NATURAL RADIOACTIVITY MEASUREMENTS AND EVALUATION OF RADIATION HAZARDS IN SOIL SAMPLES OF SHINYALU, KAKAMEGA COUNTY, KENYA

ECHESA MALACK KHABANA [B.Ed. (Sc)]

I56/CE/25851/2014

A Thesis Submitted in Partial Fulfillment of the Requirements for the Award of the Degree of Master of Science (Physics) in the School of Pure and Applied Sciences of Kenyatta University

OCTOBER, 2020
DECLARATION

This thesis is my original work and has not been presented for a degree in any other university or any other award.

Echesa Malack Khabana
156/CE/25851/2014
Department of Physics
Kenyatta University

Signature
Date

SUPERVISORS

We confirm that work reported in this thesis was carried out by the candidate under our supervision.

Dr. Nadir O. Hashim
Department of Physics
Kenyatta University

Signature
Date

Dr. Margaret W. Chege
Department of Physics
Kenyatta University

Signature
Date
DEDICATION

This thesis is dedicated to all members of my family especially my dad Eliakim Wesonga and my mum Joyce Osundwa for their continuous support and encouragement.
ACKNOWLEDGEMENTS

I sincerely thank and appreciate my research supervisors Dr. NadirO. Hashim and Dr. Margaret W. Chege for their endless support and substantial guidance throughout this research work.

Their continuous support and advice right away from proposal writing, collection and analysis of samples, progress reports and thesis writing have enabled successful completion of this research work. May Almighty God bless you abundantly.

I also appreciate members of Physics department at Kenyatta University for the time, cooperation and assistance they accorded me during the time this research work was being done. My appreciation also goes to my principal Mrs. NyongesaRukiah for the permission she granted me when I was needed in the field to collect samples, in the laboratory to analyse the samples and in the seminars to present proposal and progress reports. I also extend my sincere gratitude to the members of Physics and Mathematics departments in my school who took up my responsibilities all the times I was out of school to carry out duties related to this work.

Without forgetting members of my beloved family, I highly appreciate them for the boundless support, prayers and encouragement that propelled me to complete this work. I can’t forget AsmanAkhabale whose help and company was very instrumental when I went to the field to collect samples. I am also grateful to all my friends especially Asutsi Peter and Bundi Daniel for the encouragement and support they accorded me during this time of research.

My greatest appreciation goes to my Almighty God for the divine protection, good health, strength, guidance and inspiration throughout the time I was undertaking this research work. Without Him I would have done nothing
TABLE OF CONTENTS

DECLARATION ........................................................................................................................................ii
DEDICATION .............................................................................................................................................iii
ACKNOWLEDGEMENTS ..........................................................................................................................iv
TABLE OF CONTENTS ............................................................................................................................v
LIST OF TABLES ........................................................................................................................................viii
LIST OF FIGURES .....................................................................................................................................ix
LIST OF PLATES .........................................................................................................................................xi
LIST OF ABBREVIATIONS AND ACRONYMS .........................................................................................xii
ABSTRACT ................................................................................................................................................xiii

CHAPTER ONE .............................................................................................................................................1
INTRODUCTION ..........................................................................................................................................1
1.1 Background to the study .....................................................................................................................1
1.2 Description of the study area .............................................................................................................7
1.3 Geology of Shinyalu Constituency ....................................................................................................8
1.4 Statement of the research problem ..................................................................................................11
1.5 Objectives ..........................................................................................................................................11
1.5.1 General objective ........................................................................................................................11
1.5.2 Specific objectives ........................................................................................................................12
1.6 Rationale .............................................................................................................................................12

CHAPTER TWO .........................................................................................................................................13
LITERATURE REVIEW ................................................................................................................................13
2.1 Related studies on natural radioactivity .........................................................................................13

CHAPTER THREE ....................................................................................................................................18
THEORETICAL BACKGROUND ...............................................................................................................18
3.1 Ionizing and non-ionizing radiation ...............................................................................................18
3.2 The radioactive decay law ..............................................................................................................20
3.3 Gamma radiation .............................................................................................................................22
3.3.1 Photoelectric effect ....................................................................................................................22
3.3.2 Compton scattering ....................................................................................................................25
3.3.3 Pair production ...........................................................................................................................27
3.4 Relative predominance of the interaction process ........................................................................28
3.5 Gamma-ray emission ................................................................. 29
3.6 Secular equilibrium ........................................................................ 31
3.7 Relationship between various dosimetric quantities ....................... 35
  3.7.1 Energy fluence and kerma ......................................................... 35
  3.7.2 Fluence and dose (electrons) .................................................... 37
  3.7.3 Kerma and dose ......................................................................... 37
  3.7.4 Collision Kerma and exposure .................................................. 38

CHAPTER FOUR ............................................................................. 39
MATERIALS AND METHODS ............................................................... 39
  4.1 Sampling and sample preparation .................................................. 39
  4.2 Gamma-ray spectrometry ............................................................. 39
  4.3 NaI (Tl) gamma-ray spectrometer ................................................ 40
    4.3.1 Working Mechanism of NaI (Tl) detector ............................... 41
  4.4 Standard sample ............................................................................ 42
  4.5 Experimental procedures ............................................................. 42
    4.5.1 Energy calibration of gamma-ray spectrometer ....................... 42
    4.5.2 Background measurement ....................................................... 43
    4.5.3 Energy resolution of NaI (Tl) detector ................................... 44
    4.5.4 Detector efficiency ................................................................. 45
    4.5.5 Minimum detection limit ......................................................... 46
  4.6 Acquisition of spectral data and analysis of samples .................... 47
  4.7 Calculation of radioactivity ........................................................... 49
  4.8 Evaluation of radiological hazard parameters ............................... 50
    4.8.1 Radium equivalent activity (Ra_eq) ...................................... 50
    4.8.2 External radiation hazard Index (H_ex) .................................. 50
    4.8.3 Internal hazard index (H_in) .................................................. 51
    4.8.4 Absorbed gamma radiation dose rate (D nGyh⁻¹) .................. 51
    4.8.5 Annual effective dose rate .................................................... 52

CHAPTER FIVE ............................................................................. 53
RESULTS AND DISCUSSION ............................................................. 53
  5.1 Activity concentration of natural radionuclides ......................... 53
  5.2 Radium equivalent activity ......................................................... 57
  5.3 Hazard indices ............................................................................. 60
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4</td>
<td>Absorbed dose rate</td>
<td>61</td>
</tr>
<tr>
<td>5.5</td>
<td>Annual effective dose rate</td>
<td>62</td>
</tr>
<tr>
<td>5.6</td>
<td>Correlation between the naturally occurring radionuclides</td>
<td>63</td>
</tr>
<tr>
<td>CHAPTER SIX</td>
<td></td>
<td>65</td>
</tr>
<tr>
<td>CONCLUSIONS AND RECOMMENDATIONS</td>
<td></td>
<td>65</td>
</tr>
<tr>
<td>6.1</td>
<td>Conclusions</td>
<td>65</td>
</tr>
<tr>
<td>6.2</td>
<td>Recommendations</td>
<td>66</td>
</tr>
<tr>
<td>REFERENCES</td>
<td></td>
<td>68</td>
</tr>
<tr>
<td>APPENDIX 1</td>
<td></td>
<td>74</td>
</tr>
<tr>
<td>APPENDIX 2</td>
<td></td>
<td>75</td>
</tr>
<tr>
<td>APPENDIX 3</td>
<td></td>
<td>76</td>
</tr>
<tr>
<td>APPENDIX 4</td>
<td></td>
<td>77</td>
</tr>
<tr>
<td>APPENDIX 5</td>
<td></td>
<td>78</td>
</tr>
<tr>
<td>APPENDIX 6</td>
<td></td>
<td>79</td>
</tr>
<tr>
<td>APPENDIX 7</td>
<td></td>
<td>80</td>
</tr>
<tr>
<td>APPENDIX 8</td>
<td></td>
<td>81</td>
</tr>
<tr>
<td>APPENDIX 9</td>
<td></td>
<td>82</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 4.1: Emission probabilities, detector efficiencies and minimum detection limits measured in this research work……………………..47

Table 5.1: Mean activity concentrations of the soil samples measured in this study compared to the world average………………………..54

Table 5.2: A summary of the activity concentration of $^{238}$U, $^{232}$Th and $^{40}$K in all the sampling points…………………………………….54

Table 5.3: A summary of the activity concentration calculated in this study compared to other parts in Kenya…………………………………56

Table 5.4: A summary of values of radium equivalent activity and hazard indices……………………………………………………….58

Table 5.5: A summary of values of absorbed dose rate and annual effective dose rate…………………………………………………….59

Table 5.6: The world average and maximum acceptable safety health limits of radiological parameters…………………………………....59
LIST OF FIGURES

Figure 1.1: Percentage distribution of various sources of random exposure…………………………………………………………………………3

Figure 1.2: Map of Shinyalu constituency showing the sampling sites………10

Figure 3.1: Mechanism of photoelectric effect……………………………………23

Figure 3.2: Mechanism of Compton scattering……………………………………26

Figure 3.3: Mechanism of pair production………………………………………28

Figure 3.4: Relative dominance of photon interaction processes…………………29

Figure 3.5: Decay scheme of cobalt-60……………………………………………31

Figure 3.6: Secular equilibrium of a parent daughter radionuclide……………35

Figure 4.1: Schematic diagram of NaI (Tl) gamma-ray spectrometer……………40

Figure 4.2: NaI (Tl) scintillation detector used to detector gamma rays from radioactive source……………………………………………………41

Figure 4.3: A second order polynomial fit used to calibrate energy for NaI (Tl) detector used in this research work…………………………43

Figure 4.4: Gaussian curve representing probability distribution used in calculating energy resolution……………………………………45

Figure 4.5: A graph of efficiency against energy measured in this work………47

Figure 4.6: Gamma-ray spectrum of the background measured in this work……………………………………………………………………48

Figure 4.7: A typical gamma-ray spectrum of soil sample measured in this work after background subtraction………………………………49

Figure 5.1: A bar graph of the activity concentration of the primordial radionuclides against sampling sites in Shinyalu Constituency……57
Figure 5.2: A graph of radium equivalent activity values against sampling sites. 60
Figure 5.3: Values of hazard indices against sampling sites. 61
Figure 5.4: A graph of absorbed dose rate against sampling sites. 62
Figure 5.5: A graph annual effective dose rate against sampling sites. 63
Figure A1: Decay series of $^{238}\text{U}$. 74
Figure A2: Decay series of $^{232}\text{Th}$. 75
Figure A3: Correlation between activity concentration of $^{238}\text{U}$ and $^{232}\text{Th}$. 76
Figure A4: Correlation between activity concentration of $^{238}\text{U}$ and $^{40}\text{K}$. 77
Figure A5: Correlation between activity concentration of $^{232}\text{Th}$ and $^{40}\text{K}$. 78
LIST OF PLATES

Figure A6: Sample collection in Shinyalu Kakamega County....................79

Figure A7: Sample preparation at Kenyatta University Physics Laboratory.................................................................80

Figure A8: Acquisition of spectral data........................................81

Figure A9: Reading spectral data....................................................82
# LIST OF ABBREVIATIONS AND ACRONYMS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>Analogue to Digital Converter</td>
</tr>
<tr>
<td>DNA</td>
<td>Deoxyribonucleic acid</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>keV</td>
<td>kilo electron volt</td>
</tr>
<tr>
<td>eV</td>
<td>electron volt</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
</tr>
<tr>
<td>$H_{\text{ex}}$</td>
<td>External hazard index</td>
</tr>
<tr>
<td>$H_{\text{in}}$</td>
<td>Internal hazard index</td>
</tr>
<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
</tr>
<tr>
<td>ICRP</td>
<td>International Commission Radiation Protection</td>
</tr>
<tr>
<td>LET</td>
<td>Linear Energy Transfer</td>
</tr>
<tr>
<td>MCA</td>
<td>Multichannel Analyzer</td>
</tr>
<tr>
<td>NaI (Tl)</td>
<td>Thallium Activated Sodium Iodide Detector</td>
</tr>
<tr>
<td>NCRP</td>
<td>National Council on Radiation Protection</td>
</tr>
<tr>
<td>NORMs</td>
<td>Naturally Occurring Radioactive Materials</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PM</td>
<td>Photomultiplier</td>
</tr>
<tr>
<td>$Ra_{\text{eq}}$</td>
<td>Radium equivalent activity</td>
</tr>
<tr>
<td>ROI</td>
<td>Region of Interest</td>
</tr>
<tr>
<td>UNSCEAR</td>
<td>United Nations Scientific Committee on Effects of Atomic Radiation</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organization</td>
</tr>
</tbody>
</table>
Radioactive elements are found everywhere in the environment. Detectable amounts occur naturally in soil, rocks, water, air and vegetation and may be ingested if they enter the food chain, or, inhaled. Inhaled and ingested radionuclides lead to internal exposure. In addition, humans also receive external exposure due to the radioactive materials located outside the body. Primordial radionuclides $^{238}$U, $^{232}$Th and $^{40}$K are the main sources of external radiation exposure to the general public. Exposure to enhanced radiation levels for long periods of time may lead to health related problems like cancer. This research project aimed at measuring the concentration of primordial radionuclides in soil samples from Shinyalu region in Kakamega County and evaluating the radiation exposure to the local population. Twenty three surface soil samples were collected from selected locations in study area and analysed for the content of $^{238}$U, $^{232}$Th and $^{40}$K using a NaI (Tl) gamma ray spectrometer. Radiation hazard indices, external dose rates and the radium equivalent activity were calculated based on the activity concentration of the primordial radionuclides. The mean activity concentration for $^{238}$U, $^{232}$Th and $^{40}$K were; 189±9 Bqkg$^{-1}$ within the range of 58±3-349±17 Bqkg$^{-1}$, 151±8 Bqkg$^{-1}$ within the range of 33±2-364±18 Bqkg$^{-1}$ and 902±45 Bqkg$^{-1}$ within the range of 98±5-1718±86 Bqkg$^{-1}$ respectively. The mean values of concentration for $^{238}$U, $^{232}$Th and $^{40}$K exceeded the world average of 33 Bqkg$^{-1}$, 45 Bqkg$^{-1}$ and 420 Bqkg$^{-1}$ respectively. The values for radium equivalent activity, external gamma hazard and internal hazard indices were; 475±24 Bqkg$^{-1}$ within the range of 151±8-910±46 Bqkg$^{-1}$, 1.28±0.06 within the range of 0.41±0.02-2.46±0.12 and 1.75±0.08 within the range of 0.69±0.03-3.08±0.10 respectively. The average absorbed dose rate was found to be 216±11 nGyh$^{-1}$within the range 69±3 - 408±20 nGyh$^{-1}$ which was below the hazard limit of 1500 nGyh$^{-1}$. The annual effective dose rate was found to be 0.27±0.01 mSvy$^{-1}$ within the range 0.08 - 0.50±0.03 mSvy$^{-1}$ which is below the ICRP limit of 1 mSvy$^{-1}$ for members of general public. These results reveal no significant radiological health hazards for inhabitants within the study area.
CHAPTER ONE

INTRODUCTION

1.1 Background to the study

The exposure of human beings to ionizing radiation is a continuing and inescapable feature of life on earth. The ionizing radiation is a consequence of radioactive elements found in the environment and which can be classified in three general categories: naturally occurring primordial radionuclides which were formed at time of creation of the earth, naturally occurring cosmogenic radionuclides formed as a result of cosmic ray interactions with the atmosphere, and artificially-produced radionuclides formed due to human activities such as weapon testing, coal burning, nuclear accidents like the one at Chernobyl in 1986, nuclear power plants, use of fertilizers, spacecraft and medical treatment (Samad et al., 2013). According to Isinkaye and Emelue (2015), 87% of radiation dose received by humans are from natural sources, particularly as a result of $^{238}\text{U}$ and $^{232}\text{Th}$ and their progeny as well as $^{40}\text{K}$. Soil and rocks are the major sources of these primordial radionuclides and also a means of migration into other aspects of the environment (Felix et al., 2016).

Exposure to radiation can be classified as internal or external. Internal exposure is due to radiation source that exists inside a human body. It is caused by the intake of radioactive material through inhalation of airborne radioactive material or by ingestion through food or water containing radioactive materials. The radioactive material taken into the body emits rays and particles that result
in irradiation of the internal organs and tissues. The extent of internal radiation dose depends on the amount of radioactive material inside the body, where it goes in the body, how long it stays in the body, and the type of radiation involved. Internal dose to the respiratory track is mainly due to radon and its decay products. Radon belongs to the decay chain of $^{238}$U (Hameed et al., 2014).

External exposure occurs when all or part of the body is exposed to penetrating radiation such as gamma rays or X-rays from an external source. The external source can be equipment for instance an X-ray machine, radioactive materials in a container, or even naturally occurring radionuclides in soil and building materials. For instance, it is well known that igneous rocks such as granite composition are strongly enriched in $^{232}$Th and $^{238}$U as compared to rocks of basaltic or ultramafic composition. When these radioactive elements decay they release gamma rays.

Figure 1.1 shows the percentage distribution of various sources of radiation exposure.
Terrestrial gamma radiation contributes about 8% of the average annual radiation exposure to the public globally. The radiation is mainly emitted by naturally radioactive element $^{40}$K and elements in the decay chains of $^{238}$U and $^{232}$Th which are not only primordial radionuclides but are also universally present in most rock and soil. The radioactive elements and those in their decay chains may be transferred in small amounts to indoor air through earthen or stone building materials or to food stuff thereby becoming important sources of internal exposure. As a matter of fact, $^{222}$Rn and $^{220}$Rn in the decay chains of $^{238}$U and $^{232}$Th respectively account for the largest proportion of the total radiation exposure received by the public, contributing approximately 55% of annual average radiation dose. The radon isotopes are inert gases and if conditions are right, they can escape by diffusion and advection from the
material where they are formed to the atmosphere. The isotopes become a health risk when they build up to high levels in confined spaces such as dwellings. Internal exposure resulting from consumption of food stuff with elevated radionuclide content contributes 11% of the total exposure. The main contributor to this dose is $^{40}$K which is present in most of the foods (WHO, 2013).

Another source of natural exposure comes from cosmic radiation, contributing 8% of the average annual radiation exposure. Cosmic radiation consists of energetic protons (85%), alpha particles (14%) and about 1% nuclei of heavier elements. Cosmic radiation is usually more intense at higher altitudes. Attenuation in the atmosphere decreases the flux of the cosmic rays which means that reduced levels reach the earth’s surface and more so at lower altitudes. Thus, people who fly regularly as well as those who live at higher altitudes are more likely to receive higher doses of cosmic radiation compared to those who live at lower altitudes. Artificial sources including nuclear medicine, medical X-rays and consumer products contribute approximately 20% of the annual radiation exposure (WHO, 2016).

Interaction of the radiation with the body leads to deposition of high amounts of energy that can impair the functioning of tissues and organs. Exposure can be acute or chronic. Acute exposure is largely as a result of high radiation dose received within a short duration of time. It is associated with artificial sources of radiation such as medical procedures or nuclear war-fare. Effects of acute radiation exposure include skin redness, hair loss, radiation burns, or acute
radiation syndrome which is an acute illness caused by irradiation of the entire body by a high dose of penetrating radiation in a very short period of time. Chronic exposure involves exposure due to low radiation doses over a long period of time. It mainly results from natural sources and may involve internal exposure or external gamma irradiation. Effects of chronic exposure include cancer and cardiovascular disease (EPA, 2011).

Biological effects of radiation exposure mainly result from damage to, or alteration of the cell DNA, impairment in the natural functioning of the cell or even the death of the cell. The effects can be somatic or genetic (hereditary) in nature. Somatic effects are harm that exposed individuals suffer during their lifetime, such as radiation induced cancers (carcinogenesis), sterility, opacification of the eye lens and life shortening. Genetic effects are radiation induced mutations to an individual’s genes and cell DNA that can contribute to the defects such as visible chromosome abnormalities, proteins with altered conformations or charges, spontaneous abortions, congenital malformations, or premature death. Generic effects can be transferred to future generations.

Biological effects can also be considered in terms of stochastic effect and non-stochastic effects. Stochastic effects increases with increase in dose rate (ICRP, 2005) while non-stochastic effects have a threshold below which there is no effect. Examples of stochastic effects are radiation carcinogenesis and genetic effects while those of non-stochastic effects include organ dysfunction, fibrosis, lens opacification, blood changes and decrease in sperm count. Human
exposure to radiation also reduces the immunity of the person exposed (UNSCEAR, 2006).

Studies on the background to natural radiation are very crucial because it is the main source of exposure for humankind and also the largest contributor to the external dose of the world population (UNSCEAR, 2000). The study of the distribution of primordial radionuclides allows the understanding of the radiological implication of these elements due to the gamma ray exposure to body, irradiation of lung tissue from inhalation of radon and its daughters, and ingestion through foodstuff and water (Singh et al., 2005). In rural Kenya, soil is an important component in the building industry hence the need to analyse the radiation hazards its usage may present. The hazards vary depending upon the concentration of the natural radionuclides $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ present in the soil which in turn depend upon the local geology of each region in the world.

Given the potential impacts of radiation exposure due to the presence of primordial radionuclides and progeny in the human environments, extensive research in various places in the world has been done. In Nigeria, exposure to workers and villagers in and around some quarry sites in Ogun state was found to be 49.1 $\mu$Sv y$^{-1}$which is below the world average of 70 $\mu$Sv y$^{-1}$ (Odunaike, 2008). Measurements of natural radioactivity in sand samples collected from Baoji Weihe Sands Park in China has been studied (Lu Xinwei, 2006). The radium equivalent activity values of all sand sample were found to be lower than the limit of 370 Bq kg$^{-1}$. A study of distribution of natural radioactivity in Songkhla beach sands, Thailand found out that the specific activity of the
beach sand averaged $248 \pm 44$ Bq kg$^{-1}$ for $^{40}$K, $41 \pm 5$ Bq kg$^{-1}$ for $^{226}$Ra and $64 \pm 7$ Bq kg$^{-1}$ for $^{232}$Th (Kessaratikoon et al., 2007). The studies show the variations in activity concentrations of the naturally occurring radionuclides at various shores of water bodies which normally acts as sinks for radiation pollution. In Kenya, some researchers have done research work in different parts of the country to determine the concentration levels of the radionuclides in soil samples. A research on natural radioactivity conducted on soil sediments at the shores of Lake Nakuru shows that the average activity is $708.3 \pm 33.2$ Bq kg$^{-1}$ for $^{40}$K, $43.5 \pm 3.8$ Bq kg$^{-1}$ for $^{232}$Th and $36.9 \pm 9.1$ Bq kg$^{-1}$ for $^{238}$U, a dose rate of $71.97$ nGyh$^{-1}$ and an annual outdoor effective dose rate of $0.088 \pm 0.007$ mSv y$^{-1}$ which is less than the safety limit to public exposure of 1 mSv y$^{-1}$. These results show that Lake Nakuru being a tourist attraction site is safe for public from the effects of radiation. The results from this study provide baseline data for future monitoring of the radiation pollution of Lake Nakuru (Langat, 2012). A study conducted in Lambwe East, South Western Kenya showed that the mean estimated annual external effective dose rates due to the rocks and soil was $5.7$ mS y$^{-1}$ five times higher than recommended safety limit of 1 mSv y$^{-1}$. This region was thus considered a high background radiation (Achola, 2009).

1.2 Description of the study area.

The reported study was carried in Shinyalu constituency. This constituency is found in Kakamega County on the Eastern side of Kakamega town. It neighbours Malava Constituency in the North, Emgwen Constituency of Nandi County in the East, Sabatia Constituency of Vihiga County in the South,
Ikolomani Constituency in the South West and Lurambi Constituency in the North West. It is bounded by latitudes $0^\circ12'$ North, $0^\circ24'$ North and longitudes $34^\circ44'$ East, $34^\circ56'$ East. This constituency has an area of 445.40 km$^2$ with an approximate population of 159,475. The prevailing economic activity in this area is agriculture with tea, beans and maize being the major produce. Sugarcane and bananas are grown as well, in addition to cattle keeping but on a small scale. Other activities include brick making, quarrying, sand harvesting and tourism. The major tourist attractions include the ‘crying stone’ so named because of a crying king offended by another man who took his wife, the queen, and Kakamega Forest Reserve. The equatorial rainforest has a large variety of indigenous trees as well as species of different animals, insects and bird life.

1.3 Geology of Shinyalu Constituency

Shinyalu constituency is home to a number of hills that include Kambiri, Buyangu, Lirhanda, Ikuywa and Ilesi. The hills are characterised by granitic and metarmophic rocks. The granites consist of felsic intrusive igneous rock that is granular and pheneritic in texture and composed mainly of quartz and feldspar with minor amounts of mica, amphiboles and other minerals. The mineral composition gives granites with a red, pink, gray or white hues with dark mineral grains visible throughout the rock. The underlying rocks in Shinyaluare associated with ancient gneiss of Kavirondo and Nyanzian systems as well as basalt, phenolites and gold-bearing quartz veins. They are referred to
as Kisumu-Kakamega-Mumias granite-greenstone complex. Numerous granitic bosses and batholiths have intruded into these Nyanzian and Kavirondian systems (Shikali, 2013).

The constituency has also what is locally referred to as a “crying stone” found on Ilesi Hill. The stone is a granite rock that crystallized from magma which slowly cooled below the surface of the Earth. Due to continuous erosion it was later exposed. It consists of coarse grains of quartz, potassium and sodium feldspars, potassium oxide and small amounts of mica and silica. Naturally occurring radionuclide materials (NORM) like uranium, radium and thorium are present in a wide number of minerals that appear as crystals in granite (Turhan et al., 2008). Through the processes of weathering and erosion, the minerals from the hills and rocks are distributed to the farmlands. The constituency has two main rivers i.e. River Yala and River Isiukhu that originate from Nandi hills and Nandi escarpment respectively. During the rainy seasons, the rivers burst their banks and deposit silt from metamorphic and granitic rocks to flooded farms. Another material containing levels of uranium, thorium and potassium that can be of radiological significance is phosphate rock. This is often used as an agricultural fertilizer (Ononugbo et al., 2016).
MAP OF KENYA SHOWING THE LOCATION OF SHINYALU CONSTITUENCY

Figure 1.2: Map of Shinyalu constituency showing the sampling sites
1.4 Statement of the research problem

Typical to rural Kenya, soil is used extensively as a major building material in construction of residential houses and office complexes in Shinyalu. Since soil naturally contains radioactive elements, it can be an important source of radiation exposure to occupants of such buildings. Prolonged exposure and inhalation of these radionuclides results to serious radiation health effects such as chronic lung cancer and leukemia (Qureshi et al., 2014). Radionuclides in soils and rocks are not evenly distributed hence natural radioactivity depends primarily on the geological formations and geographical conditions, giving rise to the various levels of the radionuclides in such media (Avwiri, 2005; UNSCEAR, 2000). Since there has not been any radiological study of the area, it is therefore necessary to set up natural radioactivity level database and assess the contribution of soil to the total radiation dose received by residents in the Shinyalu constituency.

1.5 Objectives

1.5.1 General objective

To investigate the radiological hazard associated with $^{238}$U, $^{232}$Th and $^{40}$K in soil samples collected from various parts of Shinyalu constituency.
1.5.2 Specific objectives

The specific objectives of this work are as follows:

i. To determine the radioactivity concentrations of naturally occurring radionuclides (\(^{238}\text{U}, \, ^{232}\text{Th}\) and \(^{40}\text{K}\)) found in soil samples of Shinyalu constituency.

ii. To calculate the radiological parameters (radium equivalent dose, hazard indices and absorbed dose rate) due to the samples.

1.6 Rationale

Naturally occurring radionuclides arising from cosmic and and terrestrial sources are the main sources of environmental radiation. Therefore, investigating the levels of these radionuclides and their distribution in the environment provides essential radiological information.

Studies on gamma-ray emitting radionuclides are very important in that they create awareness on how this natural radiation may be detrimental to the health of the general populace. Gamma-ray spectrometry provides a reliable method for measuring the natural radiations from naturally occurring radionuclides. There is very scarce baseline information for radioactivity levels in this region and this study will make a significant contribution for setting up reference levels for studies pertaining to natural radioactivity in the soil samples of this region in future. The results from this study will also give useful information to scientific committees, government and non-governmental organizations which will be used in making decisions about soil as a building material in this region.
CHAPTER TWO

LITERATURE REVIEW

2.1 Related studies on natural radioactivity

Numerous studies have been done to evaluate the risk of radiation exposure due to naturally occurring radionuclides in the environmental samples. A study on natural radioactivity level in the soil samples of Eloor Island, India, reported an outdoor annual effective dose of between 0.1 mSv·y⁻¹ and 0.7 mSv·y⁻¹ with a mean value of 0.3 mSv·y⁻¹ (Dhanya et al., 2015). All the values were within the recommended dose of less than 1 mSv·y⁻¹. In Cyprus, a survey involving various geological formations reported maximum concentrations of $^{232}$Th, $^{238}$U, and $^{40}$K of 39.8 Bq·kg⁻¹, 39.3 Bq·kg⁻¹, and 565.8 Bq·kg⁻¹ respectively with maximum gamma absorbed dose of 51.3 nGy·h⁻¹ which is below the world average of 60 nGy·h⁻¹ (Tzortzis and Tsertos, 2004).

A study of natural radioactivity in beach sediments from north coast of Tamilnadu, India found that the maximum activity concentrations of $^{238}$U and $^{232}$Th were 30.42 Bq·kg⁻¹ and 218 Bq·kg⁻¹ respectively in Mahabalipuram beach. The highest activity concentration for $^{40}$K was 423.43 Bq·kg⁻¹ in Kovalam beach. The calculated absorbed gamma dose rate had a mean of 30.15 nGy·h⁻¹ which is less than the world average of 60 nGy·h⁻¹ and annual effective dose rate of 0.15 mSv·y⁻¹ which is more than the world average of 0.07 mSv·y⁻¹ (Ramasamy et al., 2009).
An assessment of natural radioactivity levels and radiation hazards in agricultural and virgin soil in the state of Kedah, North of Malaysia found that the mean activity concentrations of naturally occurring radionuclides $^{226}$Ra, $^{232}$Th and $^{40}$K were 102.08±3.96 Bqkg$^{-1}$, 133.96±2.92 Bqkg$^{-1}$ and 325.87±9.83 Bqkg$^{-1}$, respectively, in agricultural soils and 65.24±2.00 Bqkg$^{-1}$, 83.39±2.27 Bqkg$^{-1}$ and 136.98±9.76 Bqkg$^{-1}$, respectively, in virgin soils. The mean values of radium equivalent activity, absorbed dose rate, annual effective dose rate and external hazard index were 458.785 Bqkg$^{-1}$, 141.62 nGyh$^{-1}$ and 0.169 mSvy$^{-1}$, respectively, in agricultural soils and 214.293 Bqkg$^{-1}$, 87.47 nGyh$^{-1}$ and 0.106 mSvy$^{-1}$, respectively, in virgin soils, with average external hazard index of 0.525 (Ghazwa et al., 2016).

Not all studies result in measurements that are within the accepted values. A study on the specific activity concentration of radionuclides in soils from some districts of Abua/Odua Local Government Areas in Nigeria for instance reported (Ononugbo et al., 2016) higher values than the safe limit stipulated by UNSCEAR (2000). A study carried out at the Minjingu phosphate mines in neighbouring Tanzania found concentrations of $^{226}$Ra as high as 5760±107 Bqkg$^{-1}$ in phosphate rock and 4250 Bqkg$^{-1}$ in waste rock (Banzi et al., 2000). These values are more than 100 times the world average value. Elevated $^{226}$Ra levels were also observed in biological samples such as wild leaf vegetation with a concentration of 650±11 Bqkg$^{-1}$ and edible leaf vegetation with concentration of 393±9 Bqkg$^{-1}$. The radiation dose from ambient air over five years at the phosphate mine ranged from 1375 nGyh$^{-1}$ to 1475 nGyh$^{-1}$ with
an average of 1415 nGyh\(^{-1}\) which is higher than the global average background radiation from terrestrial sources by a factor of 28. These values suggest a possible radiation health risk to the area inhabitants resulting from external gamma irradiation as well as internal exposure from vegetables consumption. Another study involving clay samples from Aswan, South Egypt found average activity concentrations of natural radionuclides to be within the recommended safe limits (Alharbi and Taher, 2016).

A research on natural radioactivity and its associated radiological hazards in Ghanaian cement reported that the mean activity concentrations of \(^{226}\)Ra, \(^{232}\)Th and \(^{40}\)K were 35.94±0.78 Bqkg\(^{-1}\), 25.44±0.80 Bqkg\(^{-1}\) and 233±3.95 Bqkg\(^{-1}\) respectively. The mean indoor absorbed dose rate was 50.5\% less than the world average of 60nGyh\(^{-1}\) while the annual effective dose rate was 79\% less than the acceptable public safety limit of 1 mSv\(^{-1}\)(Kpeglo et al., 2011).

In Kenya, several studies on environmental radioactivity measurements are documented. In a study involving Mombasa, Malindi and Gazi along the coastal region of the country, concentration of \(^{238}\)U, \(^{232}\)Th and \(^{40}\)K was observed to be higher in Mombasa with average values of 22.8±1.8 Bqkg\(^{-1}\), 26.2±1.7 Bqkg\(^{-1}\) and 479.8±24.2 Bqkg\(^{-1}\) respectively resulting in effective dose rate lower than the ICRP acceptable dose limit of 1 mSv\(^{-1}\)by a factor of nearly 10 (Hashim, 2001). In another study, soil samples obtained from the region around titanium mines in the coastal region were also found with low radioactivity levels relative to the world averages (Osoro, 2007). Still in the coastal region of the country, soil samples from Mrima hills were found with
elevated absorbed dose rate averaging 440.7 nGy h⁻¹ which is much higher than the world average of 60 nGy h⁻¹ (Kebwaro, 2009). Away from the coastal area, Chege, (2007) studied the indoor radioactivity in some model traditional mud-walled huts near Nairobi in the central region of the country and reported radon concentration in some dwelling nearly twice the EPA recommended level of 148 Bq m⁻³. This was despite the fact that the huts remained well ventilated throughout the sampling period.

Further studies on soil and rock samples in soapstone quarries in Kisii (Kinyua et al., 2011) annual effective dose in the ranging from 1.03 mSv y⁻¹ to 1.27 mSv y⁻¹ was observed. These values exceed the permissible limits set by ICRP for members of the public. A research on assessment of human exposure to natural source of radiation on the soil in Tongaren constituency of Bungoma county, Kenya reported that the mean activity concentrations of ²³⁸U, ²³²Th and ⁴⁰K were 260.3±13.0 Bq kg⁻¹, 85.0±4.3 Bq kg⁻¹ and 981±49.1 Bq kg⁻¹, respectively. The average values of radium equivalent activity, absorbed dose rate, annual effective dose rate, external hazard and internal hazard indices were 456.4±22.8 Bq kg⁻¹, 206.4±10 nGy h⁻¹, 0.63±0.03 mSv y⁻¹, 1.24±0.06 and 1.94±0.10, respectively (Wanjala, 2016).

A study on radionuclide content of sand used for construction in Kakamega County and associated indoor radon diffusion doses found that ²²⁶Ra ranged from 36.79±8.89 Bq kg⁻¹ to 185.21±5.89 Bq kg⁻¹ with a mean of 128.05±8.89 Bq kg⁻¹, ²³²Th ranged from 51.12±2.56 Bq kg⁻¹ to 158.92±7.95 Bq kg⁻¹ with a mean of 98.37±6.41 Bq kg⁻¹ and ⁴⁰K ranged from 322.38±16.12 Bq kg⁻¹ to
960.53±48.03 Bqkg⁻¹ with a mean of 756.39±35.99 Bqkg⁻¹. The average values of radium equivalent activity, absorbed dose rate, annual effective dose rate and external hazard index were 321.67±12.4 Bqkg⁻¹, 151.76±5.65 nGyh⁻¹, 0.74±0.02 mSvy⁻¹ and 0.88±0.03, respectively (Shikali, 2013).

An assessment on radiation exposure levels associated with construction sand from Tharaka-Nithi County in Kenya reported that mean activity concentrations of $^{238}$U, $^{232}$Th and $^{40}$K were 98±4 Bqkg⁻¹, 53±3 Bqkg⁻¹ and 1069±46 Bqkg⁻¹, respectively. The mean values of radium equivalent activity, eternal hazard index, internal hazard index, outdoor absorbed dose rate, indoor absorbed dose rate, outdoor and indoor annual effective dose rates were 256±13 Bqkg⁻¹, 0.69±0.04, 0.95±0.05, 120.99±6.07 nGyh⁻¹, 166.67±8.31 nGyh⁻¹, 0.30±0.02 mSvy⁻¹ and 0.61±0.06 mSvy⁻¹, respectively (Kamunde, 2016).

A study on gamma ray spectroscopic analysis of the naturally occurring radionuclides in soils collected along the shores of Lake Victoria, Migori County, Kenya found that the mean of activity concentrations of $^{238}$U, $^{232}$Th and $^{40}$K were 64.5±3.3 Bqkg⁻¹, 146.0±4.4 Bqkg⁻¹ and 1222.8±43.3 Bqkg⁻¹ respectively. The mean values for radium equivalent activity, absorbed dose rate, annual effective dose rate, external hazard and internal hazard indices were 367.1±7.3 Bqkg⁻¹, 171.2±3.4 nGyh⁻¹, 0.420±0.008 mSvy⁻¹, 0.99±0.02 and 1.17±0.02 respectively (Okelo, 2015).
CHAPTER THREE

THEORETICAL BACKGROUND

3.1 Ionizing and non-ionizing radiation

Radiation is classified into two main categories; ionizing and non-ionizing. Ionising radiation is energy in the form of particles and waves that is able to penetrate matter and knock off electrons from atoms or molecules of materials that include air, water and living tissue. Examples of ionising radiation include electrons, protons, $\alpha$ particles, heavy ions, photons (X-rays and $\gamma$ rays) and neutrons. The minimum energy required to ionize an atom (ionization potential) ranges from a few electron volts for alkali elements to 24.5 eV for helium (noble gas). Ionisation can either be direct or indirect. Directly ionizing radiation which consists of charged particles i.e. electrons, protons, alpha particles and heavy ions deposits energy in the medium through direct Coulomb interactions with orbital electrons of atoms in the medium. Indirectly ionizing radiation consisting of neutral particles (neutrons) and photons (X-rays and gamma rays) deposits energy in the medium through a two step process. In the first step a charged particle is released in the medium (photons release electrons or positrons, neutrons release protons or heavier ions). In the second step the released charged particles deposit energy to the medium through direct Coulomb interactions with orbital electrons of the atoms in the medium. Both directly and indirectly ionizing radiations are used in the treatment of disease.
Diagnostic radiology and nuclear medicine also use ionizing radiation in the diagnosis of disease (Podgorsak, 2005).

Its highly penetrating power and ability to change the atom structure makes ionising radiation to be harnesses for good e.g. X-ray, gamma, beta and positron radiation is used for medical imaging, non-destructive testing and a variety of industrial gauges. The sterilizing effects of ionising radiation are useful for cleaning medical instruments, food irradiation and the sterile insect technique. Measurements of carbon-14 can be used to date the remains of long-dead organisms. It nonetheless has a down side in that over exposure or prolonged exposure can be dangerous to human beings.

Non-ionizing radiation on the other hand is less energetic, less penetrating and does not remove electrons from matter which makes it less dangerous to human health compared to ionising radiation. Examples include ultraviolet, visible light, infrared, microwave and radio waves. Non-ionizing radiation has valuable uses such as radar communication, cooking food (microwaves), transmitting information (radiowaves), heating, drying, cooking, warming greenhouses, infrared photography and heat-seeking missiles (infrared), seeing, ordinary photography, laser beams (visible light), spectroscopy, mineral analysis, detecting forgeries, kill bacteria, skin treatment and source of vitamin D (ultraviolet) (WHO, 2016).
3.2 The radioactive decay law

Radioactivity or radioactive decay is the spontaneous random disintegration of the nucleus of an unstable nuclide with the emission of radiation in the form of particles (beta or alpha) and electromagnetic waves (gamma photons). Unlike the particle emission, gamma decay does not occur in isolation. When a radionuclide undergoes either alpha or beta decay, the nucleus is oftentimes left in an excited state, it eventually de-excites by releasing a single or multiple gamma photons. These gamma photons are characteristic of the radioactive element involved. The disintegrating nuclide is referred to as the parent while the new element is referred to as the daughter or progeny. If the daughter is radioactive, it will act as parent giving rise to a daughter. The process proceeds until a final stable element is produced. The decay steps radionuclides go through is referred to as a decay chain/series. The process of radioactivity is not affected by external factors such as temperature, pressure or chemical composition.

The activity (A) of a radionuclide describes its rate of decay or transformation and is given the SI unit Becquerel (Bq). A Becquerel is defined as one disintegration per second. According to the radioactive decay law, the rate of decay, or activity A, of a radionuclide substance at some time t, is directly proportional to the number of radioactive nuclei N present in the substance at that particular time. This is expressed in a mathematical form as (equation 3.1);

\[ A = \frac{dN}{dt} \propto N \quad \text{(3.1)} \]
21

\[ A = \frac{dN}{dt} = -\lambda N \quad (3.2) \]

where \( \lambda \) is a constant of proportionality called decay constant. The decay constant is characteristic to the radionuclide. The negative sign denotes a decrease of activity with time.

Solution of equation 3.1 is given by the equation 3.3;

\[ N = N_o e^{-\lambda t} \quad (3.3) \]

where \( N_o \) is the initial number of parent nuclei at time \( t = 0 \) and \( t \) is the time taken for the initial number of parent nuclei \( N_o \) to decay to the present number of nuclei \( N \). To obtain the expression for the variation of activity with time, equation 3.3 is differentiated with respect to time i.e.

\[ A = \frac{dN}{dt} = \frac{d}{dt}(N_o e^{-\lambda t}) = -\lambda N_o e^{-\lambda t} \quad (3.4) \]

Equation can be rewritten as:

\[ A = A_o e^{-\lambda t} \quad (3.5) \]

where \( A_o (= -\lambda N_0) \) is the initial activity of the radioactive substance.

Equation 3.5 implies that the activity of a radioactive substance decreases exponentially with time.
3.3 Gamma radiation

Gamma radiation/ray is energetic, highly penetrating electromagnetic radiation arising from the radioactive decay of atomic nuclei transitions from a high energy state to a lower energy state. Gamma radiation can also be given off by a charged particles accelerating in an electric field as happens in accelerators. Gamma energy has low linear energy transfer (LET) which means that upon interacting with matter, gamma energy is deposited over a large distances the rays are able to travel significant distance before stopping. The gamma intensity reduces when gamma rays collide with the electrons in the shells of the atoms. They have no mass and no electrical charge and for the most part cause indirect ionization. Natural sources of gamma rays include gamma decay of terrestrial radionuclides, and secondary radiation from atmospheric interactions with cosmic ray particles.

Gamma rays interact with matter through the following three processes:

(i) Photoelectric effect

(ii) Compton scattering

(iii) Pair production

3.3.1 Photoelectric effect

The mechanism of photoelectric effect is shown in Figure 3.1. In the photoelectric effect, a photon undergoes an interaction with an electron which is bound in an atom. In this interaction, the incident photon completely disappears and an energetic photoelectron is ejected. Part of the photon energy
(equal to binding energy or work function, $E_b$) is used to free the electron from the atom shell while the rest is converted to kinetic energy ($E_e$) of the photoelectron. Thus, if $E(= h\nu)$ is the photon energy where $h$ is the Planck’s constant and $\nu$ the frequency of the incident photon, then the kinetic energy of the ejected photoelectron is given by the equation 3.6.

$$E_e = h\nu - E_b$$  

3.6

It follows from equation 3.6 that photoelectrons are only emitted if the gamma photon energy reaches or exceeds the work function of the material.

![Mechanism of photoelectric effect](image)

Figure 3.1: Mechanism of photoelectric effect (Podgorsak, 2005).

The energy level from which the electron is ejected depends upon the energy of the gamma radiation. The most likely to be ejected is a K-electron, followed by L then M if gamma energy is lower. This gives rise to discontinuities in the photoelectric absorption curves. These absorption edges occur at the binding energies corresponding to the electron shells. In other words, these discontinuities occur at wavelengths where the energy of an absorbed photon
corresponds to an electronic transition or ionization potential. When the quantum energy of the incident radiation becomes smaller than the work required to eject an electron from one or other quantum states in the constituent absorbing atom, the incident radiation ceases to be absorbed by that state. For example, incident radiation on an atom of a wavelength that has a corresponding energy just below the binding energy of the K-shell electron in that atom cannot eject the K-shell electron. The atomic attenuation coefficient (\(\tau\)) for photoelectric effect depends on the atomic number \(Z\) of the absorber and the gamma energy \((h\nu)\) according to the relation shown by equation 3.7 (Podgorsak, 2005).

\[
\tau = \frac{z^4}{(h\nu)^3}
\]

3.7

The significance of equation 3.7 is that photoelectric effect is more enhanced in materials with heavier atoms and low gamma energies.

Following photo-electric effect, the atom is usually left in an excited state. The state is short-lived and soon enough the atom recovers its equilibrium state either by redistributing the excitation energy between the remaining electrons resulting in release of further electrons (Auger cascade) which transfers a further fraction of total energy to the material (which may be a detector), or by filling the vacancy left by ejection of the photoelectron with higher energy electron with emission of characteristic X-rays (X-ray fluorescence) (Gilmore, 2008).
3.3.2 Compton scattering

The Compton Effect (incoherent scattering) represents a photon interaction with an essentially free and stationary orbital electron. The incident photon of energy ($h\nu$) is much larger than the binding energy of orbital electron. In Compton scattering, the incident photon transfers a portion of its energy to the electron which serves as its recoil kinetic energy ($E_k$) when the electron is deflected through angle $\phi$ relative to the original direction of the incident photon. Kinetic energy ($E_k$) of the electron can vary from zero to a large fraction of the incident gamma ray energy because all angles of scattering are possible. After the interaction, the incident gamma ray photon is deflected through an angle $\theta$ with respect to its original direction with reduced energy $h\nu'$, a situation referred to as Compton effect. The decrease in photon energy results in reduced photon frequency $\nu'$, Thus, the kinetic energy, $E_k$ imparted to the recoil electron is given by equation 3.8.

$$E_k = h\nu - h\nu'$$  \hspace{1cm} (3.8)

The ratio of energy of the scattered photon to energy of the incident photon is given by (Gilmore, 2008).

$$\frac{h\nu'}{h\nu} = \frac{1}{1+(1-\cos\theta)\frac{m_e}{m}\frac{c^2}{\nu}}$$  \hspace{1cm} (3.9)

where $m_e$ is the electron mass and $c$ is the speed of light in vacuum.

In terms of wavelengths and velocity equation 3.9 can be written as;
\[ \frac{\lambda}{\lambda'} = \frac{1}{1 + \frac{hc}{\lambda m_e c^2 (1 - \cos \theta)}} \]  

where \( \lambda' (= c/v') \) is the wavelength of the scattered photon, \( \lambda (= c/v) \) is the wavelength of the incident photon.

Equation 3.9a simplifies to equation 3.9b;

\[ \lambda' - \lambda = \frac{h}{m_e c} (1 - \cos \theta) \]  

A change in photon frequency results in change in photon wavelength \( \Delta \lambda \) is given by the Compton relationship:

\[ \Delta \lambda = \lambda' - \lambda = \lambda_C (1 - \cos \theta) \]  

where \( \lambda_C (= h/m_e c) \) is the Compton wavelength, with the value;

\[ \lambda_C = \frac{h}{m_e c} = 0.024 \text{Å} \]  

Figure 3.2: Mechanism of Compton scattering. An incident photon with energy \( h \nu \) interacts with a loosely bound (essentially free) atomic electron (James, 2014)
The absorption cross-section for Compton scattering $\sigma$ is related to the atomic number $Z$ of material and energy $h\nu$ of the gamma ray by equation (3.12); (Podgorsak, 2005)

$$\sigma \propto \frac{Z}{h\nu}$$

3.3.3 Pair production

This is the conversion of a photon into an electron-positron pair in the Coulomb field of a nucleus of an atom. The energy of the gamma-ray must be at least twice the rest mass of an electron which is 1022 keV for the pair production to take place. The electron and positron created share the excess gamma-ray energy (i.e. the energy in excess of the combined electron-positron rest mass) equally, losing it to the medium as they are slowed down. The net energy absorbed within the material due to this process is given by equation 3.13.

$$E_p = h\nu - 2m_e c^2$$

where $E_p$ is the combined kinetic energy of an electron-positron pair and $2m_e c^2$ is the energy threshold for pair production to happen.
Figure 3.3: Mechanism of pair production. The process takes place in the coulomb field of nucleus (https://www.world-nuclear-news.org).

The atomic attenuation coefficient for pair production $\kappa$ depends on atomic number $Z$ and is given by equation 3.14 (Gilmore, 2008);

$$\kappa \propto Z^2 \quad 3.14$$

### 3.4 Relative predominance of the interaction process

Figure 3.4 shows the regions of relative predominance of the three interaction processes with photon energy and atomic number $Z$ as parameters. In general, the photoelectric effect predominates at low photon energies, Compton effect at intermediate energies and pair production at high photon energies.
3.5 Gamma-ray emission

Gamma rays are high energy electromagnetic radiation emitted in the de-excitation of atomic nucleus. Immediately after the decay of the parent nucleus, the daughter nucleus can be either in the ground state or in excited state. In an excited state, the nucleus can relax either of two mechanisms: gamma-ray emission or internal conversion. The radiative relaxation leads to emission of one or more gamma rays with discrete energies whose sum equals the original excitation energy. During internal conversion, the nucleus transfers the excitation directly to one of the most tightly bound atomic electrons, usually a K electron. The electron leaves the atom with energy equal to the difference of the transition energy and the binding energy. The resulting vacancy leads to
emission of X-rays or electrons (called Auger electron) with the characteristic energy spectrum of the daughter elements. The probability of internal conversion increases strongly with atomic number (Z) and with decreasing excitation energy. All the alpha particles, gamma rays and internal conversion electrons emitted during the decay process have discreet, characteristic energies. The observation of these characteristic spectra showed that nuclei have discreet allowed states or energy levels analogous to the allowed sates of atomic electrons. All unstable nuclei with atomic number less than 82 decay by at least one of the three processes and sometimes by all three as shown in figure 3.5. Beta decay occurs whenever it is energetically possible. It is energetically possible if the following conditions are met for the masses of the neutral parent atoms (p) and the potential daughter atom (d).

\[ \beta^- \text{ decay: } m_p > m_d \]

\[ \beta^+ \text{ decay: } m_p > m_d + 2m_e \]

Electron capture: \( m_p > m_d \)

where \( m_p \) is the mass of the parent atom, \( m_d \) is the mass of the daughter atom and \( m_e \) is the mass of the electron.

\(^{60}\text{Co}\) decays by emitting an electron (beta decay) with a half-life of 5.272 years into an excited state of \(^{60}\text{Ni}\) which then decays very fast to the ground state of \(^{60}\text{Ni}\) via two gamma decays.
Beta decay can be to the ground state or to an excited state in the daughter nucleus. In the excited state, decays are followed by gamma-ray emission or internal conversion.

### 3.6 Secular equilibrium

This is a situation in which the quantity of a radioactive isotope remains constant because its production is equal to its decay rate. Secular equilibrium can only occur if the half-life of the daughter radionuclide, say B, is much shorter than the half-life of the parent radionuclide, say A. In such a situation, the decay rate of A is equal to the production rate of B. Suppose at the onset there are parent nuclides but no daughter nuclides. With time, the number of radionuclide B builds up as A decays, meaning that the production rate of B (or decay rate of A) is higher than its decay rate. The bridge between production of B and its decay rate narrows with time and after a relatively long time equal to
several half-lives of the shorter lived daughter, the number of B atoms decaying per unit time becomes equal to the number being produced per unit time; a condition known as secular equilibrium.

Consider a radioactive parent nucleus A decaying with a decay constant $\lambda_A$ into a daughter nucleus B which is also radioactive and decaying with a decay constant $\lambda_B$. If $N_A$ is the number of A atoms at some time $t$, then by decay law,

$$\frac{dN_A}{dt} = -\lambda_A N_A$$

3.15

With the boundary condition $N_A = N_{20}$ at $t = 0$, the solution of equation 3.15 becomes,

$$N_A = N_{20} e^{-\lambda_A t}$$

3.16

If $N_B$ is the number of atoms of B at some time $t$ then the rate of decay of B is $\lambda_B N_B$ where $\lambda_B$ is its decay constant. The rate of change of B atoms with time therefore is the difference between the production rate and the decay rate, i.e.

$$\frac{dN_B}{dt} = \lambda_A N_A - \lambda_B N_B$$

3.17

Equation 3.17 has a solution of the form;

$$N_B = g(t) e^{-\lambda_B t}$$

3.18

where $g(t)$ is the number of B atoms present when time $t = 0$. The differential form of equation 3.18 with respect to time gives the rate of change of B atoms with time, i.e.
\[
\frac{dN_B}{dt} = \left(\frac{dg}{dt} - g\lambda_B\right) e^{-\lambda_B t} \tag{3.19}
\]

Comparing equations 3.17 and 3.19 gives an indication that the LHS of the equations are equal implying that the RHS of the equations must also be equal. Therefore:

\[
\left(\frac{dg}{dt} - g\lambda_B\right) e^{-\lambda_B t} = \lambda_A N_A - \lambda_B N_B \tag{3.20}
\]

Using values of \(N_A\) and \(N_B\) given in equations 3.16 and 3.18 respectively in equation 3.20 results in the equation.

\[
\left(\frac{dg}{dt} - g(t)\lambda_B\right) e^{-\lambda_B t} = \lambda_A N_{20} e^{-\lambda_A t} - \lambda_B g(t) e^{-\lambda_B t} \tag{3.21}
\]

Equation 3.21 simplifies to equation (3.22).

\[
\frac{dg}{dt} = \lambda_A N_{20} e^{-(\lambda_A - \lambda_B)t} \tag{3.22}
\]

Integrating equation 3.22 gives

\[
g(t) = -\frac{\lambda_A N_{20}}{\lambda_A - \lambda_B} e^{-(\lambda_A - \lambda_B)t} + C \tag{3.23}
\]

where C is the constant of integration

The constant C is obtained by applying boundary conditions. If \(g(t) = 0\) at \(t = 0\), then \(C = \frac{\lambda_A N_{20}}{\lambda_A - \lambda_B}\) which when substituted in equation 3.23 gives

\[
g(t) = \frac{\lambda_A N_{20}}{\lambda_A - \lambda_B} \left(1 - e^{-(\lambda_A - \lambda_B)t}\right) \tag{3.24}
\]
Using equation 3.24 in equation 3.18 gives the number of B atoms present at some time t as

\[ N_B = \left[ \frac{\lambda_A N_{20}}{\lambda_A - \lambda_B} (1 - e^{-(\lambda_A - \lambda_B)t}) \right] e^{-\lambda_B t} \]  

which simplifies to

\[ N_B = \frac{\lambda_A N_{20}}{\lambda_A - \lambda_B} (e^{-\lambda_B t} - e^{-\lambda_A t}) \]  

Secular equilibrium is obtained when the half-life of the parent is very long compared to that of the daughter such that \( \lambda_A \ll \lambda_B \) and therefore \( \lambda_B - \lambda_A \approx \lambda_B \). So \( \lambda_A - \lambda_B = -\lambda_B \). In addition, for observation time that is much less than the half-life of the parent, \( \lambda_A t \ll 1 \) such that \( e^{-\lambda_A t} \approx 1 \). Taking this into consideration, equation 3.26 takes the form

\[ N_B = \frac{\lambda_A N_{20}}{\lambda_B} (1 - e^{-\lambda_B t}) \]

\[ N_B \lambda_B = \frac{\lambda_A N_{20}}{\lambda_B} (1 - e^{-\lambda_B t}) \]  

By definition, \( N_B \lambda_B \) represents the activity of the daughter (\( A_B \)) and \( N_{20} \lambda_A \) that of the parent (\( A_{20} \)). Thus;

\[ A_B = A_{20} (1 - e^{-\lambda_B t}) \]  

If the observation time is much longer than the half-life of the daughter, then \( e^{-\lambda_B t} \approx 0 \) and equation 3.28 reduces to;

\[ A_B = A_{20} \]
Equation 3.29 indicates that the rate of production of daughter atoms equals the rate of decay of parent atoms. When this happens, the parent and the daughter are said to be in secular equilibrium.

![Secular Equilibrium](image)

Figure 3.6: Secular equilibrium of a parent and daughter radionuclide (Sumia, 2016)

3.7 Relationship between various dosimetric quantities

3.7.1 Energy fluence and kerma

Energy fluence is the amount of energy $dE$ incident on a sphere of cross-sectional area $dA$.

Kerma is an acronym for kinetic energy released per unit mass. It is a non-stochastic quantity applicable to indirectly ionizing radiations such as photons and neutrons. It quantifies the average amount of energy transferred from indirectly ionizing radiation to directly ionizing radiation without concern as to
what happens after this transfer. The kerma is defined as the mean energy transferred from the indirectly ionizing radiation to charged particles (electrons) in the medium per unit mass.

The energy that photons transfer to electrons can be expended in two distinct ways:

i) Through soft and hard collision interactions.

ii) Thorough radiative interactions that involve bremsstrahlung and electron-positron annihilation.

Soft collision interactions are interactions which occur when a charged particle passes an atom at a considerable distance (i.e. \( b \gg a \), where \( b \) is the impact parameter and \( a \) the atomic radius). The net effect of the collision is that a very small amount of energy is transferred to an atom of the absorbing medium in a single collision.

On the other hand, hard collisions are collisions where a secondary electron (a delta electron or a delta ray) with considerable energy is ejected and forms a separate track i.e. \( b \approx a \). The electron undergoes hard collision with an orbital electron and an appreciable fraction of the electron’s kinetic energy is transferred to the orbital electron.

Kerma \( K \) consists of two components: the collision kerma \( K_{col} \) and the radiative kerma \( K_{rad} \). The collision kerma \( K_{col} \) leads to the production of electrons that dissipate their energy as ionization in or near the electron tracks in the medium, and is the result of Coulomb force interactions with atomic electrons. The
radiative kerma $K_{rad}$ leads to the production of radiative photons as the secondary charged particles slow down and interact in the medium. These interactions most prominently are bremsstrahlung as a result of Coulomb field interactions between the charged particle and the atomic nuclei, but can also result from annihilation in flight.

The total kerma $K$ is thus given by the equation 3.30:

$$K = K_{col} + K_{rad} \tag{3.30}$$

### 3.7.2 Fluence and dose (electrons)

When radiative photons escape a given region, they generate secondary electrons which are absorbed on the spot. The absorbed dose to medium $D$ is related to the particle fluence $\Phi$ by equation 3.31 (Khan, 2003).

$$D = \Phi \left( \frac{S_{col}}{\rho} \right) \tag{3.31}$$

where $(S_{col}/\rho)$ is the unrestricted mass collision stopping power of the medium at the energy of the electron. It is the average rate of energy loss by a charged particle in all soft and hard collisions.

### 3.7.3 Kerma and dose

The transfer of energy (kerma) from the photon beam to charged particles at a particular location does not lead to the absorption of energy by the medium (absorbed dose) at the same location. This is due to the non-zero (finite) range of the secondary electrons released through photon interactions. Since radiative
photons mostly escape from the organ at risk, one relates absorbed dose usually to collision kerma, the ratio of dose and collision kerma is denoted by equation 3.32 (Podgorsak, 2005).

$$\beta = \frac{D}{K_{col}}$$ 3.32

If $\beta \approx 1$ radiative photons escape the organ at risk.

### 3.7.4 Collision Kerma and exposure

Exposure $X$ is a measure of the ionization of air due to ionizing radiation from photons, i.e. gamma rays and X-rays. It is defined as the electric charge freed by such radiation in a specified volume of air divided by mass of that air. Exposure is given by the equation 3.33 (Podgorsak, 2005).

$$X = \frac{dQ}{dm}$$ 3.33

where $dQ$ is the absolute value of the total charge of the ions of one sign produced in air when all the electrons and positrons liberated or created by photons in mass $dm$ of air completely stopped in air.

The unit of exposure is coulomb per kilogram (C/kg). The unit used for exposure is the roentgen R, where $R = 2.58 \times 10^{-4}$ C/kg. In the SI unit system of units, roentgen is no longer used and the unit of exposure is simply $2.58 \times 10^{-4}$ C/kg of air (Podgorsak, 2005).
CHAPTER FOUR

MATERIALS AND METHODS

4.1 Sampling and sample preparation

Twenty three surface soil samples each weighing about 2 kg were collected from various locations of Shinyalu area. To make one representative sample, four 0.5 kg of soil samples were collected from an area of about 1 m × 1 m at a depth of 10-20 cm. The technique of sampling applied was random method to enhance statistical sensitivity of the sampling (IAEA, 2004). Extraneous materials like plant parts, pebbles and stones were removed from the soil samples. The samples were placed in polythene bags and then labelled. In the laboratory, the soil samples were crushed to smaller pieces and sieved through a mesh size of 150 µm to obtain fine powder. The sieved pieces were then dried at a temperature of 110°C for 24 hours to remove the water content and afterwards packed into polythene bags, weighed and hermetically sealed. The samples were then stored for 30 days before counting to allow $^{226}$Ra, $^{232}$Th and their short-lived decay products to reach secular equilibrium (Ramasamy et al., 2009). A gamma ray spectrometer consisting of NaI(Tl) detector and its associated electronics was then used to measure the radionuclides in the samples.

4.2 Gamma-ray spectrometry

Gamma-ray spectrometry is a technique that studies quantitatively the energy spectra of gamma-ray sources such as those used in the nuclear industry,
geochemical investigation and astrophysics. Most radioactive sources produce gamma rays of various energies and intensities. When these emissions are detected and analyzed with an energy calibrated gamma spectroscopy system, a gamma-ray energy spectrum is produced. The detector is usually energy-calibrated using specific energy peaks from standard reference sample so that each channel is assigned a specific energy value. The spectrum is typically used to identify and quantify the gamma emitters present in a gamma source given that the gamma spectrum is characteristic of the gamma emitting nuclides contained in the source.

4.3 NaI (Tl) gamma-ray spectrometer

The gamma ray spectrometer consists of a shielded NaI (Tl) detector. The system also includes an Oxford PCA-P multichannel analyzer (MCA) card and its software for spectral data acquisition and analysis. The PCA-P comprises of a high voltage supply, a charge sensitive pre-amplifier, a shaping amplifier, 80 MHz Wilkinson analogue to digital converter (ADC) with multichannel analyzer (MCA).

![Schematic diagram of NaI (TI) gamma-ray spectrometer](image)

Figure 4.1: Schematic diagram of NaI (TI) gamma-ray spectrometer
4.3.1 Working Mechanism of NaI (Tl) detector

Figure 3.7 shows the schematic of a NaI(Tl) scintillation detection system. When gamma rays from a sample enter the NaI crystal, they interact primarily with the bound K or L electrons from the iodide atoms in the crystal. The incident gamma photon energy is used to free an electron as well as supply the recoil electron with kinetic energy. This recoil electron passes through the NaI crystal and loses energy by ionisation and electronic and thermal excitations leaving the crystal atoms in excited state. On de-exciting, visible photons of light are emitted which then impinge on the photocathode thereby freeing electrons (photoelectrons) via photo-electric effect. The photo-electrons are accelerated towards the positively charged series of dynodes. A cascade of electrons is produced down the elements of the dynode to give an electrical pulse at the anode which is proportional to the energy of the incident gamma ray. The pulses are fed into the multichannel analyzer (MCA) which sorts them according to their energy and the data is presented in form of a spectrum.

![Diagram of NaI (Tl) scintillation detector](image)

Figure 4.2: NaI (Tl) scintillation detector used to detect gamma rays from radioactive source (IAEA, 2004)
4.4 Standard sample

The efficiency calibration of the system was done using thorium standard material, obtained from International Atomic Energy Agency (IAEA). Thorium standard (RGTh-I) is thorium ore diluted with silica, with $^{232}\text{Th}$ activity of 3280 Bqkg$^{-1}$ but containing some $^{238}\text{U}$ and $^{40}\text{K}$ of concentration 4900 Bqkg$^{-1}$ and 13400 Bqkg$^{-1}$ respectively.

4.5 Experimental procedures

4.5.1 Energy calibration of gamma-ray spectrometer

The gamma spectrometry detector was calibrated before it was used for analysis. The energy peaks of 662 keV of $^{137}\text{Cs}$, 1170 keV and 1330 keV of $^{60}\text{Co}$ were used to calibrate the spectrometer. The representation of photon energy as a function of channel number was done using a second order polynomial of the form given by equation 4.0. The polynomial was generated by least square fit. This is shown in figure 4.3.

\[ E = E_0 + A_1 C + A_2 C^2 \]  

4.0

where $E_0$, $A_1$ and $A_2$ are constants and $C$ is the channel number.
Figure 4.3: A second order polynomial fit used to calibrate energy for NaI (Tl) detector, used in this research work.

The values of the constants in equation 4.0 are given as $E_0 = -143.67518$, $A_1 = 5.174$ and $A_2 = -0.00193$.

### 4.5.2 Background measurement

The background radioactivity distribution in the environment around the detector was determined by counting a plastic container filled with distilled water in the same manner and in the same geometry as the samples (Huang et al., 2014). The background measurement was repeated at regular intervals for quality control.

The background radiation was subtracted from each of the recorded spectrum (Righiet al., 2009)
\[ Y_g - Y_b = Y_n \]  

where \( Y_g \) is the gross spectra count, \( Y_b \)is the background radiation and \( Y_n \) is the net spectra count of the sample.

4.5.3 Energy resolution of NaI (Tl) detector

The energy resolution of a detector measures its ability to distinguish gamma rays with close energies. It is obtained from the peak full width at half of the maximum height (FWHM). This is the width of the gamma ray peak at half of the highest point on the peak distribution. In this research work, the resolution of the gamma ray detector was obtained when a Gaussian curve was fitted to \(^{137}\text{Cs} \) full energy peak at 662 keV using the equation 4.2:

\[
y = y_o + \frac{A}{\sqrt{\pi w}} e^{-\frac{2(x-c)^2}{w^2}} \]

where \( y_o \) is the baseline offset, \( A \) is the area under the curve, \( x_c \) is the centre of the peak, and \( w \) is the full width at half maximum.

The values of the constants in equation 4.2 are given as; \( y_o = 1.052, x_c = 661.8, w = 47.049 \) and \( A = 1790.422 \).

A probability distribution used in calculating energy resolution is represented by the Gaussian curve obtained in figure 4.4.
The energy resolution of the detector system was obtained using the following equation:

\[ R = \frac{FWHM}{x_c} \times 100\% \]

\[ R = \frac{47.049}{661.8} \times 100\% = (7.11 \pm 0.01)\% \]

4.3

4.4

### 4.5.4 Detector efficiency

This is the probability that an emitted gamma ray will interact with the detector and produce a count. It is measured by comparing a spectrum from a source of known activity to the count rates in each peak to the count rates expected from the known intensities of each gamma ray. In this research work, standard IAEA certified samples of $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ were used. The peak corresponding to 1460 keV ($^{40}\text{K}$) for $^{40}\text{K}$, 1765 keV (Bi-214) for $^{238}\text{U}$ and 2615 keV (Tl-208) for
$^{232}$Th were considered in arriving at the activity levels. Certified activities and number of counts in the peaks were used in the calculation of detector efficiency using the formula given by (Mustapha et al, 2012).

$$\varepsilon = \frac{Y_n}{AP_yM_s} \quad \text{(4.5)}$$

where $\varepsilon$ is the efficiency of the detector, $Y_n$ is the peak count, $P_y$ is the emission probability of a given radionuclide in the reference sample, $A$ is the activity concentration of a given radionuclide in RGMIX and $M_s$ is the mass of standard reference sample (RGMIX).

### 4.5.5 Minimum detection limit

It is the ability of the detector to record minimum value of useful signal. The minimum detection limit, $L_D$ of the detector was calculated using the equation 4.6 (Mustapha et al, 2012);

$$L_D = \frac{1}{\varepsilon M_s P_y} \left[ \frac{2.71}{T} + 4.65 \frac{\sqrt{Y_b}}{T} \right] \quad \text{(4.6)}$$

where $T$ is the counting time, $Y_b$ is the background count, $M_s$ is the mass of the reference sample in RGMIX, $P_y$ is the emission probability of a given radionuclide in the sample and $\varepsilon$ is the detector efficiency. Values of the photon emission probabilities, detector efficiency and minimum detection limit for the various radionuclides analyzed in this research work using the standard reference sample is shown in table 4.1.
Table 4.1: Emission probabilities, detector efficiencies and minimum detection limits measured in this work.

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Energy (keV)</th>
<th>Concentration (Bqkg(^{-1}))</th>
<th>Emission Probability (P_y)</th>
<th>Efficiency (\epsilon)</th>
<th>(L_D) (Bqkg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{40})K</td>
<td>1460</td>
<td>5400</td>
<td>0.110</td>
<td>0.007387</td>
<td>0.5839</td>
</tr>
<tr>
<td>(^{238})U</td>
<td>1765</td>
<td>1260</td>
<td>0.161</td>
<td>0.004765</td>
<td>0.3512</td>
</tr>
<tr>
<td>(^{232})Th</td>
<td>2615</td>
<td>1160</td>
<td>0.360</td>
<td>0.001820</td>
<td>0.3916</td>
</tr>
</tbody>
</table>

Figure 4.5: Detector efficiency curve for measurements made in this work

4.6 Acquisition of spectral data and analysis of samples

A time of 30000 seconds for acquiring data for each sample and distilled water for determining background radiation was set. The reference sample was also
analysed. From the counting spectra, the activity concentration of $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ was determined. The peak corresponding to 1460 keV ($^{40}\text{K}$) for $^{40}\text{K}$, 1765 keV (Bi-214) for $^{238}\text{U}$ and 2615 keV (Tl-208) for $^{232}\text{Th}$ were considered in arriving at the activity levels. These peaks were chosen because they weakly interfere with other peaks hence forming pure peaks of the spectrum. The total counts were obtained after a region of interest was selected at the peak. A peak consists of a number of counts in adjacent channels. In order to obtain the region of interest (ROI) net area, the underlying continuum is subtracted from the gross area. The gross area is simply the summation of channel contents overall channels within the peak. The intensity of the background was subtracted to obtain residual intensity of sample for use in activity calculation.

Figure 4.6: Gamma-ray spectrum of the background measured in this work.
Figure 4.7: A typical gamma-ray spectrum of soil sample measured in this work after background subtraction

4.7 Calculation of radioactivity

The radioactivity concentration of the radionuclides in the sample was calculated using the following equation (Arogunjo et al., 2005):

$$A_i = \frac{S_n}{\varepsilon P_y M_s}$$

where $A_i$ is the radioactivity concentration of radionuclide $i$ in the sample, $M_s$ is the mass of the sample, $S_n$ is the net count rate under the corresponding photo peak, $\varepsilon$ is the detector efficiency at a specific gamma-ray energy and $P_y$ is the emission probability of the specific gamma-ray.
4.8 Evaluation of radiological hazard parameters

In order to evaluate the radiation hazards to the local population living in Shinyalu area due to the presence of natural radionuclides in soil, the radium equivalent activity, external hazard index, internal hazard index and annual effective dose rate were calculated from the activity concentration of natural radionuclides in the soil samples.

4.8.1 Radium equivalent activity (Ra_{eq})

The radium equivalent activity index (UNSCEAR, 2000) (Ra_{eq}) was calculated according to equation:

$$Ra_{eq} = C_{Ra} + 1.43C_{Th} + 0.077C_{K}$$  \hspace{1cm} 4.8

where $C_{Ra}$, $C_{Th}$ and $C_{K}$ are the specific activities of $^{226}$Ra, $^{232}$Th and $^{40}$K (in Bq kg$^{-1}$) respectively. 1.43 and 0.077 are conversion factors for $^{232}$Th and $^{40}$K, respectively.

4.8.2 External radiation hazard Index (H_{ex})

The external hazard index is used for the evaluation of external exposure to gamma radiation in the outdoor air. It was calculated from the expression of Ra_{eq} through the assumption that its allowed maximum value (equal to unity) corresponds to the upper limit of Ra_{eq} (370 Bq kg$^{-1}$). This index must be less than unit, in order to keep the radiation hazard insignificant.
The external hazard index, $H_{ex}$ was calculated using equation 4.9 (Ahmed, 2005).

$$H_{ex} = \frac{C_{Ra}}{370} + \frac{C_{Th}}{259} + \frac{C_{K}}{4810}$$  \hspace{1cm} 4.9

where $C_{Ra}$, $C_{Th}$ and $C_{K}$ are the activity concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K, respectively.

### 4.8.3 Internal hazard index ($H_{in}$)

Radon and its short lived products are also hazardous to the respiratory organs. To address the radiation to respiratory organs due to the radioactive inert gas radon a daughter product of radium and its short-lived secondary products, equation 4.9 as shown was modified and the index renamed internal hazard index as shown in equation 4.10. (Ahmed, 2005)

$$H_{in} = \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_{K}}{4810}$$  \hspace{1cm} 4.10

where $C_{Ra}$, $C_{Th}$ and $C_{K}$ are the activity concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K, respectively.

### 4.8.4 Absorbed gamma radiation dose rate (D nGyh$^{-1}$)

This refers to the amount of radiation absorbed or deposited per unit mass of substance.

The absorbed gamma dose rates due to gamma radiations in air at 1 m above the ground surface for the uniform distribution of the naturally occurring radionuclides ($^{238}$U, $^{232}$Th and $^{40}$K) was calculated based on the guidelines provided by (UNSCEAR, 2000).
\[ \text{D(nGy}^{-1}) = 0.462C_U + 0.604C_{Th} + 0.041C_K \]

where \( D \) is the absorbed dose rate \((\text{nGy}^{-1})\), \( C_U \), \( C_{Th} \) and \( C_K \) are the activity concentrations \((\text{Bqkg}^{-1})\) of \( ^{238}\text{U} \), \( ^{232}\text{Th} \) and \( ^{40}\text{K} \), respectively.

### 4.8.5 Annual effective dose rate

The annual effective dose rate was estimated using the dose rate data obtained from the concentration values of natural radionuclides in soil samples. Adopting the conversion factor from the absorbed dose in the air to the effective dose \((0.7 \text{ SvGy}^{-1})\) and the outdoor occupancy factor \((0.2)\) proposed by (UNSCEAR, 2000) the annual effective dose rate will be calculated from the formula,

\[ \text{Effective dose rate(m Sv y}^{-1}) = D \times 8760 \times 0.2 \times 0.7 \times 10^{-6} \]

where \( D \) is the absorbed dose in \( \text{nGy}^{-1} \).
CHAPTER FIVE

RESULTS AND DISCUSSION

The aim of this study was to measure natural radioactivity levels in soils obtained from farms in Shinyalu constituency. These activity levels were measured using NaI (Tl) detector. The soils obtained from these farms were prepared and analysed at Kenyatta University Physics Laboratory. The analysis of these soil samples included measuring the intensity and calculation of radioactivity concentration, radium equivalent activity, external and internal hazard indices, absorbed dose rate and annual effective dose rate.

5.1 Activity concentration of natural radionuclides

The activity concentrations of natural radionuclides $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ were measured and an average of 189±9 Bq kg$^{-1}$, 151±8 Bq kg$^{-1}$ and 902±45 Bq kg$^{-1}$ respectively were obtained. The minimum radioactivity concentrations for $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ were found to be 27±14 Bq kg$^{-1}$, 16±1 Bq kg$^{-1}$ and 98±5 Bq kg$^{-1}$ while the maximum values were 349±17 Bq kg$^{-1}$, 381±19 Bq kg$^{-1}$ and 1718±86 Bq kg$^{-1}$ respectively. It is observed that the activity concentrations in this region are above their respective world average value of 33 Bq kg$^{-1}$, 45 Bq kg$^{-1}$ and 420 Bq kg$^{-1}$ for $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ respectively (UNSCEAR, 2016).
Table 5.1: Mean activity concentrations of the soil samples measured in this study compared to the world average (UNSCEAR, 2016)

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>This work (Bqkg(^{-1}))</th>
<th>World (Bqkg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(UNSCEAR, 2016)</td>
</tr>
<tr>
<td>(^{238})U</td>
<td>189±9</td>
<td>33</td>
</tr>
<tr>
<td>(^{232})Th</td>
<td>151±8</td>
<td>45</td>
</tr>
<tr>
<td>(^{40})K</td>
<td>902±45</td>
<td>420</td>
</tr>
</tbody>
</table>

Table 5.2: A summary of the activity concentration of \(^{238}\)U, \(^{232}\)Th and \(^{40}\)K in all the sampling points.

<table>
<thead>
<tr>
<th>Sample site</th>
<th>Location</th>
<th>(^{40})K (Bqkg(^{-1}))</th>
<th>(^{238})U (Bqkg(^{-1}))</th>
<th>(^{232})Th (Bqkg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Itenyi</td>
<td>753±38</td>
<td>27±14</td>
<td>109±5</td>
</tr>
<tr>
<td>2</td>
<td>Mukulusu</td>
<td>1119±56</td>
<td>233±12</td>
<td>196±10</td>
</tr>
<tr>
<td>3</td>
<td>Shiswa</td>
<td>1281±64</td>
<td>58±3</td>
<td>174±9</td>
</tr>
<tr>
<td>4</td>
<td>Lubao</td>
<td>1255±63</td>
<td>97±5</td>
<td>169±8</td>
</tr>
<tr>
<td>5</td>
<td>Ivakale</td>
<td>753±38</td>
<td>291±15</td>
<td>152±8</td>
</tr>
<tr>
<td>6</td>
<td>Buyangu</td>
<td>802±40</td>
<td>78±4</td>
<td>125±6</td>
</tr>
<tr>
<td>7</td>
<td>Bulovi</td>
<td>1413±71</td>
<td>252±13</td>
<td>169±8</td>
</tr>
<tr>
<td>8</td>
<td>Lugusi</td>
<td>1432±72</td>
<td>349±17</td>
<td>163±8</td>
</tr>
<tr>
<td>9</td>
<td>Lunyu</td>
<td>769±38</td>
<td>330±16</td>
<td>109±5</td>
</tr>
<tr>
<td>10</td>
<td>Ikuywa</td>
<td>1059±53</td>
<td>136±7</td>
<td>223±11</td>
</tr>
<tr>
<td>11</td>
<td>Virhembe</td>
<td>249±12</td>
<td>174±9</td>
<td>71±4</td>
</tr>
<tr>
<td>12</td>
<td>Mukango</td>
<td>422±21</td>
<td>58±3</td>
<td>76±4</td>
</tr>
<tr>
<td>13</td>
<td>Shisembe</td>
<td>347±17</td>
<td>116±6</td>
<td>65±3</td>
</tr>
<tr>
<td>14</td>
<td>Shidodo</td>
<td>98±5</td>
<td>97±5</td>
<td>33±2</td>
</tr>
<tr>
<td>15</td>
<td>Mukhonje</td>
<td>1255±63</td>
<td>271±14</td>
<td>50±3</td>
</tr>
<tr>
<td>16</td>
<td>Mugomari</td>
<td>1409±70</td>
<td>194±10</td>
<td>16±1</td>
</tr>
<tr>
<td>17</td>
<td>Malimili</td>
<td>851±43</td>
<td>155±8</td>
<td>250±13</td>
</tr>
<tr>
<td>18</td>
<td>Shitochi</td>
<td>791±40</td>
<td>194±10</td>
<td>207±10</td>
</tr>
<tr>
<td>19</td>
<td>Museno</td>
<td>429±21</td>
<td>78±4</td>
<td>109±5</td>
</tr>
<tr>
<td>20</td>
<td>Shirulu</td>
<td>531±27</td>
<td>213±11</td>
<td>364±18</td>
</tr>
<tr>
<td>21</td>
<td>Lugose</td>
<td>689±34</td>
<td>291±15</td>
<td>158±8</td>
</tr>
<tr>
<td>22</td>
<td>Shiasava</td>
<td>1718±86</td>
<td>233±12</td>
<td>381±19</td>
</tr>
<tr>
<td><strong>MEAN</strong></td>
<td><strong>902±45</strong></td>
<td><strong>189±9</strong></td>
<td><strong>151±8</strong></td>
<td></td>
</tr>
</tbody>
</table>
It is also observed that the activity concentration of $^{40}$K is highest in all the sampling sites. The high activity concentration of $^{40}$K may be attributed to the excessive use of inorganic fertilizers that are rich in potassium. It is also the most abundant radionuclide element under consideration. Some soils recorded high activity concentrations of $^{238}$U and $^{232}$Th due to the presence of weathered particles of granite rocks which dominate part of the geology of this region. These granite rocks are highly associated with naturally occurring radionuclides. These rock particles were eroded from hills present in this region and also Nandi hills that border this constituency on the eastern part. The weathered rock particles after being eroded spread and settled non-uniformly on the farms in this area. The eastern part of Shinyalu has fairly high activity concentration because of its closeness to rift valley.

Major rivers in this constituency i.e. Isiukhu and Yala deposit a lot of radioactive materials from granitic and metamorphic rocks to the farms adjacent to them during rainy seasons. The source of river Isiukhu is Nandi escarpment and that of river Yala is Nandi hills. The Nandi escarpment and the Nandi hills have a number of rocks formed from volcanic activities like granite and pumice which contain radioactive elements (Hassan et al., 2010). Farms adjacent to rivers Yala and Isiukhu are irrigated during dry season using water obtained from these rivers. The water contain radioactive elements acquired by the rivers from granitic rocks of Nandi hills and Nandi escarpment. The high levels of natural radionuclide concentration in some parts of this region might also have resulted from sand harvesting and quarrying. During quarrying and
sand harvesting radioactive rich igneous rocks, sand stones, monazites, murram and quartzite are exposed to agents of weathering and dispersed in the region (Shikali, 2013). The natural radioactivity levels of \(^{238}\text{U}\), \(^{232}\text{Th}\) and \(^{40}\text{K}\) in this region have been compared with published values of other parts of the country.

Table 5.3: A summary of the activity concentration calculated in this study compared to other parts in Kenya.

<table>
<thead>
<tr>
<th>Place of study</th>
<th>Activity concentration in Bq kg(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(^{238}\text{U})</td>
</tr>
<tr>
<td>Shinyalu constituency</td>
<td>189±9 (27-349)</td>
</tr>
<tr>
<td>(This work)</td>
<td></td>
</tr>
<tr>
<td>Migori county (Lake shore)</td>
<td>64.5±3.3 (34.4-103.2)</td>
</tr>
<tr>
<td>(Okelo, 2015)</td>
<td></td>
</tr>
<tr>
<td>Tongaren constituency</td>
<td>260.3±13.0 (34.6-484.8)</td>
</tr>
<tr>
<td>(Wanjala, 2016)</td>
<td></td>
</tr>
<tr>
<td>Mombasa</td>
<td>22.8±1.8 (14.4-33.3)</td>
</tr>
<tr>
<td>(Hashim et al., 2004)</td>
<td></td>
</tr>
<tr>
<td>Kibwezi District</td>
<td>130.6±38.7 (34.4-103.2)</td>
</tr>
<tr>
<td>(Mutie, 2011)</td>
<td></td>
</tr>
<tr>
<td>Mrima Hill</td>
<td>207.03±11.3 (67.0-354.3)</td>
</tr>
<tr>
<td>(Kebwaro, 2009)</td>
<td></td>
</tr>
<tr>
<td>Kwale T mines</td>
<td>20.9±7.6 (7.4-40.6)</td>
</tr>
<tr>
<td>(Osoro, 2007)</td>
<td></td>
</tr>
<tr>
<td>Malindi</td>
<td>21.3±3 (16.4-40.2)</td>
</tr>
<tr>
<td>(Hashim et al., 2004)</td>
<td></td>
</tr>
</tbody>
</table>
These variations in the activity concentrations in the soil of the various locations of the country was due to the geological and geographical conditions of the area and the extend of fertilizer applied to the agricultural lands.

The continuous application of inorganic fertilizers on farms has contributed to an increase in activity concentrations of naturally occurring radioactive materials in Shinyalu constituency.

![Figure 5.1: The activity concentration of the primordial radionuclides against sampling sites in Shinyalu constituency.](image)

5.2 Radium equivalent activity

Radium equivalent activity was calculated using equation 4.8. The mean value for radium equivalent was found to be $475\pm24 \text{ Bq kg}^{-1}$ within a minimum of
151±8 Bqkg⁻¹ and a maximum of 910±46 Bqkg⁻¹. This average value is higher than the world average value of 89 Bqkg⁻¹ and the permissible healthy limit of 370 Bqkg⁻¹ (UNSCEAR, 2016). A summary of values of radiological parameters is shown in table 5.4 and table 5.5.

Table 5.4: A summary of values of radium equivalent activity, external hazard index and internal hazard index

<table>
<thead>
<tr>
<th>Sample site</th>
<th>Location</th>
<th>Ra_{eq}(Bqkg⁻¹)</th>
<th>H_{ex}</th>
<th>H_{in}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Itenyi</td>
<td>485±24</td>
<td>1.31±0.07</td>
<td>2.04±0.10</td>
</tr>
<tr>
<td>2</td>
<td>Mukulusu</td>
<td>599±30</td>
<td>1.62±0.08</td>
<td>2.25±0.11</td>
</tr>
<tr>
<td>3</td>
<td>Shiswa</td>
<td>406±20</td>
<td>1.10±0.05</td>
<td>1.25±0.06</td>
</tr>
<tr>
<td>4</td>
<td>Lubao</td>
<td>435±22</td>
<td>1.17±0.06</td>
<td>1.44±0.07</td>
</tr>
<tr>
<td>5</td>
<td>Ivakale</td>
<td>567±28</td>
<td>1.53±0.08</td>
<td>2.32±0.12</td>
</tr>
<tr>
<td>6</td>
<td>Buyangu</td>
<td>318±16</td>
<td>0.86±0.04</td>
<td>1.07±0.05</td>
</tr>
<tr>
<td>7</td>
<td>Bulovi</td>
<td>602±30</td>
<td>1.63±0.08</td>
<td>2.31±0.12</td>
</tr>
<tr>
<td>8</td>
<td>Lugusi</td>
<td>692±35</td>
<td>1.87±0.09</td>
<td>2.81±0.14</td>
</tr>
<tr>
<td>9</td>
<td>Lunyu</td>
<td>544±27</td>
<td>1.47±0.07</td>
<td>2.36±0.12</td>
</tr>
<tr>
<td>10</td>
<td>Ikuywa</td>
<td>536±27</td>
<td>1.45±0.07</td>
<td>1.81±0.09</td>
</tr>
<tr>
<td>11</td>
<td>Virhembe</td>
<td>295±15</td>
<td>1.80±0.04</td>
<td>0.33±0.02</td>
</tr>
<tr>
<td>12</td>
<td>Mukango</td>
<td>200±10</td>
<td>0.54±0.03</td>
<td>0.70±0.03</td>
</tr>
<tr>
<td>13</td>
<td>Shisembe</td>
<td>236±12</td>
<td>0.64±0.03</td>
<td>0.95±0.05</td>
</tr>
<tr>
<td>14</td>
<td>Shidodo</td>
<td>151±8</td>
<td>0.41±0.02</td>
<td>0.67±0.03</td>
</tr>
<tr>
<td>15</td>
<td>Mukhonje</td>
<td>439±22</td>
<td>1.19±0.06</td>
<td>1.92±0.10</td>
</tr>
<tr>
<td>16</td>
<td>Mugomari</td>
<td>326±16</td>
<td>0.88±0.04</td>
<td>1.40±0.07</td>
</tr>
<tr>
<td>17</td>
<td>Malimili</td>
<td>578±29</td>
<td>1.56±0.08</td>
<td>1.98±0.10</td>
</tr>
<tr>
<td>18</td>
<td>Shitochi</td>
<td>550±28</td>
<td>1.49±0.07</td>
<td>2.01±0.10</td>
</tr>
<tr>
<td>19</td>
<td>Museno</td>
<td>266±13</td>
<td>0.72±0.04</td>
<td>0.93±0.05</td>
</tr>
<tr>
<td>20</td>
<td>Shirulu</td>
<td>775±39</td>
<td>2.09±0.10</td>
<td>2.67±0.13</td>
</tr>
<tr>
<td>21</td>
<td>Lugose</td>
<td>569±28</td>
<td>1.54±0.08</td>
<td>2.32±0.12</td>
</tr>
<tr>
<td>22</td>
<td>Shing’oto</td>
<td>440±22</td>
<td>1.19±0.06</td>
<td>1.66±0.08</td>
</tr>
<tr>
<td>23</td>
<td>Shiasava</td>
<td>910±46</td>
<td>2.46±0.12</td>
<td>3.08±0.10</td>
</tr>
<tr>
<td><strong>MEAN</strong></td>
<td></td>
<td><strong>475±24</strong></td>
<td><strong>1.28±0.06</strong></td>
<td><strong>1.75±0.08</strong></td>
</tr>
</tbody>
</table>
Table 5.5: A summary of values of absorbed dose rate and annual effective dose rate

<table>
<thead>
<tr>
<th>Sample site</th>
<th>Location</th>
<th>D (nGyh⁻¹)</th>
<th>E_{air}(mSvy⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Itenyi</td>
<td>222±11</td>
<td>0.27±0.01</td>
</tr>
<tr>
<td>2</td>
<td>Mukulusu</td>
<td>272±14</td>
<td>0.33±0.02</td>
</tr>
<tr>
<td>3</td>
<td>Shiswa</td>
<td>198±10</td>
<td>0.24±0.01</td>
</tr>
<tr>
<td>4</td>
<td>Lubao</td>
<td>198±10</td>
<td>0.24±0.01</td>
</tr>
<tr>
<td>5</td>
<td>Ivakale</td>
<td>257±13</td>
<td>0.32±0.02</td>
</tr>
<tr>
<td>6</td>
<td>Buyangu</td>
<td>144±7</td>
<td>0.18±0.01</td>
</tr>
<tr>
<td>7</td>
<td>Bulovi</td>
<td>276±14</td>
<td>0.34±0.02</td>
</tr>
<tr>
<td>8</td>
<td>Lugusi</td>
<td>318±16</td>
<td>0.39±0.02</td>
</tr>
<tr>
<td>9</td>
<td>Lunyu</td>
<td>249±12</td>
<td>0.31±0.02</td>
</tr>
<tr>
<td>10</td>
<td>Ikuywa</td>
<td>241±12</td>
<td>0.30±0.02</td>
</tr>
<tr>
<td>11</td>
<td>Virhembe</td>
<td>133±7</td>
<td>0.16±0.01</td>
</tr>
<tr>
<td>12</td>
<td>Mukango</td>
<td>90±5</td>
<td>0.11±0.01</td>
</tr>
<tr>
<td>13</td>
<td>Shisembe</td>
<td>107±5</td>
<td>0.13±0.01</td>
</tr>
<tr>
<td>14</td>
<td>Shidodo</td>
<td>69±3</td>
<td>0.08±0.00</td>
</tr>
<tr>
<td>15</td>
<td>Mukhonje</td>
<td>207±11</td>
<td>0.25±0.01</td>
</tr>
<tr>
<td>16</td>
<td>Mugomari</td>
<td>157±8</td>
<td>0.19±0.01</td>
</tr>
<tr>
<td>17</td>
<td>Malimili</td>
<td>258±13</td>
<td>0.32±0.02</td>
</tr>
<tr>
<td>18</td>
<td>Shitochi</td>
<td>247±12</td>
<td>0.30±0.02</td>
</tr>
<tr>
<td>19</td>
<td>Museno</td>
<td>119±6</td>
<td>0.15±0.01</td>
</tr>
<tr>
<td>20</td>
<td>Shirulu</td>
<td>340±17</td>
<td>0.42±0.02</td>
</tr>
<tr>
<td>21</td>
<td>Lugose</td>
<td>258±13</td>
<td>0.32±0.02</td>
</tr>
<tr>
<td>22</td>
<td>Shing oto</td>
<td>204±10</td>
<td>0.25±0.01</td>
</tr>
<tr>
<td>23</td>
<td>Shiasava</td>
<td>408±20</td>
<td>0.50±0.03</td>
</tr>
</tbody>
</table>

**MEAN** 216±11 0.27±0.01

Table 5.6: The world average and maximum acceptable safety health limit of radiological parameters (UNSCEAR, 2016).

<table>
<thead>
<tr>
<th></th>
<th>Ra (Bqkg⁻¹)</th>
<th>H_{ex}</th>
<th>H_{in}</th>
<th>D (nGyh⁻¹)</th>
<th>E (mSvy⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>World average</strong></td>
<td>89</td>
<td>1</td>
<td>1</td>
<td>60</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>Acceptable public safety limit</strong></td>
<td>370</td>
<td>6</td>
<td>6</td>
<td>1 500</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 5.2: Radium equivalent activity values against sampling sites.

5.3 Hazard indices

The external hazard index and the internal hazard index were calculated using equations 4.9 and 4.10 respectively. The mean external hazard index was found to be 1.28±0.06 within a minimum of 0.41±0.02 and a maximum of 2.46±0.12. The average internal hazard index was to be 1.75±0.08 within a minimum of 0.33±0.02 and a maximum of 3.08±0.10. The average values of both external hazard index and internal hazard index were slightly above 1 which is the world average but below 6 an acceptable public safety limit. The internal
hazard index is higher than the external hazard index because the short lived radon is exhaled and concealed in a room and thus increasing the concentration. A comparison of external hazard index and internal hazard index obtained in this study is shown in figure 5.3.

![Figure 5.3: Values of hazard indices against sampling sites](image)

**5.4 Absorbed dose rate**

The absorbed dose rate was calculated using equation 4.11. The absorbed dose rate in air at a height of 1 m above the ground level was obtained from the different sites ranged from 69±3 nGyh⁻¹ to 408±20 nGyh⁻¹ with an average
value of $216\pm11\ nGyh^{-1}$. The mean absorbed dose rate is higher than the world average value of $60\ nGyh^{-1}$ but lower than maximum allowed health limit of $1500\ nGyh^{-1}$ as proposed by UNSCEAR (2016).

![Graph](image)

Figure 5.4: Absorbed dose rate against sampling sites.

### 5.5 Annual effective dose rate

The annual effective dose rate in the soil samples was calculated using equation 4.12. The annual effective dose rate ranged from $0.08\ mSvy^{-1}$ to $0.50\pm0.03\ mSvy^{-1}$ with a mean of $0.27\pm0.01\ mSvy^{-1}$. This average value of annual effective dose rate is above the world average of $0.07\ mSvy^{-1}$ but below the maximum allowed limit of $1\ mSvy^{-1}$ of radiation exposure to the public.
(ICRP, 1991). Thus the area under study is safe for people to live. A bar graph of annual effective dose rate calculated in this work is shown in figure 5.6.

![Bar graph of annual effective dose rate](image)

**Figure 5.5:** Annual effective dose rate against sampling sites

### 5.6 Correlation between the naturally occurring radionuclides

The correlations between $^{238}$U and $^{232}$Th, $^{232}$Th and $^{40}$K and between $^{238}$U and $^{40}$K are computed from the mean activity concentrations obtained.

It is observed that, the correlations between $^{232}$Th and $^{40}$K, $^{238}$U and $^{232}$Th and between $^{238}$U and $^{40}$K are weak at correlation coefficients of 0.21972, 0.19865 and 0.34384 respectively. The low correlations between $^{238}$U, $^{232}$Th and $^{40}$K indicate that individual results for any one radionuclide concentration in each
pair are not good predictors of individual values for the other. The regression plots indicate that there is much diversity in terms of distribution of thorium, uranium and potassium in the region. This could be due to difference in the types of rocks from which the soil originated, difference in solubility of minerals containing these radionuclides and difference in the extend of fertilizer application to the agricultural lands in this region.
CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The natural radioactivity levels of $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ have been measured in soil samples of Shinyalu using gamma ray spectroscopy. The activity concentrations for $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ ranged from $(27\pm 14 - 349\pm 17)$ Bq kg$^{-1}$, $(16\pm 1 - 381\pm 19)$ Bq kg$^{-1}$ and $(98\pm 5 - 1718\pm 86)$ Bq kg$^{-1}$ with their average values being $189\pm 9$ Bq kg$^{-1}$, $151\pm 8$ Bq kg$^{-1}$, and $902\pm 45$ Bq kg$^{-1}$ respectively. The activity concentrations for $^{238}\text{U}$ and $^{40}\text{K}$ obtained in the soil samples of Tongaren constituency by Wanjala (2016) are higher than the activity concentrations for $^{238}\text{U}$ and $^{40}\text{K}$ obtained in this study. The activity concentration for $^{232}\text{Th}$ obtained in this study is higher than that reported by Wanjala (2016) in Tongaren constituency. The activity concentrations of $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ in the soil samples of Shinyalu are higher than the world average values of 33 Bq kg$^{-1}$, 45 Bq kg$^{-1}$ and 420 Bq kg$^{-1}$ for $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ respectively. The higher activity concentration of $^{40}\text{K}$ may be attributed to continuous use of fertilizers rich in potassium on the farms in this study area. The presence of weathered particles of granite rocks in this region may be the reason for high activity concentrations of $^{238}\text{U}$ and $^{232}\text{Th}$. The origin of rivers Isiukhu and Yala is Nandi escarpment and Nandi hills respectively. The origin of these two rivers contain metamorphic and granitic rocks that contributes minerals having $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$. 
The average absorbed dose rate was found to be 216±11 nGyh\(^{-1}\) with a minimum of 69±3 nGyh\(^{-1}\) and a maximum of 408±20 nGyh\(^{-1}\). This average value is above the world average value of 60 nGyh\(^{-1}\) but lower than the acceptable safety limit of 1 500 nGyh\(^{-1}\) (UNSCEAR, 2008). The average radium equivalent activity was found to be 475±24 Bqkg\(^{-1}\) in the range of 159±8 Bqkg\(^{-1}\) to 910±46 Bqkg\(^{-1}\). This average value is above the world acceptable safety limit of 370 Bqkg\(^{-1}\).

The average annual effective dose rate of 0.27±0.01 mSvy\(^{-1}\) in the range of 0.08 mSvy\(^{-1}\) to 0.50±0.03 mSvy\(^{-1}\) was obtained. This average value is less than the acceptable safety limit of 1 mSvy\(^{-1}\). The external hazard index and the internal hazard index were found to be 1.28±0.06 and 1.75±0.08 in the range of 0.41±0.02 to 2.46±0.12 and 0.33±0.02 to 3.08±0.10 respectively. These average values are lower than the acceptable safety limit of 6 (UNSCEAR, 2002). This is a clear indication that the radiological health hazard associated with naturally occurring radionuclides in the soil samples of Shinyalu is insignificant. Therefore this study area possesses insignificant gamma emitting radionuclides which may be detrimental to the health of the general populace in the area. The result of this study could be helpful in radiological mapping of the area and as a baseline data for future studies.

### 6.2 Recommendations

This study was done using soil samples from farms of Shinyalu constituency. I therefore recommend more studies to be carried out on other building materials like rocks, fabricated bricks, murrum and sand harvested from rivers Isiukhu and
Yala in order to determine their contributions to the total radiation dose received by residents in Shinyalu constituency. Further research to be carried in crops grown in this region to determine if elevated radionuclides have been transferred to them. Radioactivity levels due to naturally occurring radioactive materials inside houses in this region is also required to be determined. To reduce further accumulation of radionuclides in the soil, farmers in Shinyalu constituency are advised to use more of organic fertilizers than inorganic ones on their farms.
REFERENCES


Ghazwa, A., Fauziah, B.S.H. and Abdul, I.R. (2016). Assessment of natural radioactivity levels and radiation hazards in agricultural and virgin soil in the


Figure A1: Decay series of $^{238}\text{U}$ (Gilmore, 2008)
Figure A2: Decay series of $^{232}$Th (Gilmore, 2008)
Figure A3: Correlation between activity concentration of uranium-238 and thorium-232
APPENDIX 4

Figure A4: Correlation between activity concentration of uranium-238 and potassium-40
Figure A5: Correlation between activity concentration of thorium-232 and potassium-40
APPENDIX 6

Figure A6: Sample collection in Shinyalu Kakamega County
Figure A7: Sample preparation at Kenyatta University Physics Laboratory
APPENDIX 8

Figure A8: Acquisition of spectral data
Figure A9: Reading spectral data