-3}.

The surface exhalation rate (E_A) was obtained from the following expression:

$$E_A = \frac{CV\lambda}{A[T + (1/\lambda)\{e^{-\lambda T} - 1\}]} \tag{4}$$

The above equation is modified to estimate the mass exhalation rate (E_M),

$$E_M = \frac{CV\lambda}{M[T + (1/\lambda)\{e^{-\lambda T} - 1\}]} \tag{5}$$

where

E_A is measured in Bq m^{-2} h^{-1} and E_M in Bq kg^{-1} h^{-1},
V is the effective volume of the can (m^3),
C is the total radon exposure as measured by LR-115 solid state nuclear track detectors (Bq m^{-3} h),
T is the exposure time (h),
λ is the decay constant for radon (h^{-1}), and
A is the area of the can (m^2) and M is mass of the sample.

The radon concentration (C_{Rn} Bq m^{-3}) was calculated by using Equation (6),

$$C = \frac{\rho}{K.T} \tag{6}$$

where

ρ is the track density cm^{-2},
K is the sensitivity factor, and
T is the exposure time (h).

Analysis of radon in water and dose estimation

About 1,000 ml of the water sample was collected from the Cauvery River in the rainy season following the standard procedure (Badhan *et al.* 2010). The radon activity in the water sample was measured using a RAD-7 detector with a RAD-H2O accessory (Durridge Co., USA). Before using the RAD0-7 detector, the radon activity accumulated in the detector had to be removed using a desiccant tube for 10 minutes in the open circuit. The collected water sample was taken in a 250 ml vial and connected to the aerator, which is connected to the detection chamber. After that the setup of the RAD-7 detector required connection to the closed loop which enables collection of the radon gas from the water sample into the air (Durridge Company Inc 2012). For a period of 5–20 minutes, the air was circulated in a closed loop for uniform mixing of radon with air. The alpha activity was detected by the detection chamber, and the calcium chloride in the glass bulb absorbed the moisture and the result was recorded. The obtained result gives the radon concentration present in the sample (Mohammed 2014).

There are two types of dose to be assessed due to the consumption of radon in the water, i.e., the ingestion dose and the inhalation dose. The inhalation and ingestion of this drinking water can cause greater damage to the lungs and stomach due to the dissolved radon. The amount of water consumed by a person in a day gives the dose delivered by the ingestion.

Using United Nations Scientific Committee on the Effect of Atomic Radiation (UNSCEAR) reports, established equations can be used to estimate the annual mean effective doses delivered to the public through the ingestion and inhalation of the radon dissolved in the water (UNSCEAR 2000):

$$D_{Ig}\ (\mu\text{Sv y}^{-1}) = C_{RnW} \times C_W \times EDC \tag{7}$$

where

D_{Ig} is the effective dose for ingestion,
C_{RnW} is the radon concentration in the water (Bq l^{-1}),
C_W is the weighted estimate of water consumption (1,095 l y^{-1}), and
EDC is the effective dose coefficient for ingestion (3.5 nSv Bq^{-1}).

$$D_{In}(\mu\text{Sv y}^{-1}) = C_{RnW} \times R_{aW} \times I \times F \times DCF \tag{8}$$

where

D_{In} is the effective dose for inhalation,
C_{RnW} is the radon concentration in the water (Bq l^{-1} or kBq m^{-3}),
R_{aW} is the radon in the air to the radon in the water (10^{-4}),
F is the equilibrium factor between the radon and its progenies (0.4),
I is the average indoor occupancy time per individual (7,000 h y^{-1}), and
DCF is the dose conversion factor for radon exposure (9 nSv $(\text{Bq h m}^{-3})^{-1}$).

The tissue weighting factors of lung and stomach were multiplied by the ingestion and inhalation dose to calculate the dose contribution from the radon in the water (Rangaswamy *et al.* 2016).

RESULT AND DISCUSSION

Activity concentration of radionuclides

The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in the Cauvery River sediment samples were measured using the HPGe gamma ray spectrometer and are shown in Figure 2. The activity concentration in the sediment ranged from 30.7 ± 1.75 Bq kg^{-1} to 207.7 ± 4.55 Bq kg^{-1} for ^{226}Ra, from 8.4 ± 0.91 Bq kg^{-1} to 356.4 ± 5.97 Bq kg^{-1} for ^{232}Th, and from 11.3 ± 1.75 Bq kg^{-1} to 746.8 ± 8.64 Bq kg^{-1} for ^{40}K. Variation in the activity concentration was observed in the sediment samples from location to location. The mean activity of ^{40}K was higher than the activity of ^{226}Ra and ^{232}Th. This may be due to the geochemical mobility and insolubility nature of the water (Ramasamy *et al.* 2011). There is no plausible increasing or decreasing trend in activity concentration. These variations are due to the variation in drainage pattern of the study area, which could be attributed to the physical and chemical sorting processes from location to location. Human activities and natural process also contribute to the variations. The variation of activity concentration is high due to the leaching of soil-bearing minerals and weathering of rocks in the river catchment area. The river basin contains Archean granitoid gneisses (amphibolite-facies) and intrusive, Closepet granite, Precambrian granulite, and supracrustal belts of rocks, volcanic rocks, felsic volcanic rocks, and caustic and chemical sedimentary rocks (Kaliprasad & Narayana 2016a, 2016b). In acid igneous rocks, thorium concentration can be 10 times higher than sedimentary rocks. The Cauvery River basin has the highest soil erosion (more than 400 t $\text{ha}^{-1}\ \text{y}^{-1}$), as reported by Brema & Hauzinger (2016). The soil erosion contributes in the transportation of radionuclides from soil phase to sediment phase. The activity concentrations were in the order of $^{40}\text{K} > {}^{232}\text{Th} > {}^{226}\text{Ra}$; this ranking of isotopes may reflect that ^{226}Ra was lower as compared to ^{232}Th and ^{40}K because of the soluble

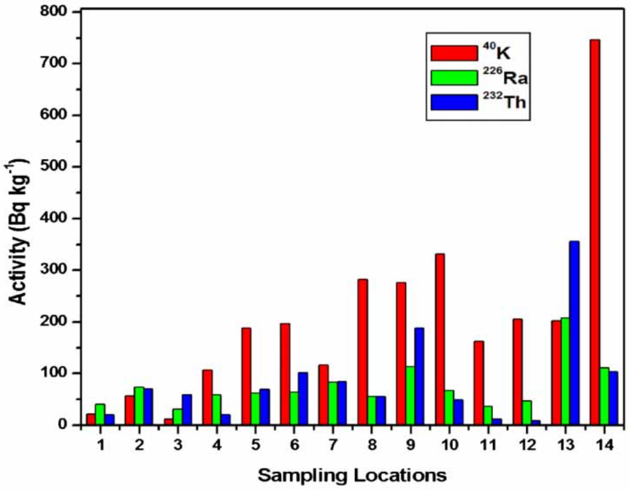

Figure 2 | Activity concentration of ^{226}Ra, ^{232}Th, ^{40}K in Cauvery River sediment samples.

nature of ^{226}Ra and lower concentration of ^{226}Ra in parent rock. The radionuclide ^{226}Ra is more readily leached from sediments before the final deposition than the other two radionuclides because radium migrates as a cation competing with other alkaline earth cations (Mitchell *et al.* 2013). The concentration of ^{232}Th was found to be high as compared to the concentration of ^{226}Ra in all the sampling locations as thorium has an insoluble nature in water and it has low geochemical mobility. This means that thorium exists only in the tetravalent state and its compounds are generally insoluble in water (Faure & Mensing 2005, chapter 10; Mitchell *et al.* 2013).

The activity concentration of the present study was compared with the literature values as shown in Table 1. In all the locations, the average concentration of ^{40}K was lower and the average concentration of ^{226}Ra and ^{232}Th was higher than the Indian and world average values (world average values of ^{226}Ra, ^{232}Th, and ^{40}K are 35, 30, and 400 Bq kg^{-1}, respectively, and average Indian values are 29, 64, and 400 Bq kg^{-1} for ^{226}Ra, ^{232}Th, and ^{40}K, respectively) (UNSCEAR 2000). The locations K6, K9, K13, and K14 showed high activity of ^{232}Th and ^{226}Ra. The elevated level of ^{232}Th may be due to its accumulation from the weathering of rocks and soil run-off during the rainy season. The activity of ^{40}K was found to be lower when compared with Kallada and Vaigai Rivers in India, but the activity of ^{226}Ra was higher compared with the literature values. ^{232}Th activity was found to be lower than the Kallada River, India, but its value is higher than the other rivers as seen in Table 1.

The vital objective of measuring the activity concentration of radionuclides in the sediment was to assess the doses delivered to the public and the activity utilization index, because in southern Karnataka and adjacent areas, residential houses and other building constructions are mostly built using the sediment (sand) from the Cauvery River. The following equations are used to calculate the radiological hazard parameters and the corresponding calculated values are shown in Table 2.

Absorbed dose rate (*D*)

In order to calculate the dose rate in the air using the activity concentration and conversion factors of ^{226}Ra, ^{232}Th, and ^{40}K. The absorbed dose rate (D in nGy h^{-1}) was calculated using Equation (9) (Nuclear Energy Agency-Organisation for Economic Co-operation and Development (NEA-OECD) 1979; Yadav *et al.* 2015):

$$D = 0.462\, C_{Ra} + -0.604\, C_{Th} + 0.0417\, C_K \tag{9}$$

where, C_{Ra}, C_{Th}, and C_K are the activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K, respectively. The mean dose rate was found to 95.05 nGy h^{-1}, which is higher than the recommended value by UNSCAR (UNSCEAR 2000).

Table 1 | Comparison of present study with literature values

Activity in Bq kg^{-1}				
^{40}K	^{226}Ra	^{232}Th	River	Reference
207.3	75.1	85.5	Cauvery	Present study
423.0	48.6	88.0	Kallada, Kerala	Venunathan *et al.* (2016)
52.94	–	12.94	Nile River, Egypt	El-Gamal *et al.* (2007)
–	30	39	Sava River, Serbia	Bikit *et al.* (2006)
774	77	–	Tejo River, Portugal	Madruga *et al.* (2014)
625	–	41.8	Hong Kong	Yu *et al.* (1994)
272	35.9	65.5	Karnaphuli, Bangladesh	Chowdhury *et al.* (1999)
255	57.5	27.4	Shango, Bangladesh	Chowdhury *et al.* (1999)
448.24	–	33.8	Vaigai, India	Ramasamy *et al.* (2014)
400	35	30	World Average	UNSCEAR (2000)

Table 2 | Radiological hazard indices of sediment sample

	Dose D (nGy h^{-1})	AEED (μSv y^{-1}) outdoor	AEED (μSv y^{-1}) indoor	Raq (Bq kg^{-1})	Hazard index H_{ex}	Hazard index H_{in}	AUI(I)	ELCR	AGDE
Mean	95.0	116.5	466.1	213.4	0.58	0.78	1.74	0.41	654.8
Minimum	30.8	37.7	150.9	65.9	0.18	0.28	0.49	0.13	213.1
Maximum	319.7	392.1	1,568.4	733.1	1.98	2.54	6.24	1.37	2,195.5
Median	76.3	93.7	374.6	169.1	0.46	0.63	1.33	0.33	527.9
St. Dev	77.2	94.8	379.1	177.6	0.48	0.60	1.51	0.33	531.6

AEED, Annual effective equivalent dose; Raq, Radium equivalent activity; H_{ex}, External hazard indices; H_{in}, Internal hazard indices; AUI(I), Activity utilization index; ELCR, Excess life time cancer risk; AGDE, Annual gonadal dose equivalent.

Annual effective equivalent dose

The annual effective dose rate for indoor and outdoor in units of μSv y^{-1} was calculated using the following formula (Krieger 1981),

$$\text{AEED (Outdoor)}(\mu\text{Sv y}^{-1}) = \text{Dose rate}\left(\text{nGy h}^{-1}\right) \times 8760\ \text{h} \times 0.2 \times 0.7\ \text{Sv Gy}^{-1} \times 10^{-3} \quad (10)$$

$$\text{AEED (Indoor)}(\mu\text{Sv y}^{-1}) = \text{Dose rate}\left(\text{nGy h}^{-1}\right) \times 8760\ \text{h} \times 0.8 \times 0.7\ \text{Sv Gy}^{-1} \times 10^{-3} \quad (11)$$

The calculated annual effective equivalent dose (AEED) was found to be 116 μSv y^{-1} and 466 μSv y^{-1} for outdoor and indoor, respectively. The mean value of AEED is lower than the recommended value, except in a few locations.

Radium equivalent activity (*Ra$_{Eq}$*)

The radium equivalent is a single index or number to describe the gamma output from combining ^{226}Ra, ^{232}Th, and ^{40}K in the samples from an individual location. The mean radium equivalent activity was found to be 213.40 Bq kg^{-1} for the sediment samples. The radium equivalent (Bq kg^{-1}) was calculated using Equation (12) (UNSCEAR 2010),

$$Ra_{eq} = C_{Ra} + 1.43\ C_{Th} + 0.077\ C_K \quad (12)$$

where C_{Ra}, C_{Th}, and C_K are the activity of ^{226}Ra, ^{232}Th, and ^{40}K, in Bq kg^{-1}, respectively.

Hazard index

The external and internal hazard indices were calculated using Equations (13) and (14) (Krieger 1981; UNSCEAR 2010):

$$H_{ex} = (C_{Ra}/370 + C_{Th}/259 + C_K/4810) < 1 \quad (13)$$

$$H_{in} = (C_{Ra}/185 + C_{Th}/259 + C_K/4810) < 1 \quad (14)$$

where C_{Ra}, C_{Th}, and C_K are the activity of ^{226}Ra, ^{232}Th, and ^{40}K, respectively. The mean H_{ex} and H_{in} was found to be 0.57 and 0.77, respectively.

Annual gonadal dose equivalent

The UNSCAR has formulated equations to estimate the dose received by the body organs like the thyroid, lungs, bone marrow, bone surface cell, and the gonads. The annual gonadal dose equivalent (AGDE) (μSv y^{-1}) was calculated using Equation (15) (Krieger 1981):

$$AGDE = 3.09\ C_{Ra} + 4.18\ C_{Th} + 0.31\ C_K \quad (15)$$

where C_{Ra}, C_{Th}, and C_K are the activity concentration of ^{226}Ra, ^{232}Th, and ^{40} K in Bq kg^{-1}, respectively. The *AGDE* values varied from 213.12 μSv y^{-1} to 2,195.47 μSv y^{-1} with an average value of 654.76 μSv y^{-1}.

Excess life time cancer risk (ELCR)

The mean value of the estimated ELCR is 0.407, which is below the recommended limit. The ELCR was estimated using Equation (16) and is presented in Table 2.

$$ELCR = AEDE \times DL \times RF \quad (16)$$

where $AEDE$ is the annual effective dose equivalent, DL is the duration of life (70 years), and RF is the risk factor (Sv^{-1}), fatal cancer risk per Sievert. As per the International Commission on Radiological Protection (ICRP) recommendation, the risk factor for stochastic effect to the public is 0.05.

Activity utilization index (I)

In South India, the river sediment is used as construction material for plastering. Therefore, the Cauvery River sediment was also examined via calculating the AUI (I). The Activity Utilization Index (I) was calculated using Equation (17) (Ramasamy *et al.* 2011):

$$I = (C_{Ra}/50)f_{Ra} + (C_{Th}/50)f_{Th} + (C_K/500)f_K \quad (17)$$

where C_{Ra}, C_{Th}, and C_K are the mean activity of ^{226}Ra, ^{232}Th, and ^{40}K in Bq kg^{-1} in the sediment, and f_{Ra}, f_{Th}, and f_K are the fractional contributions to the total dose rate of ^{226}Ra, ^{232}Th, and ^{40}K. The mean activity utilization index is 1.75, which is below the recommended value, except for the K9, K13, and K14 locations. Therefore, the sediment can be used as construction material, except in high activity locations.

Radon exhalation rate

A passive 'can technique' used with the LR-115 SSNT detector was applied to measure the radon activity and radon exhalation rate in the sediment samples of the Cauvery River and is tabulated in Table 3. The mean activity of radon was found to be 135.7 Bq m^{-3} varying from 50.9 ± 10.9 Bq m^{-3} to 277.8 ± 25.3 Bq m^{-3}. The radon exhalation rate ranged from 122.8 ± 26.2 mBq m^{-1} h^{-1} to 669.6 ± 61.1 mBq m^{-1} h^{-1} with a geometric mean value of 327.1 mBq m^{-1} h^{-1} and the corresponding radium content varied from 49.9 ± 5.1 mBq kg^{-1} to 272.3 ± 12.0 mBq kg^{-1} with a geometric mean of 133.0 mBq kg^{-1}. Variation was observed in the radon exhalation rate in the sediment samples. This may due to the formation of sediment in the river drainage. Radon emanation from the sediment depends on the granulometric content of the sediment and the size of the grain. The ^{226}Ra activity and radon activity showed good correlation, with the coefficient of $R = 0.728$ (Figure 3).

Table 3 | Radon activity and radon exhalation rate in Cauvery River sediment samples

Sampling location	Effective radium content C_{Ra} (mBq kg^{-1})	Radon surface exhalation E_S (mBq m^{-1} h^{-1})	Radon mass exhalation E_M (mBq kg^{-1} h^{-1})	Radon activity (Bq m^{-3})
K1	95.8 ± 7.1	235.5 ± 36.2	87.3 ± 13.4	97.6 ± 15.0
K2	136.1 ± 8.9	334.8 ± 43.2	124.2 ± 16.0	138.9 ± 17.9
K3	68.0 ± 6.0	167.4 ± 30.5	62.1 ± 11.3	69.5 ± 12.6
K4	49.9 ± 5.1	122.7 ± 26.1	45.5 ± 9.7	50.9 ± 10.8
K5	85.3 ± 6.7	209.9 ± 34.2	77.8 ± 12.6	87.0 ± 14.2
K6	53.1 ± 5.3	130.6 ± 26.9	48.4 ± 10.0	54.2 ± 11.2
K7	97.1 ± 7.1	238.8 ± 36.5	88.6 ± 13.5	99.1 ± 15.1
K8	54.0 ± 5.3	132.8 ± 27.2	49.2 ± 10.1	55.1 ± 11.3
K9	364.9 ± 13.9	897.3 ± 70.7	332.9 ± 26.2	372.2 ± 29.3
K10	192.9 ± 10.1	474.4 ± 51.4	176.0 ± 19.0	196.7 ± 21.3
K11	83.9 ± 6.6	206.4 ± 33.9	76.6 ± 12.5	85.6 ± 14.1
K12	108.9 ± 7.5	267.8 ± 38.6	99.4 ± 14.3	111.1 ± 16.0
K13	272.3 ± 12.1	669.7 ± 61.1	248.5 ± 22.6	277.8 ± 25.3
K14	199.7 ± 10.2	491.1 ± 52.3	182.3 ± 19.4	203.7 ± 21.7

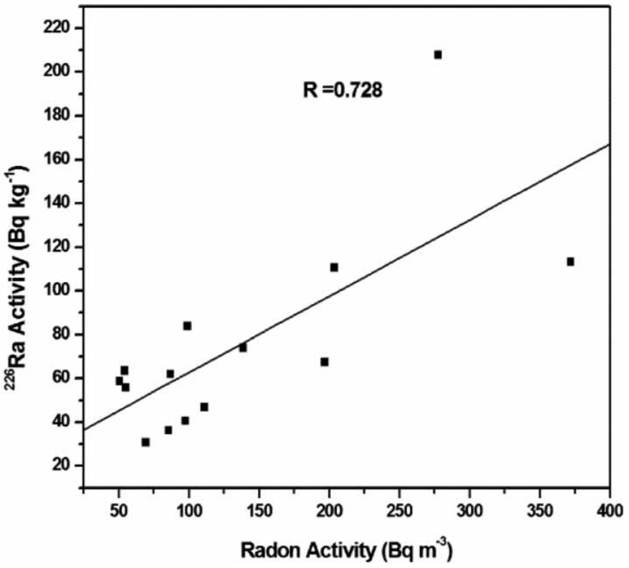

Figure 3 | ^{226}Ra and radon activity in sediment samples of Cauvery River.

Table 4 | ^{222}Rn in water and dose rate in water samples

Sampling location	Radon in water (Bq l^{-1})	Inhalation μSv y^{-1}	Ingestion μSv y^{-1}	Effective dose μSv y^{-1}	Lungs μSv y^{-1}	Stomach μSv y^{-1}
K1	1.00	2.52	5.69	8.21	0.303	0.682
K2	0.80	2.02	4.55	6.58	0.242	0.546
K3	1.40	3.54	7.98	11.52	0.425	0.957
K4	0.20	0.50	1.14	1.64	0.060	0.136
K5	1.20	3.03	6.82	9.85	0.363	0.819
K6	0.19	0.47	1.07	1.54	0.057	0.128
K7	0.40	1.01	2.28	3.30	0.121	0.274
K8	0.39	1.00	2.26	3.27	0.120	0.272
K9	0.19	0.49	1.12	1.61	0.059	0.134
K10	0.46	1.16	2.62	3.79	0.139	0.315
K11	0.57	1.43	3.24	4.67	0.172	0.388
K12	0.21	0.54	1.22	1.77	0.065	0.147
K13	0.40	1.01	2.28	3.30	0.121	0.274
K14	0.28	0.70	1.58	2.28	0.084	0.190

Radon concentration

In the present study, the RAD-7 detector was used to measure the radon concentration in the Cauvery River water samples and the obtained results are presented in Table 4. The radon concentration in the water samples varied from 0.19 kBq m^{-3} to 1.40 kBq m^{-3} with an average value of 0.55 kBq m^{-3}. The variation may be due to the source of radon in individual locations, tributaries connected to the mainstream, water flow, and climatic variation. The Environmental Protection Agency (EPA) recommended the maximum allowable concentration of radon in the water to be 11 kBq m^{-3} (European Commission (EC) 2001). Using the ICRP recommendations, the estimated dose due to radon in the water was calculated. The measured value of radon was below the recommended value of UNSCEAR and the US EPA. The effective dose due to the intake of radon in the water was estimated using the measured activity of ^{222}Rn as shown in Table 5. The effective dose of radon intake ranged from 1.61 μSv y^{-1} to 11.52 μSv y^{-1} with an average value of 4.54 μSv y^{-1}. The ^{222}Rn concentration found in the present study is comparable with the ^{222}Rn values reported for the other regions (Table 5). The present study values are lower than the values reported

Table 5 | Comparison of ^{222}Rn activity (kBq m^{-3}) in water samples

Present work	Region	Literature value kBq m^{-3}	Reference
0.19–1.40 kBq m^{-3}	Turkey	0.091	Canbazoğlu *et al.* (2012)
	Switzerland	10.4–38.3	Buchli & Burkart (1989)
	Egypt	0.074–2.33	Abbady *et al.* (1995)
	Kenya	0.8–4.7	Otwoma & Mustapha (1998)
	Cyprus	0.1–5.0	Sarrou & Pashalidis (2003)
	Kuwait	0.74	Maged (2009)
	Syria	13	Jonsson (1991)
	Bangladesh	2.04–9.38	Alam *et al.* (1999)
	Iran	0.21–3.89	Behtash *et al.* (2012)
	Kali river	0.16–1.79	Rajashekara *et al.* (2007)
	Sharavathi river	1.19–9.92	Rajashekara *et al.* (2007)

for the Sharavathi River, Bangladesh, and Syria. The radon concentration reported for Turkey, Egypt, Kali River, and Kuwait are comparable to the present measured values of the Cauvery River water.

CONCLUSION

Systematic studies were carried out to understand the distribution of natural radionuclide concentration and radon exhalation rate in the sediment samples and radon in the Cauvery River water. The average concentration of ^{226}Ra and ^{232}Th was higher than the Indian and world average values. Some locations show elevated levels of ^{232}Th and ^{226}Ra. The HPGe gamma spectroscopy measured via ^{226}Ra activity and the radon activity measured by the passive can technique showed good correlation. The mean value of radon in the water was within the internationally recommended level. The dose contributed from radon in the water to the stomach and lungs and the effective dose was calculated and compared with the recommended levels of the ICRP. The data collected in the present study will be useful in drawing up regulations for radiation protection. The sediment is safe to be used for construction purposes, except for some extreme values, and the water is safe for drinking purposes.

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