Natural Radionuclides and Radon Exhalation Rate in the Soils of Cauvery River Basin

CS Kaliprasad¹, PR Vinutha² and Y Narayana¹

¹Department of Physics, Mangalore University, Mangalagangothri, India. ²Department of Physics, Bearys Institute of Technology, Mangalore, India.

ABSTRACT: In this study, systematic measurement of activity concentrations of ⁴⁰K, ²²⁶Ra, and ²³²Th and radon exhalation rate has been done in soil samples of Cauvery River environment. The activity was measured using HPGe gamma-ray spectrometer, and the mean values of ⁴⁰K, ²²⁶Ra, and ²³²Th in the soil samples were found to be 182 ± 4, 34 ± 2, and 19 ± 1 Bq kg⁻¹, respectively. The radon exhalation rate was measured by “Can technique” using SSNTD (LR-115) films. The mean values of radium concentration, surface exhalation, and mass exhalation rate were found to be 118.95, 293.61, and 108.53 mBq kg⁻¹ h⁻¹, respectively. The radiological hazard indices due to natural radioactivity were calculated and compared with international recommended values, which are lower than the recommended level. The radon exhalation rate is lower than the recommended level.

KEYWORDS: Cauvery, radon, gamma dose, radioactivity, soil

Introduction

Soil is the top surface of the earth’s crust and it is formed due to the weathering of rocks. The soil contains radionuclides headed by the radioactive decay series ²³⁸U, ²³²Th, and singly occurring ⁴⁰K. ²³⁸U and ²³²Th contribute about 30% to 60% of the internal radiation dose, and the worldwide average annual effective dose per person ranges from 1.4 to 2.4 mSv y⁻¹, which depends on the concentration of natural radionuclides present in a particular location.¹ Radon (²²²Rn) is a naturally occurring radioactive isotope of ²³⁸U series, which has half-life of 3.82 days. Radon is one of the significant sources of natural radiation. The radon decay products which are attached in aerosol cause greater biological effect through inhalation and can lead to lung cancer on prolonged exposure.² ²¹⁸Po, ²¹⁴Ph, ²¹⁸Bi, and ²¹⁴Po are the short-lived decay products of radon; these decay products give rise to maximum dose through emission of alpha and beta particles. Therefore, the studies on radon exhalation rate, radionuclides distribution, and its associated dose rate in the soil are significant. The riverine environs are of greater interest due to the population, which lives near river basin. The soils found near river basin are also used for construction of materials such as bricks and plastering material to walls in areas of South Karnataka, India. The published data on radionuclides concentration in riverine environs are sparse, and therefore, an attempt was made in the present investigation to study natural radionuclides distribution and radon exhalation rate in the soils of Cauvery River basin.

Materials and Methods

Sample collection and preparation

The sampling stations along Cauvery River are indicated in Figure 1. Sampling station K1 corresponds to the upper reaches of the river and K14 corresponds to the lower reaches. The soil samples from the river basin were collected following standard procedures.² The collected soil samples were brought to the laboratory and oven dried at 110°C till constant dry weight was obtained. The dried samples were sieved through 250-μm mesh and then stored in a sealed polyvinyl chloride container for 30 days to attain secular equilibrium between radium and its progeny.³

Activity measurement

The activity concentrations of ⁴⁰K, ²²⁶Ra, and ²³²Th in soil were measured using a high-resolution N-type HPGe (NGC 3019, DSG) detector–based gamma spectrometry system. The detector was shielded using thick lead blocks to avoid interference of external gamma radiations. The output of the detector was analyzed using a 16-K multi channel analyzer (MCA-3 series/ P7882; Fast ComTec). The spectrometer was calibrated using International Atomic Energy Agency (IAEA) standard reference materials. The standards used were RG-U, RG-Th, and RG-K for uranium, thorium, and potassium, respectively. The gamma spectrum was obtained with a counting period of 20 000 seconds. The peaks corresponding to 1.46 MeV (⁴⁰K), 609.31 keV (²¹⁸Bi), and 911.07 keV (²²³Ac) were considered for evaluating the activity levels of ⁴⁰K, ²²⁶Ra, and ²³²Th, respectively.⁴

Radon exhalation rate

The radon exhalation rate in the soil samples of the Cauvery River was determined by “Sealed Can Technique” using SSNTD detectors. About 100 g of the dried and sieved (250 μm) soil sample was taken in each “Can” (diameter: 7.0 cm and height: 10.5 cm),...
Air, Soil and Water Research

and LR-115 Type II SSNT detector (3 cm × 3 cm) was fixed on the top inside of each “Can.” The “Can” was kept airtight for 4 hours to allow the radon and its progeny to reach equilibrium. The equilibrium activity of the emergent radon was calculated based on the geometry of the “Can” and the time of exposure. The LR-115 film inside the can was exposed to radon for 90 days. The films (detectors) were removed and then etched in 2.5 N NaOH at 60°C ± 1°C for a period of 60 minutes in an etching bath at constant temperature to enlarge the tracks produced from the alpha particles emitted from the decay of radon. The background track density of the detector was measured using unexposed detectors under the same etching condition. The enlarged alpha tracks were counted using spark counter. Precounting was done at 900 V and finally track density was determined at 450 V, in the plateau region of the counter.

The effective radium concentration $C_{Ra}$ can be calculated using the following formula:\(^7\)

\[ C_{Ra} = \frac{\rho h A}{MKT} \]  

where $\rho$ is the track density (0.056 tracks cm$^{-2}$ d$^{-1}$ [Bq m$^{-1}$]), $T$ is the effective exposure time in an hour, $h$ is the distance between detector films and 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$^{-3}$.

Surface exhalation rate $E_A$ is obtained from the following expression:\(^8\)

\[ E_A = \frac{CV \lambda}{A \left[ T + \frac{1}{\lambda} (e^{-\lambda T} - 1) \right]} \]  

This formula is also modified to calculate the mass exhalation rate $E_M$:

\[ E_M = \frac{CV \lambda}{M \left[ T + \frac{1}{\lambda} (e^{-\lambda T} - 1) \right]} \]  

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 can (m$^3$), $C$ is the integrated radon exposure as measured by LR-115 solid-state nuclear track detectors (Bq m$^{-3}$ h), $T$ is the exposure time (h), $\lambda$ is the decay constant for radon (h$^{-1}$), $A$ is the area of the can (m$^2$), and $M$ is mass of the sample.

Results and Discussions

Activity concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K

The activity concentrations of $^{226}$Ra, $^{232}$Th, and $^{40}$K in soil samples of Cauvery River basin were measured using HPGe gamma-ray spectrometer, and the results are presented in Table

![Figure 1. Cauvery River basin map.](image-url)
1. The measured activity ranged from 18 ± 1 to 65 ± 3 Bq kg⁻¹ for ²²⁶Ra, 3 ± 0.5 to 47 ± 2 Bq kg⁻¹ for ²³²Th, and 14 ± 1 to 531 ± 7 Bq kg⁻¹ for ⁴⁰K. The measured activity of the radionuclides varied from location to location. These variations are mostly due to the changes in local geology. The physical and chemical sorting processes also contributed to the variation of radionuclides in the soil from different locations. The mean activity of ⁴⁰K, ²²⁶Ra, and ²³²Th is 182 ± 4, 34 ± 2, and 19 ± 1 Bq kg⁻¹, respectively. In all the locations, activity concentration is in the order of ⁴⁰K > ²²⁶Ra > ²³²Th; the concentration of ²³²Th is much lower than the ²²⁶Ra and ⁴⁰K. The ⁴⁰K activity concentration dominates over ²²⁶Ra and ²³²Th activity. The activity concentrations of ⁴⁰K were found to be lower in upper reaches of the river and higher values were observed in lower reaches. The ⁴⁰K in the upper reaches decreases by leaching process and may also be diluted with increase in organic matter and soil water contents. In all the locations, the average concentration of ²²⁶Ra, ²³²Th, and ⁴⁰K is lower than the world average values (world average of ²²⁶Ra, ²³²Th, and ⁴⁰K is 35, 30, and 400 Bq kg⁻¹, respectively, United Nations Scientific Committee on the Effects of Atomic Radiation [UNSCEAR]). The average concentration of ²²⁶Ra is higher than the concentration of ²³²Th; ⁴⁰K is lower than the Indian average values (29, 64, and 400 Bq kg⁻¹ for ²²⁶Ra, ²³²Th, and ⁴⁰K, respectively, UNSCEAR, 2000). The measured activity concentrations of Cauvery River soil samples were compared with other river environs, which is presented in Table 2. The activity of ²²⁶Ra in Cauvery River basin soil sample is less than the activity of ²²⁶Ra in Nethravathi River of Karnataka and is also below the world average value. The activity concentration of Kallada River basin shows (343.4, 60.3, and 98.1 Bq kg⁻¹ for ⁴⁰K, ²²⁶Ra, and ²³²Th, respectively) higher activity than Cauvery River activity concentration. The activity concentration of Cauvery River is comparable with Wei River of China and Büyük Menderes River of Turkey. The values are comparable with Chao Phraya, Thailand (364.49 and 42.95 Bq kg⁻¹ for ⁴⁰K and ²³²Th, respectively); Dez, Iran (289, 25, and 33 Bq kg⁻¹ for ⁴⁰K, ²²⁶Ra, and ²³²Th, respectively); and Pra River, Ghana. The activity concentration of ⁴⁰K was found to be higher in all river environments compared with this study.

The statistical analysis of ²²⁶Ra, ²³²Th, and ⁴⁰K activity is shown in Table 3. Figure 2 shows the frequency distribution of natural radionuclides in soil samples of Cauvery River. The kurtosis values which are positive indicate peaked distribution and negative kurtosis indicates the flat distribution. The skewness for a normal distribution is 0 and indicates the values are near to the mean value. Positive skewness indicates the few values are above the median values. The skewness and kurtosis values which are near to 0 indicate that there is no extreme deviation from the mean value.

To assess the radiologic risk of the river basin soil, various radiological hazard indices were computed and the results are shown in Table 4. The hazard indices were calculated using the following equations.

**Absorbed dose rate (D)**

To calculate the dose rate in the air using the activity concentrations and conversion factors of ²²⁶Ra, ²³²Th, and ⁴⁰K, the
absorbed dose rate \( (D \text{ in nGy h}^{-1}) \) was calculated using the following equation\textsuperscript{19,20}:

\[
D = 0.462C_{Ra} - 0.604C_{Th} + 0.0147C_{K}
\]  

(4)

where \( C_{Ra}, C_{Th}, \) and \( C_{K} \) are the activity concentrations of \( ^{226}\text{Ra}, ^{232}\text{Th}, \) and \( ^{40}\text{K} \), respectively. The mean dose rate was found to be 35 nGy h\(^{-1}\), which is lower than the world (57 nGy h\(^{-1}\)) and Indian (56 nGy h\(^{-1}\)) average calculated by UNSCEAR.\textsuperscript{1}

### Annual effective equivalent dose

The annual effective dose rate for indoor and outdoor in units of \( \mu\text{Sv y}^{-1} \) was calculated using the following formula\textsuperscript{21}:

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

(5)

\[
AEED(\text{Outdoor}) \left( \mu\text{Sv y}^{-1} \right) = Dose \text{ rate} \left( \text{nGy h}^{-1} \right) \times 8760 \times 0.8 \times 0.7 \times 10^{-3}
\]

(6)

where \( D \) is the dose rate. The mean annual effective equivalent dose (AEED) for outdoor and indoor was 43 and 170 \( \mu\text{Sv y}^{-1} \), respectively. The mean value of AEED is lower than the recommended value (outdoor: 70 \( \mu\text{Sv y}^{-1} \) and indoor: 450 \( \mu\text{Sv y}^{-1} \)).

### Radium equivalent activity (Raeq)

The radium equivalent is a single index or number which describes the total gamma output from the combination of \( ^{226}\text{Ra}, ^{232}\text{Th}, \) and \( ^{40}\text{K} \) radionuclides in the sample from individual location. The radium equivalent (Bq kg\(^{-1}\)) was calculated using the following equation (UNSCEAR, 2010):
where $C_{Ra}$, $C_{Th}$, and $C_{K}$ are the activity of $^{226}$Ra, $^{232}$Th, and $^{40}$K in Bq kg$^{-1}$, respectively. The mean radium equivalent value was found to be 75.28 Bq kg$^{-1}$ for soils of Cauvery River basin, which is lower than the safety limit (370 Bq kg$^{-1}$).

Hazard index

The external and internal external hazard indices were calculated using the following equations$^{22,23}$:

$$H_{ex} = \left( \frac{C_{Ra}}{370} + \frac{C_{Th}}{259} + \frac{C_{K}}{4810} \right) \leq 1$$  \hspace{1cm} (8)

$$H_{in} = \left( \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_{K}}{4810} \right) < 1$$  \hspace{1cm} (9)

where $C_{Ra}$, $C_{Th}$, and $C_{K}$ are the activity of $^{226}$Ra, $^{232}$Th, and $^{40}$K, respectively. The mean external hazard index and internal hazard index values were 0.20 and 0.29, respectively.

Annual gonadal dose equivalent

The UNSCEAR has formulated equations to estimate the dose received by the body organs such as the thyroid, lungs, bone marrow, bone surface cell, and the gonads. The annual gonadal dose equivalent (AGDE) (μSv y$^{-1}$) was calculated using the following equation$^{21}$:

$$AGDE = \left( \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_{K}}{4810} \right) \times 10^{-3}$$

Table 4. Radiological hazard indices of soil sample.

| ABSORBED DOSE, nGy h$^{-1}$ | AEED, µSv y$^{-1}$ | HAZARD INDEX | ALI (I) | ELCR × 10$^{-3}$ | AGDE |
|-----------------------------|-------------------|--------------|--------|------------------|------|
|                             | OUTDOOR           | INDOOR       | $H_{ex}$ | $H_{in}$         |      |
| 38.6                        | 47.3              | 189.2        | 0.23    | 0.40             | 0.753 |
| 27.8                        | 34.1              | 136.3        | 0.16    | 0.21             | 0.435 |
| 24.4                        | 30.0              | 119.8        | 0.14    | 0.21             | 0.413 |
| 16.1                        | 19.8              | 79.1         | 0.09    | 0.16             | 0.279 |
| 26.7                        | 32.8              | 131.1        | 0.15    | 0.22             | 0.397 |
| 44.7                        | 54.8              | 219.1        | 0.25    | 0.30             | 0.494 |
| 48.6                        | 59.6              | 238.5        | 0.29    | 0.38             | 0.795 |
| 22.2                        | 27.2              | 108.9        | 0.13    | 0.22             | 0.384 |
| 37.4                        | 45.8              | 183.3        | 0.22    | 0.30             | 0.565 |
| 53.4                        | 65.5              | 261.9        | 0.31    | 0.42             | 0.804 |
| 23.2                        | 28.4              | 113.8        | 0.13    | 0.17             | 0.225 |
| 23.1                        | 28.4              | 113.5        | 0.14    | 0.17             | 0.225 |
| 63.3                        | 77.7              | 310.6        | 0.38    | 0.53             | 1.100 |
| 37.9                        | 6.5               | 186.0        | 0.23    | 0.35             | 0.748 |

Abbreviations: AEED, annual effective equivalent dose; AGDE, annual gonadal dose equivalent; ALI, activity utilization index.

Figure 2. Frequency distribution of $^{226}$Ra, $^{232}$Th, and $^{40}$K in monsoon soils of Cauvery.
where \( CRa, CTh \), and \( CK \) are the activity concentrations of \(^{226}\text{Ra}, ^{232}\text{Th}, \) and \(^{40}\text{K} \) in Bq kg\(^{-1} \), respectively. The average value of AGDE is 241.94 μSv y\(^{-1} \), which is lower than the world average value of 0.30 mSv y\(^{-1} \).

Excess lifetime cancer risk

The mean value of the estimated excess lifetime cancer risk (ELCR) is 0.149 × 10\(^{-3} \), which is lower than the world average 1.45 × 10\(^{-3} \).\(^{24} \) The ELCR was estimated using the following equation and is presented in Table 4:

\[
\text{ELCR} = \text{AEDE} \times \text{DL} \times \text{RF}
\]

where \( \text{AEDE} \) is the annual effective dose equivalent, \( \text{DL} \) is the duration of life (70 years), and \( \text{RF} \) 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 soil is used as construction material for plastering. Therefore, the Cauvery River soil was also examined via calculating the activity utilization index (AUI) (I). The AUI (I) was calculated using the following equation\(^{21} \):

\[
I = (C_{Ra} / 50) f_{Ra} + (C_{Th} / 50) f_{Th} + (C_{K} / 500) f_{K}
\]

where \( C_{Ra}, C_{Th}\), and \( C_{K} \) are the mean activity of \(^{226}\text{Ra}, ^{232}\text{Th}, \) and \(^{40}\text{K} \) in soil and \( f_{Ra}, f_{Th}\), and \( f_{K} \) are the fractional contributions to the total dose rate of \(^{226}\text{Ra}, ^{232}\text{Th}, \) and \(^{40}\text{K} \). The mean AUI is 0.55, which is below the recommended safety limit (<2). Therefore, the soils may be used as construction material.

Radon exhalation measurement

The radium activity and radon exhalation rates in the soil samples were measured using “Can technique” and the results are given in Table 5. The activity concentration of effective radium content (\( C_{Ra} \)) ranged from 25.7 to 394.02 mBq kg\(^{-1} \), radon surface exhalation (\( E_{S} \)) ranged from 63.61 to 973.23 mBq m\(^{-1} \) h\(^{-1} \), radon mass exhalation (\( E_{M} \)) ranged from 23.45 to 359.49 mBq kg\(^{-1} \) h\(^{-1} \), and radon activity ranged from 26.39 to 403 Bq m\(^{-3} \), respectively. It can be observed from the results that the radon exhalation rate varied appreciably from one sample to another. The high radium concentration in soil was found at locations K5 and K9. The mass exhalation rate and surface exhalation rate in soil samples were found to be high at K5 and K9. The variation in exhalation depends on the type of soil, emanation factor of radon from them, radium content, and diffusion coefficient of radon.

Conclusions

The measured activity concentrations of \(^{226}\text{Ra}, ^{232}\text{Th}, \) and \(^{40}\text{K} \) in the study were found to vary from place to place. The \(^{40}\text{K} \) activity concentration dominates over \(^{226}\text{Ra} \) and \(^{232}\text{Th} \). The radiological doses as absorbed dose (D), AEED, and AGDE were estimated using the activity concentrations of \(^{226}\text{Ra}, ^{232}\text{Th}, \) and \(^{40}\text{K} \) and...
standard equations given by UNSCEAR and IAEA. The obtained results show that dose rates are lower than the world average. To assess the radiologic risk parameters, radium equivalent ($R_{eq}$), internal hazard index ($H_{int} < 1$), external hazard index ($H_{ext} < 1$), AUI (AUI < 2), and ELCR values were calculated. All the hazard indices are less than the safety limit. Hence, there is no significant radiologic risk to the population from soils in the study area. The radon exhalation rate was measured using the “Can technique.” The results of this study show the variation in radon exhalation due to the variation in geological condition of the locations and properties of the soil. The soil is safe for its use as a construction material. This data will be helpful to establish new regulations and safety limits regarding the radiation dose and radon activity in Cauvery River basin.

**Author Contributions**

All the authors contributed equally and there is no conflict of interest.

**REFERENCES**

1. UNSCEAR. United Nations Scientific Committee on the Effects of Atomic Radiation—sources and effects of ionizing radiation. Report to General Assembly, with Scientific Annexes. New York, NY: United Nations; 2000.
2. EML Procedure Manual. (Ed. Volchk Hl, dePlanque G). 26th ed. New York, NY: Environment Measurement Laboratory; 1983.
3. Radhakrishna AP, Somasekara HM, Narayana Y, Siddappa K. A new natural background radiation area on the southwest coast of India. Health Phys. 1993;65:390–395.
4. Narayana Y, Rajashekara KM, Siddappa K. Natural radioactivity in some major rivers of costal Karnataka on the south west coast of India. J Environ Radioactiv. 2005;95:98–106.
5. Kaliprasad CS, Narayana Y. Radon concentration in water, soil and sediment of Hemavathi River environments [published online ahead of print January 22, 2017]. Indoor Build Environ. doi:10.1177/1420326X16688522.
6. Qureshi AA, Kakar DM, Akram M, et al. Radon concentrations in coal mines of Baluchistan, Pakistan. J Environ Radioact. 2000;48:203–209.
7. Singh AK, Jojo PJ, Khan AJ, Prasad R, Ramchandran TV. Calibration of track detectors and measurement of radon exhalation rate from solid samples. Radiat Prot Environ. 1997;3:129–133.
8. Mahur AK, Kumar R, Mishra M, Sengupta D, Prasad R. An investigation of radon exhalation rate and estimation of radiation doses in coal and flyash samples. Appl Rad Isot. 2008;66:401–406.
9. Venunathan N, Kaliprasad CS, Narayana Y. Natural radioactivity in sediment and river bank soil of Kallada River of Kerala, South India and its associated Radiation risk. Rad Prot Dosimet. 2016;171:273–276.
10. Cowart JB, Burnett WC. The distribution of uranium and thorium decay series radionuclides in environment—a review. J Environ Qual. 1994;23:651–662.
11. Yadav M, Rawat M, Dangwal A, Prasad M, Gusain GS, Ramola RC. Analysis of natural radionuclides in soil samples of Purola area of Garhwal Himalaya, India. Radiat Prot Dosim. 2015;167:215–218.
12. Narayana Y, Rajashekara KM, Siddappa K. Natural radioactivity in some major rivers of costal Karnataka on the south west coast of India. J Environ Radioactiv. 2005;95:98–106.
13. Kurnaz A, Kucukomeroglu R, Kesser R, et al. Determination of radioactivity levels and hazards of soil and sediment samples in Firtina Valley (Rize, Turkey). Appl Radiat. 2007;65:1281–1289.
14. Adukpo OK, Faamu A, Lawlivi H, et al. Distribution and assessment of radionuclides in sediments, soil and water from the lower basin of river Pra in the Central and Western Regions of Ghana. J Radioanal Nucl Chem. 2015;303:1679–1685.
15. Akozcan S. Annual effective dose of naturally occurring radionuclides in soil and sediment. Toxicol Environ Chem. 2014;96:379–386.
16. Nasrabadi MN, Mostajaboddavati M, Hajializani G. Natural radioactivity distribution in riverbank soils along the Dez River basin of Iran. World J Environ Res. 2014;4:7–22.
17. Lu X, Zhang X, Wang F. Natural radioactivity in sediment of Wei River, China. Environ Geol. 2008;53:1475–1481.
18. Santawamaitre T. An Evaluation of the Level of Naturally Occurring Radioactive Materials in Soil samples along the Chao Phraya River Basin [PhD thesis]. Guildford, UK: University of Surrey; 2012.
19. Yadav M, Rawat M, Dangwal A, Prasad M, Gusain GS, Ramola RC. Analysis of natural radionuclides in soil samples of Purola area of Garhwal Himalaya, India. Radiat Prot Dosimetry. 2015;167:215–218.
20. NEA-OECD. Nuclear Energy Agency, Exposure from Natural Radioactivity in Building Materials, Reported by NEA Group of Experts, OECD. Paris, Italy: NEA-OECD; 1979.
21. Krüeger R. Radioactivity of construction materials. Betonwerk Fertigteil Techn. 1991;47:468–473.
22. UNSCEAR. Sources and Effects of Ionizing Radiation: Report to the General Assembly, with Scientific Annexes. Vol 1. New York, NY: United Nations; 2010.
23. Ramasamy V, Suresh G, Meenakshisundaram V, Ponnusamy V. Horizontal and vertical characterization of radionuclides and minerals in river sediments. Appl Radiat Isot. 2011;69:184–195.
24. Qureshi AA, Tariq S, Ud Din K, Manzoor S, Calligaris C, Waezaed A. Evaluation of excessive lifetime cancer risk due to natural radioactivity in the rivers sediments of Northern Pakistan. J Radiat Res Appl Sci. 2014;7:438–444.