Risk Assessment of Resident Farmers in Kilimambogo, Kenya, Using RESRAD Computer Code

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Abstract

The concentration of radionuclides in the any given place is determined by the geology of the area. The levels of primordial radionuclides present in soil samples harvested from Kilimambogo region in Kenya was measured using a Thallium activated Sodium Iodide, NaI (TI) gamma spectrometry technique. RESRAD computer code was used to evaluate and model the dose exposure and the cancer risks for the residential farmer from the RESidual RADioactive materials for up to 1000 years. The mean activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in soil samples were found to be 46 ± 6 Bq kg^{-1}, 57 ± 6 Bq kg^{-1} and 603 ± 46 Bq kg^{-1} The total maximum received dose by the resident farmer was projected to be 3.477mSv y^{-1} at t= 470.9 years for all nuclides summed and all component pathways, with ^{226}Ra, ^{232}Th and ^{40}K contributing maximum doses of 5.026 × 10^{-6} mSv y^{-1}, 2.919 mSv y^{-1} and 0.558 mSv y^{-1} respectively. This was more than three-fold higher than the recommended dose limit of 1 mSv y^{-1} proposed by the International Commission on Radiological Protection (ICRP), and more than ten-fold dose limit of 0.25 mSv y^{-1} recommended in the RESRAD Code for members of the general public. The highest cancer risk from all the pathways was projected to be 7.583 × 10^{-3} at t = 30 years and the least, 4.558 × 10^{-3} at t=1000 years. Inhalation of radon and the decay products were projected to contribute the highest cancer risk of 3.306 × 10^{-3} at t= 0 years making radon the highest contributor to cancer risk.

Keywords Cancer risks, RESRAD Code, Radionuclides, Annual Effective Doses.

1 Introduction

The concentration levels of radionuclides are widely distributed and mostly depend on the local geology, hence they vary from place to place. Their levels largely depend on the type of the rock from which the soils originated from, with the igneous rocks such as granite having the highest radiation [1]. Many radionuclides naturally occur in terrestrial soils, rocks and building materials which upon decay produce an external radiation field that we are all exposed to. The decay of these radionuclides in soil produces gamma radiation which cross the soil-air interface thereby producing radiation exposure to man. Some human activities such as quarrying, processing of quarried rocks and application of phosphate fertilizers can enhance the natural background radiation levels leading to technologically enhanced naturally occurring radioactive materials, (TENORM), [2, 3]. It was therefore of paramount importance to establish the exposure levels and the cancer risks of the resident farmer from the activity concentration levels measured in soil samples.

1.1 Radiation exposure pathways

Radiation exposure to human beings can either be internal or external. Internal exposure is usually as a result of inhalation of radon, thoron and their progenies, or ingestion of foods and/or drinks contaminated with the radionuclides. Ingestion mainly occurs when the radionuclides present in the environment enter the food chain. The radionuclides are transferred from the atmosphere to the plants, the primary recipients of radioactive contamination. The contamination may also occur directly where the radionuclides are deposited on the above-ground parts of the plants. Also, indirect contamination takes place when the radionuclides are taken from the soil by the root system of plants through the sorption process, [4]. Animals that consume plants, regarded as the secondary recipients, plants as well as the animal products all form the human diet. Animal pathways therefore include ingestion of animal products such as meat, milk, eggs and fish. A schematic representation of the different pathways described in the RESRAD computer code is shown in Figure 1 [5].

1.2 Dose analysis using RESRAD code

RESRAD is a computer model designed to estimate radiation doses and risks from RESidual RADioactive materials by the Argonne National Laboratory (ANL). It uses pathway analysis to evaluate radiation exposure and associated risks, and to derive clean-up criteria or authorized limits for radionuclides concentration in contaminated source medium. The code easily adapts to user specific exposure scenarios to compute potential annual doses and lifetime risks to persons exposed to residual radioactive materials in soil [6, 7, 8]. Radionuclides are known to move from the source to man through the different exposure pathways. The water-independent pathways are assumed to contribute to the dose as soon as a family establishes a residence and a garden on the site. On the other hand, the contribution from water-dependent pathways is normally delayed until radionuclides transported by groundwater reach a point of water withdrawal (i.e., well or pond) [5, 9].

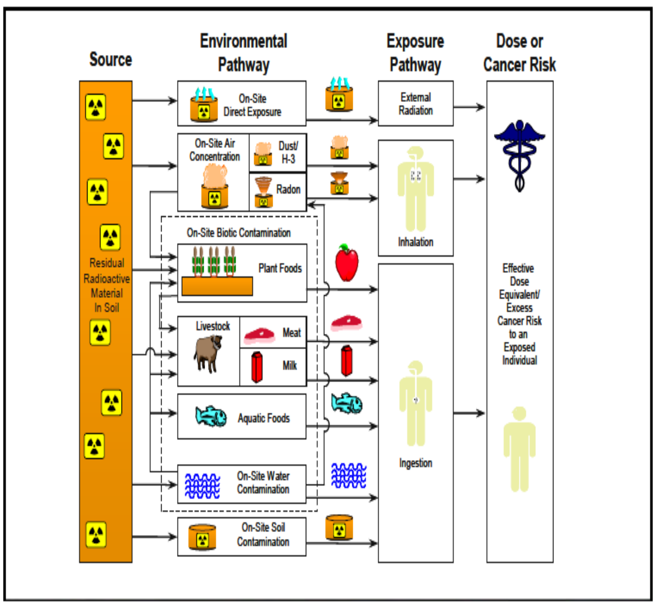

Figure 1. Schematic representation of RESRAD pathways

Radionuclide transport through the food pathways are determined by the quantities of different foods consumed (dietary factors), the fraction of the diet from foods that are contaminated by radionuclides from the contaminated zone, the cover depth and contaminated zone thickness relative to the root zone of the plants, the various transfer factors from root or foliage to plants and from fodder or water to meat or milk, and the concentrations of radionuclides in water that have percolated through the contaminated zone [5].

1.3 Exposure Scenario

These are patterns of human activity that can affect the release of radioactivity from the contaminated zone and the amount of exposure received at the exposure location. There are many potential exposure scenarios, such as subsistence farming and industrial worker. The actual scenario of a site depends on factors such as the location of the site, zoning of the land, physical characteristics of the site, among others.

1.3.1 Resident Farmer Scenario

In the resident farmer scenario, a family is assumed to move onto the site after it has been released for use without radiological restrictions, build a home, and raise crops and livestock for family consumption. Members of the family could incur a radiation dose by direct radiation from radionuclides in the (1) soil, (2) inhalation of resuspended dust (3) inhalation of radon and its decay products, (4) ingestion of food from crops grown in the contaminated soil, (5) ingestion of milk from livestock raised in the contaminated area, (6) ingestion of meat from livestock raised in the contaminated area, (7) ingestion of fish from a nearby pond contaminated by water percolating through the contaminated zone, (8) ingestion of water from a well or pond contaminated by water percolating through the contaminated zone, and (9) ingestion of contaminated soil [5].

2. Materials and Methods

2.1. Sampling

The soil samples were collected along the slopes and the environs of Mt. Kilimambogo, Kenya by random sampling technique. Figure 2 shows the geology map of the study region.

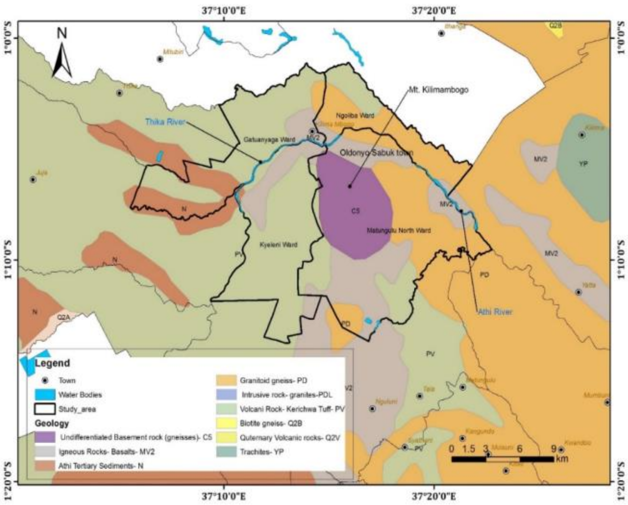

Figure 2. A Map showing the study area

2.2. Sample preparation

Soil samples were crushed and thoroughly mixed to ensure homogeneity and sieved in a 1 mm mesh sieve. Samples were then oven dried at about 110ºC for about 24 hours to completely remove the moisture. About 500 g of each of the samples were then put in clean and dry plastic containers, sealed and stored for approximately 30 days. This was to ensure that radioactive equilibrium between ^{226}Ra and ^{232}Th and their daughter radionuclides was reached [10,11], and that, radon and thoron gases did not escape from the samples.

2.3. Sample analysis

2.3.1. Activity Concentration

A NaI (Tl) scintillation detector was used to determine the activity concentration of the samples. It uses the principle of emission of light by a scintillator material when struck by any form of radiation. It has a scintillator, a photocathode, a photomultiplier tube and the associated electronics. The activity concentration of the samples was determined using equation (1) [12,13].

$$A_S = \frac{N}{\varepsilon P_\gamma M_S T} \quad (1)$$

Where As is the activity concentration of the sample in Bq kg^{-1}, N is the net counts under the photon peak for each sample in a given energy of interest, T is the counting time; ε is peak efficiency at the given energy of interest, Pγ is the photon emission probability and Ms, the mass of the sample in kilograms.

2.4 Dose modeling

RESRAD code is a tool that assists in developing criteria for evaluating human radiation doses and excess lifetime cancer risk to an on-site resident, a maximally (occupationally) exposed individual or a member of a critical population group associated with exposure to radiological contamination. The software allows users to specify the features of their site and try to predict the doses received by an individual any time up to 100,000 years. The source term is adjusted to account for physical radioactive decay and ingrowth, erosion, leaching and mixing of the radionuclides. The program tries to model a site through the use of more than 150 variables which have default values assigned but could be changed to suite site specific needs. The software can be used to evaluate exposure to any scenario by considering the different exposure pathways like soil, inhalation of dust or radon, ingestion of plant foods, water and so on as shown in Figure 1 [5,14]. It also evaluates potential radiation exposures and cancer risks at current time (time=0 years) as well as at many future times determined by input specifications of the user.

In the present study, the resident farmer scenario was chosen as the critical receptor in the risk assessment. The parameter values were carefully selected to achieve a realistic estimation of the doses and their risks using RESRAD onsite computer code. Where possible, site-specific parameters were used to replace the default parameters. The main input parameters included the measured activity concentrations of the NORMs in soil samples, and the exposure times. The derived activity concentrations were used to calculate the exposure of the resident farmer in the study region. The results of the radiation doses were fed into the RESRAD computer code to calculate the excess cancer morbidity risks for all of the pathways summed over duration of up to 1000 years [7, 15].

The total dose received by an individual as a result of exposure from 0 external, inhalation and ingestion should not exceed 0.25 mSv y^{-1} recommended in the RESRAD Code for members of the general public. Equation (2) [5] was used to calculate the doses received.

$$(\mathrm{Dose})_{i,p}(t) = \mathrm{DCF}_{i,p} \times \mathrm{ETF}_{i,p}(t) \times \mathrm{SF}_i(t) \times \mathrm{S}_i(0) \quad (2)$$

Where $DCF_{i,p}$ is the dose conversion factor; $ETF_{i,p}$ (t), the environmental transport factor; $SF_i(t)$, the source factor and $S_i(0)$, the soil concentration at time, t = 0.

2.5 Cancer Risk Model

RESRAD was used to determine the lifetime risk of the resident farmer, getting cancer as a result of exposure to radiation using equation (3) [5, 16];

$$(\text{Cancer risk})_{j,1}(t) = \sum_{i=1}^{M} ETF_{j,i}(t) \times SF_{ij}(t) \times S_i(O) \times BRF_{ij} \times RC_{j,1} \times ED \quad (3)$$

Where $RC_{j,1}$ is the risk coefficient for external radiation; ED is the exposure duration; BRF_{ij} is the branching factor that is the fraction of the total decay of radionuclide i that results in the ingrowth of radionuclide j. $SF_{ij}(t)$ = source factor; *i, j* = index of radionuclide for the radionuclides in the decay chain of radionuclide *i*), $Si(0)$ = initial soil concentration of radionuclide *i* at time 0. ETF at time t for the external ground radiation pathway was evaluated using equation (4) [5];

$$ETF_{i1}(t) = F0_1 \times FS_{i1}(t) \times FA_{i1}(t) \times FCD_{i1}(t) \quad (4)$$

Where, FO_1 = occupancy and shielding factor; $FS_{i1(t)}$ = shape factor; $FA_{i1(t)}$ = nuclide-specific area factor and $FCD_{i1}(t)$ = depth-and-cover factor. The occupancy and shielding factor (FO_1) is the fraction of a year that an individual remains on the site and the reduction in the external exposure rate due to on-site buildings or other structures while the individual is indoors. This was determined using equation (5) [5];

$$FO_l = f_{otd} + (f_{ind} \times F_{sh}) \quad (5)$$

Where; f_{otd} is the fraction of a year spent outdoors, on site; f_{ind} is the fraction of a year spent indoors, on site and F_{sh} is the indoor shielding factor for external gamma radiation. It is assumed that the indoor levels of external radiation are 30% lower than the outdoor levels.

3. Results and discussion

3.1 Activity concentration of the soil samples

The mean and range of activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in soil samples as measured in the study region was as tabulated in Table 1. The mean activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K in the soil samples were 46 ± 6 Bq kg^{-1}, 57 ± 6 Bq kg^{-1} and 603 ± 46 Bq kg^{-1} in Kilimambogo region.

3.2 Dose estimation using RESRAD Code

The RESRAD computer code was used to estimate the doses received by the resident farmer as a result of continuous exposure to external radiation, ingestion and inhalation of NORM in Kilimambogo region. Measured soil concentrations of ^{226}Ra, ^{232}Th and ^{40}K were used in RESRAD code to determine the TEDE as shown in Table 2.

An adult resident farmer in Kilimambogo region stays most of the time in the contaminated zone and is assumed to receive the highest dose from the environment. The total effective dose equivalent (TEDE) was calculated for water dependent and water independent pathways for ground, inhalation, radon, plant, meat, milk and soil basically consisting of all exposure pathways except for the ingestion of aquatic foods. The summary of the dose contributions for individual radionuclide and pathways for water independent and water dependent pathways at t = 0 years were as shown in Table 2 (a) and (b). The doses contributed by the radionuclides were 0.724 mSv y^{-1}, 1.261 mSv y^{-1} and 0.026 mSv y^{-1} from ^{226}Ra, ^{232}Th and ^{40}K and having a total projected dose of 2.012 mSv y^{-1} for all pathways. The total maximum received dose by the resident farmer was projected to be 3.477 mSv y^{-1} after 470.9 years, with ^{226}Ra, ^{232}Th and ^{40}K contributing 5.026×10^{-6} mSv y^{-1}, 2.919 mSv y^{-1} and 0.558 mSv y^{-1} respectively as indicated in Table 2 (c) and (d). This is contrary to the dose constrain of 0.25 mSv y^{-1} for the general public.

Table 1. Mean and range of the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in soil samples

	^{226}Ra (Bq kg^{-1}) Mean (Range)	^{232}Th (Bq kg^{-1}) Mean (Range)	^{40}K (Bq kg^{-1}) Mean (Range)
Soil samples	46 ± 6 (21 ± 5-103 ± 25)	57 ± 6 (27 ± 2– 101±6)	603 ± 46 (108 ± 2 – 1495 ± 32)

Table 2. Total effective dose contributions for individual radionuclides and pathways for water dependent and water independent pathways for the resident farmer scenario (inhalation excludes radon)

a) Water independent pathways at time t=0 years

Radionuclide/ path-way	Ground (mSv y^{-1})	Inhalation (mSv y^{-1})	Radon (mSv y^{-1})	Plant (mSv y^{-1})	Meat (mSv y^{-1})	Milk (mSv y^{-1})	Soil (mSv y^{-1})
^{40}K	0.25	8.691E-06	0.000	0.2585	0.1198	0.04975	2.811 E-04
^{226}Ra	0.1778	6.912E-05	0.9494	0.111	3.088E-03	3.610 E-03	9.491 E-04

^{232}Th	0.00598	7.827E-04	7.345E-05	0.01688	3.434 E-04	4.209 E-04	8.53 E-04
Total TEDE	**0.433**	**8.805 E-04**	**0.9495**	**0.3864**	**0.1233**	**0.05378**	**2.083 E-03**

b) Water dependent pathways at time t=0 years

Radionuclide/ Pathway	Water (mSv y^{-1})	Radon (mSv y^{-1})	Plant (mSv y^{-1})	Meat (mSv y^{-1})	Milk (mSv y^{-1})	**All pathways (mSv y^{-1})**
^{40}K	0.03151	0.000	0.003226	0.006152	0.004809	**0.7244**
^{226}Ra	0.01254	0.001022	0.001361	2.699 E-04	1.961 E-04	**1.261**
^{232}Th	9.895 E-04	2.029E-04	9.248 E-05	7.358 E-06	1.966 E-05	**0.02644**
Total TEDE	**0.04504**	**0.001022**	**0.004679**	**0.006429**	**0.005025**	**2.012**

* Sum of all water independent and dependent pathways

c) **Water independent pathways at time t=470.9 years**

Radionuclide/ path-way	Ground (mSv y^{-1})	Inhalation (mSv y^{-1})	Radon (mSv y^{-1})	Plant (mSv y^{-1})	Meat (mSv y^{-1})	Milk (mSv y^{-1})	Soil (mSv y^{-1})
^{40}K	2.592E-07	8.995E-12	0.000	2.675E-07	1.241E-07	5.152E-08	2.910E-10
^{226}Ra	0.0477	3.726E-05	0.2466	0.05946	0.005634	0.001643	0.001862
^{232}Th	0.2381	1.182E-03	0.0111	0.2697	0.006956	0.008627	0.003298
Total TEDE	**0.2859**	**1.1219E-03**	**0.2577**	**0.3292**	**0.01259**	**0.01027**	**0.00516**

d) **Water dependent pathways at time t=470.9 years**

Radionuclide/ Pathway	Water (mSv y^{-1})	Radon (mSv y^{-1})	Plant (mSv y^{-1})	Meat (mSv y^{-1})	Milk (mSv y^{-1})	**All pathways (mSv y^{-1})**
^{40}K	2.959E-06	0.000	3.048E-07	6.013E-07	4.580E-07	**5.026E-06**
^{226}Ra	2.151	0.006580	0.2602	0.1191	0.01951	**2.919**
^{232}Th	0.01714	4.582E-08	0.001616	1.609E-04	3.652E-04	**0.5583**
Total TEDE	**2.168**	**0.006580**	**0.2618**	**0.1193**	**0.01988**	**3.477**

* Sum of all water independent and dependent pathways

The summary of the dose contribution by the radionuclides to the total doses at 470.9 years, 0, 1, 3, 10, 30, 100 and 1000 years is as tabulated in Table 3.

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Table 3. Total effective dose contributions for individual radionuclides for summed pathways for the resident farmer scenario

Dose per Radionu-clide/ Time	t = 470.9 years	t =0 years	t =1 year	t = 3 years	t =10 years	t =30 years	t =100 years	t = 300 years	t =1000 years
^{40}K (mSv y^{-1})	5.026E-06	0.7244	0.7180	0.7055	0.6669	0.508	0.3126	8.170E-04	6.774E-13
^{226}Ra (mSv y^{-1})	2.919	1.261	1.279	1.310	1.419	1.692	2.267	2.814	2.543
^{232}Th (mSv y^{-1})	0.5583	0.02644	0.0739	0.1645	0.3854	0.5484	0.5632	0.5605	0.5512
Total TEDE (mSv y^{-1})	**3.477**	**2.012**	**2.071**	**2.18**	**2.471**	**2.831**	**3.143**	**3.375**	**3.094**

For the residents of Kilimambogo, the graphical representation of the RESRAD deduced doses for the summation of ^{40}K, ^{226}Ra and ^{232}Th for all summed up pathways and for all component pathways for all nuclides summed are shown in Figures 3 and 4 respectively. The maximum doses that would be received by a resident adult farmer from the radionuclides would be 0.7244 mSv y^{-1} for ^{40}K at 0 years, 2.919 mSv y^{-1} for ^{226}Ra at 470.9 years and 0.563 mSv y^{-1} for ^{232}Th at 100 years.

Since the primordial radionuclides have been in existence since the creation of the earth, it implies that an adult resident of Kilimambogo region receives the highest dose contributed highly by ^{226}Ra followed by ^{232}Th. It was observed that the dose limit is exceeded throughout one’s lifetime

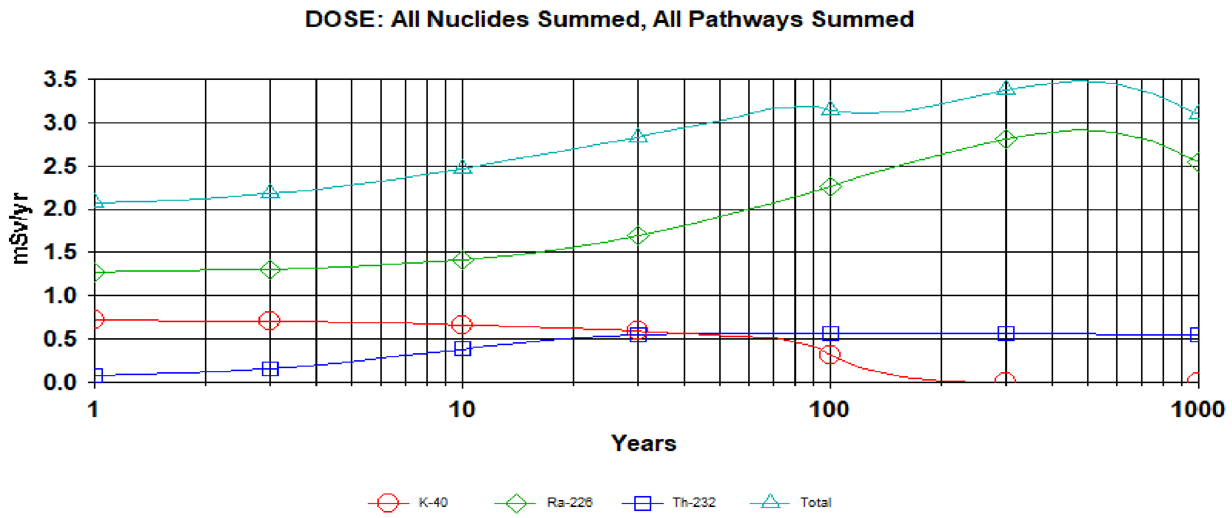

Figure 3. Annual dose for ^{40}K, ^{226}Ra and ^{232}Th for all summed up pathways for a resident farmer scenario

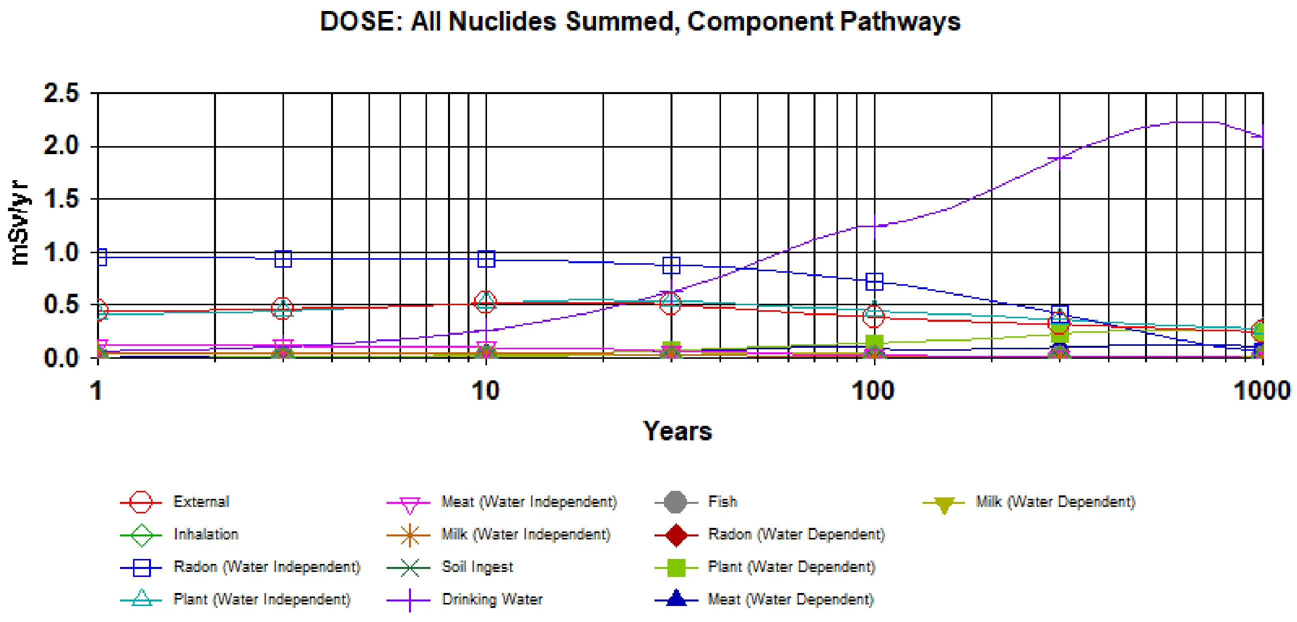

Figure 4. Annual dose for all radionuclides for component pathways for a resident farmer scenario

3.3 Cancer risks estimation using RESRAD Code

RESRAD code was used to calculate the excess cancer incidence risk from radiation exposure by using the slope factors recommended by the United States. Environmental Protection Agency. The code evaluates the health risks raised due to exposure to naturally occurring radionuclides present in the soil. The excess cancer risks received by the resident farmer were analysed for 0, 1, 3, 10, 30, 100, 300 and 1000 years. The excess cancer risk for inhalation of radon was evaluated from radon-222 (and progeny; Po-218, Pb-214 and Bi-214) and radon-220 (thoron) (and progeny; Po-216, Pb-212 and Bi-212).

The excess cancer risks summed from individual radionuclides and their progenies for the different pathways were summarized in Table 4 for the water independent and water dependent pathways. The highest risk from all the pathways was projected to be 7.583 × 10^{-3} at t = 30 years and the least, 4.558 × 10^{-3} at t=1000 years. Inhalation of radon and the decay products were projected to contribute the highest cancer risk under the water independent pathways with the highest being 3.306 × 10^{-3} at t= 0 years. Inhalation of contaminated dust particles on the other hand was projected to make the least contributions to the cancer risks.

Table 4. Excess cancer risks for all nuclides and pathways for the resident farmer scenario

(a) Water independent pathways

Pathway/ Time	Ground	Inhalation	Radon	Plant	Meat	Milk	Soil
t =0 years	6.120E-04	4.296 E-07	3.306E-03	1.345 E-03	5.499 E-04	2.321 E-04	2.956 E-06
t =1 year	1.059E-03	4.768 E-07	3.297 E-03	1.365 E-03	5.386 E-04	2.280 E-04	3.530 E-06
t = 3 years	1.102E-03	6.189 E-07	3.281 E-03	1.395 E-03	5.121 E-04	2.184 E-04	4.747 E-06
t =10 years	1.236E-03	1.100 E-06	3.228 E-03	1.402 E-03	4.283 E-04	1.862 E-04	7.921 E-06
t =30 years	1.211E-03	1.521 E-06	3.059 E-03	1176 E-03	2.582 E-04	1.159 E-04	1.148 E-05
t =100 years	9.364E-04	1.555 E-06	2.509 E-03	7.619 E-04	6.303 E-05	3.361 E-05	1.250 E-05
t = 300 years	7.611 E-04	1.447 E-06	1.428 E-03	5.964 E-04	2.532 E-05	1.857 E-05	9.38 E-06
t =1000 years	5.988 E-04	1.317 E-06	2.089 E-04	4.729 E-04	1.341 E-05	1.510 E-05	5.543 E-06

(b) Water dependent pathways

Pathway/ Time	Water	Radon	Plant	Meat	Milk	**All pathways**
t =0 years	9.566 E-05	3.504 E-06	1.354 E-05	2.474 E-05	1.904 E-05	**6.205E-03**
t =1 year	1.413 E-04	3.597 E-06	2.002 E-05	3.254 E-05	2.521 E-05	**6.715 E-03**
t = 3 years	2.341 E-03	3.786 E-06	3.341 E-05	5.061 E-05	3.780 E-05	**6.873E-03**
t =10 years	5.334 E-04	4.433 E-06	7.660 E-05	1.072 E-04	7.651 E-05	**7.287E-03**
t =30 years	1.195 E-03	6.190 E-06	1.727 E-04	2.228 E-04	1.522 E-04	**7.583 E-03**
t =100 years	1.945 E-03	1.136 E-05	2.849 E-04	2.617 E-04	1.493 E-04	**6.971 E-03**
t = 300 years	2.378 E-03	1.995 E-05	3.536 E-04	1.569 E-04	2.779 E-05	**5.776 E-03**
t =1000 years	2.626 E-03	2.212 E-05	3.907 E-04	1.734 E-04	3.011 E-05	**4.558 E-03**

For the resident farmer, the graphical representation of the RESRAD deduced cancer risks for the summation of ^{40}K, ^{226}Ra and ^{232}Th for all summed up pathways and for component pathways for all nuclides were as shown in Figures 5 and 6 respectively.

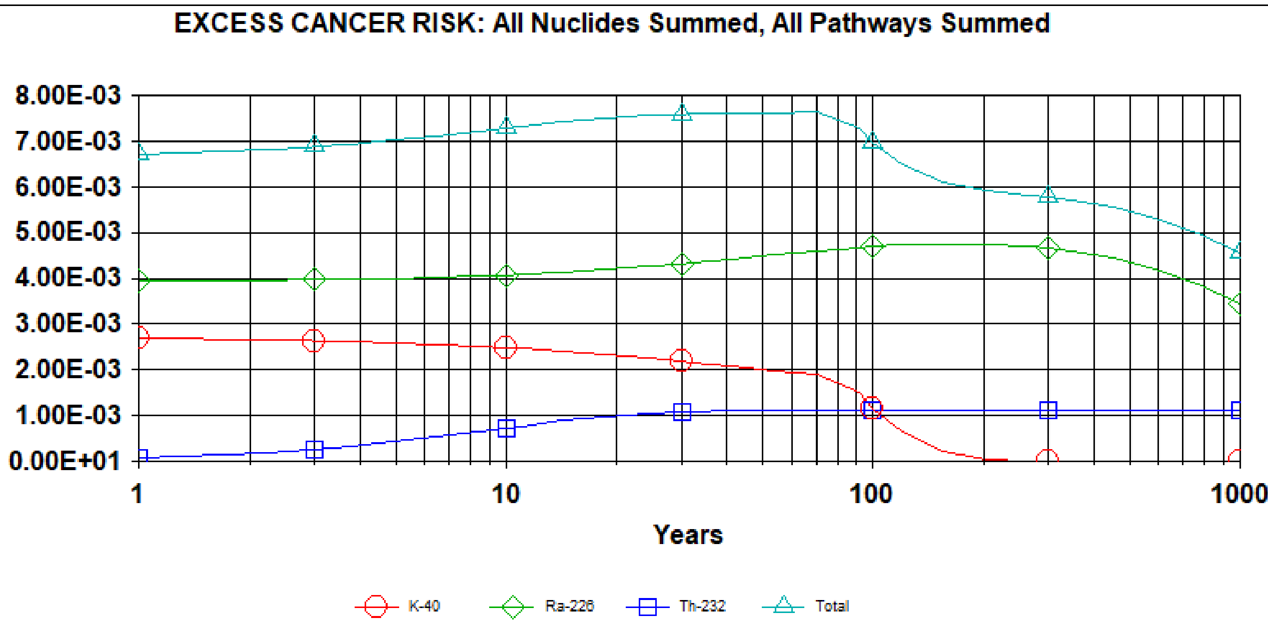

Figure 5. Annual excess cancer risk for ^{40}K, ^{226}Ra and ^{232}Th for all summed up pathways for resident farmer scenario

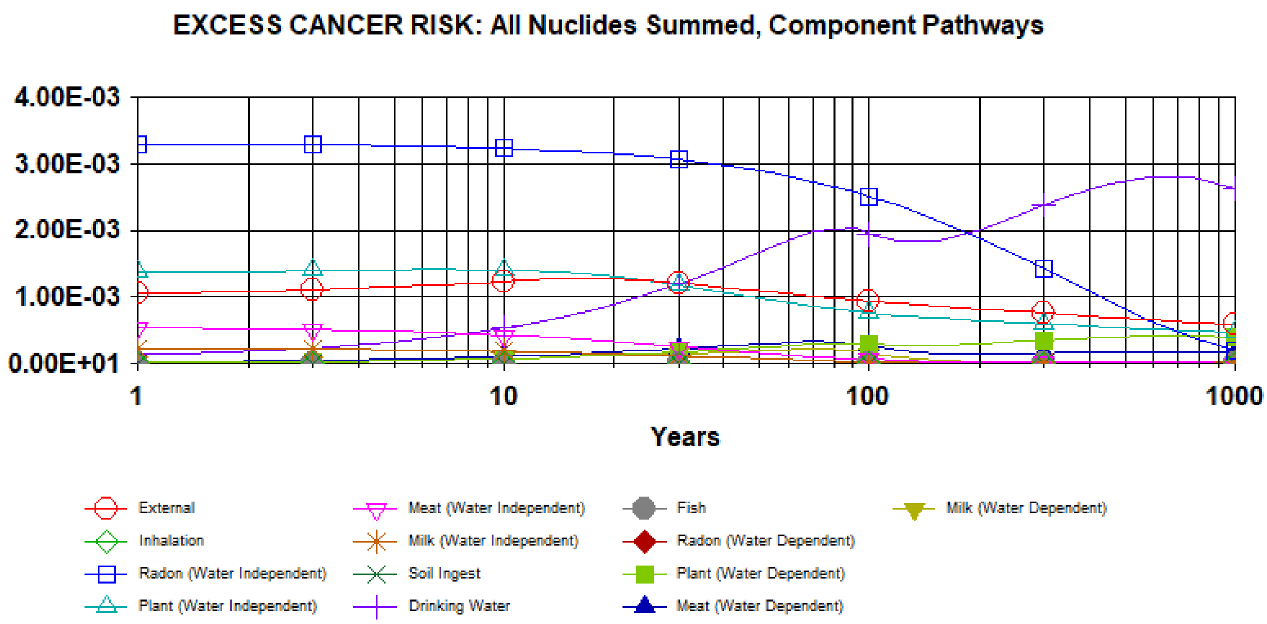

Figure 6. Annual excess cancer risk for all radionuclides for component pathways for resident farmer scenario

4. Conclusion

The total maximum received dose by the resident farmer was projected to be 3.477 mSv y^{-1} at t= 470.9 years with ^{40}K, ^{226}Ra and ^{232}Th contributing 5.02×10^{-6} mSv y^{-1}, 2.919 mSv y^{-1} and 0.5583 mSv y^{-1} respectively. This is contrary to the dose constrain of 0.25 mSv y^{-1} used in RESRAD for the general public. The excess cancer risks simulated using the RESRAD computer code for the resident farmer was evaluated for all radionuclides and for the water independent and water dependent pathways. The highest risk from all the pathways for the resident farmer was projected to be 7.583×10^{-3} at t= 30 years.

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