



# Radiological Assessment Due to Natural Radioactivity in Rocks and Associated Health Impacts in Chetambe Hills, Kenya

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## Abstract

A radiological assessment due to natural radioactivity in rocks and associated health impacts in Chetambe hills, Kenya has been done using NaI (TI) detector employing gamma ray spectrometry technique. The activity concentrations of <sup>238</sup>U in the rock samples ranged from a minimum of  $33 \pm 1.65$  Bq/Kg to a maximum of  $119 \pm 5.97$  Bq/Kg with an average of  $68 \pm 3.23$  Bq/Kg. The activity concentrations of <sup>232</sup>Th varied from a minimum  $15 \pm 0.75$  Bq/Kg to a maximum of  $167 \pm 8.39$  Bq/Kg with an average of  $72 \pm 3.48$  Bq/Kg while the activity concentrations of <sup>40</sup>K varied from a minimum of  $50 \pm 2.5$  Bq/Kg to a maximum of  $2042 \pm 6.43$  Bq/Kg with an average of  $866 \pm 5.78$  Bq/Kg. The averages for the three radionuclides all exceeded 33 Bq/Kg, 45 Bq/Kg and 420 Bq/Kg for <sup>238</sup>U, <sup>232</sup>Th and <sup>40</sup>K respectively. The absorbed dose rate (D<sub>r</sub>) ranged from a minimum of  $33 \pm 1.67$  nGy/h to a maximum of  $230 \pm 11.53$  nGy/h with an average of  $111 \pm 7.32$  nGy. The AEDR<sub>in</sub> ranged from a minimum of  $0.1 \pm 0$  mSv/y to a maximum of  $0.8 \pm 0.04$  mSv/y with an average of  $0.4 \pm 0.02$  mSv/y. AEDR<sub>out</sub> ranged from a minimum of  $0.2 \pm 0.01$  mSv/y to a maximum of  $0.5 \pm 0.02$  mSv/y with a mean of  $0.2 \pm 0.01$  mSv/y. The radium equivalent for the study area varied from a minimum of  $74 \pm 3.74$  Bq/kg to a maximum of  $492 \pm 24.61$  Bq/kg with a mean value of  $238 \pm 6.34$  Bq/kg which was below the world average value of 370 Bq/kg. The internal hazard indices varied from a minimum of  $0.2 \pm 0.01$  mSv/y to a maximum of  $1.3 \pm 0.06$  mSv/y with mean of  $0.6 \pm 0.02$  mSv/y while external hazard indices varied from a minimum of  $0.3 \pm 0.01$  mSv/y to a maximum of  $1.6 \pm 0.08$  mSv/y with an average of  $0.8 \pm 0.03$  mSv/y. The mean values of H<sub>in</sub> and H<sub>ex</sub> were both below the unity. The ELCR<sub>out</sub> values varied from  $0.2 \pm 0.09$  to  $1.9 \pm 0.08$  with a mean of  $0.9 \pm 0.06$  that was below the acceptable

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limit of  $2.9 \times 10^{-4}$ . The values for  $ELCR_{in}$  ranged from  $0.4 \pm 0.03$  to  $2.9 \pm 0.07$  with a mean value of  $1.4 \pm 0.05$  which was equally lower than the world average of  $2.9 \times 10^{-4}$ . Thus radiation exposure from the rocks does not pose a health risk to the general public.

## Subject Areas

Geology

## Keywords

Natural Radioactivity, Health Impact, Chetambe Hills

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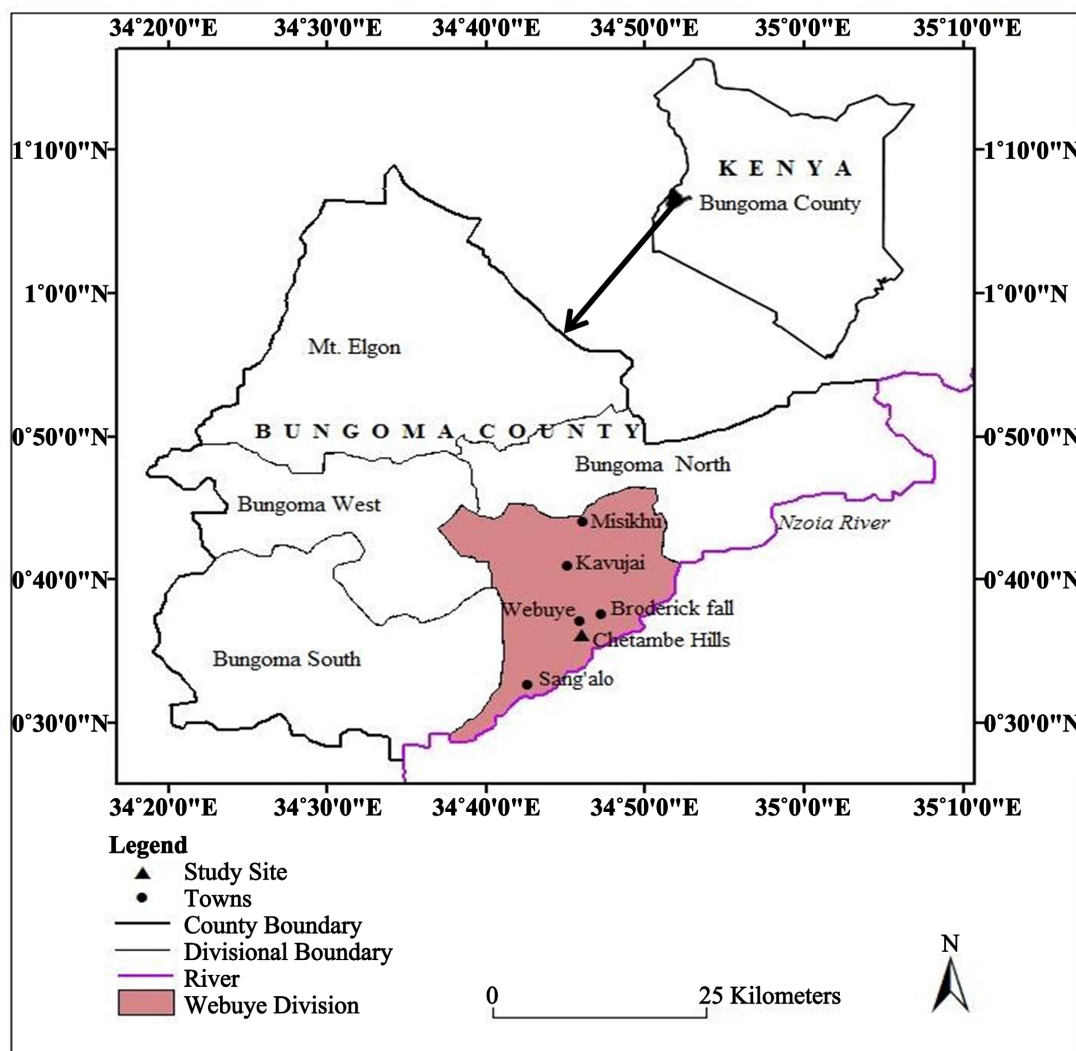
## 1. Introduction

The existence of naturally occurring radionuclides dates back to the formation of the earth [1]. Exposure to ionizing radiations of primordial origin by human population can be a result of terrestrial radiations. Continuous exposure to ionizing radiation may lead to the damage of germ cells that may result in birth defects and limb deformations [2]. Natural radioactivity in rocks emanates from the daughter radionuclides of  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and singly occurring  $^{40}\text{K}$  [3] that are significantly found in the environment. The levels of radionuclides of  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  vary from place to place depending on the geological and geographical location [4]. The three radionuclides have very long half-lives;  $4.468 \times 10^9$  years,  $1.405 \times 10^{10}$  years and  $1.22 \times 10^9$  years for  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  respectively [5]. According to [6], assessment and quantification of natural radioactivity levels in the environment are important in determining the safety standards in the utilization of rocks, soils and water. According to [7], individuals exposed to excess  $^{232}\text{Th}$  have an increased risk of bone cancer while ingestion of high concentration of  $^{238}\text{U}$  can cause lung cancer and kidney damage. Rocks from Chetambe hills are used as construction materials in Bungoma County and the neighboring counties of Transoia and Kakamega [8]. This research was prompted by the outcry of the residents of the study area whose cancer cases have escalated. They were quoted by the star newspaper of 2/11/2023 complaining of the burden of moving long distances seeking for medication. Therefore, there was a need for an assessment of the study area since it is dominated by rocks of granitic nature according to the geological mapping by [9]. Granitic rocks are associated with high concentrations of  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  [10].

## 2. Study Area

The study area is located in Bungoma County. The Hills rise steeply to a height of 1685 m above sea level. Chetambe Hills area was previously called the Broderick falls area bounded by latitudes  $0^{\circ}30'\text{N}$  and  $1^{\circ}00'\text{N}$  and by longitudes  $34^{\circ}30'\text{E}$  and  $35^{\circ}00'\text{E}$ . The area of study is characterized by biotite gneisses, migmatites, granitic

and granodioritic intrusives [9] that are highly rich in  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ . Bungoma East sub County where the study area is located has a population of 114,548 persons [11]. Bungoma County has an estimated size of 2207 km<sup>2</sup> of which Chetambe Hills covers approximately 58 km<sup>2</sup> [8]. (See **Figure 1**)



**Figure 1.** Location of Chetambe hills area (Survey of Kenya, 1969).

### Rock Sample Collection and Preparation

According to [12], proper contamination analysis of a specific place depends on proper sample collection, preparation and good storage methods so that the results obtained are credible and reliable. A total of 20 rock samples were collected at different locations of the study area. The sampling points were recorded using a hand held Global Positioning System (GPS) model. The samples were collected and put in containers and labelled according to its location to avoid mix up. The samples were then dried in the oven for 24 hours at 110°C and then ground to a fine powder, then sieved through a 2.00 mm sieve. 500 g of each of the rock samples were put in airtight containers and be kept for a minimum of 30 days to allow

for secular equilibrium between  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{222}\text{Rn}$  and their progeny [13]. The NaI (Ti) detector was used in the analysis of the levels of natural radioactivity.

### 3. Experimental Techniques

#### 3.1. Efficiency Calibration of NaI (Ti) Detector

The efficiency calibration of the detector is a crucial process because it helps in ascertaining the quality and reliability of the results obtained. In this research calibration of the detector was done using the standard reference materials supplied by IAEA with known activity concentrations using Equation (1) [14].

$$\mathcal{E} = \frac{N}{A \times P_y \times M \times T} \quad (1)$$

where  $\mathcal{E}$  is the efficiency of the detector,  $N$  is the net area under the photo peak,  $T$ ,  $P_y$  is the emission probability,  $m$  is the mass of the sample in Kg,  $T$  is the counting time and  $A$  is the activity concentration.

#### 3.2. Energy Calibration of NaI (Ti) Detector

The energy calibration of NaI (Ti) detector was done by relating the channel number with photo energy using the gamma line of  $^{214}\text{Pb}$ ,  $^{214}\text{Bi}$ ,  $^{228}\text{Ac}$ ,  $^{40}\text{K}$  with energies 351 KeV, 609 KeV, 911 KeV, 1765 KeV and 1460 KeV using Equation (2) [15].

$$E = a \times ch + b \quad (2)$$

where  $E$  is the energy,  $a$  and  $b$  are constants and  $ch$  is the channel number. The activity concentrations of  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  in the soil and rock samples were determined using the counts 351 KeV ( $^{214}\text{Pb}$ ) and 609 KeV ( $^{214}\text{Bi}$ ), 911 KeV ( $^{228}\text{Ac}$ ) for  $^{232}\text{Th}$  and 1460 KeV for ( $^{40}\text{K}$ ).

#### Radiological Risk Measurements in Rock Samples using NaI (TI) detector

#### 3.3. Activity Concentrations in the Rocks

The activity concentrations of the samples in Bq/Kg were determined using Equation (3) [13].

$$A_i \left( \text{Bq} \cdot \text{kg}^{-1} \right) = \frac{N_{ci}}{\mathcal{E} \times Y_i \times m \times t} \quad (3)$$

where  $A_i$  is the activity concentrations of the  $i^{\text{th}}$  radio nuclide in  $\text{Bq} \cdot \text{kg}^{-1}$ ,  $\mathcal{E}$  is the efficiency of the detector at the energy of the  $i^{\text{th}}$  radionuclide,  $N_{ci}$  is the net counts of the  $i^{\text{th}}$  radionuclide in the corresponding photo peak after background subtraction,  $Y_i$  is the emission probability of the  $i^{\text{th}}$  radionuclide,  $m$  is the mass of the sample in kg and  $t$  is the counting time.

#### 3.4. Absorbed Dose Rate ( $D_r$ )

The absorbed dose rate was determined using Equation (4) [10] by applying the conversion factors of 0.462, 0.604 and 0.0147 for  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  respectively.

$$D_r = 0.462A_u + 0.604A_{Th} + 0.0417A_k \quad (4)$$

where  $A_u$ ,  $A_{Th}$  and  $A_k$  are activity concentrations of  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  in  $\text{Bq}\cdot\text{kg}^{-1}$  respectively.

### 3.5. Annual Effective Dose Rate (AEDR)

In assessing both AEDR (in) and AEDR (out) to individuals, the occupancy factor was put into consideration [16]. According to [10] recommendations, the occupancy factors of 0.2 and 0.8 for outdoor and indoor occupancy factors were used. The values imply that a person on average spends 4.8 hours outdoors and 19.2 indoors. AEDR (in) and AEDR (out) were computed using Equations (5a) and (5b) respectively [17].

$$\text{AEDR (in)} = D_r \times 8760 \times 0.8 \times 0.7 \times 10^{-6} \quad (5a)$$

$$\text{AEDR (out)} = D_r \times 8760 \times 0.2 \times 0.7 \times 10^{-6} \quad (5b)$$

where AEDR (in) and AEDR (out) are Annual Effective Doses for indoor and outdoor environments respectively,  $D_r$  is the absorbed dose rate in air in  $\text{nGy/h}$ , 0.7 ( $\text{Sv/Gy}$ ) is the conversion factor for absorbed dose rate in air to an effective dose, 0.8 is the indoor occupancy factor while 0.2 is the outdoor occupancy factor.

### 3.6. Radium Equivalent ( $Ra_{eq}$ )

Radium equivalent refers to the weighted sum of  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ . Radium equivalent was used to estimate the uniform activity and radiation exposure rates and was determined following Equation (6) [18].

$$Ra_{eq} = A_u + 1.43A_{Th} + 0.077A_k \quad (6)$$

where  $A_u$ ,  $A_{Th}$  and  $A_k$  are activity concentrations of  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  in  $\text{Bq}\cdot\text{kg}^{-1}$  respectively

While 1.43 and 0.077 are conversion factors.

### 3.7. Internal and External Hazard Indices ( $H_{in}$ and $H_{ex}$ )

The internal hazard is due to inhalation of the radionuclides and their short lived progenies. The internal hazard index will be evaluated using Equation (7) [19].

$$H_{in} = \frac{A_u}{185} + \frac{A_{Th}}{259} + \frac{A_k}{4810} \quad (7)$$

where  $A_u$ ,  $A_{Th}$  and  $A_k$  are activity concentrations of  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  in  $\text{Bq}\cdot\text{kg}^{-1}$  respectively

The external exposure results from direct radiation. To account for the exposure in the samples  $H_{ex}$  was determined using Equation (8) [19].

$$H_{ex} = \frac{A_u}{370} + \frac{A_{Th}}{259} + \frac{A_k}{4810} \quad (8)$$

where  $A_u$ ,  $A_{Th}$  and  $A_k$  are activity concentrations of  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  in  $\text{Bq}\cdot\text{kg}^{-1}$  respectively.

The external hazard index should be less than unity for the radiation hazard to be negligible.

### 3.8. Excess Life Time Cancer Risk (ELCR)

The excess life time cancer risk due to exposure to the radiation was determined using Equation (9a) and (9b) [20].

$$\text{ELCR}_{\text{in}} = \text{AEDR}_{\text{in}} \times L_f \times R_f \quad (9a)$$

$$\text{ELCR}_{\text{out}} = \text{AEDR}_{\text{out}} \times L_f \times R_f \quad (9b)$$

where ELCR is the excess life time cancer risk, AEDR is the annual effective dose rate,  $L_f$  is the average life expectancy (70 years in Kenya),  $R_f$  is the associated risk factor which is 0.05 [21].

## 4. Results and Discussions

### 4.1. Activity Concentrations of Rock Samples

The rock samples were labelled R<sub>1</sub> to R<sub>20</sub> with their corresponding coordinates for longitude and latitude including the activity taking place at the sampled point. The activity concentrations of <sup>238</sup>U, <sup>232</sup>Th and <sup>40</sup>K of all the rock samples were calculated using Equation (1) and their results summarized as shown in **Table 1**.

**Table 1.** Activity concentrations of <sup>238</sup>U, <sup>232</sup>Th and <sup>40</sup>K of the samples in this work.

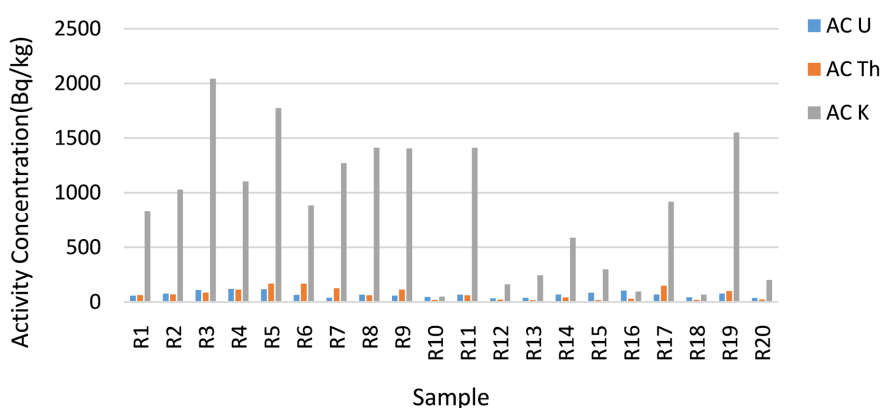
Sample	Sample point activity	Long (E)	Lat (N)	Activity concentration (Bq/kg)		
				<sup>238</sup> U	<sup>232</sup> Th	<sup>40</sup> K
R <sub>1</sub>	Maize growing	34°48'	0°33'	58 ± 2.92	62 ± 3.11	830 ± 4.19
R <sub>2</sub>	Residence	34°49'	0°34'	76 ± 3.81	69 ± 3.48	1028 ± 1.42
R <sub>3</sub>	Maize growing	34°42'	0°31'	109 ± 5.46	84 ± 4.24	2042 ± 3.43
R <sub>4</sub>	Quarrying	34°47'	0°35'	119 ± 5.97	113 ± 5.65	1102 ± 5.13
R <sub>5</sub>	Quarrying	34°43'	0°32'	116 ± 5.84	167 ± 8.39	1774 ± 4.73
R <sub>6</sub>	Falls view H	34°52'	0°36'	63 ± 3.17	167 ± 8.39	883 ± 3.19
R <sub>7</sub>	Road construction	34°48'	0°29'	38 ± 1.92	124 ± 6.22	1271 ± 3.55
R <sub>8</sub>	Maize/bean growing	34°45'	0°38'	66 ± 3.31	60 ± 3.01	1410 ± 2.53
R <sub>9</sub>	Car wash	34°46'	0°33'	58 ± 2.92	113 ± 5.65	1405 ± 2.28
R <sub>10</sub>	Church (SA)	34°42'	0°37'	45 ± 2.28	18 ± 0.94	50 ± 2.52
R <sub>11</sub>	Borehole drilled	34°45'	0°41'	66 ± 3.33	60 ± 3.01	1410 ± 70.53
R <sub>12</sub>	Residence	34°43'	0°36'	33 ± 1.65	20 ± 1.03	161 ± 8.05
R <sub>13</sub>	Residence	34°44'	0°34'	38 ± 1.92	15 ± 0.75	244 ± 12.21
R <sub>14</sub>	Near spring	34°25'	0°37'	68 ± 3.42	41 ± 2.07	588 ± 29.41
R <sub>15</sub>	Near spring	34°32'	0°36'	83 ± 4.19	16 ± 0.84	299 ± 14.95
R <sub>16</sub>	Residence	34°45'	0°32'	104 ± 5.23	30 ± 1.57	94 ± 4.73
R <sub>17</sub>	school	34°46'	0°35'	68 ± 3.42	147 ± 7.35	917 ± 45.86
R <sub>18</sub>	Church (SDA)	34°41'	0°38'	43 ± 2.15	18 ± 0.94	66 ± 3.32
R <sub>19</sub>	Brick making	34°39'	0°37'	76 ± 3.81	99 ± 4.99	1551 ± 77.59
R <sub>20</sub>	Quarrying (Misikhu)	34°35'	0°27'	35 ± 1.77	22 ± 1.13	201 ± 10.05

## Continued

AVER	$68 \pm 3.23$	$72 \pm 3.48$	$866 \pm 5.78$
MAX	$119 \pm 5.97$	$167 \pm 8.39$	$2042 \pm 6.43$
MIN	$33 \pm 1.65$	$15 \pm 0.75$	$50 \pm 2.5$

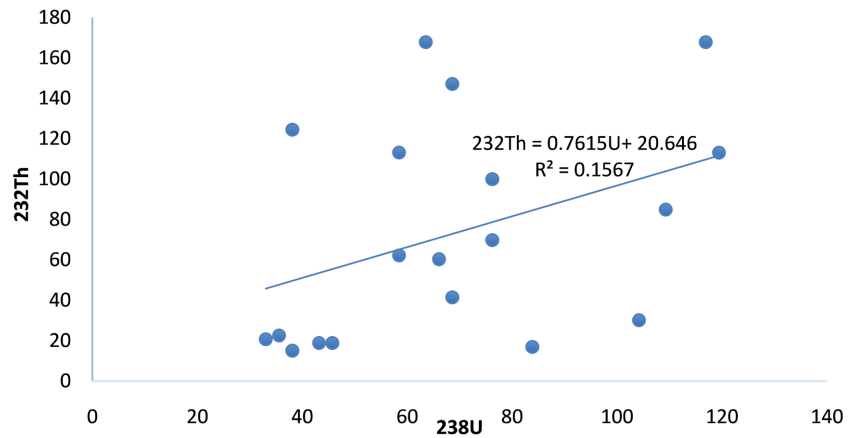
The results from the study indicate a spatial distribution of the three radionuclides:  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  activity in rock samples from one rock sample to the other with some samples having higher radiation levels than others. The activity concentrations for the three radionuclides were notably high at the quarries, maize growing points and brick making site. The activity concentrations of  $^{238}\text{U}$  varied from a minimum of  $33 \pm 1.65$  Bq/Kg to a maximum of  $119 \pm 5.97$  Bq/Kg with an average of  $68 \pm 3.23$  Bq/Kg. The activity concentrations of  $^{232}\text{Th}$  varied from a minimum  $15 \pm 0.75$  Bq/Kg to a maximum of  $167 \pm 8.39$  Bq/Kg with an average of  $72 \pm 3.48$  Bq/Kg while the activity concentrations of  $^{40}\text{K}$  varied from a minimum of  $50 \pm 2.5$  Bq/Kg to a maximum of  $2042 \pm 6.43$  Bq/Kg with an average of  $866 \pm 5.78$  Bq/Kg. The averages for the three radionuclides all exceeded the world averages of 33 Bq/Kg, 45 Bq/Kg and 420 Bq/Kg for  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  respectively [10]. but within the world reported range [2].

The high levels of activity concentrations of  $^{238}\text{U}$  can be attributed to geological formation of the study area characterized by granitic rocks that are highly rich in  $^{238}\text{U}$ . In addition, the high levels of  $^{238}\text{U}$  can also be because of the enrichment by phosphate fertilizers (DAP) used for growing of crops at the study area that contains  $^{238}\text{U}$  [22]. The elevated levels of  $^{232}\text{Th}$  could be due to the presence of granitic rocks at the study area. On the other hand, the higher activity concentrations of  $^{40}\text{K}$  could be attributed to the presence of granites and rhyolites that are rich in potassium bearing minerals or the potassium rich fertilizers used in replenishing the soils [23]. The results were also represented as shown in **Figure 2** which shows the concentrations of the radionuclides in the order  $^{238}\text{U} < ^{232}\text{Th} < ^{40}\text{K}$ .

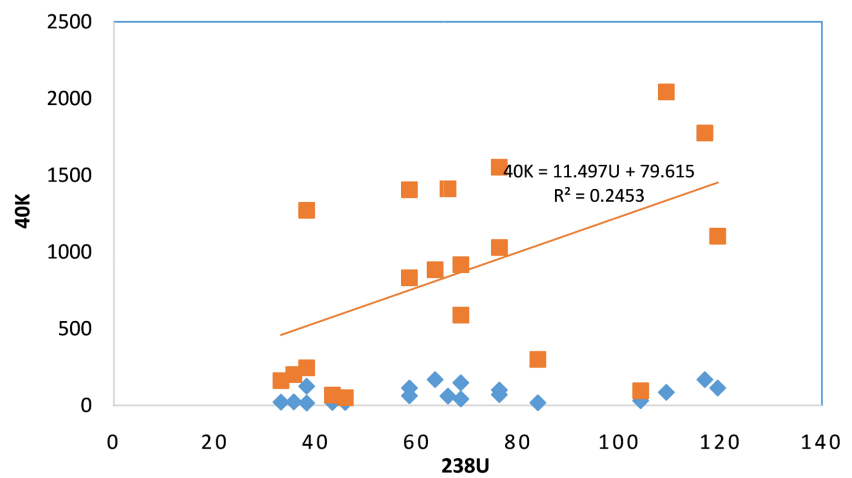


**Figure 2.** Activity concentrations of the rock samples in this work.

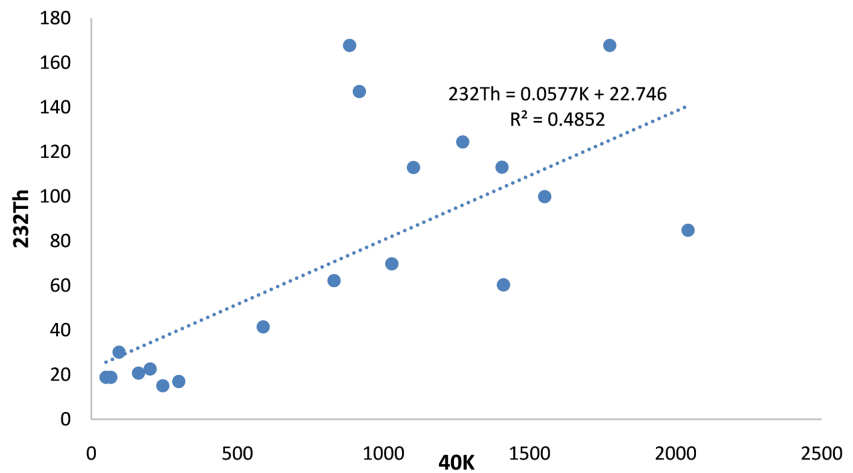
For a comprehensive analysis, correlation graphs were also drawn as shown in **Figures 3(a)-(c)**.



(a)



(b)



(c)

**Figure 3.** (a) Correlation between  $^{238}\text{U}$  and  $^{232}\text{Th}$ ; (b) Correlation between  $^{238}\text{U}$  and  $^{40}\text{K}$ ; (c) Correlation between  $^{238}\text{Th}$  and  $^{40}\text{K}$ .

From **Figures 3(a)-(c)**, it is clear that there exists a weak relationship between the three radionuclides as seen from the  $R^2$  values.

The findings from this research are in agreement with those of [15] in Chiewo hills where the highest average values of the activity concentrations were 3017.8 Bq/kg for  $^{40}\text{K}$ .

#### 4.2. $D_r$ , AEDR (in) and AEDR (out)

The  $D_r$ , AEDR (in) and AEDR (out) were determined using respective equations and finally the results tabulated in **Table 2**.

**Table 2.**  $D_r$ , AEDR (in) and AEDR (out) for all the rock samples collected and measured in this work.

Sample	Sample point activity	Long (E)	Lat (N)	$D_r$ (nGy/h)	AEDR <sub>in</sub> (mSv/y)	AEDR <sub>out</sub> (mSv/y)
R <sub>1</sub>	Maize growing	34°48'	0°33'	99 ± 4.96	0.3 ± 0.01	0.2 ± 0.01
R <sub>2</sub>	Residence	34°49'	0°34'	120 ± 6.32	0.4 ± 0.02	0.2 ± 0.01
R <sub>3</sub>	Maize growing	34°42'	0°31'	187 ± 9.36	0.6 ± 0.03	0.4 ± 0.02
R <sub>4</sub>	Quarrying	34°47'	0°35'	168 ± 8.43	0.6 ± 0.03	0.4 ± 0.02
R <sub>5</sub>	Quarrying	34°43'	0°32'	230 ± 11.53	0.8 ± 0.04	0.5 ± 0.02
R <sub>6</sub>	Falls view H	34°52'	0°36'	169 ± 8.47	0.6 ± 0.03	0.4 ± 0.02
R <sub>7</sub>	Road construction	34°48'	0°29'	148 ± 7.41	0.5 ± 0.02	0.3 ± 0.01
R <sub>8</sub>	Maize/bean growing	34°45'	0°38'	126 ± 6.32	0.4 ± 0.02	0.3 ± 0.01
R <sub>9</sub>	Car wash	34°46'	0°33'	155 ± 7.78	0.5 ± 0.02	0.3 ± 0.01
R <sub>10</sub>	Church (SA)	34°42'	0°37'	33 ± 1.67	0.1 ± 0	0 ± 0
R <sub>11</sub>	Borehole drilled	34°45'	0°41'	126 ± 6.32	0.4 ± 0.02	0.3 ± 0.01
R <sub>12</sub>	Residence	34°43'	0°36'	33 ± 1.69	0.1 ± 0	0.1 ± 0
R <sub>13</sub>	Residence	34°44'	0°34'	36 ± 1.8	0.1 ± 0	0.1 ± 0
R <sub>14</sub>	Near spring	34°25'	0°37'	80 ± 4.01	0.2 ± 0.01	0.1 ± 0
R <sub>15</sub>	Near spring	34°32'	0°36'	59 ± 2.96	0.2 ± 0.01	0.1 ± 0
R <sub>16</sub>	Residence	34°45'	0°32'	67 ± 3.36	0.2 ± 0.01	0.1 ± 0
R <sub>17</sub>	school	34°46'	0°35'	160 ± 8.01	0.5 ± 0.02	0.3 ± 0.01
R <sub>18</sub>	Church (SDA)	34°41'	0°38'	33 ± 1.65	0.1 ± 0	0.1 ± 0
R <sub>19</sub>	Brick making	34°39'	0°37'	161 ± 8.07	0.5 ± 0.02	0.3 ± 0.01
R <sub>20</sub>	Quarrying (Misikhu)	34°35'	0°27'	37 ± 1.89	0.1 ± 0	0.1 ± 0
AVER				111 ± 7.32	0.4 ± 0.02	0.2 ± 0.01
MAX				230 ± 11.53	0.8 ± 0.04	0.5 ± 0.02
MIN				33 ± 1.69	0.1 ± 0	0.2 ± 0.01

The Absorbed dose rate ( $D_r$ ) ranged from a minimum of  $33 \pm 1.67$  nGy/h to a maximum of  $230 \pm 11.53$  nGy/h with an average of  $111 \pm 7.32$  nGy/h which was above the 60 nGy/h [10]. The values are not uniformly distributed owing to the different activity concentrations of the three radionuclides. Since the absorbed

dose rate is determined from the activity concentrations with conversion factors, then the sample with the highest activity concentration of the three radionuclides also had a higher absorbed dose rate *i.e.* R<sub>5</sub>. Despite their higher values, they were below the world safety limit of 1500 nGy/h [24]. The findings from this study are similar to those of [2] average experimental value of 114 ± 34 nGy/h.

The results on the activity concentrations and absorbed dose rates of this study were compared with those other areas and represented in **Table 3**.

**Table 3.** Comparison of activity concentrations and absorbed dose rates in rocks in this study with others.

Author/Year	Country/place	Activity concentrations (Bq/Kg)			Absorbed dose rate (nGy/h)
		<sup>238</sup> U	<sup>232</sup> Th	<sup>40</sup> K	
Present study	Kenya (Chetambe hills)	68 ± 3.23	72 ± 3.48	866 ± 5.78	111 ± 7.32
Kebwaro <i>et al.</i> , 2011	Kenya (Mrima hills)	207 ± 11.3	500.7 ± 20.0	805.4 ± 20.0	440.7
Otuoma <i>et al.</i> , 2012	Kenya (Chiewo hills)	195.3	915.6	409.5	108 - 1596.4

From the comparison **Table 3**, it is clear that despite the regional difference, the activity concentrations and absorbed dose rates both from the current study and those other two regions were higher than their world averages except for <sup>40</sup>K in Chiewo hills.

The AEDR<sub>in</sub> ranged from a minimum of 0.1 ± 0 mSv/y to a maximum of 0.8 ± 0.04 mSv/y with an average of 0.4 ± 0.02 mSv/y that was below the permissible limit of 1 mSv/y although above the 0.07 mSv/y [10]. On the other hand, AEDR<sub>out</sub> ranged from a minimum of 0.2 ± 0.01 mSv/y, a maximum of 0.5 ± 0.02 mSv/y with a mean of 0.2 ± 0.01 mSv/y that was below the permissible limit 1 mSv/y [25]. These findings disagree with those from the study done by [26] in which the AED was found to 0.985 mSv/y.

#### 4.3. Radium Equivalent ( $Ra_{eq}$ ), Internal ( $H_{in}$ ) and External ( $H_{ex}$ ) Hazard Indices

Radium Equivalent ( $Ra_{eq}$ ), Internal hazard index ( $H_{in}$ ) and external ( $H_{ex}$ ) hazard index ( $H_{ex}$ ) were determined for all the samples and their values represented in **Table 4**.

**Table 4.** Radium equivalent ( $Ra_{eq}$ ), Internal ( $H_{in}$ ) and External ( $H_{ex}$ ) hazard indices for all the rock samples collected and measured in this work.

Sample	Sample point activity	Long (E)	Lat (N)	$Ra_{eq}$ (Bq/Kg)	$H_{in}$ (mSv/y)	$H_{ex}$ (mSv/y)
R <sub>1</sub>	Maize growing	34°48'	0°33'	210 ± 10.54	0.5 ± 0.02	0.7 ± 0.03
R <sub>2</sub>	Residence	34°49'	0°34'	254 ± 12.73	0.6 ± 0.03	0.8 ± 0.04
R <sub>3</sub>	Maize growing	34°42'	0°31'	387 ± 19.36	1 ± 0.05	1.3 ± 0.06
R <sub>4</sub>	Quarrying	34°47'	0°35'	365 ± 18.25	0.9 ± 0.04	1.3 ± 0.06
R <sub>5</sub>	Quarrying	34°43'	0°32'	492 ± 24.61	1.3 ± 0.06	1.6 ± 0.08
R <sub>6</sub>	Falls view H	34°52'	0°36'	370 ± 18.52	1 ± 0.05	1.1 ± 0.05

## Continued

R <sub>7</sub>	Road construction	34°48'	0°29'	313 ± 15.65	0.8 ± 0.04	0.9 ± 0.04
R <sub>8</sub>	Maize/bean growing	34°45'	0°38'	260 ± 13.02	0.7 ± 0.03	0.8 ± 0.04
R <sub>9</sub>	Car wash	34°46'	0°33'	327 ± 16.38	0.8 ± 0.04	1 ± 0.05
R <sub>10</sub>	Church (SA)	34°42'	0°37'	76 ± 3.82	0.2 ± 0.01	0.3 ± 0.01
R <sub>11</sub>	Borehole drilled	34°45'	0°41'	260 ± 13.02	0.7 ± 0.03	0.8 ± 0.04
R <sub>12</sub>	Residence	34°43'	0°36'	74 ± 3.74	0.2 ± 0.01	0.2 ± 0.01
R <sub>13</sub>	Residence	34°44'	0°34'	78 ± 3.91	0.2 ± 0.01	0.3 ± 0.01
R <sub>14</sub>	Near spring	34°25'	0°37'	172 ± 8.64	0.4 ± 0.02	0.6 ± 0.03
R <sub>15</sub>	Near spring	34°32'	0°36'	131 ± 6.55	0.3 ± 0.01	0.5 ± 0.02
R <sub>16</sub>	Residence	34°45'	0°32'	154 ± 7.71	0.4 ± 0.02	0.6 ± 0.03
R <sub>17</sub>	school	34°46'	0°35'	348 ± 17.42	0.9 ± 0.04	1.1 ± 0.05
R <sub>18</sub>	Church (SDA)	34°41'	0°38'	75 ± 3.75	0.2 ± 0.01	0.3 ± 0.01
R <sub>19</sub>	Brick making	34°39'	0°37'	337 ± 16.89	0.9 ± 0.04	1.1 ± 0.05
R <sub>20</sub>	Quarrying (Misikhu)	34°35'	0°27'	83 ± 4.16	0.2 ± 0.01	0.3 ± 0.01
AVER				238 ± 6.34	0.6 ± 0.02	0.8 ± 0.03
MAX				492 ± 24.61	1.3 ± 0.06	1.6 ± 0.08
MIN				74 ± 3.74	0.2 ± 0.01	0.3 ± 0.01

Samples R<sub>3</sub> and R<sub>5</sub> had the highest radium equivalent values  $387 \pm 19.36$  Bq/kg and  $492 \pm 24.61$  Bq/kg that were as a result of their high values of activity concentrations in the respective radionuclides. They were even higher than the world average of 370 Bq/kg. The radium equivalent for the study area varied from a minimum of  $74 \pm 3.74$  Bq/kg to a maximum of  $492 \pm 24.61$  Bq/kg. The mean value of radium equivalent from this study was  $238 \pm 6.34$  Bq/kg which was below the world average value of 370 Bq/kg. The values of the internal hazard index varied from a minimum of  $0.2 \pm 0.01$  mSv/y to a maximum of  $1.3 \pm 0.06$  mSv/y with mean of  $0.6 \pm 0.02$  mSv/y. The external hazard indices varied from a minimum of  $0.3 \pm 0.01$  mSv/y to a maximum of  $1.6 \pm 0.08$  mSv/y with an average of  $0.8 \pm 0.03$  mSv/y. The external and internal hazard indices from the various samples were different because of the difference in the activity concentrations of the radionuclides in the respective samples. Despite some samples having their internal and external hazard indices higher; they were below the world average level of 1 mSv/y [10].

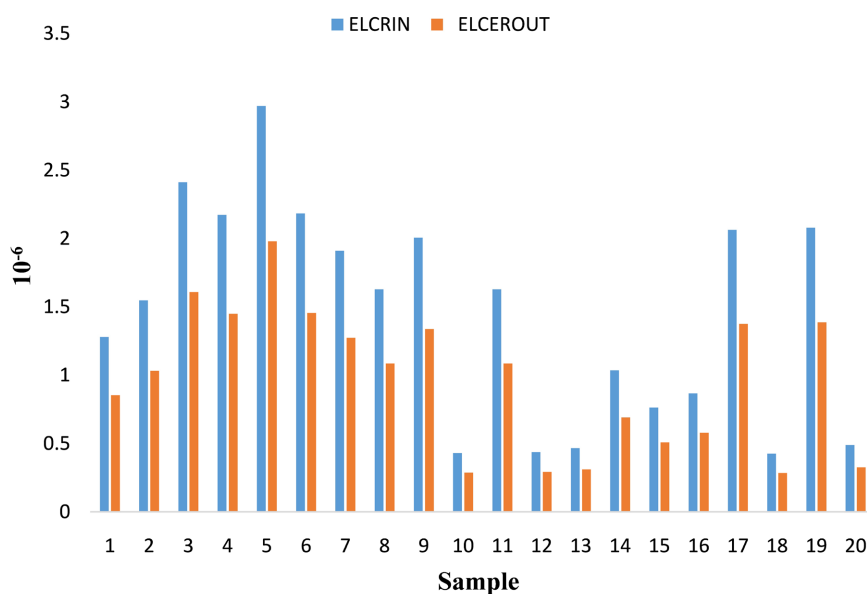
#### 4.4. $ELCR_{in}$ and $ELCR_{out}$

$ELCR_{in}$  and  $ELCR_{out}$  were determined using equations 9a and 9b respectively and their values represented in **Table 5**.

The  $ELCR_{out}$  values were in the range of  $0.2 \pm 0.09$  to  $1.9 \pm 0.08$  with a mean value of  $0.9 \pm 0.06$  that was below the acceptable limit of  $2.9 \times 10^{-4}$ . The values for  $ELCR_{in}$  ranged from  $0.4 \pm 0.03$  to  $2.9 \pm 0.07$  with a mean value of  $1.4 \pm 0.05$  which was equally lower than the world average of  $2.9 \times 10^{-4}$ .

**Table 5.** ELCR<sub>in</sub> and ELCR<sub>out</sub> for all the rock samples collected and determined in this study.

Sample	Sample point activity	Long (E)	Lat (N)	ELCR <sub>in</sub> 10 <sup>-6</sup>	ELCR <sub>out</sub> 10 <sup>-6</sup>
R <sub>1</sub>	Maize growing	34°48'	0°33'	1.2 ± 0.08	0.8 ± 0.06
R <sub>2</sub>	Residence	34°49'	0°34'	1.5 ± 0.06	1.0 ± 0.04
R <sub>3</sub>	Maize growing	34°42'	0°31'	2.4 ± 0.03	1.6 ± 0.02
R <sub>4</sub>	Quarrying	34°47'	0°35'	2.1 ± 0.08	1.4 ± 0.05
R <sub>5</sub>	Quarrying	34°43'	0°32'	2.9 ± 0.07	1.9 ± 0.08
R <sub>6</sub>	Falls view H	34°52'	0°36'	2.1 ± 0.09	1.4 ± 0.06
R <sub>7</sub>	Road construction	34°48'	0°29'	1.9 ± 0.02	1.2 ± 0.08
R <sub>8</sub>	Maize/bean growing	34°45'	0°38'	1.6 ± 0.03	1.0 ± 0.09
R <sub>9</sub>	Car wash	34°46'	0°33'	2.0 ± 0.01	1.3 ± 0.04
R <sub>10</sub>	Church (SA)	34°42'	0°37'	0.4 ± 0.02	0.2 ± 0.09
R <sub>11</sub>	Borehole drilled	34°45'	0°41'	1.6 ± 0.05	1.0 ± 0.09
R <sub>12</sub>	Residence	34°43'	0°36'	0.4 ± 0.02	0.2 ± 0.08
R <sub>13</sub>	Residence	34°44'	0°34'	0.4 ± 0.03	0.3 ± 0.02
R <sub>14</sub>	Near spring	34°25'	0°37'	1.0 ± 0.04	0.6 ± 0.03
R <sub>15</sub>	Near spring	34°32'	0°36'	0.7 ± 0.05	0.5 ± 0.01
R <sub>16</sub>	Residence	34°45'	0°32'	0.8 ± 0.06	0.5 ± 0.08
R <sub>17</sub>	school	34°46'	0°35'	2.0 ± 0.06	1.3 ± 0.08
R <sub>18</sub>	Church (SDA)	34°41'	0°38'	0.4 ± 0.03	0.2 ± 0.09
R <sub>19</sub>	Brick making	34°39'	0°37'	2.0 ± 0.08	1.3 ± 0.09
R <sub>20</sub>	Quarrying (Misikhu)	34°35'	0°27'	0.4 ± 0.09	0.3 ± 0.06
AVER				1.4 ± 0.05	0.9 ± 0.06
MAX				2.9 ± 0.07	1.9 ± 0.08
MIN				0.4 ± 0.03	0.2 ± 0.09

**Figure 4.** Graph of ELCR<sub>in</sub> and ELCR<sub>out</sub> of all the samples in this research.

The  $ELCR_{in}$  and  $ELCR_{out}$  values from this research were represented in **Figure 4**.

From **Figure 4**, it can be seen that  $ELCR_{in}$  was higher than  $ELCR_{out}$  for all the samples which can be attributed to the higher values of  $AEDR_{in}$  than  $AEDR_{out}$ .

## 5. Conclusions and Recommendations

A radiological assessment due to natural radioactivity in rocks and associated health impacts has been done in this research. The average activity concentrations of  $^{238}U$ ,  $^{232}Th$  and  $^{40}K$  were all higher than the permissible values. However, the other radiological parameters were within the permissible limits as already discussed. Therefore, escalated cancer cases in the study area may not be a result of radiation exposure from natural radioactivity from the rocks since the radiation exposure from the rocks does not pose a health risk to the general public.

This study recommends further studies in soils so as to have comprehensive data on natural radioactivity and hence clarity of the possible cause of cancer in the study area.

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## Conflicts of Interest

The authors declare no conflict of interest

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