THE UNIVERSITY OF ZAMBIA

SCHOOL OF NATURAL SCIENCES

DEPARTMENT OF PHYSICS

MAPPING AND EVALUATION OF NATURAL RADIOACTIVITY LEVELS AT THE PROPOSED NUCLEAR RESEARCH CENTRE SITE IN CHONGWE

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A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN PHYSICS

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AUTHOR'S DECLARATION

I, Sampa Muwowo, do declare that this dissertation represents my own work and that it has neither in part nor in whole, been presented as substance for award of any degree at this or any other institution of learning or research. Where other people's work has been used, acknowledgement has been made.

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APPROVAL

The University of Zambia approves the dissertation of Sampa Muwowo as fulfilling part of the requirements for the award of the degree of Master of Science in Physics.

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ABSTRACT

In Chongwe at the site proposed for the Centre for Nuclear Science and Technology (CNST) soil, plant and water samples from the dam nearby had the activity concentrations of natural radionuclides measured. The natural radionuclides whose activity concentrations were measured are Uranium-238 (^{238}U), Thorium-232 (^{232}Th) and Potassium-40 (^{40}K), using a hyper pure germanium (HPGe) detector. The absorbed dose rates (ADR), annual effective dose rates (AED), external hazard indexes (H_{ex}) and radium equivalent indexes (Ra_{eq}) were determined from the measured activity concentrations. The average value of activity concentration in soil samples of ^{40}K was 120.39±5.37 Becquerel/kilogram (Bq/kg), for ^{238}U was 4.75±0.23 Bq/kg and for ^{232}Th was 9.63±0.35 Bq/kg. The average values in soil samples of ADR, AED, H_{ex} , Ra_{eq} were 13.00±1.32 non Grays (nGy/h), 0.02±0.001 millisieverts/year (mSv/y), 0.07±0.01 and 27.33±3.09 Bq/kg, respectively. The average values of activity concentration in plant samples of ^{40}K, ^{238}U, ^{232}Th were 172±5.34 Bq/kg, 9.91±0.89 Bq/kg and 9.81±1.76 Bq/kg respectively. The average value in plant samples of ADR was 16.44±6.71 nGy/h. In plant samples, the average value of AED was 0.019±0.01 mSv/y while average H_{ex} was 0.092±0.04 and Ra_{eq} was 34.89±13.41 Bq/kg. The average values of activity concentrations in water samples of ^{40}K, ^{238}U,and ^{232}Th were 44.82±0.053 Bq/l, 7.83±0.32 Bq/l and 3.03±0.22 Bq/l respectively. The average value in water samples of ADR was 5.90±2.52 nGy/h while AED was 0.01±0.00 mSv/y and H_{ex} was 0.03±0.01. The average value of Ra_{eq} in water samples was 14.56±3.70 Bq/kg. The results of average values of activity concentration of ^{40}K,^{238}U and ^{232}Th for all the samples were observed to be lower than the world average values of 420 Bq/kg,33 Bq/kg and 45 Bq/kg, respectively as reported in the United Nations Committee on the Effects of Atomic Radiation (UNSCEAR) report of 2000. The average values of ADR for all samples were lower than world average value of 59 nGy/h. The average values of AED dose rates for all samples were below both the world average of 2.40 mSv/y and the annual exposure limit of 1 mSv/y as recommended by International Commission on Radiological Protection (ICRP). The average values of H_{ex} for all samples were below unity, the safety limit index set by ICRP which showed that radioactivity at the site was negligible. The average values of Ra_{eq} for all the samples were below both the world average value of 58 Bq/kg and the recommended maximum activity value of 370 Bq/kg ,set by ICRP for radiation to be considered not to be hazardous at an area. The data acquired showed that natural ionising radiation at the proposed site for the Centre is below general public exposure limit of 1 mSv/y at the moment.

To my late father, Mr. Hastings Muwowo, my mother Lillian Yambayamba, my sister and brothers

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LIST OF ABBREVIATIONS, SYMBOLS AND ACRYNOMS

A - Source Activity

A - Area of the Peak of Interest

ADR - Absorbed Dose Rate

AED - Annual Effective Dose

A_i - Area of the ith Interfering Peak

A_k - Activity concentration of ^{40}K

A_{Th} - Activity concentration of ^{232}Th

A_u - Activity concentration of ^{238}U

B_1 - Sum of Counts in the Low Energy Continuum Region

B_2 - Sum of Counts in the High Energy Continuum Region

BH - Borehole

BNC - Bayonet Nut Coupling

Bq/ kg - Becquerel per kilogram

Bq/m^3 - Becquerel per metre cubic

CBU - Copperbelt University

CCS - Chambeshi Copper Smelter

C_f - Sample Mass Conversion Factor

CNST - Centre for Nuclear Sciences and Technology

C - Sample mass

$C_{Th,}$ - Activity Concentration of ^{232}Th

C_U - Activity Concentration of ^{238}U

C_K - Activity Concentration of ^{40}K

D - Dose Rate

D_0 - Uncorrected Daughter Activity

$D_{0, Corr}$ - Corrected Daughter Activity

DSA - Digital Spectrum Analyser.

E - Photo peak energy

E - East

ETOL - Energy Tolerance Selected

f_i - Fraction of the ith Peak.

FWHM - Full Width at Half Maximum

G - Gross Counts

Ge - Germanium

G - gram

GPS - Global Positioning Satellite

GRZ - Government of the Republic of Zambia

Gy - Grays

h - Calculated height of the Peak of Interest

H - hour

H_{ex} - External Hazard Index

h_i - Calculated Height of the ith Interfering Peak

HPGe - Hyper Pure Germanium detector

HVPS - High Voltage Power Supply

IAEA - International Atomic Energy Agency

I_b - Number of Counts above the Continuum that are due to the Environmental Background

ICRP - International Commission on Radiological Protection

ICRU - International Commission on Radiation Units

id - identification

K_c - Correction Factor for the Nuclide Decay during Counting

Kev - Kilo Electron Volt

K_{PD} - Branching ratio from the parent to the daughter.

k_{PD} - Branching Ratio from the Parent to the Daughter.

K_w - Decay Correction Factor

L_D - Detection Limit

m - metre

MCA - Multichannel Analyser

MeV - Mega Electron Volt

mm - Millimetres

mSv- millisieverts

MW- mega watt

n - Number of Energy Lines

N -Total number of Peaks

NISIR - National Institute for Scientific and Industrial Research

NORM - Naturally Occurring Radioactive Material

R - Correction Factor for random Summing

Ra_{eq} - Radium Equivalent

RPA - Radiation Protection Authority

S - Net Peak Area

S - Sample

S - South

Sv - sievert

$t_{1/2}$ - Half-life.

T_b - Live Time of the Background Spectrum in Seconds,

t_c - Elapsed Real Clock Time During the Measurement

t_{decay} - Elapsed Decay Time

T_l - Live Time of the Measurement

T_s - Live Time of the Sample Spectrum in Seconds

t_w - Elapsed Clock Time from Time the Sample was Taken to the Beginning of the

t_w - Decay Time

U_f - Unit Conversion Factor

U_f - Conversion Factor required to have the Activity in μCi

U_f - Factor to Convert the Activity

UNSCEAR-United Nations Scientific Committee on the Effects of Atomic Radiation

UN - United Nations

V - Sample mass or volume,

WHO - World Health Organisation

W - Water

ZEMA - Zambia Environmental Management Agency

γ - Gamma rays

$D_{0,Corr}$ - Uncorrected Daughter Activity

$\sigma^2_{D_{0,Corr}}$ - Corrected Daughter Activity

^{14}C - Carbon -14

^{152}Eu - Europium-152

^{210}Pb - Lead-210

^{212}Pb - Lead-212

^{214}Bi - Bismith-214

^{214}Pb - Lead-214

^{224}Ra - Radon-224

^{226}Ra - Radon-226

^{228}Ac - Actinium-228

^{228}Ra - Radon-228

^{232}Th - Thorium-232

^{238}U - Uranium-238

^{40}K - Potassium-40

b_i - Coefficient determined by the calculation of the photo peak efficiency at energy E

P_0 - Weighted mean parent activity

Y - Branching Ratio

Y_i - Branching Ratio of the ith Peak

α - Alpha particle

β - Beta particle

ΔE_i - Difference between the reference energy and the measured energy for the ith peak

Δt - Elapsed time from the sample taking time to the start of the measurement

ε - Non-Attenuation Corrected Detection Efficiency

$\varepsilon(E)$ - Efficiency at Energy E

ε' - Attenuation corrected Efficiency

$\mu(E)$ - Mass Attenuation at Gamma Energy

ρt - Average Sample Mass per unit Area

σ_{D0} - Uncertainty

σ_h - Calculated Uncertainty of the Peak Height of the Peak of Interest,

σ_{hi} - Calculated Uncertainty of the Peak Height

σ_K - Uncertainty of the Composite Decay Correction Factor

σ_K - Uncertainty of the Composite Decay Correction Factor

σP_0 - Uncertainty

σ_R - User Defined Random Uncertainty

σ_S - Uncertainty of the Net Peak Area S

σ_V - Uncertainty of the Sample Quantity

σ_V - Uncertainty of the Sample Quantity V

σ_Y - Uncertainty of the Branching Ratio Y

$\sigma\varepsilon'$ - Uncertainty of the Effective Efficiency

CHAPTER ONE

1.0 INTRODUCTION

Naturally occurring radioactive material (NORM) is an acronym used to describe radioactive materials that exist naturally in the environment [1]. They emit ionising radiation during their spontaneous decay that is responsible for much of human population's radiation dose [2]. However, their contribution to any health and safety hazards is minimal [2]. To determine the status of natural radioactivity at area of interest, an evaluation of the status of activity concentration of radionuclides present in rocks, soils, water, vegetation and air is undertaken [2]. It is a safety requirement to evaluate the status of radiation from natural radioactivity before artificial radioactive sources and devices are introduced at a site [7]. The results obtained may be referred to as baseline data that will serve as a reference to ascertain possible changes to environmental radioactivity during operations, at the close of nuclear activities and during remediation of the area.

1.1 Background

The Government of the Republic of Zambia (GRZ) is committed to setting up a Centre for Nuclear Sciences and Technology (CNST) in Silverest area of Chongwe, Lusaka province [4]. The Centre is envisaged to have a 10 megawatt (MW), water cooled Research Reactor for research, education, training, radioisotope production as a source of neutrons and neutron therapy [4]. A gamma irradiator with a Cobalt-60 source for research in sterilisation of medical products, irradiation of food and agriculture products will be installed at the Centre [3]. The Centre will also have a Linear Accelerator for research and production of radioisotopes [4]. Analytical laboratories will be setup near the above mentioned facilities for research and Radioisotope processing [4].

When operational the Research Reactor will require low enriched uranium (LEU) fuel rods which will be transported to the Centre in specialised packages to ensure safety during transportation. The production of radioisotopes in research reactors, linear accelerators has stages such as target fabrication and irradiation. Target fabrication is a method used to mount a material to be irradiated and is done by methods such as electroplating and electro deposition [6]. In a Research Reactor the target, material could be Uranium-235 (^{235}U) and is bombarded with thermal neutrons to produce a Molybdenum-99/Technetium-99m (99Mo/^{99m}Tc) radioisotope generator [6]. In a Linear Accelerator, irradiation of the target material is done by bombarding the target with high energy particles. The target material could be Thallium-203 (^{203}Tl), which is used for the production of Thallium-201 (^{201}Tl) [6].

The irradiated targets will be packed in appropriate shielding containers and transported to radioisotope processing laboratories [6]. From these processes, the facilities will be producing a variety of radioactive waste in the form of gases, liquids, solids and spent fuel rods from LEU fuel [5]. The radioactive wastes will require interim storage at the Centre before eventual transfer to a permanent site on long term storage [5]. These stages of operation present a probability of accidental release of radioactive materials in the surrounding environment if not managed properly.

To protect the public and environment from contamination by radioactive materials the area where the Centre will be constructed and its surroundings will require monitoring during and after its operational lifetime. This study aims at providing independent data on the pre-operational status of natural radioactivity at the proposed site for the Centre and surrounding areas. The data will be used as baseline data for future reference when assessing for radioactivity contamination of the environment at the site and the surroundings.

1.2 Sources of natural background ionising radiation in the environment

All human beings receive natural background ionising radiation from NORM and exposure rate worldwide is between 1 to 10 millisieverts (mSv) annually, but this level of dose is of minimal risk to human health since its concentration is very low in most areas [1].

Terrestrial radiation is embedded in soils, rocks, water, air and vegetation. The major portion of natural ionising radiation originates from Potassium-40 (^{40}K), the decay series of both Uranium-238 (^{238}U) and Thorium-232 (^{232}U) [1]. These radionuclides have been here on Earth since the Earth's formation [1]. Human bodies are a source of natural radiation since birth we are born with natural radionuclides within our bodies with ^{40}K, Carbon-14 (^{14}C) and Lead -210 (^{210}Pb) being the most dominant [10]. The dose level inside our bodies depends on the kind of food or water a person consumes and locality [2].

Cosmogenic radioactivity emanates from the interaction of Cosmic rays that originate from stars like our sun and supernovas with certain types of atoms of our earth's atmosphere [10]. However, most of this radiation never reaches the Earth because it is either deflected by the Earth's magnetic field or absorbed by the Earth's atmosphere [10]. Figure 1, shows the sources of background natural ionising radiation in the environment.

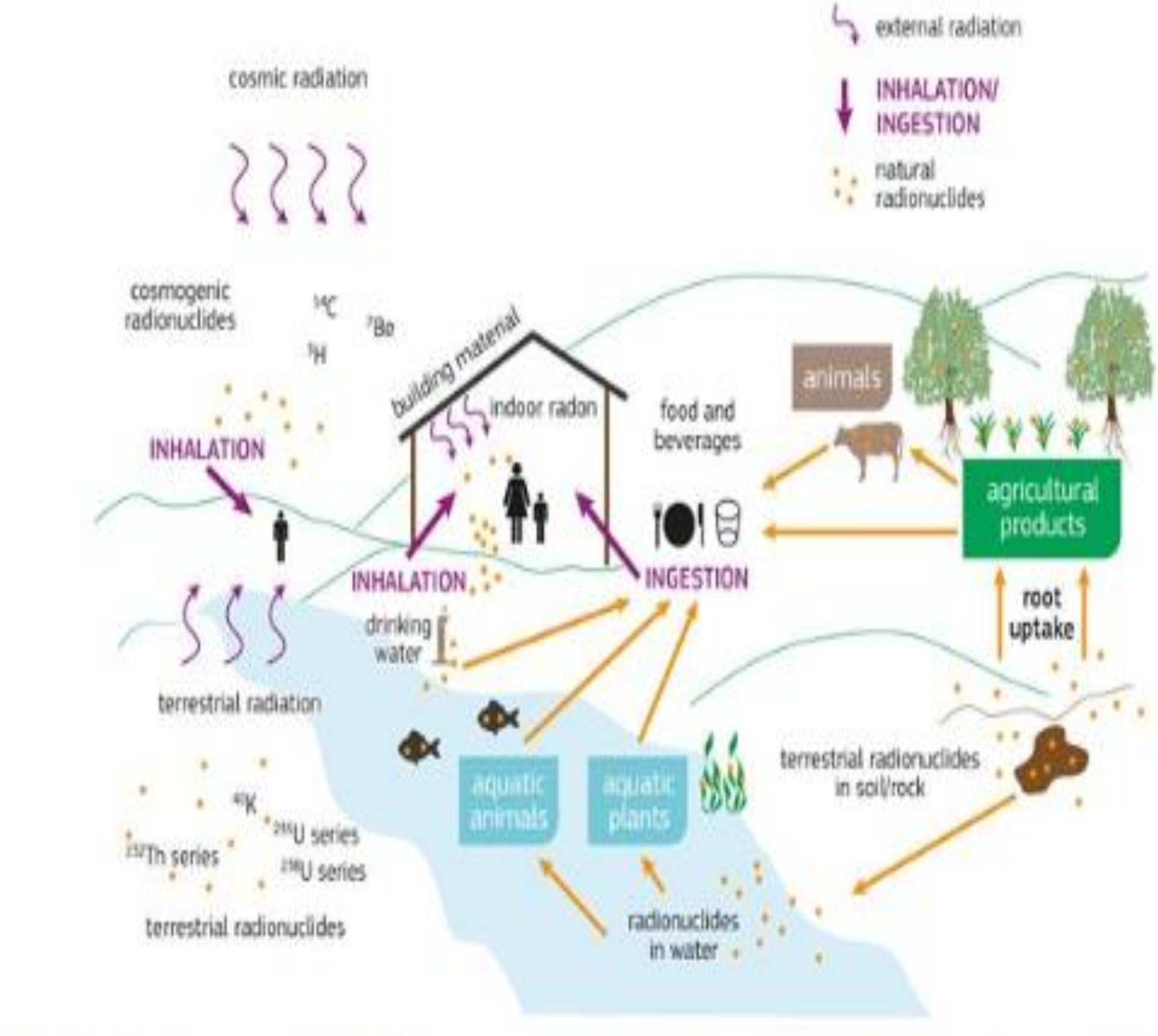

Figure 1: Sources of background natural ionising radiation in the environment [2]

1.3 Decay modes of ^{40}K, ^{238}U and ^{232}U

All matter found on earth such as soils, plants, water and air contain natural radionuclides. The most abundant being ^{40}K, the decay series of ^{238}U and ^{232}Th which makes an understanding of them important for the purposes of radiation protection [45]. Natural radionuclides ^{40}K, decay series of ^{238}U and ^{232}Th decay randomly from unstable nuclides to stable nuclides of lower atomic mass by releasing alpha (α), beta (β) and gamma (γ) ionising radiation in the environment [1].

Both ^{238}U and ^{232}Th decay by emitting alpha particles in the environment [49]. During alpha decay, the decay is followed by the release of an alpha particle that has two protons and two neutrons [8]. Alpha particles are released when Radium-226 (^{226}Ra) one of the decay products of ^{238}U decays to produce Radon-222 (^{222}Rn) gas [51]. Alpha particles are also emitted when Radium-224 (^{224}Ra) a decay product of ^{232}Th decays to Radon-220 (^{220}Rn) gas [51]. The gaseous radionuclides ^{222}Rn and ^{220}Rn are naturally occurring radioactive gases, which concentrate in air and enclosed spaces such as buildings and underground mines [51]. These radioactive gases also dissolve in underground water sources such as boreholes and then accumulate [51]. An example of α decay is given by equation (1.1)

$$^{226}_{92}\mathrm{Ra} \rightarrow {}^{222}_{90}\mathrm{Rn} + {}^{4}_{2}\alpha \qquad 1.1$$

Where ${}^{4}_{2}\alpha$ is an alpha particle.

Beta decay occurs in three ways namely: Beta minus decay (β^-) takes place in a nucleus with a large quantity of neutrons. In β^- decay, the emission of a β^- particle is accompanied by the release of an antineutrino ($\bar{\upsilon}_e$). Equation (1.2) shows this decay, where essentially a neutron (n) decays into a proton (p) and a β^-.

$$\mathrm{n} \rightarrow \mathrm{p} + \beta^- + \mathrm{n} + \bar{\upsilon}_\mathrm{e} \qquad 1.2$$

The other is Positron or β^+ plus decay and occurs in nuclei with less neutrons or with more protons. With this decay a β^+ particle is emitted and then followed by the release of a neutrino (v_e). In β^+decay, a proton (p) turns into a neutron (n) by emission of a β^+particle and a neutrino as indicated by equation (1.3).

$$\mathrm{p} \rightarrow \mathrm{n} + \beta^+ + \upsilon_\mathrm{e} \qquad 1.3$$

The third type of beta decay is electron capture. As the name implies electron capture is beta decay in which an electron mostly from an orbital shell of low energy is captured by the nucleus of an atom. The captured electron reacts with one of the protons in the nucleus forming a neutron and producing an electron- neutrino. The neutrons do not leave the nucleus only the neutrinos are emitted. Electron capture thus occurs whenever the mass of the original uncharged atom is larger than that of the final atom. The basic process is given by equation (1.4).

$$p + \beta^- \rightarrow n + \upsilon_e \qquad 1.4$$

Potassium-40 undergoes beta decay together with the decay chains of ^{238}U and ^{232}Th there by releasing beta particles in the environment.

Gamma decay occurs when a nucleus of an atom with surplus energy radiates the surplus energy as gamma rays which are simply high energy photons and are part of the electromagnetic spectrum [13]. Potassium-40 initially undergoes beta decay emitting beta particles, then undergoes gamma decay releasing gamma radiation in the environment. The decay series of ^{238}U and ^{232}Th also undergo gamma decay releasing gamma radiation in the environment from their decaying daughters. Shown in Table 1 is a summary of the decay of ^{40}K, ^{238}U,^{232}Th and their respective radioactive decay products [56].

Table 1: Principal natural radionuclides and their decay products

Nuclide	Half life	Major radiations
Uranium -238 series	4.47×10^9 years	alpha
Thorium -234	24.1days	beta, gamma
Protactinium-234	1.17 Minutes	beta, gamma
Uranium-236	245,000 years	alpha
Thorium-230	77000 years	alpha
Radium-226	1600 years	alpha, gamma
Radon-222	3.83days	alpha
Polonium-218	3.05 minutes	alpha
Lead-214	26.8minutes	beta, gamma,
Bismuth-214	19.7 Minutes	beta, gamma,
Polonium-214	164 µseconds	alpha
Lead-210	22.2 years	beta, gamma,
Bismuth-210	5.01 days	beta
Polonium-210	138 Days	alpha
Lead-206	Stable	
Thorium -232 Series	14.1×10^9 years	alpha
Radium-228	5.75 years	beta
Actinium 228	6.13 Hours	beta, gamma
Thorium-228	1.91 Years	alpha, gamma
Radium-224	3.66 days	alpha, gamma
Radon-220	55.6 seconds	alpha
Polonium-216	3.05 Seconds	alpha
Lead-212	10.64 Seconds	beta, gamma,
Bismuth-212	60.6 Seconds	beta, gamma,
Polonium-212	0.35 µseconds	alpha,beta,gamma,
Thalium-208	3.07 Seconds	beta, gamma,
Lead-208	Stable	
Non-series radionuclide		
Potassium-40	1.28×10^9	beta, gamma

1.3 Radiation Dosimetry

Radiation dosimetry is a method used to quantitatively measure the quantity of energy deposited in matter that has been exposed to ionising radiation [13]. A body can be irradiated with ionising radiation from outside or inside if radionuclides have been inhaled or ingested. The amount of energy deposited in living tissue is expressed in terms of a quantity called dose [13]. The absorbed dose is the radiation energy deposited per unit mass to an irradiated body and is measured in joules per kilogram, a unit called Gray (Gy). The equivalent dose is the product of absorbed dose and a radiation factor that takes into consideration the manner in which various types of radiation may cause biological harm to a tissue or organ [13]. Its units are Sieverts (Sv) or joules per kilogram. The effective dose is the equivalent dose multiplied by organ factors by taking into account the level to which different tissues and organs may be harmed and is expressed in Sieverts (Sv) or joules per kilogram [13]. The International Commission on Radiation Units and Measurements (ICRU) is an organisation that creates and formulates internationally accepted recommendations on quantities, units and measurement procedures to be used when handling ionising radiation [17].

1.5 Radiation Protection

Ionising radiation can negatively affect the health of the human body because of its ability to produce effects at cell level that can result in the death or modification of cells due to direct damage to deoxyribonucleic acid (DNA) strands [13]. When a large number of cells are damaged in this manner, the effects can lead to organ dysfunction [13]. These effects are categorized as deterministic and stochastic.

Deterministic effects together with their severity are directly proportional to the amount of dose uptake and the exposure can either be acute or chronic [13]. Acute exposure is when a large dose of radiation is delivered to a tissue or organ over a short time [10]. The effects could include tissue burns, damage to internal body organs, vomiting, headache and fever that may lead to death in extreme cases [10]. When individuals are exposed to radiation over a lengthy period of time chronic exposure occurs [13]. The resulting effects of chronic exposure can only be seen after a lengthy period of time [13]. The effects may include development of cancer, genetic mutation and sterility in males [13].

Stochastic effects can either be somatic or hereditary and are chance events without the threshold of occurrence, however the probability of the effects occurring increases with dose uptake [10]. Somatic effects appear shortly after a person has been exposed to a high dose of ionising radiation such as reddening of the skin while others such as cancer take time to develop to be diagnosable [10]. Hereditary effects arise when reproductive cells are damaged by ionising radiation resulting into negative genetic alterations. The negative genetic alterations can be transmitted from one generation to the next leading to birth of descendants with severe health defects [13].

Since ionising radiation can trigger effects which are detrimental to human health it has become necessary to create organisations whose role is to protect the general public and the environment from ionising radiation. The aim of radiation protection is to as much as possible stop the deterministic effects and to minimise the risk of stochastic effects to a reasonably attainable level. The dose limit values are set so that deterministic effects are ruled out. To keep the risk of stochastic damage from ionising radiation as minimal as possible three general principals have been set out in radiation protection for dealing with ionising radiation 18]. One of them is justification where each new application of radioactive materials by man must be justified in advance [18].

The other is dose limitation which implies that doses of radiation that people are exposed to during justified use of radiation must not go beyond set limit values [18]. These limit values differ for the general population and for those exposed to radiation due to the nature of their work. For workers in a radiation environment, the limit on the effective dose to the whole body is 20 mSv/y [18]. This is averaged over five years and the effective dose must not go beyond 50 mSv/y [18]. For the general public, effective dose limit to the whole body is 1 mSv/y [18]. The last principal is legal requirement for optimisation that an activity that is linked with radiation exposure and contamination must be justified [18]. This principal requires that any unnecessary radiation exposure and contamination must avoided. Locally in Zambia, the monitoring of the use of ionising radiation and facilities that produce it, is undertaken by Radiation Protection Authority (RPA) [11]. Internationally two United Nations (UN) agencies, International Atomic Energy Agency (IAEA) and United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) are involved in ionising radiation protection. The IAEA promotes the peaceful and safe use of nuclear science by providing safety standards [7]. The UNSCEAR assess all sources of ionising radiation for the impact they may have on the health of human beings and the environment [12]. The other organisation is the International Commission on Radiological Protection (ICRP). Its mandate is to provide appropriate standards of protection for mankind from ionising radiation without limiting the useful exposure to ionising radiation [18]

1.5 Location and description of the proposed study area

The study area considered under this investigation is located between latitudes 15° 23'18.8" S and longitude 28° 28'34.5" E in Silverest area of Chongwe District in Zambia. It covers an area of about 363,100 m^2. It is accessible by two roads, the Palabana road from the North West and the Silverest road from the North East which are both connected to the Great East Road linking Lusaka to Eastern Zambia. Shown in Figure 2, shows location map of the CNST in read boarder lines.

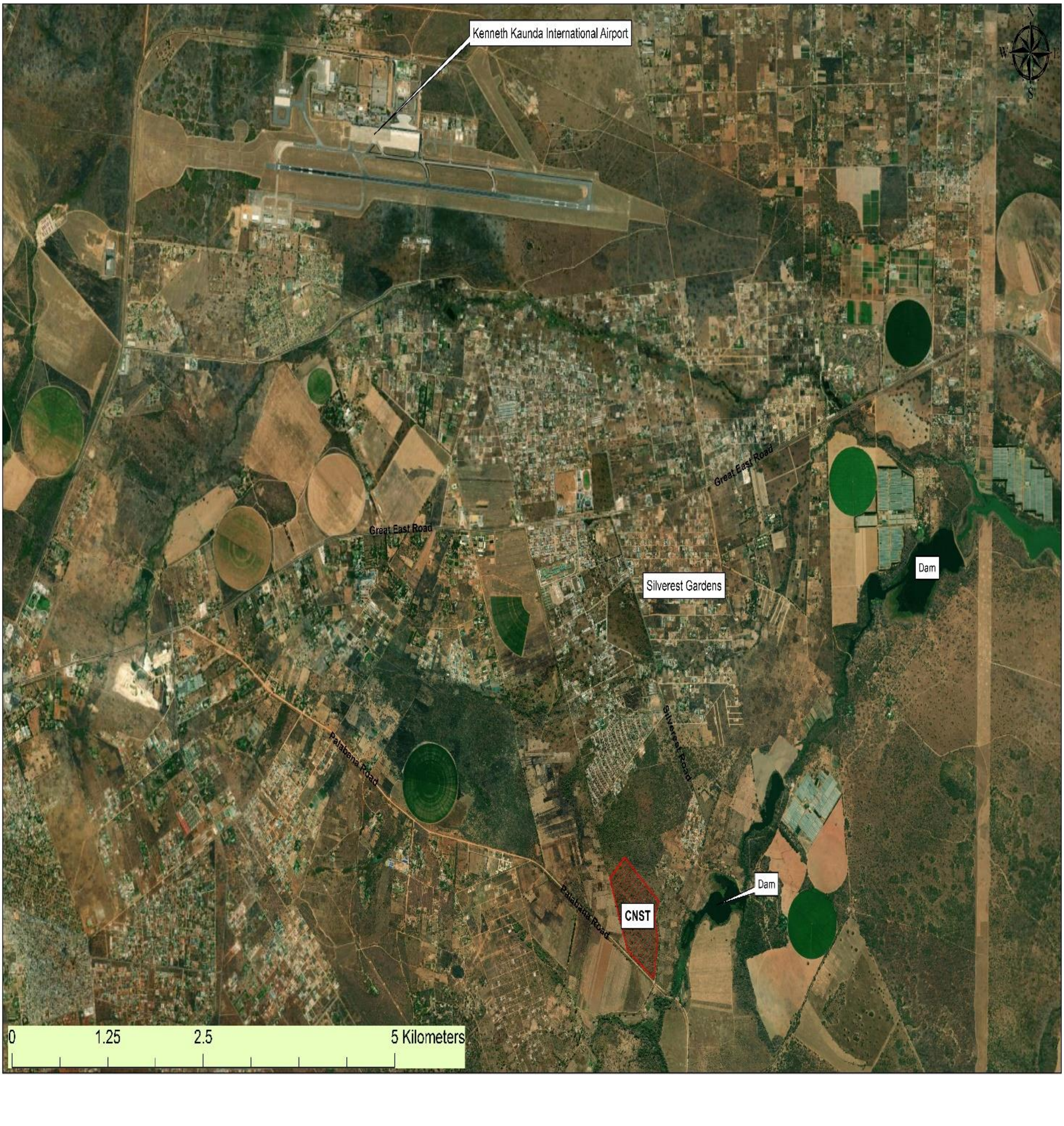

Figure 2: Map showing location of the Centre for Nuclear Sciences and Technology (CNST)

(a) Climate and vegetation

The study area has a tropical continental highland climate where from April to mid-November is a dry season [15]. The dry season is divided into cool dry season from April to late July and hot dry season from August to mid-November [15]. Starting from the middle of November to March the area experiences a hot wet season with annual rainfall ranging between 800mm to 880 mm [15]. The most common vegetation types of the area are grass, acacia and brachystegia woodlands. Because of massive deforestation the trees are mostly in form of shrubs and the area is almost bare in the dry season [15]

(b) Topography, Geology and Soils

The study area has a flat and undulating plain terrain (pen plain) with its elevation being between 1000 m and 1300 m above sea level [14]. The type of soil at the site is leptosols that is mostly gravel while the geology of the area is dominated by schist, quartzite and basement complex rocks (gneiss and granite mainly) [14].

1.6 Statement of the problem

It is a safety requirement before commissioning nuclear facilities to evaluate the status of natural radioactivity of water, soil or rocks and plants of the region where the facilities are to be constructed [7]. There is no existing baseline on dose mapping and evaluation of natural radioactivity for the proposed site for the CNST in Zambia. The data acquired from this study can be used as baseline when determining the effects of the facilities on the environment in future investigations. This safety requirement is needed for the protection of the people and the environment from effects that may arise due to normal or accidental releases of radioactive materials [7]. This study provided independent baseline data on the pre-operational status of natural radioactivity at the Centre's planned location which may be referred to when monitoring the environment at the site during the lifetime of the Centre and beyond.

1.7 Aim of the Study

The aim of the study was to measure the activity concentrations in soil, plant, water samples from a nearby dam of natural radionuclides ^{40}K, ^{238}U and ^{232}Th at the proposed site for the construction of the Centre pre-operational from which the absorbed dose rate (ADR), annual effective dose (AED), external hazard index (H_{ex}) and radium equivalent (Ra_{eq}) were determined.

1.8 Research Objectives

The research objectives of this research were to:

a) evaluate the activity concentration of natural radionuclides ^{238}U, ^{232}Th and ^{40}K in soil, plant samples at the site where the Centre will be constructed and water samples from the nearby dam,

b) determine the absorbed dose rate, annual effective dose, external hazard index and radium equivalent from the measured activity concentration for all samples,

c) tabulate the determined activity concentration, absorbed dose rate, annual effective dose, external hazard index and radium equivalent for all samples from the proposed site for the Centre preoperational to create baseline data for future reference and

d) compare the results with those from other parts of the world where similar work has been undertaken.

1.9 Hypothesis

The CNST will be constructed in an area that is used for both agriculture and human settlement hence the measured activity concentrations of ^{40}K, ^{238}U and ^{232}Th should be preferably be below or equivalent to the worldwide average activity concentrations which are 420 Bq/ kg ,33 Bq/kg and 45 Bq /kg respectively as reported by UNSCEAR report of 2000 [12].

1.2.0 Significance of the Study

The area in Chongwe where the Centre will be constructed is used for agriculture, has a significant human population in the surroundings and is near a dam where effluents from the Centre may eventually end up. The Centre will handle a variety of radioactive materials, some generated at the site and others imported. In order to avoid radioactive contamination in form of solids, liquids and aerosols, a robust environmental monitoring system at the Centre is required. The Pre-operational status of natural radioactivity at the proposed site would be part of the environmental monitoring system for any normal or accidental release of artificial radioactive materials in the environment [14]. Results from this study may be used as baseline data or as a known base state from which changes are measured on the status of natural radioactivity of the area as part of an environmental monitoring system [49]. The baseline data may be referred to when monitoring the environment for possible radioactive contamination from artificial sources that will be at the Centre during the Centre's operational life cycle and beyond [7]. The baseline data is also an important part of the licensing procedure required by regulatory authorities such as Zambia Environmental Management Agency (ZEMA) and RPA [14]. The baseline data from the study is also a requirement by IAEA to be undertaken when selecting a site for construction of a nuclear research reactor [7].

1.2.1 Outline of the Dissertation

The first Chapter explains the concept of NORM, plans to establish the Centre, Dosimetry and a description of the site where the Centre will be constructed. It also contains the problem statement, aim, objectives, hypothesis, and significance of the study, outline of the dissertation and scope of the dissertation. A review of literature relevant to the study is presented in Chapter two while the methods and materials used in this work are in Chapter three. The results, data analysis and research findings are presented in Chapter four. The discussion is given in Chapter five while the conclusion and recommendations are presented in chapter six.

1.2.2 Scope of the Dissertation`

During the study, soil and plant samples were collected from the proposed site for the Centre while water samples were collected from the dam near the site. The samples were prepared for radioactivity counting. The activity concentrations in Becquerel/kilogram (Bq/kg) of the natural radionuclides ^{40}K, ^{238}U and ^{232}Th of all samples were measured by gamma spectrometry using a hyper pure germanium (HPGe) detector. The detector was kept inside a lead shield and it was in thermal contact with the Cold finger in Dewar flask that was filled with liquid nitrogen. A DSA-1000 Digital Spectrum Analyser and a personal computer equipped with Genie 2000 spectroscopy software was used for data acquisition, display and analysis of gamma spectrometry data. The absorbed dose rate in Grays/hour (Gy/h), annual effective dose, external hazard index and radium equivalent were determined from the measured activity concentration for each sample to create baseline data. The results from the study were compared with results from similar studies from other parts of the world.

CHAPTER TWO

LITERATURE REVIEW

2.0 Studies on natural radioactivity

The Chapter provides a review of literature relevant to the research objectives of this dissertation. Emphasis is placed on work that has been done on the status of natural radioacivity in various areas of the world and the purpose for which the work was undertaken. This is precceded by similar work in Zambia on the status of natural radioacivity which is confined to the Copperbelt province of the country.

Studies on the status of terrestrial radiation have been undertaken around the world for a variety of reasons. One reason for these studies is that they are a requirement by regulatory authorities of all countries before granting an operating license to operate facilities that are sources of artificial ionising radiation. Among the areas where these studies where undertaken was in southern Thailand [20] and at Savar in Bangladesh [29] at sites designated for setting up nuclear power plants and research reactor respectively. The data obtained on the status of natural radioactivity of a site can be used as the baseline data for radiological monitoring of the environment during and after the facilities cease operations.

The other reason for these studies is to acquire baseline data on the status of natural radioactivity of an area of interest and its surroundings before establishing industries whose activities may result in elevated levels of NORMs. These industries include oil refining hence a study of levels of natural radioactivity was done at Ras Tanura in the east of Saudi Arabia. The study was undertaken to evaluate the radiological impacts on the area because of emissions [21] from the refining processes of crude oil. The other industries that may lead to elevated levels of NORM are mining of metals like Uranium and industrial chemicals like Phosphates. In Namibia at Henties Bay, an assessment of natural radionuclide levels in sediment samples was undertaken to provide baseline data for monitoring the possibility of radioactivity pollution by a uranium mine in the vicinity of the bay [25]. At Richards Bay in South Africa a study of the levels natural radioactivity in soil samples was undertaken near a phosphate rocks storage facility [26]. The report on the work was to be used as baseline data for monitoring future radioactivity levels in soils at Richards Bay due to phosphate rocks stored at the area.

The determination of the level natural radioactivity is also undertaken for purposes of industrial, agricultural and urban planning. This is done by assessing the health risks associated with the exposure to natural radioactivity present at an area of interest. The purpose is to safeguard the environment and people from the dangerous effects of ionising radiation. In Kuwait and Cyprus studies were done as part of these countries programmes of producing a radioactivity map for the whole country since they are small [23,27]. The large countries of Sudan in Elfao, Iraq in Wassit governorate and Turkey along the Izmir-Ankara Highway studies on the level of natural radioactivity and associated health risks were also undertaken with the aim of eventually producing a radioactivity map of each country [24,22,28]. A summary of data with countries were work on the status of natural radioactivity and associated radiological hazards has been undertaken is shown in Table 2 with references [20-29].

Table 2: Summary of selected countries with areas were measurement of the status of natural radioactivity with associated radiological hazards has been undertaken.

Country	^{238}U Bq /kg	^{232}Th Bq /kg	^{40}K Bq/kg	ADR nGy/h	AED mSv	H_{ex}	Ra_{eq} Bq/kg
Thailand (South Thailand)	30	49	344	58	71	0.34	126
Saudi Arabia (Ras Tanura)	39.00	7.73	278.00	29.30	0.04	0.20	62.10
Kuwait	18.60	12.40	387.00	Nil	Nil	Nil	Nil
Sudan (Elfao)	20.00	27.00	322.00	39.00	Nil	Nil	Nil
Namibia (Henties Bay)	176.00	40.00	350.00	105.00	129.30	0.70	256.00
South Africa (Richards Bay)	28.00	32.00	140.00	39.00	0.30	0.20	86.00
Cyprus	45.60	27.05	453.00	15.00	30.75	Na	Na
Turkey (Rize Province)	43.60	89.75	474.00	83.55	103.00	0.53	125.00
Iraq (Wassit Governorate)	19.00	18.00	206.00	29.00	0.03	0.20	62.00
Bangladesh (Savar Area)	23.00	42.00	740.00	67.08	0.08	0.38	Na

2.2 Studies of natural radioactivity in Copperbelt province of Zambia

In Zambia studies done on natural radioactivity are mostly confined to the Copperbelt province. This province has been the main mining area of copper. The copper ore was found to be associated with some uranium mineralisation [30]. The following studies were undertaken with respect to natural radioactivity of the area:

(a) determine the activity concentration of natural radionuclides in waste water from Mopani Copper Mine Kitwe site (MCM) for the purpose of developing a treatment process for radionuclides present in waste water from the mine [30],

(b) determine the level of activity concentrations of ^{238}U in waste water from selected copper mines on the Copperbelt [31],

(c) evaluate the level of NORM in the slurry discharged into tailings dams during the mining and processing of copper at Nkana mine in Kitwe [32],

The RPA with the support of the IAEA undertook a study on slag dumps at Lumwana Copper Mine in Solwezi (LCM) and Chambeshi Copper Smelter in Kalulushi (CCS). The purpose of the work was to develop measures to undertake during remediation of slag dump sites [33]. The other study was the radiation dose mapping survey whose purpose was to collect data on the distribution of radiation in copper mining and non- copper mining areas of selected towns on the Copperbelt province [34,35]. Summary in Table 3 gives studies of the status of natural radioactivity which were done in Copperbelt province of Zambia [30-35].

Table 3: Studies of the status of natural radioactivity on Copperbelt province of Zambia

Study Area	Identified (I) Radionuclides and range in Bq/kg or Bq/m^3						ADR Sv/h
	Ra-226	Ra-228	Ra-224	K-40	U-238	Th-238	
MCM Kitwe	0.09-0.20	0.03-0.07	69.80-66.10	1720-1595	-	-	-
Chambeshi Mine	-	-	-	-	57.57-340.00	-	-
Chingola mine	-	-	-	-	34.98-76.50	-	-
Chingola Surface	-	-	-	-	2076.50-82.90	-	-
Kitwe Surface	-	-	-	-	7.92- 93.68	-	-
Nkana mine	57.00- 104.00	47.30- 80.80	56.80- 66.10	1720-1595	-	-	-
CCS Kalulushi	-	-	-	-	-	-	$(1.0\text{-}15)\times10^{-9}$
Lumwana mine							$(0\text{-}1.5)\times10^{-5}$
mining areas	I			I		I	$(0.05\text{-}1)\times10^{-6}$
Non-mining areas	I			I		I	$(0.20\text{-}1)\times10^{-6}$

The results from the study of the status of natural radioactivity at the proposed site for the Centre were added to the database of radiometric mapping in Zambia.

CHAPTER THREE

3.0 METHODS AND MATERIALS

The Chapter presents the research methodology and materials used in the research. The first section gives the methods used for sample collection and preparation for counting purposes. It is followed by the description of the gamma spectrometry that was used in this study. The hyper pure germanium (HPGe) detector and Genie 2000 spectra software manufactured by Mirion Technologies (Canberra, industries Inc.) were used to evaluate the activity concentrations of the samples. The Chapter concludes by giving the methods applied when evaluating activity concentration, ADR, AED, H_{ex} and Ra_{eq}. Figure 3, is map of the study with the area for the CNST marked by red boundary lines.

Figure 3: Map of Study area CNST

3.1 Sample collection

Twenty leptosols soil samples which were mostly gravel and ten plant samples (grass and shrubs) were collected from the proposed site for the Centre and surrounding areas. Five water samples were collected from the dam near the proposed site for the Centre. Each sampling point was marked using a hand held Germin, Global Positioning Satellite System (GPS), receiver system.

The soil samples were collected using an auger hole (manual driller) to a depth of 0.25 m to 0.50 m to ensure that the sampled soil is natural to the area. Each soil sample was packed in a polythene bag to avoid contamination and given a sample identification (id), Borehole (BH) with a number. The identifications labelled on the bag were in accordance with the GPS location where each sample was collected. Plant samples were harvested using a matchet and packed in polythene bags which were given sample identification (id), Sample (S) with a number. The identifications labelled on each bag where in accordance with the GPS location where each sample was collected. Water samples collected were put in high density polyethylene sampling bottles and each sample was given sample identification (id), Water (W) with a number which was labelled on each bottle in accordance with the GPS location where each sample was collected.

To avoid cross contamination of sample materials each soil and plant sample was placed in at least three polyethylene bags. Water samples were placed in high density polyethylene bottles to avoid cross contamination. To avoid oxidation-reduction, complexation and volatilisation reactions occurring in the water, which can change the chemical identity of the substances in the solution, hydrochloric acid (HCl) acid was added to the bottles. The samples were each sealed then placed in plastic cooler boxes which worked as shielding containers to minimize external radiation exposure during transportation. The samples were transported from the proposed site for the Centre to the Copperbelt University (CBU) in Kitwe where the samples were prepared for analysis at the Environmental Engineering Laboratory. Gamma spectroscopy analysis of the samples was undertaken at the Centre for Energy Development at National Institute for Scientific and Industrial Research (NISIR) in Lusaka. Tables 4, 5, 6 show the sample codes with their coordinates for soil, plant and water accordingly.

Table 4: Soil sampling locations with their coordinates

S/N	Sample id	Latitude ^{o} S	Longitude ^{o} E
1	BH 1	15^o 24'23"	28^o 28'31"
2	BH 2	15^{o}20' 02"	28^{o}28'36"
3	BH 3	15^{o}07'12"	28^{o}28'36"
4	BH 4	15^{o}21'26"	28^{o}28'30"
5	BH 5	15^{o}18'14"	28^{o}28'36"
6	BH 6	15^{o}17'10"	28^{o}28'28"
7	BH 7	15^{o}16'08"	28^{o}28'24"
8	BH 8	15^{o}26'39"	28^{o}28'49"
9	BH 9	15^{o}25'39"	28^{o}28'42"
10	BH 10	15^{o}27'31"	28^{o}28'35"
11	BH 11	15^{o}28'50"	28^{o}28'45
12	BH 12	15^{o}29'23"	28^{o}28'44"
13	BH 13	15^{o}14'19"	28^{o}28'43
14	BH 14	15^{o}13'11"	28^{o}28'36"
15	BH 15	15^{o}19'16"	28^{o}28'41"
16	BH16	15^{o}31'19"	28^{o}28'28"
17	BH 17	15^{o}23'05"	28^{o}28'33"
18	BH 18	15^{o}11'31"	28^{o}28'41"
19	BH 19	15^{o}23'12"	28^{o}28'30"
20	BH 20	15^{o}30'28"	28^{o}28'44"

Table 5: Plant sampling locations with their coordinates

S/N	Sample id	Latitude ^{o} S	Longitude ^{o} E
1	S1	15^{o} 24’23”	28^{o} 28’31”
2	S2	15^{o} 07’12”	28^{o} 28’31”
3	S3	15^{o}11’31”	28^{o} 28’41”
4	S4	15^{o}13’11”	28^{o} 28’36”
5	S5	15^{o}21’26”	28^{o} 28’30”
6	S6	15^{o}16’08”	28^{o} 28’24”
7	S7	15^{o} 20’02”	28^{o} 28’36”
8	S8	15^{o}11’31”	28^{o} 28’41”
9	S9	15^{o} 28’50”	28^{o} 28’45
10	S10	15^{o} 26’39”	28^{o} 28’49”

Table 6: Water sampling locations with their coordinates

S/N	Sample id	Latitude ^{o} S	Longitude ^{o} E
1	W1	15^{o}26’39”	28^{o}28’49”
2	W2	15^{o}23’30”	28^{o}28’57”
3	W3	15^{o}28’21	28^{o}28’57”
4	W4	15^{o}23’19”	28^{o}29’9”
5	W5	15^{o}23’13”	28^{o}2’99”

3.2 Sample preparation

Soil samples had a high moisture content so they were left to dry for a period of two weeks on trays at room temperature in the environmental engineering laboratory at CBU in Kitwe. The dried samples were pulverised using a Mininua laboratory micro powder pulveriser, model SF. The final grain-size of the samples were obtained by using a 0.2 mm mesh screen. Then from each sample a mass averaging 50 g was obtained using a Denver Instruments analytical balance model M-220D and placed in a petri dish. In order to avoid detector contamination and sample cross contamination each petri dish before use was cleaned with a solution of ethylenediaminetetra acetic acid (EDTA) and dried. Then each petri dish was labelled with sample identification (id), using the coding described earlier with a sample number, date of preparation and net mass as shown in Figure 4.

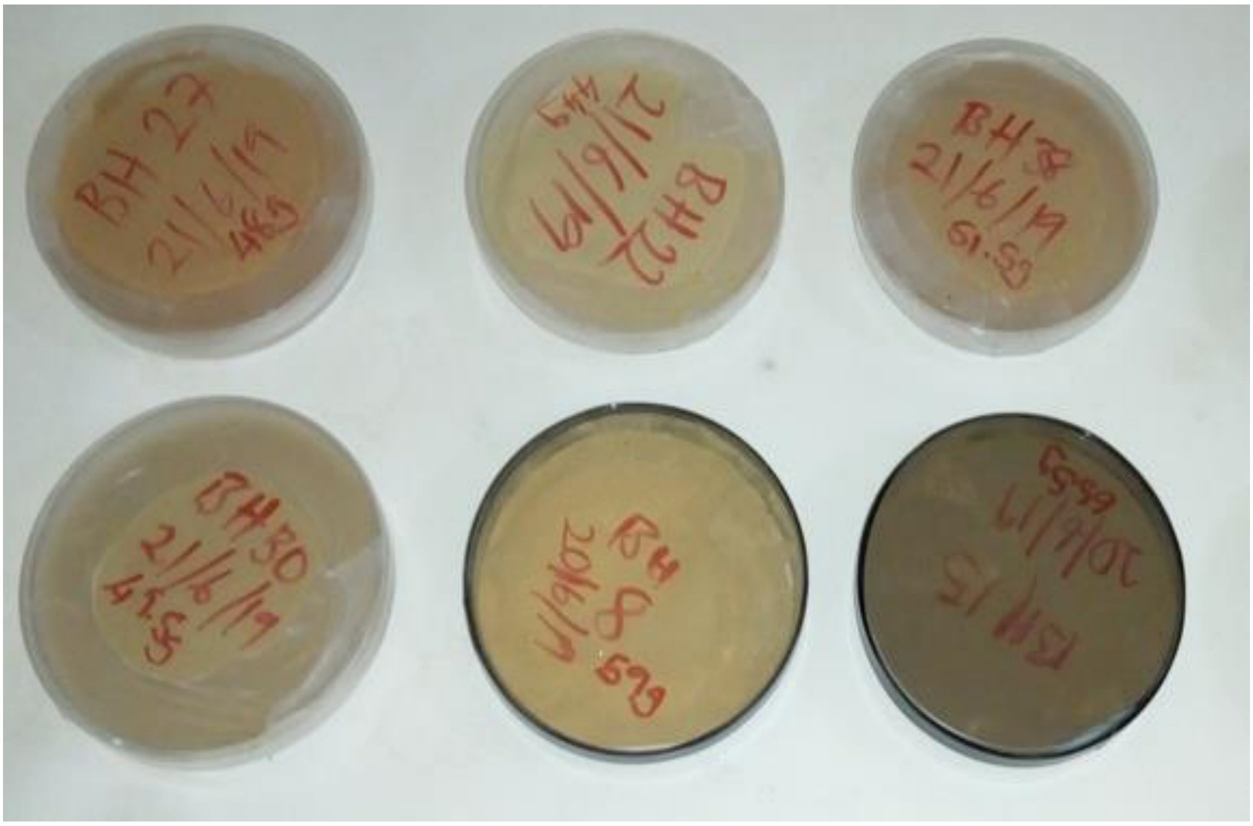

Figure 4: Soil Samples stored in petri dishes

Plant samples were sun dried for a period of seven days and then oven dried at a temperature of 80°C for two days using a Fisher Scientific laboratory oven. The dried samples were then pulverised using a Mininua laboratory micro powder pulveriser, model SF. A 0.2 mm mesh screen was used to sieve the grass samples and a mass of 30 g was separated from each sample using a Denver Instruments analytical balance model M220D. The separated samples were placed in petri dishes. Before use every petri dish was cleaned with a solution of EDTA and dried to avoid detector contamination and sample cross contamination. Each petri dish was given sample identification (id), using the coding described earlier with a sample number, date of sample preparation and net mass as shown in Figure 5.

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Figure5: Plant samples stored in petri dishes

A pipette of volume 30 ml was used to transfer water samples from the sampling bottle to a petri dish. As a precaution to minimise detector contamination and sample cross contamination each petri dish used was cleaned using a solution of EDTA. Each petri dish was given sample identification (id), using the coding described earlier with a sample number, date of sample preparation and net mass as shown in Figure 6.

Figure 6: Water samples stored in petri dishes

The petri dishes for all the samples were then sealed with insulating tape around their opening to stop moisture accumulation. The samples were stored for a period of four weeks in order to ensure they attain secular equilibrium of ^{238}U up to ^{210}Pb and ^{232}Th up to ^{208}Pb which are their respective decay daughter products [39]. Secular equilibrium is a condition in which the decay rate of parent radionuclide becomes equal to that of daughter radionuclide and only occurs if the half-life of parent is much larger than that of the daughter radionuclide [13]. The significance of the attainment of secular equilibrium by samples before undergoing activity counting is that the measured activity of one of the radionuclide in a decay chain can be assigned to the other radionuclides within the chain.

3.3 Detector system

In this study gamma ray spectrometry was used to determine the activity concentrations of ^{40}K and decay series of ^{238}U and ^{232}Th. This is because these nuclides produce gamma rays with energy and intensity that are sufficient to be measured by gamma ray spectrometry. Gamma ray spectrometry was used because it is less time consuming because of its ability of measuring more than one radionuclide at the same time. It is simpler because sample preparation for counting is easier since all that is needed is to weigh an appropriate amount of the sample. Then place the weighed sample in a counting vessel similar to the calibration geometry and do the counting. However, both beta-particle counting and alpha spectrometry require tedious sample preparation methods before identifying and quantifying the radionuclide under study which are time consuming.

When a gas proportional counter is to be used to do beta particle counting chemical methods must be done on a sample to separate the radionuclide under study from any other beta emitting radionuclides before counting. The measurements should also be undertaken on chemically isolated pure beta emitting radionuclides to ensure that beta decay is never accompanied by gamma-ray emission which can make taking measurements difficult [50]. Beta counting method is suitable for detection of unknown high activities which are mostly fission products [51]. Since most fission products emit beta radiation, beta counting is used to detect high activity concentrations when there is a high degree of contamination from artificial sources [51].

Samples destined for alpha spectrometry require radiochemical sample preparation methods which are time consuming. These sample preparations methods are meant to remove as many impurities from the sample as possible before mounting the sample for counting. Alpha spectrometry is suitable for determination of alpha emitting nuclides, which are elements beyond uranium in the periodic table which are mostly artificial.

A HPGe co-axial detector was used for this study instead of a Sodium Iodide (NaI) detector since a NaI detector has a high energy efficiency that enables it to be suitable for detecting high energy gamma radiation from a single radionuclide . Since gamma radiation that was to be measured was of low energy and from multiple radionuclides HPGe detector was chosen for this study because of its high resolution (ability to separate closely spaced gamma lines) and linearity [8]. The HPGe co-axial detector used in this study was manfactured by Mirion Technologies (Canberra, Inc.) model GC 3520, diameter 76 mm and relative efficiency 35 % [35]. It is made of pure germanium, with an n-type contact on the outer surface, p-type contact on the surface of the inside of the well and of cylindrical shape as shown in figure 7. It had a resolution of 1.2 keV full width at half maximum (FWHM) at 1.22 kilo electron volt (keV) and 2 keV FWHM at 1.33 mega electron volt (MeV) [36]. Figure 7, shows the cross sectional view of HPGe Detector.

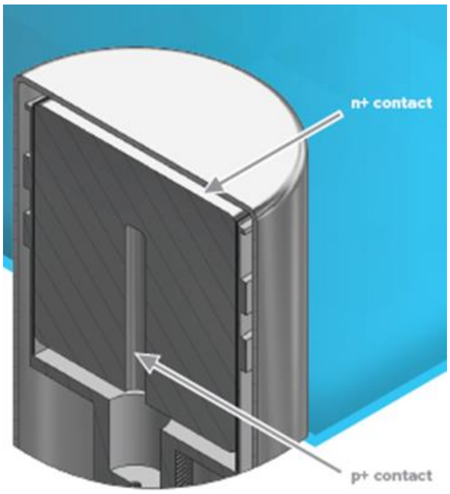

Figure 7: Cross sectional view of HPGe Detector [35]

Figure 8, shows the experimental setup of the gamma spectrometry used in this work.

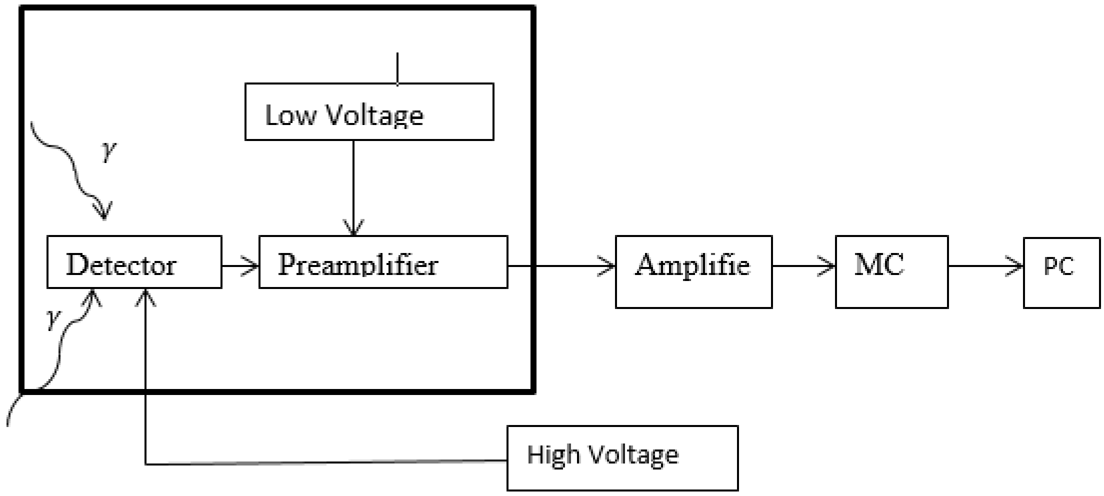

Figure 8: Experimental setup of the Gamma spectrometry

During counting the detector was shielded from radiation coming from outside sources by placing it inside a purpose built lead shield. The shielding used was manufactured and supplied by Mirion Technologies (Canberra Inc.), model is 747 with inside dimensions of 28 centimetres (cm) diameter by 40.5 cm height, wall thickness of 10 cm made from low background lead [36]. The outer jacket was made from low carbon steel with thickness of 9.8 mm. The graded lining is 1 mm tin and 1.6 mm copper while the gross mass of the shielding is 1088 kg. Figure 9, shows the inside of the lead Shield showing detector holder.

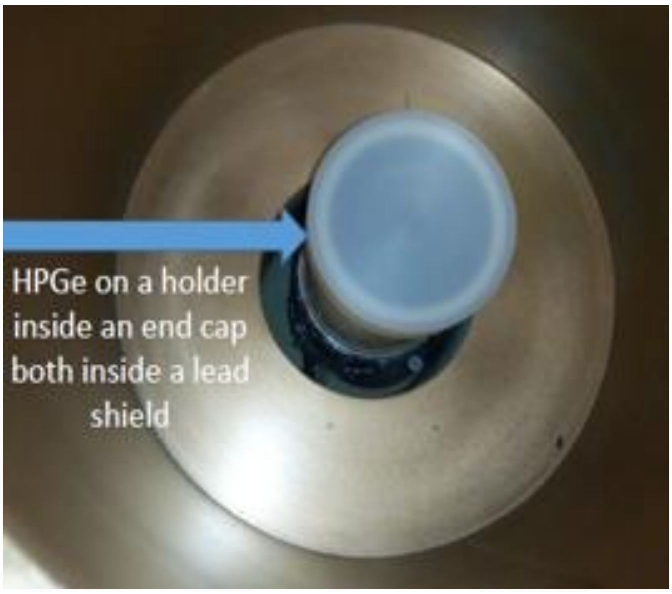

Figure 9: Inside the lead Shield showing detector holder and end cap

Figure 10, shows the Dewar Detector assembly.

Figure 10: Dewar Detector Assembly [36]

The operation of the HPGe detector is based on the use of the depletion region which is between the p and n type semiconductor material. When photons (gamma rays) interact with this region, charge carriers (electrons and holes) are produced. The presence of an electric field produced by the high voltage biases the detector, enabling charge carriers to move either to the anode or cathode electrodes. Electrons move to the anode with energy that is proportional to the energy an incoming photon initially transferred to the detector and holes move to the cathode. At the anode a preamplifier which is charge sensitive converts charge into a voltage pulse which is proportional to the energy deposited in the detector by the photon. To ensure maximum performance of the preamplifier, it has been deliberately placed near the detector by the manufacturer to create an integrated detector/pre-amplifier system. For this, work a model 2000 charge sensitive preamplifier manufactured by Mirion Technologies (Canberra Inc.) was used.

3.4 Multi-Channel Analyser

The multichannel analyser **(**MCA) that was used for pulse acquisition and analysis is a 16K channel integrated digital spectrum analyser (DSA)-1000 manufactured and supplied by Mirion Technologies (Canberra Inc.). Signals transferred from the preamplifier to the DSA-1000 were digitised at the start of the signal processing chain which enabled spectroscopy amplifier functions such as filtering, baseline restoration and pileup rejection to be done digitally. The MCA was connected to the spectroscopy equipment and computer equipped with Genie 2000 spectroscopy software. Figure 11 shows the DSA-1000 Digital Spectrum Analyser.

Figure 11: DSA-1000 Digital Spectrum Analyser [35]

3.5 Genie 2000   Software (Spectral analysis software)

The Genie 2000 has a set of functionalities for acquisition and analysis of spectra from Multichannel Analysers originating from the gamma detector. The software was used to control the MCA, for spectral display and manipulation, basic spectrum analysis and reporting. Fig 12, shows the flowchart for spectrum analysis used by the software. The package uses a set of algorithms to perform analytical functions described in the following paragraphs.

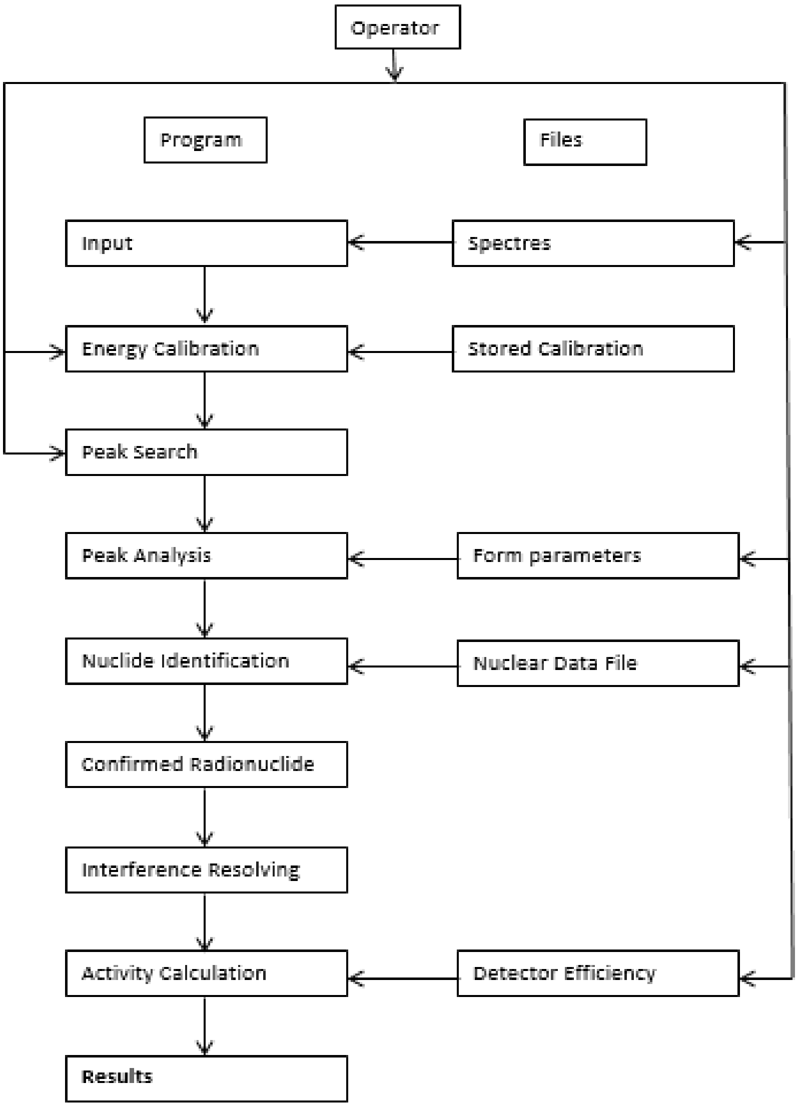

Figure 12: Flowchart of spectrum analysis

(a) Interactive Spectral Analysis Algorithm

The interactive spectral analysis algorithm of the Genie 2000 software was used to calibrate, update nuclide libraries and to visually inspect spectra for multiplet peaks. All spurious peaks were discarded. The Algorithm was also used to refine analysis through interaction by way of physically adding, editing, deleting peaks and peak regions.

(b) Efficiency Calibration Algorithm

Efficiency calibration of the HPGe detector was done using the Genie 2000 software and the reference standard was Europium -152 (^{152}Eu). This reference standard was used because of its convenient half-life of 13 years and because it produces a wide range of gamma-ray energies when decaying [8]. The standard was manufactured on 1st July, 2006 by Eckert & Ziegler. It had an activity of 3.949 MBq, concentration of 1.094 MBq/g and a half-life of 13.33±0.04 years. Efficiency calibration of the detector was done on 1st May, 2019. The standard was prepared by adding a volume of 40 µl of the standard to 30 ml of distilled water on a petri dish using a pipette. The petri dish with its solution served as the standard geometry to be employed during measurements. The standard reference source was then placed on the detector. The Gamma spectroscopy was setup as shown in figure 8 with Genie 2000 software being set in efficiency calibration mode. The nuclide in the standard was selected from the list in the library of the software which in our case was ^{152}Eu. Information such as assay date, peak, activity units and uncertainty of the standard were entered in the Genie 2000 standard nuclide library. The Genie 2000 software efficiency algorithm calculated the efficiency using equation (3.5).

$$\varepsilon(E) = \frac{S}{T_1.Y.A.K_w.U_f} \qquad 3.5$$

where $\varepsilon(E)$ is efficiency when energy is E, S is net peak area for calibration peak, T_1 is time during measurements ,in seconds, Y is branching ratio of the calibration nuclide at this energy, A is radionuclide activity at the reference time , U_f is conversion factor to convert the activity A from other activity units to units of Bq , K_w is decay correction factor used to decay correct the activity A to the activity at the time of the start of acquisition and is calculated using equation (3.6) by the algorithm.

$$K_w = e - \frac{ln(2)\, t_w}{t_{1/_2}} \qquad 3.6$$

where t_w is time passed from the start of the acquisition to the time at which the calibration source activities are measured, in seconds and $t_{1/2}$ is half-life of the calibration radionuclide used. The uncertainty of a peak area was calculated using equation (3.7).

$$\sigma_{area} = \sqrt{\left[{}^{A}/_{h}\right]^2 \sigma_h{}^2 + \sum_i \left[{}^{f_i A_i}/_{h_i}\right]^2 \sigma_{h_i}{}^2} \qquad 3.7$$

where A is area for the peak of interest, h is determined height of the peak of interest, σ_h is calculated uncertainty of the peak of interest's height, A_i is area of the ith interfering peak, h_i is calculated height of the ith interfering peak, σ_{hi} is determined uncertainty of the peak height of the ith interfering peak and f_i is the fraction of the ith peak. The Genie 2000 software generated the dual efficiency calibration curve shown in figure 3.9 using equation (3.8) which is the dual polynomial function. The equation produced a dual efficiency curve, which is a combination of two curves, with the first curve being for lower energies and the second curve for higher energies. The duality of efficiency calibration curve is significant because the model supports two separate curves, with one curve for the low energy region and the other for the high energy region on one single plot with a single point common to both.

$$ln(\varepsilon) = \sum_{i=0}^{n} b_i \,.\, (lnE)^i \qquad 3.8$$

where b_i is a coefficient determined by the calculation, ε is the photo peak efficiency at energy E and E is the photo peak energy. The energy values of the standard with efficiency and percentage error were updated in the system files of the Genie 2000 on the date of calibration. Table 7, shows the point sources used for energy calibration and Figure 13, shows a graph of the energy calibration curve.

Table 7: Point sources used for energy calibration

Radionuclide	Energy (keV)
^{152}Eu	121.78
	344.3
	778.9
	964
	1085.8
	1112.07
	1408.08

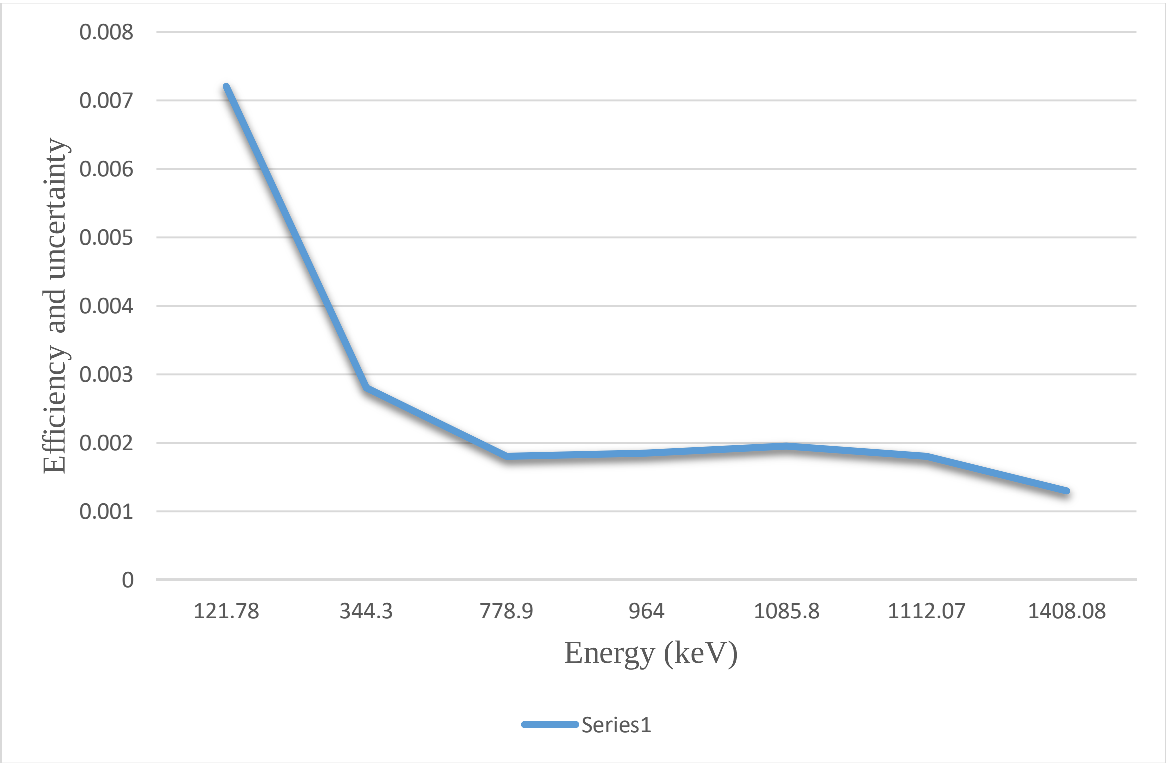

Figure 13: Plot of Energy Calibration Curve

(c) Nuclide Identification and Quantification Algorithm

In order to identify a nuclide, the nuclide identification algorithm considers all energy lines of a nuclide entered into the analysis library with full branching ratios and half-life of the radionuclide. To positively identify a nuclide, there has to be at least one gamma energy within the person doing the measurement's or user's selected energy tolerance of the observed peak in the spectrum. The value of the energy tolerance is chosen by the user and might be fixed energy or variable energy in keV. When a fixed energy tolerance value is chosen for peak matching only the energy value is entered in the library. When the variable energy tolerance value is selected the tolerance becomes the product of the number entered and FWHM calculated at the energy of the peak. When deciding if an energy line in the library matches the peak being searched for, the tolerance value is used specify the value to be used. The tolerance value is also used when adding new search results to existing peak records. Only peaks with energies outside the tolerance of existing peak records will be added as new peaks. The number of peaks that can be seen is decided by the number of branching ratios of the peaks with similar spectrum peaks. The branching ratios of the peaks without matching spectrum peaks are not considered. The algorithm then calculates the confidence index and the corrected decay activity per unit volume or mass for each energy with a matching peak in the spectrum for all identified nuclides. The calculated nuclide confidence value is then multiplied by the penalty function equation (3.9).

$$f(\Delta E_i) = e^{\frac{\frac{0.16}{ETOL^2}\cdot(\Delta E_i)^2 Y_i}{\sum_i Y_i}} \qquad 3.9$$

where $ETOL$ is energy tolerance, ΔE_i is difference between the reference energy and the measured energy for the ith peak, 0.16 is an empirical constant and Y_i is the ratio of branching of the ith peak**.** If at least one matching energy is found, the confidence index is further reduced to equation (3.10).

$$index' = index - 1.6\frac{\sum_j^n Y_i w(E_j)\,\delta(MDA)_j}{\sum_i^N Y_i\, w(E_j)} \qquad 3.10$$

where n is the number of energy lines from the library for this nuclide that did not have a similar observed peak in the spectrum, N is the total number of peaks in the library for this nuclide, Y_i is the ratio of branching of the ith peak, $\delta(MDA)$ is minimum detectable activity (MDA) which is dependent on whether the MDA test is enabled or not. The weighting factors $w\ (E_j\ )$ in equation (3.10) were calculated from equation (3.11) .

$$w(E_j) = \sqrt{\varepsilon}\ .\ e^{-\mu\rho t(E_j)} \qquad 3.11$$

where ε is the efficiency at gamma energy E_j excluding the correction due to attenuation, $\mu(E_j)$ is the mass attenuation in units of cm^2/g at gamma energyE_j, ρt is the average mass per area of the sample in units of g/cm^2.Then finally the value of the confidence index from equation 3.6 was multiplied by the decay time penalty function equation (3.12).

$$g(\Delta t) = e^{\left[-p\left[\frac{\Delta t}{T_{\frac{1}{2}}}\right]^2\right]} \qquad 3.12$$

where P is a constant of value $5.1 \times\ 10^{-03}$, Δt is the elapsed time from the time of taking the sample to the time to start the measurements in seconds and $t_{1/2}$ is the half-life of the radionuclide. Radionuclides which pass the above tests with a confidence index greater than the user selected energy tolerance are considered as identified.

(d) Activity Calculation Algorithm

The activity per unit volume or mass of the sample, C, on the sample date (decay corrected) for each energy line in the library that is similar with a line in the spectrum is calculated using equation (3.13) .

$$C = \frac{S}{V.\varepsilon.'\,T_{1.}.Y.U_f\ .K_c.K_w} \qquad 3.13$$

where S is net peak area, U_f is factor of conversion required to have the activity in μCi (the fixed internal storage unit), V is sample mass or volume, ε' is attenuation corrected efficiency calculated by equation (3.14) .

$$\varepsilon' = \varepsilon.^{e-\mu(E)\rho t} \qquad 3.14$$

where ε is non attenuation is corrected detection efficiency at the peak energy in question, $\mu(E)$ is mass attenuation (in units of cm^2/g) at gamma energy E, ρt is the average sample mass per unit area, T_1 is live time in seconds, Y is branching ratio and K_w is equation 3.2, K_c is correction factor for the nuclide decay during counting calculated using equation (3.15)

$$K_c = \frac{t_{\frac{1}{2}}}{ln(2).t_c}\left[1 - e - \frac{ln(2).t_c}{t_{\frac{1}{2}}}\right] \qquad 3.15$$

where $t_{1/2}$ is half-life of the radionuclide of interest, t_c is real clock time passed during the measurement with similar units as the half-life of the calibration radionuclide used. The uncertainty of the activity was calculated from equation (3.16).

$$\sigma_C = C\sqrt{[\sigma_R/_{100}]^2 + [\sigma_S/_S]^2 + [\sigma_V/_V]^2 + [\sigma_{\varepsilon'}/_{\varepsilon'}]^2 + [\sigma_Y/_Y]^2 + [\sigma_K/_K]^2} \qquad 3.16$$

where σ_R is random uncertainty , σ_S is uncertainty of the net peak area S, σ_V is uncertainty of the sample quantity V, $\sigma_{\varepsilon'}$ is uncertainty of the effective efficiency, ε' is attenuation corrected efficiency calculated by using equation 3.9, σ_Y is uncertainty of the branching ratio Y, σ_K is uncertainty of the composite decay correction factor, $K = K_c.K_W$ where K_c is equation (3.15) and K_w is Equation (3.6) and ε' is the attenuation corrected efficiency calculated by equation (3.14).

(e) Minimum Detectable Activity (MDA) Calculation Algorithm

Minimum detectable activity (MDA) and was calculated per unit mass or volume using equation (3.17).

$$MDA = \frac{L_D}{T_{1\,.}\varepsilon.' V. K_{C.} K_W. C_{F.} U_f} \qquad 3.17$$

where L_D is detection limit, T_1 is collection live time in seconds, ε' is attenuation corrected efficiency and was calculated by using equation 3.9, V is mass or volume of the sample, C_f is sample mass conversion factor or volume conversion factor, U_f is unit conversion factor from Bq to the selected unit of activity for recording. Equation (3.18) was used to calculate the uncertainty of the MDA.

$$\sigma_{MDA} = MDA\sqrt{\left[{}^{\sigma_R}/_{100}\right]^2 + \left[{}^{\sigma_S}/_S\right]^2 + \left[{}^{\sigma_V}/_V\right]^2 + \left[{}^{\sigma_{\varepsilon'}}/_{\varepsilon'}\right]^2 + \left[{}^{\sigma_Y}/_Y\right]^2 + \left[{}^{\sigma_K}/_K\right]^2} \qquad 3.18$$

where σ_R is random uncertainty , σ_S is uncertainty of the net peak area S, σ_V is uncertainty of the sample quantity V, $\sigma_{\varepsilon'}$ is uncertainty of the effective efficiency, ε' is attenuation corrected efficiency calculated by equation 3.9, σ_Y is uncertainty of the branching ratio Y, σ_K is uncertainty of the composite decay correction factor, $K = K_c.K_W$ where K_c is equation (3.1.5) and K_w is Equation (3.6) and ε' is the attenuation corrected efficiency calculated by equation 3.14.

(f)Background Subtraction and Reference Peak Correction Algorithm

The background subtract algorithm subtracted the environmental background peaks from sample spectra using equation (3.19).

$$S = R\left[G - \left[{}^{N}/_{2n}\right](B_1 + B_2) - {}^{T_S}/_{T_b} - I_b\right] \qquad 3.19$$

where G are the total number of counts, R is correction factor for random summing, I_b is number of counts above the continuum that are due to the environmental background, T_S is live time of the sample spectrum in seconds, T_b is live time of the background spectrum in seconds, I_b is net peak area of the peak in the background spectrum , B_1 is sum of counts in the low energy continuum region and B_2 is sum of counts in the high energy continuum region.

(g) Parent/Daughter Decay Correction Algorithm

The Algorithm is used when the parent nuclide and its daughters are not in equilibrium so that correct nuclide activities are measured. Where no parent is specified or identified the correction will not be done and the software goes to the following nuclide in the loop. When the parent nuclide has been specified or identified, the correction is calculated and applied to the current nuclide. The correction was done based on sample time, acquisition start time and passed acquisition live time. The correction was also done using both nuclide parent and daughter. information stored in the nuclide library. The corrected daughter activity was calculated from equation (3.20).

$$D_{o,Corr} = D_o - k_{PD}P_o \frac{\lambda_D}{\lambda_D - \lambda_P}\left[\frac{\lambda e^{-\lambda p^t decay}\left(1 - e^{-\lambda P^t real}\right)}{\lambda_P e^{-\lambda D^t decay}\left(1 - e^{-\lambda D^t real}\right)} - 1\right] \quad 3.20$$

where $D_{o,Corr}$ is corrected daughter activity, D_o is uncorrected daughter activity, k_{PD} is branching ratio from the parent to the daughter, P_o is weighted mean parent activity, the daughter decay parameter (λ_D) was calculated from the nuclide's half-life using equation (3.21).

$$\lambda_D = \frac{ln2}{t_{1/2}} \quad 3.21$$

the parent decay parameter (λ_P) was calculated from a nuclide's half-life using equation (3.22).

$$\lambda_p = \frac{ln2}{t_{1/2}} \quad 3.22$$

$t_{1/2}$ nuclide's half-life t_{decay} is the elapsed decay time between the sample time and the acquisition start time in seconds, t_{real} is the elapsed acquisition real time in seconds. The uncertainty in this quantity was calculated using equation (3.23).

$$\sigma^2_{D_{o,corr}} = \sigma^2_{D_o} + \left[\frac{\partial D_{o,Corr}}{\partial k_{PD}}\right]^2 + \left[\sigma_{P_o}\frac{\partial D_{o,Corr}}{\partial P_o}\right]^2 \left[\sigma_{\lambda_P}\frac{\partial D_{o,Corr}}{\partial \lambda_P}\right]^2 \left[\sigma_{\lambda_D}\frac{\partial D_{o,Corr}}{\partial \lambda_D}\right]^2 \quad (3.23)$$

where $\sigma^2_{D_{o,corr}}$ is corrected daughter's activity,$D_{o,Corr}$ is uncorrected daughter's activity , σD_o is daughter's uncertainty, P_o is parent's weighted parent activity , σP_o is parent's uncertainty and k_{PD} is the branching ratio from the parent to the daughter.

3.1.3 Calculation of ADR, AED, H_{ex} and Ra_{eq}

(a) Absorbed dose rate

The ADR was calculated from the measured activity concentrations of ^{40}K,^{238}U and ^{232}Th using UNSCEAR report of 2000 guidelines on how to calculate the absorbed dose rate (D) due to gamma radiation in air at 1m above the ground by using equation (3.24).

$$D(\mathrm{nGy} / \mathrm{h}) = 0.462C_U + 0.621C_{Th} + 0.0417C_K \quad 3.24$$

where D is dose rate in nGy/h, C_U, C_{Th}, C_K are the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K, respectively .

(b) Annual effective dose outdoors

To estimate AED outdoors, equation (3.25) was used. The conversion coefficient used was 0.7 Sv/Gy from absorbed dose in air to effective dose received by adults and the fraction of time spent outdoors used was 0.2 as recommended by UNSCEAR report of 2000 .

$$\mathrm{AED}\left(^{\mathrm{mSv}}/_{\mathrm{y}}\right) = \mathrm{ADR}\left(^{\mathrm{nGy}}/_{\mathrm{h}}\right).1^{-6}.(24\mathrm{h}.365.25\mathrm{d}).(0.2).(0.7)\mathrm{Sv} / \mathrm{Gy} \quad 3.25$$

Where d is day, h is hour

(c) External hazard index (H_{ex})

The H_{ex} is used to assess the health effects from the radioactivity of the earth's surface materials emitting gamma radiation. The activity concentration values of ^{40}K, ^{238}U and ^{232}Th were converted into a single quantity called H_{ex} using equation (3.26). The value of H_{ex} must not exceed the limit of unity for the radiation hazard to be considered negligible at an area.

$$H_{eq} = \frac{C_U}{370\,\mathrm{Bq/kg}} + \frac{C_{Th}}{259\,\mathrm{Bq/kg}} + \frac{C_K}{4810\,\mathrm{Bq/kg}} \leq 1 \qquad 3.26$$

where H_{ex} is external hazard index, C_U, C_{Th}, . C_K are the activity concentrations of ^{238}U,^{232}Th and ^{40}K in that order.

(d) Radium equivalent (Ra_{eq})

The Ra_{eq} concept allows a single number to describe the combined gamma radiation output from ^{40}K, ^{238}U and ^{232}Th from a sample. The recommended maximum value of Ra_{eq} by ICRP is 370 Bq/kg for radioactivity to be considered to be considered harmless at an area [47]. Radium equivalent was calculated using equation (3.27).

$$Ra_{eq} = A_U + 1.43A_{Th} + 0.077A_K \qquad 3.27$$

where R_{eq} is radium equivalent, A_u, AT_h , A_k are activity concentrations of ^{238}U, ^{232}Th and ^{40} K, respectively.

CHAPTER FOUR

4.0 RESULTS AND DATA ANALYSIS

In this chapter measured results and data analysis of all samples collected from the proposed site for the construction of the Centre are presented. The results are presented in the following order: soil samples, plant samples and finally water samples from the nearby dam. For each sample the measured activity concentrations of ^{40}K, Lead-214 (^{214}Pb), Bismuth-214 (^{214}Bi), Actinium-228 (^{228}Ac), Lead 212 (^{212} Pb) have been presented. The activity concentrations of ^{238}U and ^{232}Th were calculated from ^{214}Pb, ^{214}Bi and ^{228}Ac, ^{212} Pb respectively. For each sample, the determined activity concentrations, ADR, AED ,H_{ex} and Ra_{eq} are presented in form of Tables and Bar graphs. The obtained results were compared with world average values and results from sites earmarked for setting up nuclear facilities from countries were similar studies were undertaken.

4.1 Measurement of activity concentrations and determination of ADR, AED H_{ex} and Ra_{eq}

The activity concentrations of ^{40}K for all samples were determined directly by using its gamma-ray at 1460.8 keV. The activity concentrations of ^{238}U and ^{232}Th were determined from their respective decay products when the samples reached a state of secular equilibrium. This is because the activity concentrations of ^{238}U and ^{232}Th cannot be measured directly. Therefore, gamma-ray transitions associated with the decay of their daughter radionuclides were used to measure the activity concentration of each radionuclide for each sample. An interference corrected activity report of ^{40}K, ^{214}Pb, ^{214}Bi, ^{228}Ac and ^{212}Pb was generated by the Genie 2000 for each sample. The report contained the weighed mean activity, weighed mean activity uncertainty of ^{40}K, ^{214}Pb, ^{214}Bi, ^{228}Ac and ^{212}Pb. The activity concentrations of ^{238}U were determined by assuming that they have a weighted average of the activity concentrations of the gamma-rays of ^{214}Pb (295.1keV, 351.9keV), ^{214}Bi (609.3keV) and (1120.29keV) including its specific gamma ray at 186.2 keV. The interference correction due to Uranium-235(^{235}U) was taken into account and was subtracted from the spectra. The activity concentrations of ^{232}Th were measured assuming that they have a weighted average of the activity concentrations of the gamma rays 338.4 keV, 911.2 keV and 969.11keV of ^{228}Ac and 238.6 keV of ^{212}Pb.

4.2 Measured activity concentrations in soil samples

Table 8, gives measured results of activity concentration of ^{40}K and decay series of ^{238}U, ^{232}Th from which their activity concentrations were calculated in soil samples.

Table 8: Activity concentrations of ^{40}K , decay series of ^{238}U and ^{232}Th in soil samples

Sample	^{40}K (Bq/kg)	^{238}U	Series(Bq/kg)	^{232}Th	Series(Bq/kg)
id		^{214}Pb	^{214}Bi	^{228}Ac	^{212}Pb
BH 1	123.40±4.97	4.30±0.14	4.60±0.17	10.84±0.24	9.91±0.35
BH2	150.45±6.12	2.85±0.13	3.22±0.17	8.58±0.25	7.27±0.30
BH3	94.60±3.90	5.46±0.17	5.65±0.18	11.40±0.25	10.23±0.38
BH4	140.67±6.99	4.73±0.36	5.90±0.39	10.47±0.53	7.87±0.46
BH5	140.06±9.51	8.07±0.64	8.17±0.63	8.90±0.44	8.07 ±6.45
BH6	115.31±5.10	2.85±0.16	3.22±0.22	9.60±0.32	7.42±0.31
BH7	143.24±6.23	3.56±0.19	3.35±0.23	9.23±0.34	8.59±0.35
BH8	139.29±5.58	2.96±0.12	3.54±0.16	6.80±0.20	5.90±0.23
BH9	118.57±5.43	4.56±0.21	4.26±0.29	11.68±0.39	10.43±0.44
BH10	93.74±4.43	3.72±0.17	3.92±0.21	9.77±0.30	8.75±0.35
BH11	66.84±3.30	9.78±0.28	8.64±0.30	12.56±0.32	11.70±0.46
BH12	107.44±4.36	4.28±0.14	4.50±0.14	10.52±0.23	9.67±0.34
BH13	122.97±5.60	5.52±0.24	6.11±0.31	12.20±0.40	10.78±0.44
BH14	112.61±5.09	4.75±0.21	4.96±0.28	12.37±0.39	10.73±0.42
BH15	142.31±6.50	1.95±0.22	2.78±0.26	7.35±0.37	5.20±0.29
BH16	113.18±4.62	3.44±0.13	3.10±0.17	9.86±0.24	7.59±0.28
BH17	112.90±4.64	4.44±0.15	5.017±0.19	12.48±0.27	11.11±0.41
BH18	128.15±5.20	3.29±0.13	4.06±0.18	9.41±0.23	7.64±0.30
BH19	137.16±5.79	5.03±1.91	4.74±0.24	10.88±31.23	8.89±0.35
BH20	104.89±4.30	7.02±0.20	7.04±0.22	12.16±6.35	10.64±0.40

The following steps show how the activity concentrations of ^{40}K, ^{238}U, ^{232}Th, ADR, AED, H_{ex} and Ra_{eq} were calculated. Sample BH 1 was used to show how calculations were done for all samples from Table 8.

(a) Determination of the existence of ^{40}K, ^{238}U and ^{232}Th

Activity concentration (AC) of ^{40}K for the sample was obtained directly from a gamma photo peak of 1460.8 keV, for BH1 the measured value is shown by equation (4.28).

$$\mathrm{AC} = 123.40 \pm 4.97 \mathrm{Bq/kg} \qquad 4.28$$

Activity concentration of ^{238}U was determined by calculating the average activity of its daughter radionuclides, ^{214}Pb and ^{214}Bi as shown.

$$\mathrm{AC} = \left(\frac{^{214}Pb + {}^{214}Bi}{2}\right) \mathrm{Bq/kg}$$

Replacing into the equation with the activity concentrations of ^{214}Pb and ^{214}Bi from Table 8.

$$\mathrm{AC} = \frac{4.30 \pm 0.14 + 4.60 \pm 0.17}{2}$$

$$\mathrm{AC} = 4.45 \pm 0.16 \ \mathrm{Bq/kg}$$

Activity concentration of ^{232}Th was measured by calculating the mean activity of its daughter radionuclides, ^{212}Pb and ^{228}Ac as shown.

$$\mathrm{AC} = \left(\frac{^{212}Pb + {}^{228}Ac}{2}\right) \mathrm{Bq/kg}$$

Replacing into the equation with the activity concentrations of ^{212}Pb and ^{228}Ac from Table 8.

$$\mathrm{AC} = \left(\frac{9.91 \pm 0.35 + 10.84 \pm 0.24}{2}\right) \mathrm{Bq/kg}$$

$$\mathrm{AC} = 10.38 \pm 0.30 \ \mathrm{Bq/kg}$$

(b) Calculation of Absorbed Dose Rate

Equation 4.29 was used

$$\mathrm{D\ (n\ Gy/h)} = 0.462 C_U + 0.621 C_{Th} + 0.0417 C_K \qquad 4.29$$

where activity concentrations of C_U (^{238}U) ,C_{Th} (^{232}Th), C_K (^{40}K) were 4.45 ± 0.16,10.38 ± 0.30 and 123.40 ± 4.97 respectively. Replacing the values of activity concentrations in the above equation.

$$\mathrm{D(n\ Gy/h)} = 0.462(4.45) + 0.621(10.38) + 0.0417(123.40)$$

$$\mathrm{ADR} = 13.65\ \mathrm{nGy/h}$$

(c) Estimates of Annual Effective Dose outdoors

Equation (4.30) was used

$$\mathrm{AED(mSv/y)} = \mathrm{ADR\ (nGy/h)}.1^{-6}.(24\ \mathrm{h}.365.25\ \mathrm{d}).(0.2).(0.7)\mathrm{Sv/Gy} \qquad 4.30$$

Replacing calculated ADR which was $13.65\,\mathrm{nGy/h}$ in the equation and calculating AED.

$$\mathrm{AED(mSv/y)} = 13.65.1(1^{-6}).(24\ \mathrm{h}.365\ 1\ /\ 4\ \mathrm{d}).(0.2).(0.7)\mathrm{Sv/Gy}$$

$$\mathrm{AED} = 0.023\ (\mathrm{mSv\ /\ y})$$

(d) Calculation of External Hazard index

Equation (4.31) was used

$$\mathrm{H_{eq}} = \frac{\mathrm{C_U}}{370\,\mathrm{Bq/kg}} + \frac{\mathrm{C_{Th}}}{259\,\mathrm{Bq/kg}} + \frac{\mathrm{C_K}}{4810\,\mathrm{Bq/kg}} \leq 1 \qquad 4.31$$

where activity concentrations of C_U (^{238}U), C_{Th} (^{232}Th), C_K (^{40}K) were $\mathbf{4.45 \pm 0.16, 10.38 \pm 0.30}$ and $\mathbf{123.40 \pm 4.97}$ respectively. Replacing values of activity concentration in the equation, the units $\mathbf{Bq/kg}$ cancel out and we get the answer.

$$\mathrm{H_{ex}} = \frac{4.45}{370} + \frac{10.38}{259} + \frac{123.40}{4810} \leq 1$$

$$H_{ex} = 0.08$$

(e) Calculation of Radium Equivalent

Equation (4.32) was used

$$Ra_{eq} = A_U + 1.43A_{Th} + 0.077A_K \qquad 4.32$$

where activity concentration of A_U (^{238}U) , A_{Th} (^{232}Th), A_K (^{40}K) are 4.45 ± 0.16, 10.38 ± 0.30 and 123.40 ± 4.97 respectively.

$$Ra_{eq} = 4.45 + 1.43(10.38) + 0.077(123.40)$$

$$Ra_{eq} = 28.80 \text{ Bq/kg}$$

(a) Activity concentrations of ^{40}K, ^{238}U and ^{232}Th in soil samples

The minimum and maximum values of activity concentration of ^{238}U where 2.36 ± 0.14 Bq/kg and 9.21 ± 0.65 Bq/kg for ^{232}Th they were 2.056 ± 0.22 Bq/kg and 12.13 ± 0.63 Bq/kg while for ^{40}K they were 66.84 ± 3.30 Bq/kg and 150.45 ± 9.51 Bq/kg. The average values of activity concentrations of ^{238}U, ^{232}Th and ^{40}K were 4.75 ± 0.23 Bq/kg, 9.63 ± 0.35 Bq/kg and 120.39 ± 5.37 Bq/kg respectively. Table 9 shows the determined activity concentrations of ^{40}K, ^{238}U and ^{232}Th in soil samples.

Table 9: Activity concentrations of ^{40}K , ^{238}U and ^{232}Th in soil samples

Sample id	^{40}K (Bq/kg)	^{238}U (Bq/kg)	^{232}Th (Bq/kg)
BH1	123.40±4.97	4.45±0.16	10.38±0.30
BH2	150.45±6.12	3.03±0.15	7.92±0.27
BH3	94.59±3.90	5.56±0.18	10.80±0.32
BH4	140.67±6.99	5.31±0.38	9.17±0.49
BH5	140.06±9.51	8.07±0.64	8.49±3.44
BH6	115.31±5.10	3.03±0.18	8.51±0.31
BH7	143.24±6.23	3.45±0.21	8.91±0.34
BH8	139.29±5.58	3.25±0.14	6.35±0.22
BH9	118.57±5.43	4.41±0.25	11.06±0.41
BH10	93.74±4.23	3.82±0.19	9.25±0.32
BH11	66.84±3.30	9.21±0.29	12.13±0.40
BH12	107.44±4.36	4.37±0.15	10.10±0.28
BH13	122.97±5.60	5.82±0.28	11.41±0.42
BH14	112.61±5.09	4.86±0.25	11.55±0.41
BH15	142.31±6.50	2.36±0.24	6.28±0.33
BH16	113.18±4.62	3.72±0.15	8.73±0.26
BH17	112.90±4.64	4.73±0.17	11.77±0.34
BH18	128.15±5.20	3.67±0.15	8.53±0.26
BH19	137.16±5.79	4.89±0.21	9.88±0.33
BH20	104.89±4.30	7.03±0.21	11.40±0.32

Table 10 shows the minimum, maximum activity concentrations and average activity concentrations of ^{40}K, ^{238}U and ^{232}Th in soil samples.

Table 10: Minimum, maximum activity concentrations and average activity concentrations of ^{40}K, ^{238}U and ^{232}Th in soil samples

	Mean	Activity	in Bq/kg
Nuclide	^{40}K	^{238}U	^{232}Th
Minimum	66.84±3.30	2.36±0.14	2.056±0.22
Maximum	150.45±9.51	9.21±0.65	12.13±0.63
CNST Average	120.39±5.37	4.75±0.23	9.63±0.35

Table 11, shows a comparison of the average activity concentrations of ^{40}K, ^{238}U and ^{232}Th in soil samples from the CNST with those from sites from other countries and the world average values as reported by the UNSCEAR report of 2000 [12]. From the Table it is observed that the average activity concentration values of ^{40}K, ^{238}U and ^{232}Th at the Centre are the lowest and are far lower than the world average values.

Table 11: Comparison of average activity concentrations in soils of ^{40}K, ^{238}U and ^{232}Th in the current study to studies from sites from other countries and world average values.

Country/Study Area	Mean	Activity	Bq/kg	Ref
Nuclide	^{40}K	^{238}U	^{232}Th	
Zambia (CNST)	120.39±5.37	4.75±0.23	9.63±0.35	-
India (Kudankulam)	238.80	148.10	29.90	[43]
Bangladesh(Rooppur)	379.60	17.90	26.60	[39]
Taiwan (Gung-Liao)	435.74	24.22	26.39	[44]
World Average	420	33	45	[12]

Figure 14, shows those activity concentrations of ^{40}K, ^{238}U, ^{232}Th at all sample points in soils were far below the world average values of 420 Bq/kg, 33 Bq/kg and 45 Bq/kg respectively [12].

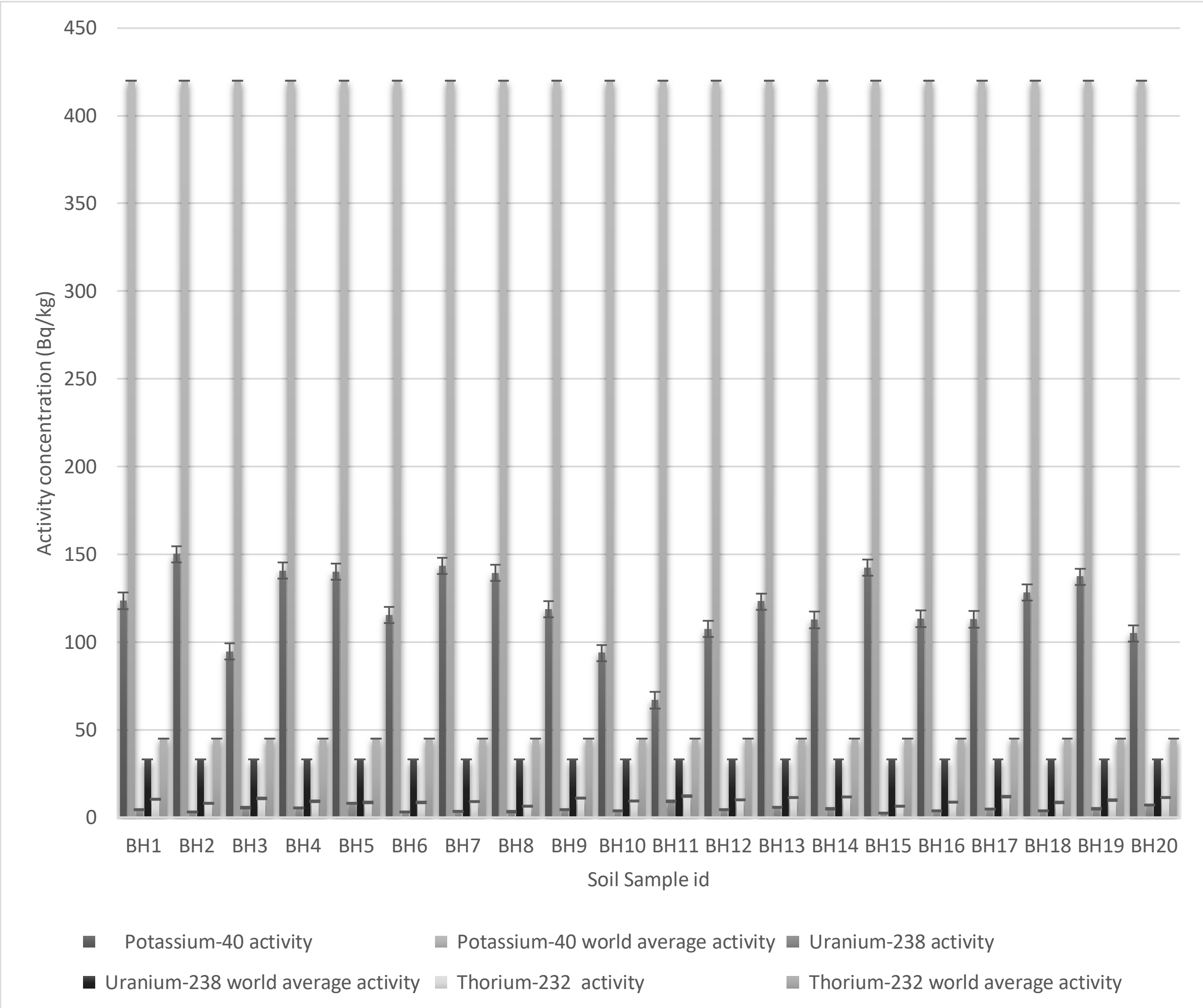

Figure 14: Activity concentrations of ^{40}K, ^{238}U and ^{232}Th of 20 soil samples

(b) Determined ADR, AED, H_{ex} and Ra_{eq} in soil samples

The ADR values for the soil samples ranged from 10.85 nGy/h to 14.90 nGy/h with an average value of 13.00 ± 1.32 nGy/h.The AED ranged from 0.01 mSv/y to 0.02 mSv/y with an average value of 0.02 ± 0.01 mSv/y. The AED at all sample points and the average were far below the annual exposure limit to radiation of 1 mSv/y as recommended by ICRP [52]. The H_{ex} values ranged from 0.06 to 0.09 with an average of 0.07 ± 0.01.The values of H_{ex}

at all sample points with the average were below unity the recommended limit set by ICRP for radiation to be non-hazardous at an area [46]. The Ra_{eq} values ranged from 21.80 Bq/kg to 31.70 Bq/kg with an average of 27.33 ± 3.09 Bq/kg. The values of Ra_{eq} at all sample points and the average were less than 370 Bq/kg the recommended limit of activity set by ICRP for radiation to be non-hazardous at an area [47]. Table 12, shows the determined ADR, AED, H_{ex} and Ra_{eq} in soil samples.

Table 12: Determined ADR, AED, H_{ex} and Ra_{eq} in soil samples.

Sample id	ADR (nGy/h)	AED (mSv/y)	H_{ex}	Ra_{eq} (Bq/kg)
BH1	13.65	0.02	0.08	28.80
BH2	12.60	0.01	0.07	25.95
BH3	13.22	0.02	0.08	28.28
BH4	14.02	0.02	0.08	29.26
BH5	10.85	0.01	0.06	21.80
BH6	11.49	0.01	0.06	24.07
BH7	13.10	0.02	0.07	27.23
BH8	11.25	0.01	0.06	23.05
BH9	13.85	0.02	0.08	29.35
BH10	11.42	0.01	0.06	24.27
BH11	14.57	0.02	0.09	31.70
BH12	12.80	0.02	0.07	27.08
BH13	14.90	0.02	0.08	31.61
BH14	14.11	0.02	0.08	30.05
BH15	10.92	0.01	0.06	22.30
BH16	11.86	0.01	0.07	24.91
BH17	14.20	0.02	0.08	30.25
BH18	12.34	0.01	0.07	25.73
BH19	14.11	0.02	0.08	29.58
BH20	14.70	0.02	0.08	31.41

Table 13 shows the minimum, maximum and average values of ADR, AED, H_{ex} and Ra_{eq} in soil samples

Table 13: Minimum, maximum and average values of ADR, AED, Hex and Raeq in soil samples from the Centre

Quantity	ADR (nGy/h)	AED (mSv/y)	H_{ex}	Ra_{eq} (Bq/kg)
Minimum	10.85	0.01	0.06	21.80
Maximum	14.90	0.02	0.09	31.70
CNST Average	13.00±1.32	0.02±0.01	0.07±0.01	27.33±3.09

Table 14 shows the average values of ADR, AED, H_{ex} and Ra_{eq} in soil samples at the proposed site for the CNST with values of areas from other countries planned for setting up of nuclear facilities. The values of ADR, AED, H_{ex} and Ra_{eq} are the lowest at the CNST with those from Kudankulam, India being highest. The average values of ADR and AED at the CNST were also far lower than the world average values respectively as reported by the UNSCEAR report of 2000 [12]. The average value of H_{ex} at the CNST was the lowest of all other sites, but the world average is not available (-). The average value of Ra_{eq} at the CNST is the lowest of all other areas and is far less than the world average value [23].

Table 14: Comparison of average ADR, AED, H_{ex}, Ra_{eq} in soil samples in this study to sites from other Countries.

Country/Region	ADR (nGy/h)	AED (mSv/y)	H_{ex}	Ra_{eq} (Bq/kg)	Ref
Zambia (CNST)	13.00±1.32	0.02±0.01	0.07±0.01	27.33±3.09	-
India (Kudankulam)	111.70	0.14	0.70	1839	[43]
Bangladesh (Rooppur)	17	0.96	0.22	85	[39]
Taiwan (Gung-Liao)	46.63	57.19	0.27	98.18	[44]
World Average	59	2.40	-	58	[12,23]

(i) Absorbed dose rate

Figure 15, shows that the absorbed dose rates at all sample points were far below the world average value of 59 nGy/h [12].

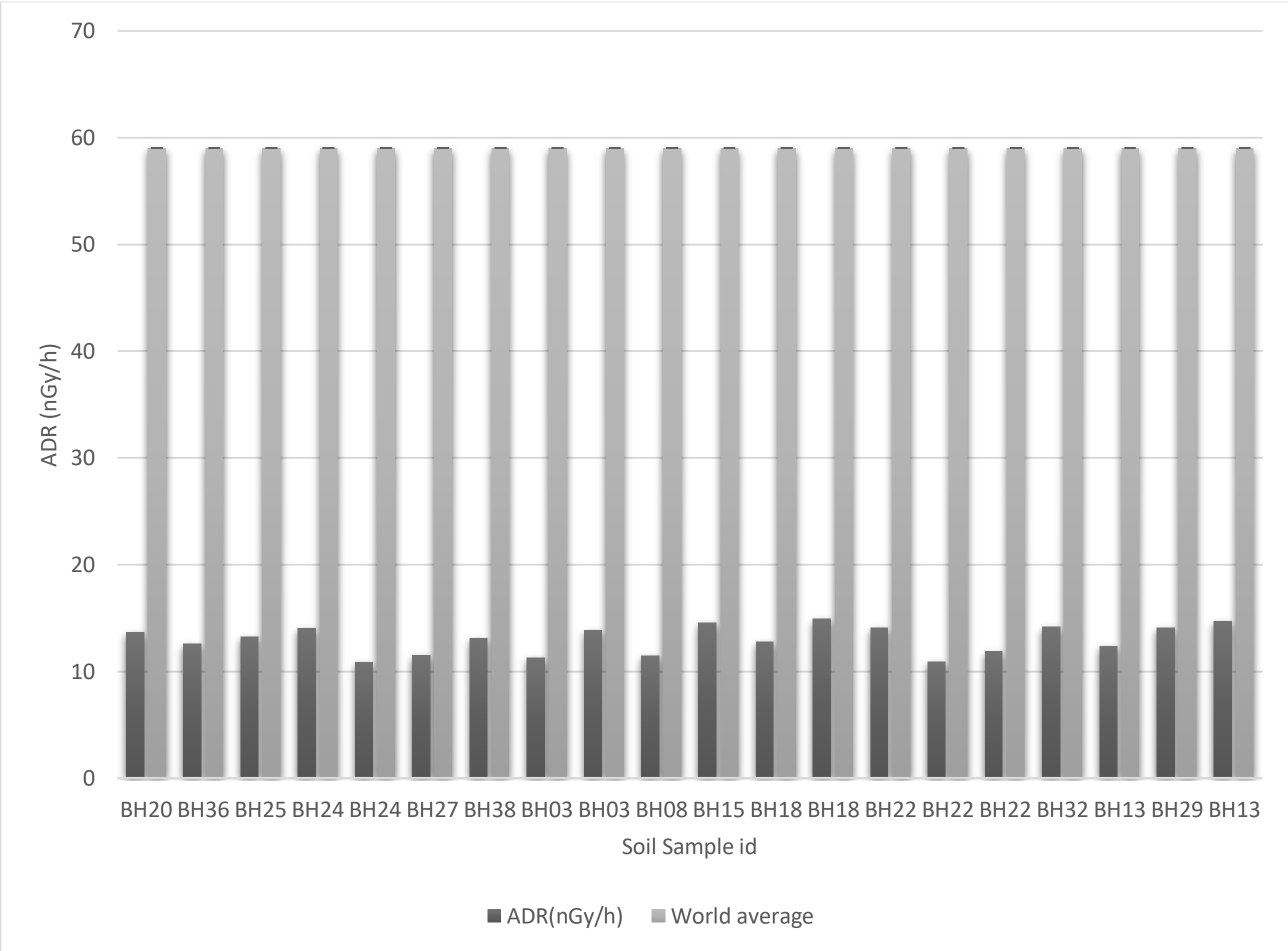

Figure 15: Absorbed dose rates of 20 soil samples

(ii) Annual effective dose rate

Figure 16, shows that the AED rate at all sample points were far below the world average of 2.40 mSv/y [12] and annual exposure limit to radiation of 1 mSv/y as recommended by ICRP [52].

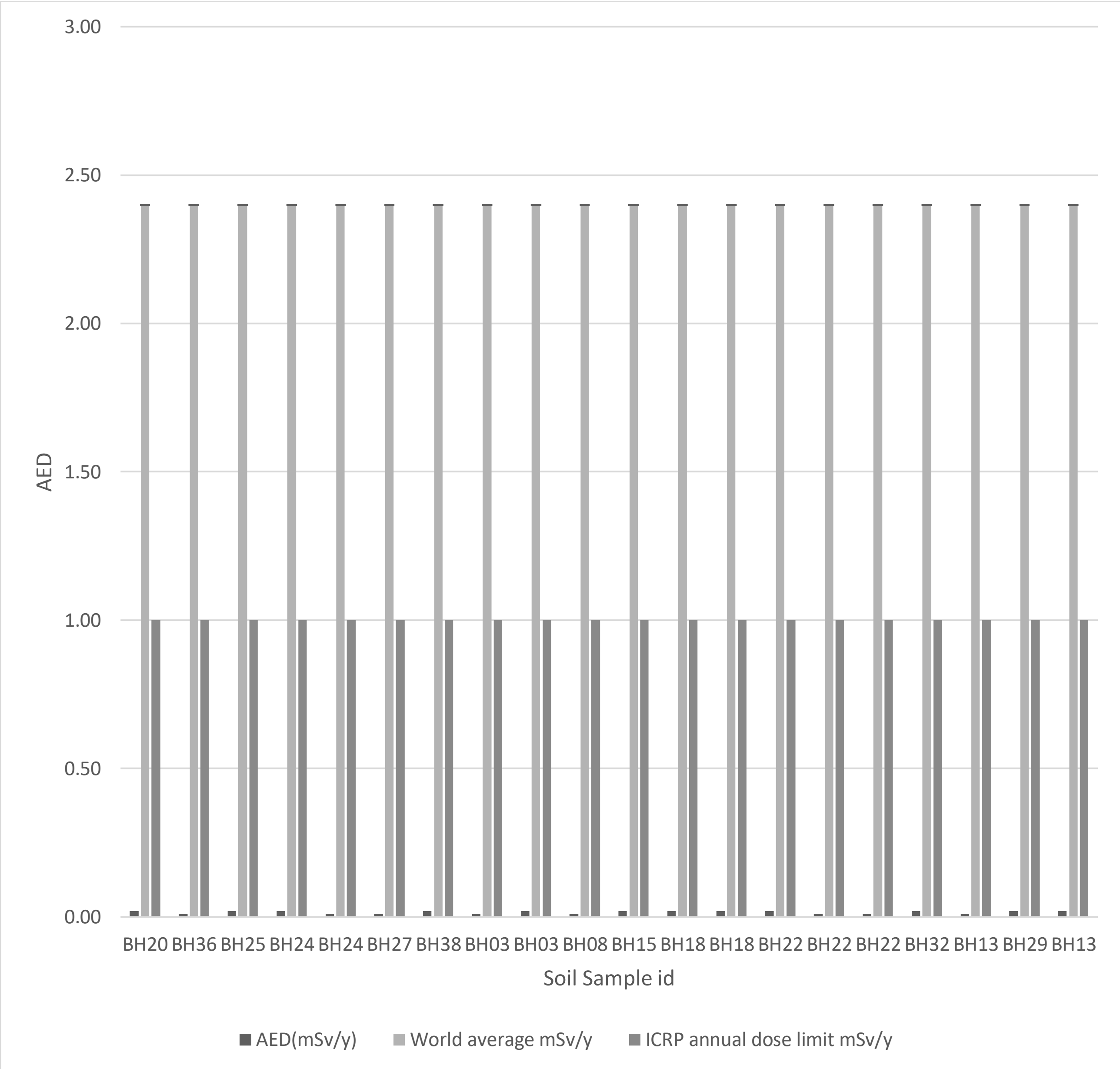

Figure 164: Annual effective dose rate of 20 soil samples

(iii) External hazard index

Figure 17, shows that the values of H_{ex} at all sample points were far below unity the recommended limit by ICRP for radiation to be considered as being non-hazardous at an area [46].

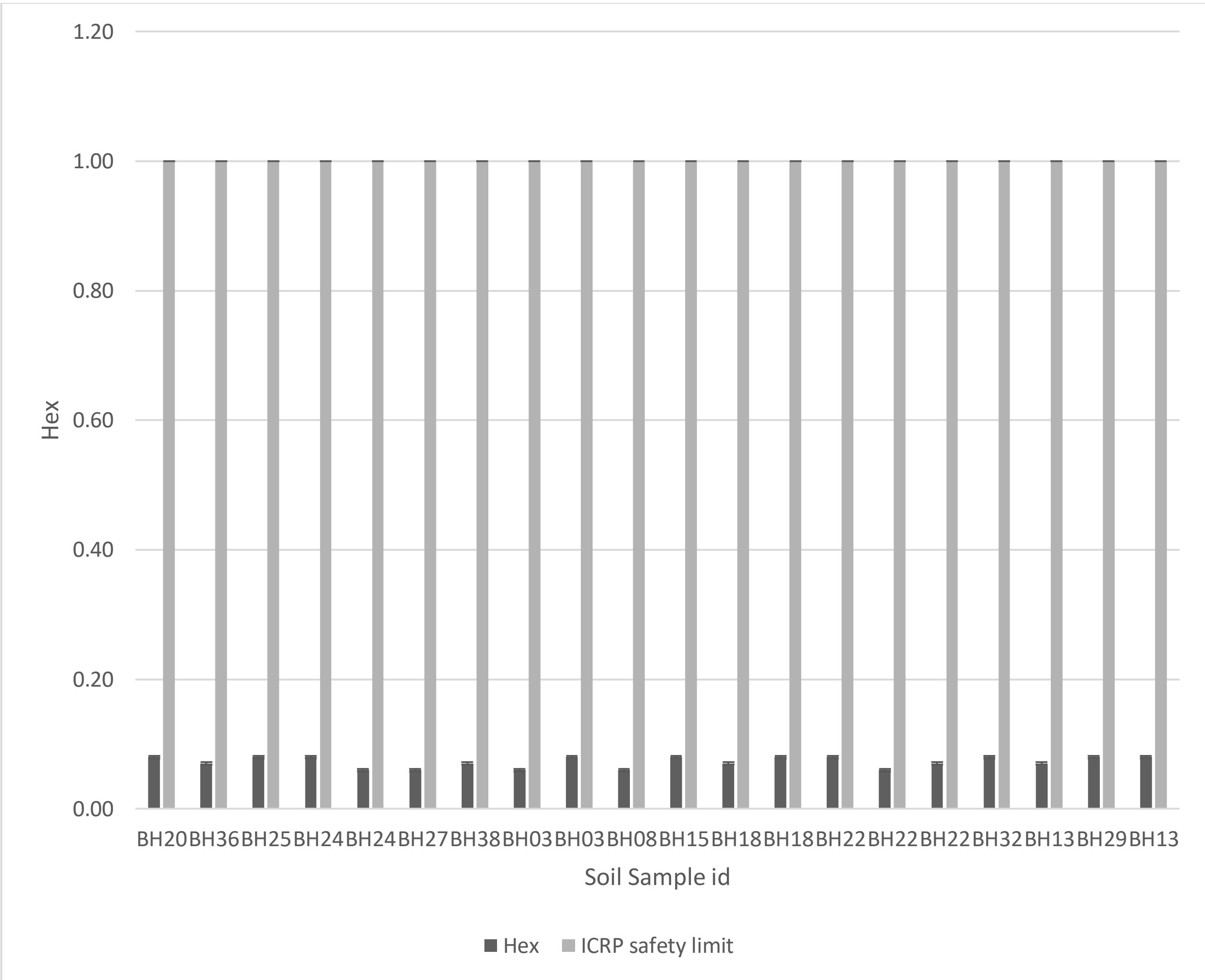

Figure 17: External Hazard index of 20 soil samples

(iv) Radium equivalent

Figure 18, shows that the Ra_{eq} values at all sample were below both the world average value of 58 Bq/kg [23] and 370 Bq/kg the recommended limit of activity set by ICRP for radioactivity to be non-hazardous at an area [47].

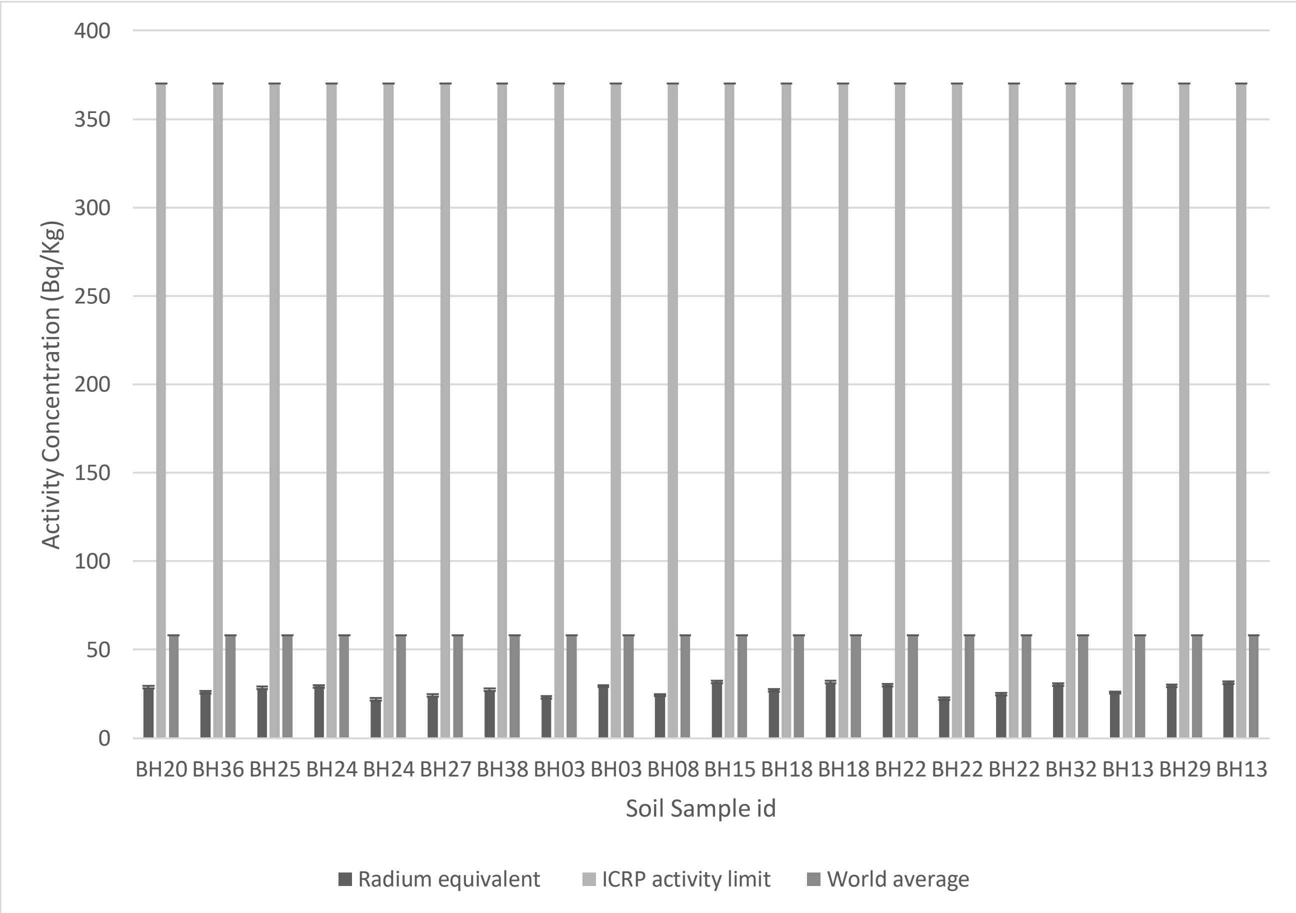

Figure 18: Radium equivalent of 20 soil samples

4.3 Measured activity concentrations in plant Samples

Table 15, gives measurements of specific activity concentrations for decay series of ^{238}U, ^{232}Th and ^{40}K for plant samples from which their mean activity concentrations were calculated ,although some measurements were below the detectable limit (BDL).

Table 15: Measured specific activities for ^{40}K, ^{214}Pb, ^{214}Bi, ^{228}Ac and ^{212}Pb in plant Samples

Sample id	^{40}K (Bq/kg)	^{238}U Series	(Bq/kg)	^{232}Th Series	(Bq/kg)
		^{214}Pb	^{214}Bi	228Ac	^{212}Pb
S1	94.39±3.93	5.97±0.18	6.04±0.22	11.55±0.37	7.55±0.41
S2	296.72±16.03	29.16±1.5	26.95±5.00	BDL	17.08±1.10
S3	BDL	17.13±0.03	15.16±0.42	6.64±0.49	5.11±0.84
S4	135.70±8.99	8.73±0.64	10.90±0.19	BDL	7.87±1.46
S5	206.06±0.51	9.07±0.36	11.17±0.93	9.10±0.84	8.07 ±6.45
S6	BDL	3.85±0.49	3.22±0.60	10.60±1.20	7.42±0.78
S7	136.24±5.23	3.56±0.89	4.35±8.03	9.23±0.40	8.59±1.37
S8	229.29±6.58	4.96±0.12	5.54±0.10	18.09±0.58	22.90±0.23
S9	89.57±11.43	6.56±0.41	8.26±0.11	11.54±1.91	9.43±10.14
S10	193.74±12.43	9.72±0.29	7.92±0.01	11.87±0.73	13.84±0.45

(a) Determined activity concentrations of ^{40}K, ^{238}U and ^{232}Th in plant samples

The minimum activity concentration of ^{40}K was below the detection limit (BDL) while the maximum was $296.72 \pm 16.03\ Bq/kg$ and the average activity was $172.71 \pm 5.34\ Bq/kg$. The observed minimum activity concentration of ^{238}U was $3.53 \pm 5.46\ Bq/kg$ while the maximum was $28.05 \pm 3.25\ Bq/kg$ with an average of $9.91 \pm 0.89 Bq/kg$. The observed minimum activity concentration of ^{232}Th was 3.93±0.73 Bq/kg while the maximum was $20.49 \pm 0.40 Bq/kg$ and the average was $9.81 \pm 1.76\ Bq/kg$. Table 16, shows determined activity concentrations for ^{40}K ,^{238}U and ^{232}Th in plant samples.

Table 16: Determined activity concentrations of ^{40}K ,^{238}U and ^{232}Th in plant samples.

Sample id	^{40}K (Bq/kg)	^{238}U (Bq/kg)	^{232}Th (Bq/kg)
S1	94.39±3.93	6.00±0.20	9.55±0.39
S2	296.72±16.03	28.05±3.25	8.54±0.55
S3	BDL	16.14±0.22	5.87±0.66
S4	135.70±8.99	9.81±0.41	3.93±0.73
S5	206.06±0.51	10.12±0.64	8.58±3.64
S6	BDL	3.53±0.45	9.01±0.99
S7	136.24±5.23	3.53±0.54	9.01±0.99
S8	229.29±6.58	5.25±0.11	20.49±0.40
S9	89.57±11.43	7.41±0.26	10.48±6.02
S10	193.74±12.43	8.86±0.15	12.85±0.59

Table 17 shows the values of minimum, maximum and average activity concentrations of ^{40}K, ^{238}U and ^{232}Th in plant samples.

Table 17: Minimum, maximum and average activity concentrations of ^{40}K, ^{238}U and ^{232}Th in plant samples

	Average	Activity	Bq/kg
Nuclide	^{40}K	^{238}U	^{232}Th
Minimum	BDL	3.53±5.46	3.93±0.73
Maximum	296.72±16.03	28.05±3.25	20.49±0.40
CNST Average	172.71±5.34	9.91±0.89	9.81±1.76

Table 18, shows a comparison between the determined average activity concentrations of ^{40}K, ^{238}U and ^{232}Th in plant samples from the proposed site, with those from other areas of the world. It can be seen that the activity concentrations of the three radionuclides at the Centre were the second highest to those from Kudankulam, India and those from Angra, Brazil were the lowest.

The average values from the Centre were also compared with world average values as reported in the UNSCEAR report of 2000 [12] and are far lower than the word average values.

Table 18: Comparison of average activity concentrations in plant samples for ^{40}K, ^{238}U and ^{232}Th in this study to studies from sites from other countries

	Average	Activity	Bq/kg	Ref
Country/Region	^{40}K	^{238}U	^{232}Th	
Zambia (CNST)	172.71±5.34	9.91±0.89	9.81±1.76	-
Bangladesh (Chittagong)	134.95	1.26	3.66	[41]
Brazil (Angra)	0.01	BDL	BDL	[42]
India (Kudankulam)	947	1.72	BDL	[43]
World Average	420	33	45	[12]

Figure 19, shows that the activity concentrations of ^{40}K, ^{238}U, ^{232}Th in plant samples at every sample point were far lower than the world average values of $420\ Bq/kg$, $33\ Bq/kg$ and $45\ Bq/kg$ respectively [12].

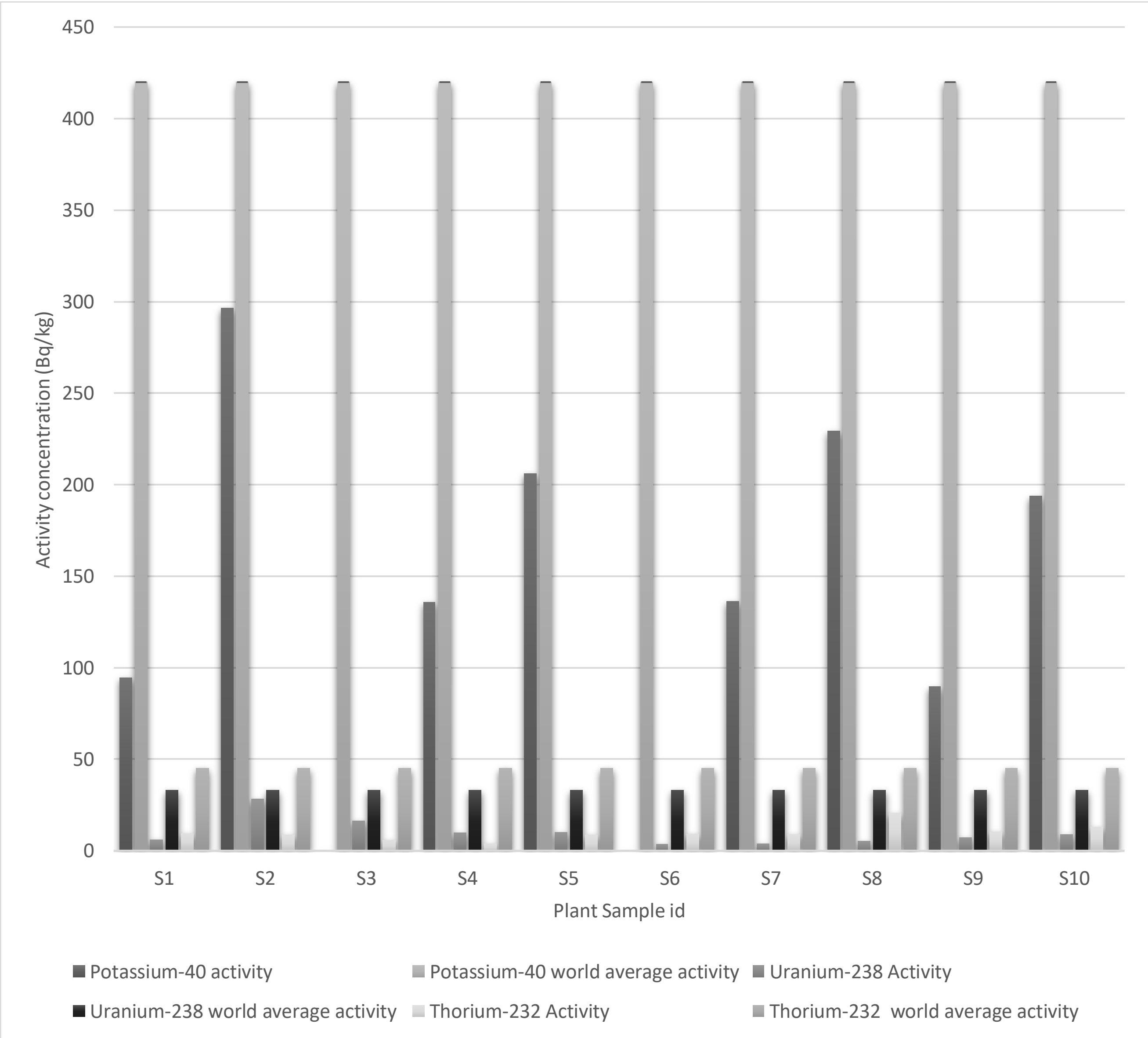

Figure 19: Activity concentrations of ^{40}K, ^{238}U and ^{232}Th of 10 plant samples

(b) Determined ADR, AED, H_{ex} and Ra_{eq} in plant samples

The calculated ADR values ranged from $7.23\ \mathrm{nGy/h}$ to $30.64\ \mathrm{nGy/h}$ with an average of $16.44 \pm 6.71\ \mathrm{nGy/h}$. The estimated AED values ranged from $0.01\ \mathrm{mSv/y}$ to $0.04\ \mathrm{mSv/y}$ while the average was $0.019 \pm 0.01\ \mathrm{mSv/y}$. The AED values are less than the annual dose radiation limit of $1\ \mathrm{mSv/y}$ as recommended by ICRP [52]. The H_{ex} values had a range of 0.04 to 0.17 with an average of 0.092 ± 0.04. The H_{ex} values at all sample points and average is less than 1 which is the non-hazardous limit of radiation recommended by ICRP [46]. Radium equivalent values had a range of $16.41\ \mathrm{Bq/kg}$ to $63.11\ \mathrm{Bq/kg}$ and the average is $34.89 \pm 13.41\ \mathrm{Bq/kg}$. Radium equivalent values at all sample points and average are less than $370\ \mathrm{Bq/kg}$ which is the recommended limit of activity set by ICRP for radiation to be considered not to be hazardous at an area [47]. Table 19 shows determined ADR, AED, H_{ex} and Ra_{eq} in plant samples

Table 19: Determined ADR, AED, H_{ex} and Ra_{eq} in plant samples.

Sample id	ADR (nGy/h)	AED (mSv/y)	H_{ex}	Ra_{eq} (Bq/kg)
S1	12.64	0.01	0.07	26.92
S2	30.64	0.04	0.17	63.11
S3	11.10	0.01	0.07	24.53
S4	12.63	0.01	0.07	28.88
S5	18.60	0.02	0.10	38.26
S6	7.23	0.01	0.04	16.41
S7	13.04	0.02	0.07	27.18
S8	24.71	0.03	0.14	52.20
S9	13.66	0.02	0.08	29.29
S10	20.15	0.02	0.11	42.15

The minimum, maximum and average values of ADR, AED, H_{ex} and Ra_{eq} in plant samples are shown in Table 20.

Table 20: Minimum, maximum and average ADR, AED, H_{ex} and Ra_{eq} in plant samples

Quantity	ADR (nGy/h)	AED (mSv/y)	H_{ex}	Ra_{eq} (Bq/kg)
Minimum	7.23	0.01	0.04	16.41
Maximum	30.64	0.04	0.17	63.11
CNST Average	16.44±6.71	0.02±0.01	0.09±0.04	34.89±13.41

As can be seen from Table 21, the values of ADR, AED, H_{ex} and Ra_{eq} at the site for the Centre were second highest to values from Kudankulam, India with those from Angra, Brazil being lowest. The average values of ADR and AED were also far lower than the world average values as reported by the UNSCEAR report of 2000 [12]. The world average value of H_{ex} is not available (-) but average value of H_{ex} at the Centre was the second highest. The average value of Ra_{eq} at the Centre was second highest among other sites but it was far less than the world average value of 58 Bq/kg [23].

Table 21: Comparison of ADR, AED, H_{ex}, R_{eq} in plant samples in this study to plant samples from sites of other Countries

Country/Region	ADR (nGy/h)	AED (mSv/y)	H_{ex}	Ra_{eq} (Bq/kg)	Ref
Zambia (CNST)	16.44±6.71	0.02±0.01	0.09±0.04	34.89±13.41	-
Bangladesh (Chittagong)	8.48	BDL	0.04	16.88	[41]
Brazil (Angra)	BDL	BDL	BDL	BDL	[42]
India (Kudankulam)	39.49	BDL	0.20	72.92	[43]
World Average	59	2.4	-	58	[12,23]

(i) Absorbed dose rate

The ADR in plants at all sample points were far below the world average value of 59 nGy/h [12] as in shown Figure 20.

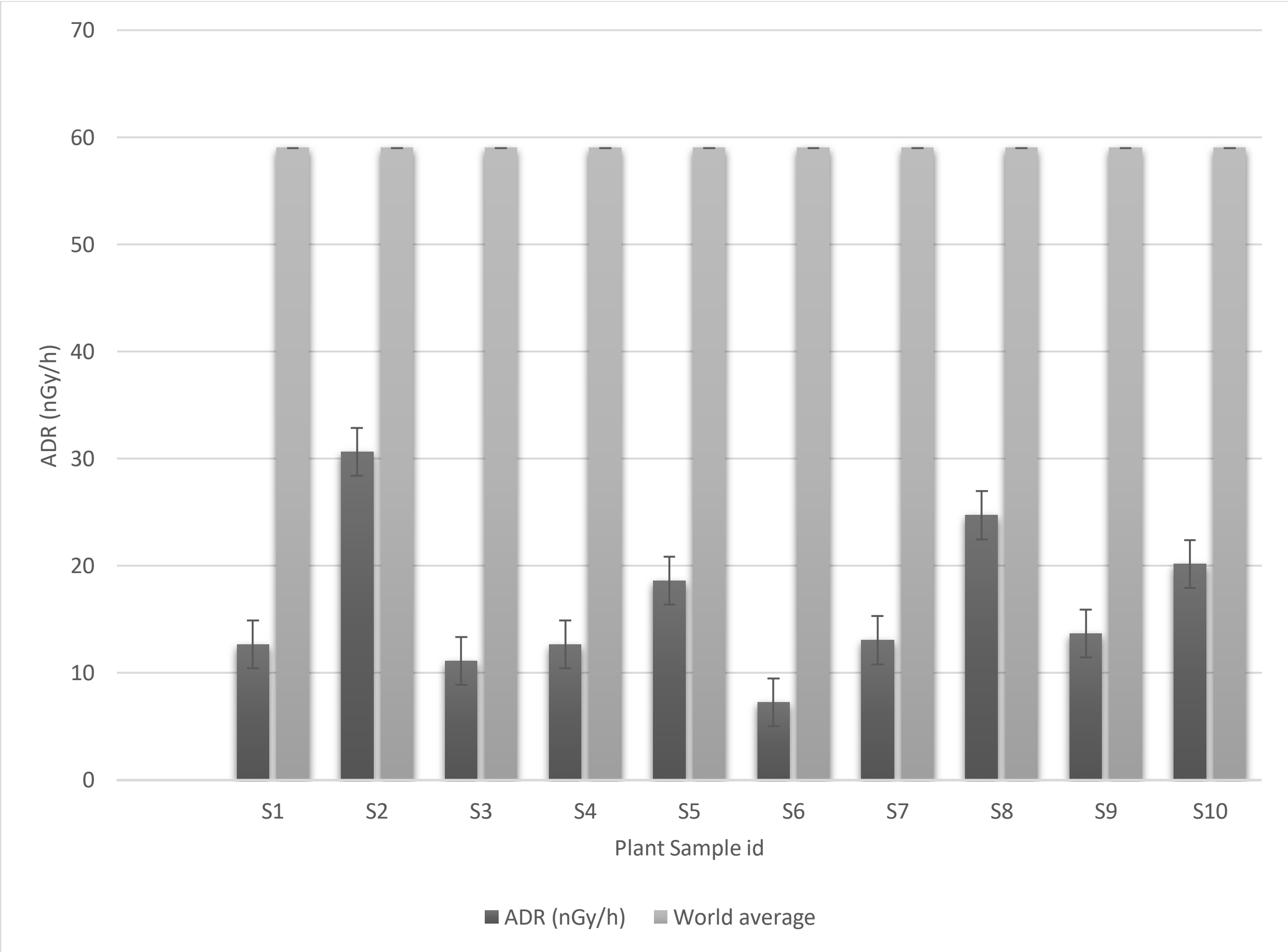

Figure 20: Absorbed dose rate of 10 plant samples

(ii) Annual effective dose rate

The AED rates at all sample points were far below the world average value of 2.40 mSv/y [12] and were less than the annual dose radiation limit of 1 mSv/y as recommended by ICRP [52] as shown in Figure 21 .

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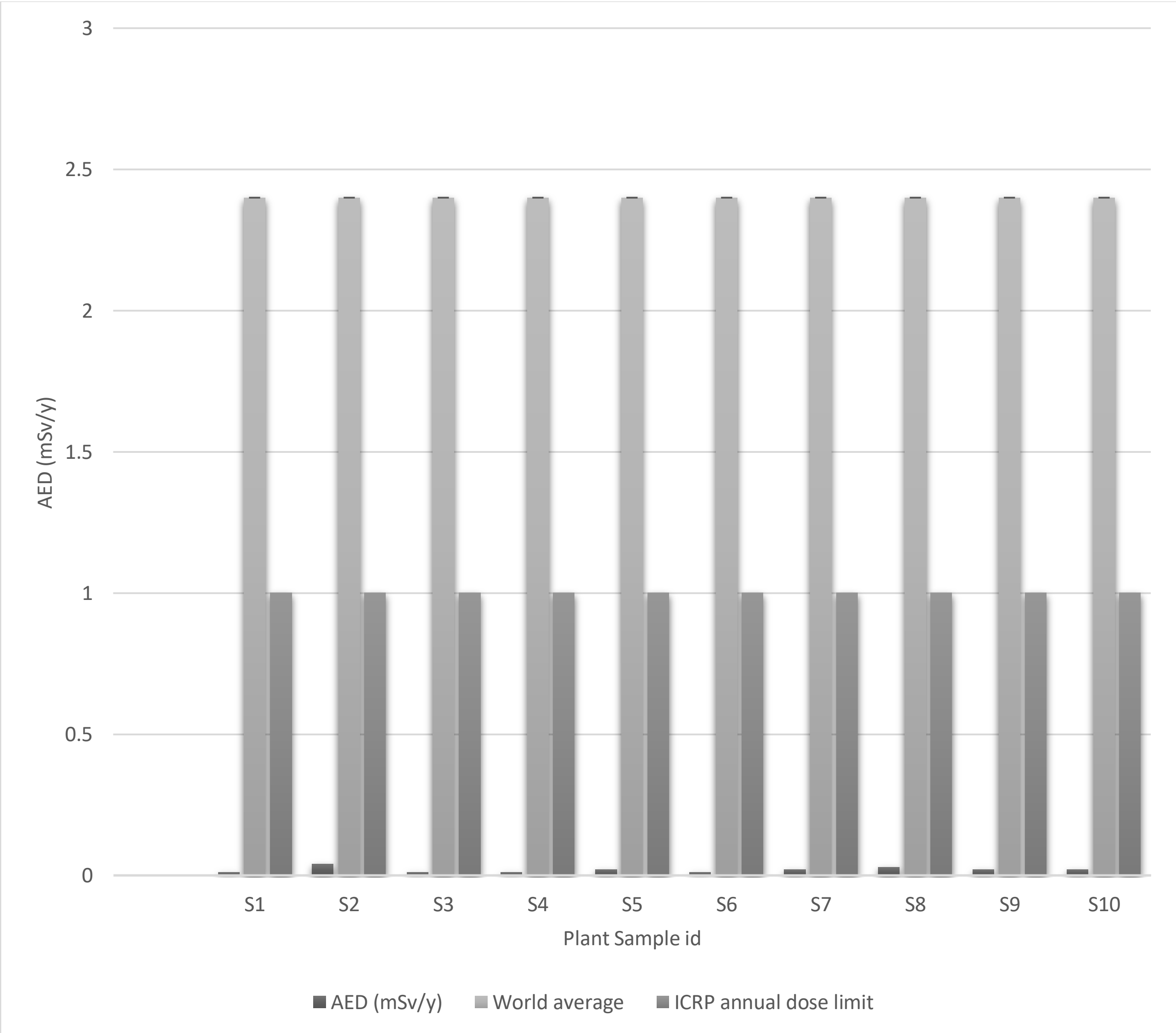

Figure 21: Annual effective dose rate of 10 plant sample

(iii) External hazard index

Figure 22 shows that H_{ex} at all sample points and were less than unity the non-hazardous limit of radiation recommended by ICRP [46].

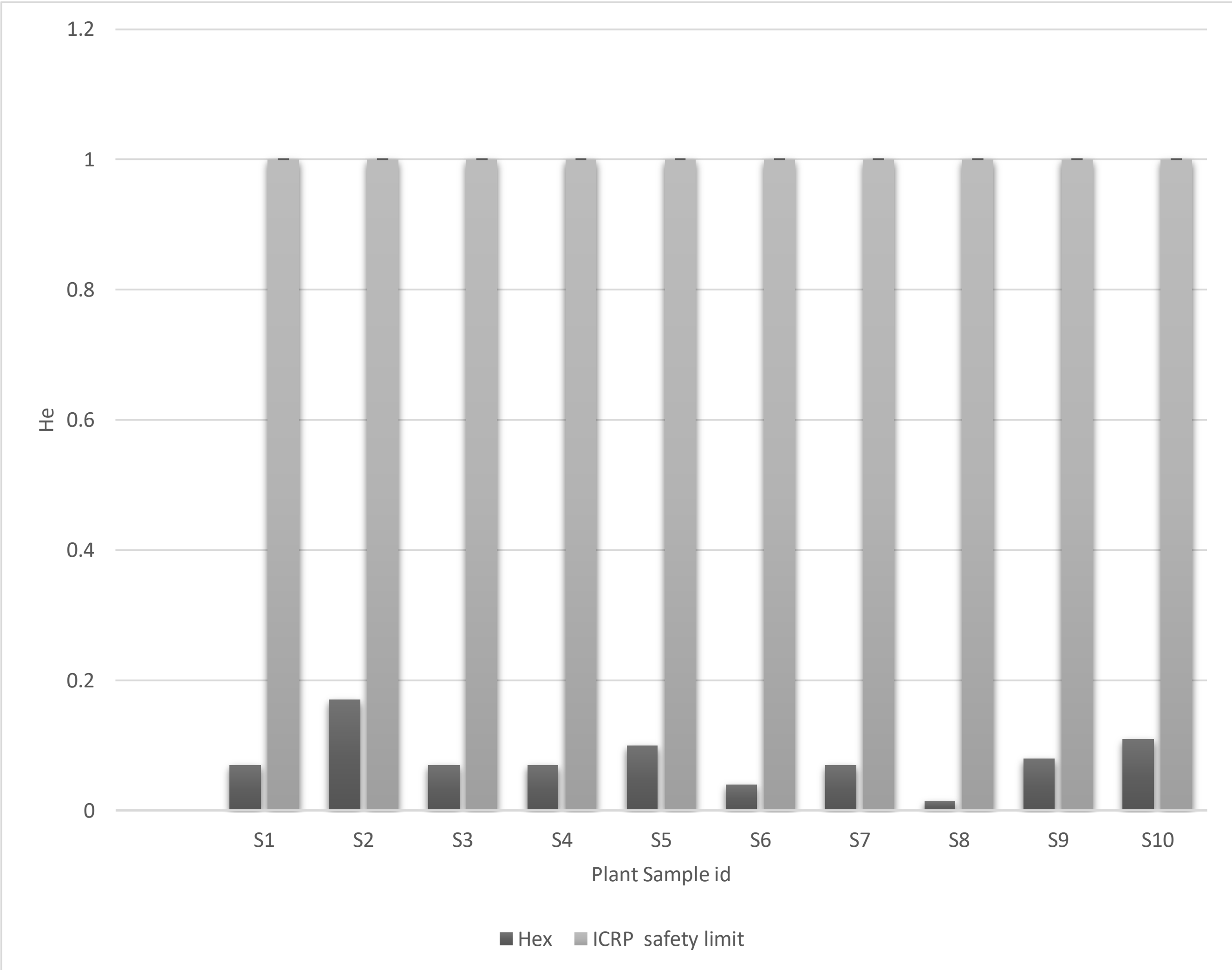

Figure 22: External hazard index of 10 plant samples

(iv) Radium equivalent

Figure 23 shows that the Ra_{eq} at all sample points were below both the world average 58 Bq/kg [23] and 370 Bq/kg the recommended limit of activity by ICRP for radiation to be non-hazardous at an area [47].

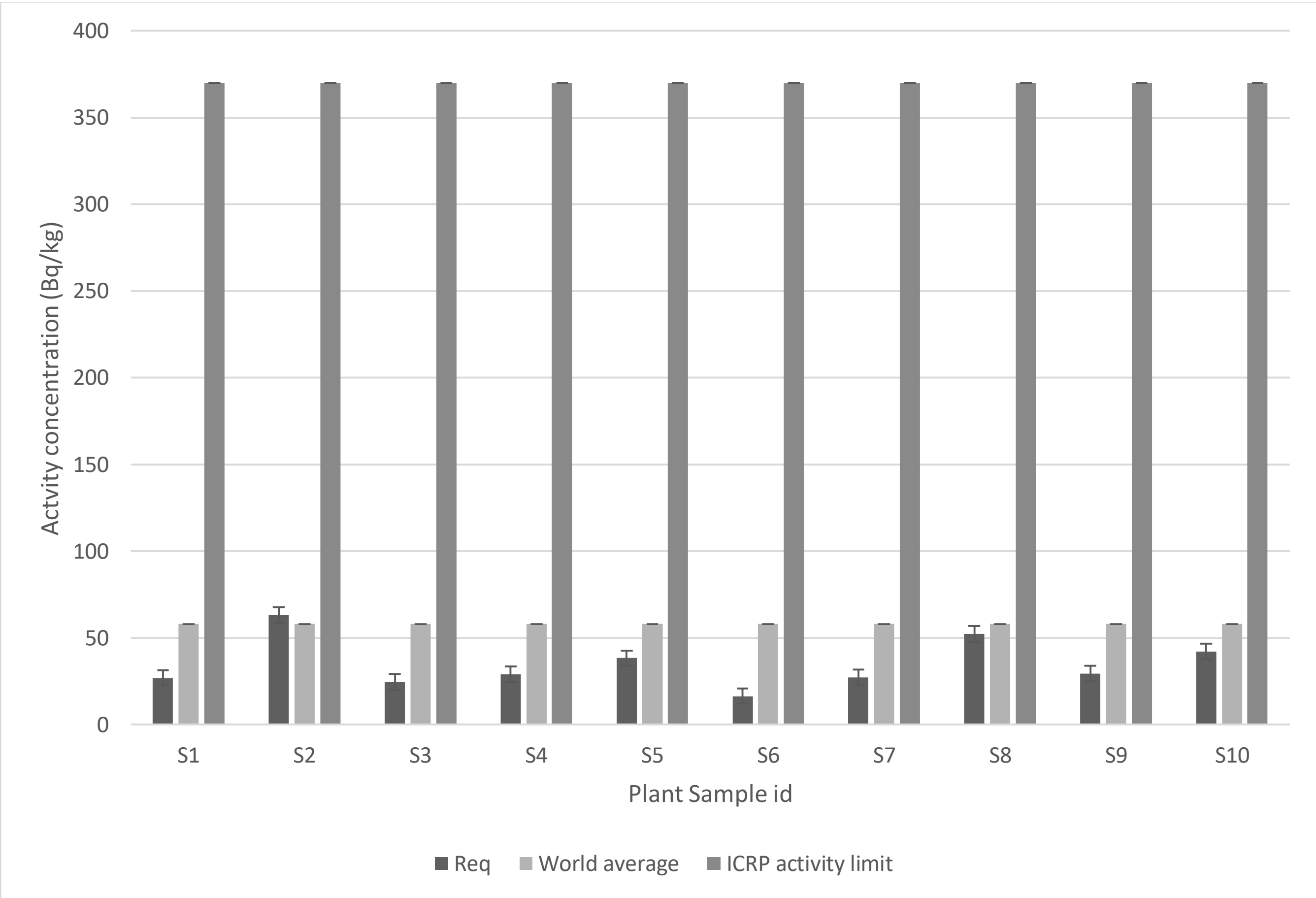

Figure 23:Radium equivalent of 10 plant samples

4.3 Measured activity concentrations in water samples

Table 22 gives measurements of activity concentrations of decay series of ^{238}U and ^{232}Th from which their activity concentrations were calculated and ^{40}K for water samples.

Table 22: Measured specific activity concentrations of ^{40}K, ^{214}Pb, ^{214}Bi, ^{228}Ac and ^{212}Pb

Sample id	^{40}K (Bq/kg)	^{238}U Series	(Bq/kg)	^{228}Ac Series	(Bq/kg)
		^{214}Pb	^{214}Bi	^{232}Ac	^{212}Pb
W1	43.47±0.26	BDL	BDL	BDL	BDL
W2	41.28±0.21	8.77±1.41	14.31±1.29	BDL	4.08±1.04
W3	54.60±0.35	BDL	15.75±0.18	BDL	5.41±0.35
W4	36.67±0.22	BDL	14.80±0.39	BDL	8.71±9.31
W5	48.06±0.20	9.07±0.94	BDL	BDL	BDL

(a) Determined activity concentrations of ^{40}K, ^{238}U and ^{232}Th in water samples

The minimum activity concentrations of ^{40}K was $36.67 \pm 0.22\ Bq/l$ while the maximum was $54.60 \pm 0.35\ Bq/l$ and the average was $44.82 \pm 0.05\ Bq/l$. The minimum activity concentration of ^{238}U was below detectable limit while the maximum was $11.54 \pm 0.13\ Bq/l$ and the average was $7.83\ \pm 0.32\ Bq/l$. The minimum activity concentration of ^{232}Th was below detectable limit while the maximum was $4.35 \pm 0.46\ Bq/l$ and the average was $3.03 \pm 0.22\ Bq/l$. Table 23, gives the determined activity concentrations of ^{40}K ,^{238}U and ^{232}Th in water samples.

Table 23: Determined activity concentrations of ^{40}K ,^{238}U and ^{232}Th in water samples.

Sample ID	^{40}K (Bq/kg)	^{238}U (Bq/kg)	^{232}Th (Bq/l)
W1	43.47±0.26	BDL	BDL
W2	41.28±0.21	11.54±0.13	2.04±0.52
W3	54.60±0.35	7.87±0.90	2.7±0.17
W4	36.67±0.22	7.4±0.19	4.35±0.46
W5	48.06±0.21	4.53±0.47	BDL

Table 24, shows the values of minimum, maximum and average activity concentrations of ^{40}K, ^{238}U and ^{232}Th in water samples.

Table 24: Minimum, maximum and average activity concentrations for ^{40}K , ^{238}U and ^{232}Th in water samples.

	Mean	Activity	Bq/l
Nuclide	^{40}K	^{238}U	^{232}Th
Minimum	36.67±0.22	BDL	BDL
Maximum	54.60±0.35	11.54±0.13	4.35±0.47
CNST Average	44.82±0.05	7.83±0.32	3.03±0.22

The determined average values of activity concentrations of ^{40}K, ^{238}U and ^{232}Th in water samples in the dam near the proposed site for the CNST were compared with those from areas of other countries in Table 25. The activity concentrations of the three radionuclides at Centre are the second highest among other sites, although they were far lower than the world average values as reported by the UNSCEAR report of 2000 [12].

Table 25: Comparison of average activity concentrations in water samples of ^{40}K, ^{238}U and ^{232}Th in this study to studies from sites from other countries.

	Mean	Activity	Bq/l	Ref
Country/Region	^{40}K	^{238}U	^{232}Th	
Zambia (CNST)	44.82±0.05	7.83±0.32	3.03±0.22	-
Bangladesh (Rooppur)	379.60	175.50	247.8	[39]
Ghana (GHARR-1)	10.75	0.60	2.13	[40]
Brazil (Angra)	3.7×10^{-3}	BDL	BDL	[42]
World average	420	33	45	[12]

Figure 24, shows that the activity concentrations of ^{40}K, ^{238}U, ^{232}Th in water samples at all sample points were below the world average values of $420\ Bq/l$, $33\ Bq/l$ and $45\ Bq/l$ respectively.

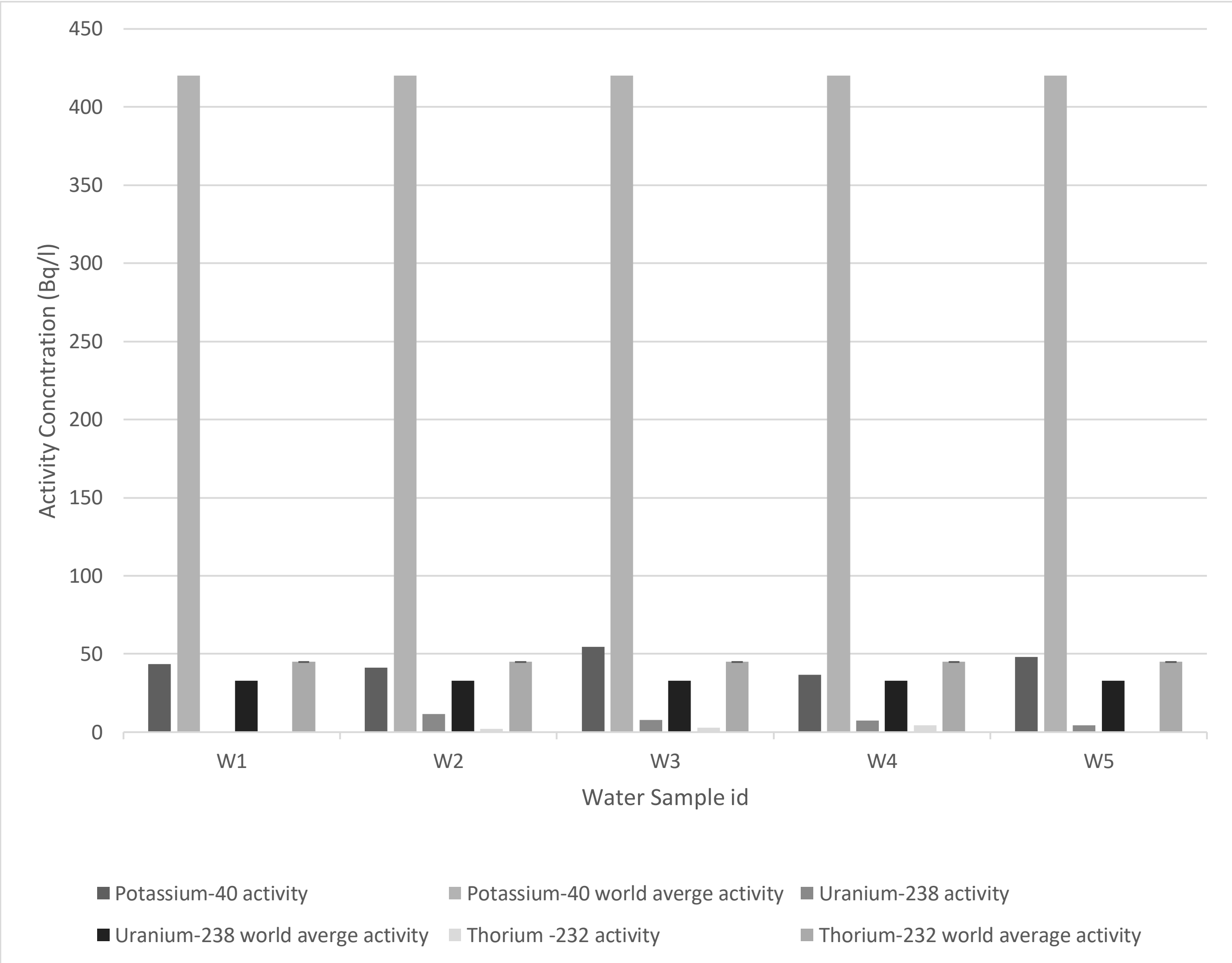

Figure 24: Activity concentrations of ^{40}K, ^{238}U and ^{232}Th of 5 water samples

(b) Determined ADR, AED, H_{ex} and Ra_{eq}

The calculated ADR values ranged from 1.81 nGy/h to 8.32 nGy/h and the average was 8.32± 2.52 nGy/h. The values of AED ranged from below detectable limit to 0.01 mSv with an average of 0.01 ± 0.00 mSv/y. The AED and was far below the ICRP recommended annual radiation dose limit of 1 mSv/y [52]. The H_{ex} ranged from below detectable limit to 0.04 and the average of 0.03 ± 0.01. The H_{ex} is less than unity the recommended non-hazardous limit of radiation set by ICRP [46]. The determined Ra_{eq} values ranged from below detectable limit to 17.63 Bq/kg with an average of 14.56 ± 3.70 Bq/kg. Radium equivalent was less than 370 Bq/kg the recommended non-hazardous limit of activity set by ICRP [47]. Table 26, shows the determined ADR, AED, H_{ex} and Ra_{eq}.

Table 26: Determined ADR, AED, H_{ex} and Ra_{eq}

S/NO	Sample id	ADR (nGy/h)	AED (mSv/y)	Hex	Ra_{eq} (Bq/kg)
1	W1	1.81	BDL	BDL	BDL
2	W2	8.32	0.01	0.04	17.63
3	W3	7.59	0.01	0.01	15.93
4	W4	7.65	0.01	0.04	16.44
5	W5	4.10	BDL	0.02	8.23

Table 27, shows a comparison of ADR, AED, H_{ex}, Ra_{eq} in water samples in this study to those of other sites from other countries.

Table 27: Minimum, maximum and average ADR, AED, Hex and Raeq

Quantity	ADR (nGy/h)	AED (mSv/y)	H_{ex}	Ra_{eq} (Bq/l)
Minimum	1.81	0.01	0.01	8.23
Maximum	8.32	0.01	0.04	17.63
CNST Average	5.90±2.52	0.01±0.00	0.03±0.01	14.56±3.70

Table 28, shows a comparison of ADR, AED, H_{ex}, Ra_{eq} in Water samples in this study to those from sites of other countries. The average values of ADR, AED, H_{ex} and Ra_{eq} at the site for the Centre were the second highest among other sites from other Countries. The average values of ADR and AED in water were also far lower than the world average values as reported by the UNSCEAR report of 2000 [12]. The average value of H_{ex} in water samples is not available while the average value of Ra_{eq} at the Centre was far less than the world average value of 58 Bq/kg [23].

Table 28: Comparison of ADR, AED, Hex, Ra_{eq} in water samples in this study with studies from other parts of the world.

Country/Region	ADR (nGy/h)	AED (mSv/y)	H_{ex}	Ra_{eq} (Bq/l)	Ref
Zambia (CNST)	5.90±2.52	0.01±0.00	0.03±0.01	14.56±3.70	-
Bangladesh (Rooppur)	250.79	0.30	1.50	558.78	[39]
Ghana (GHARR-1)	0.09	0.53	BDL	4.4	[40]
Brazil (Angra)	BDL	BDL	BDL	BDL	[42]
World average	59	2.40	-	58	[12,23]

(i) Absorbed dose rate

Figure 25, shows that the absorbed dose rate values at all sample points were below the world average value of 59 nGy/h [12].

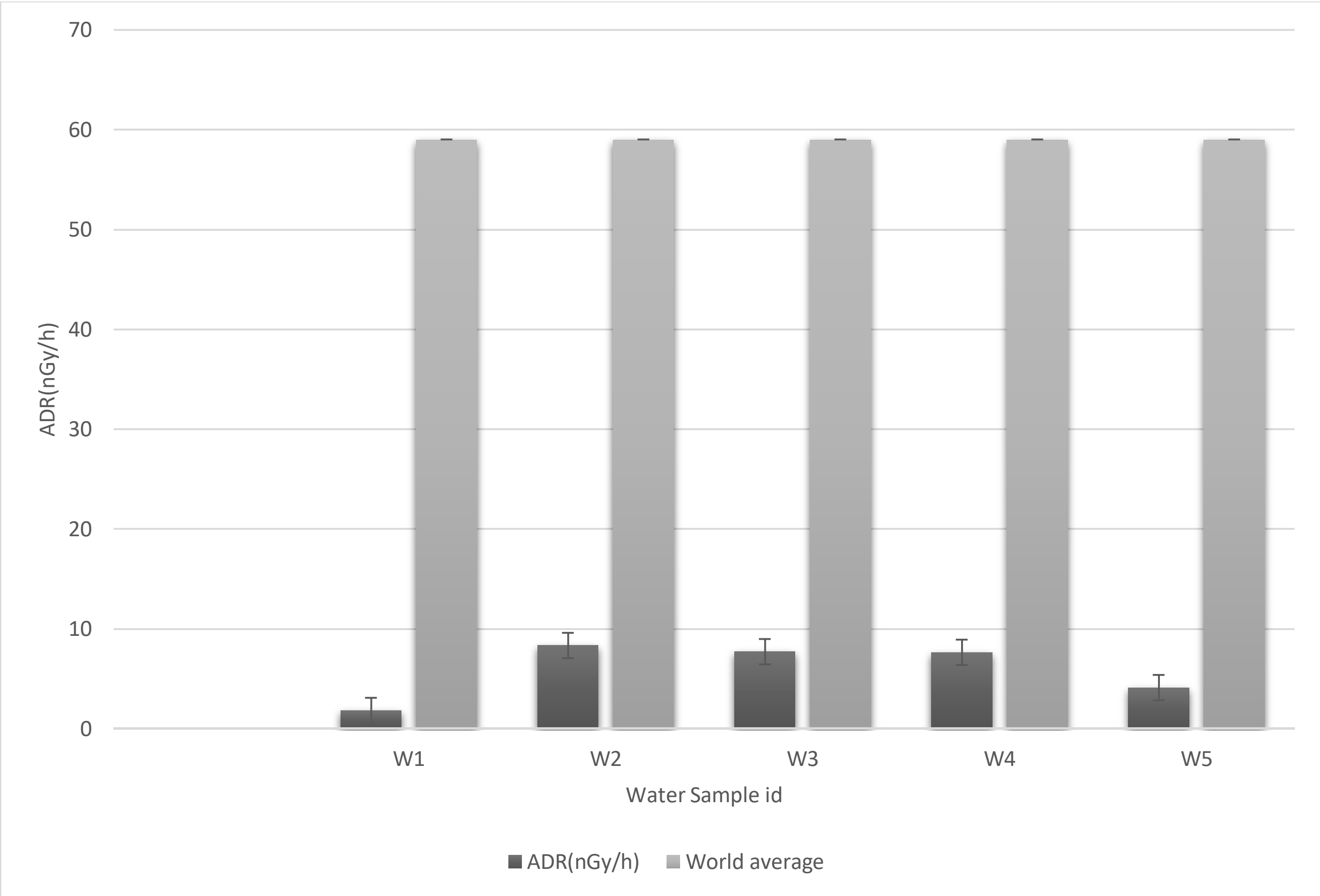

Figure 25: Absorbed dose rate of 5 water samples

(ii) Annual effective dose

Figure 26, shows that the AED at all sample point was far below the world average value of 2.40 mSv/y and was far below the recommended annual radiation dose limit of 1 mSv/y by ICRP [52].

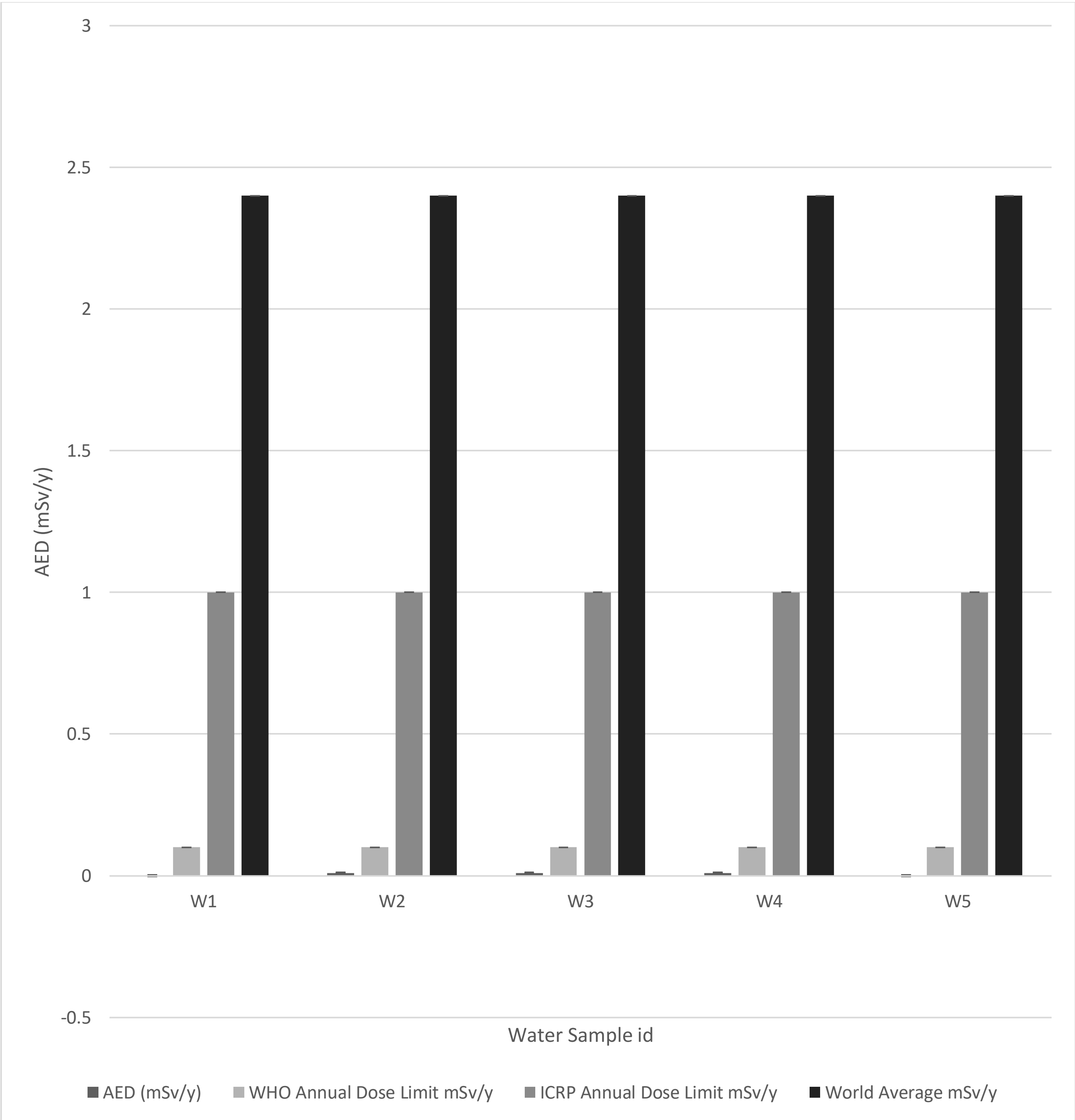

Figure 26: Annual effective dose rate of 5 water samples

(iii) External hazard index

Figure 27, shows that the values of H_{ex} at all sample points were less than unity the recommended non-hazardous limit of radiation set by ICRP [46].

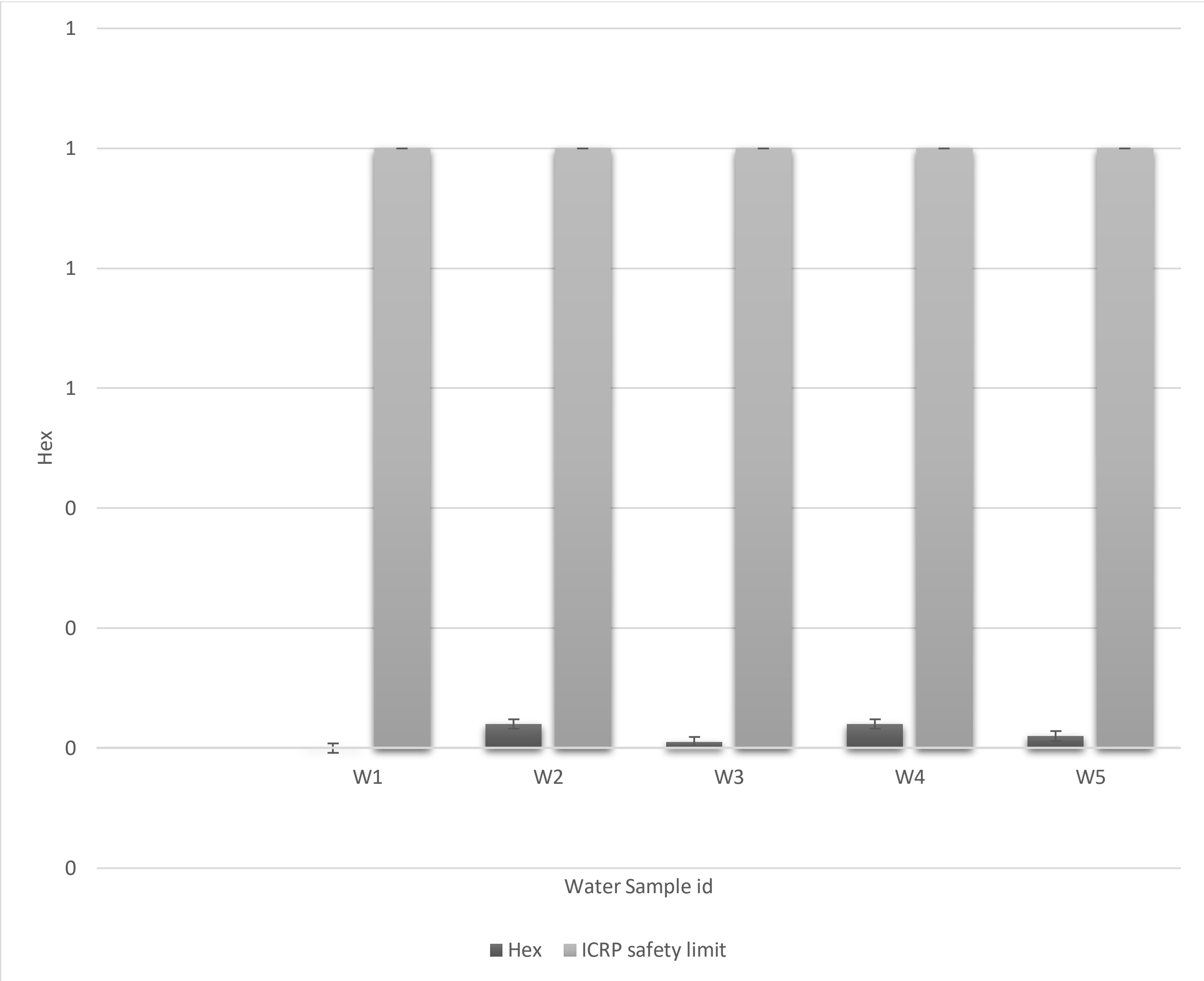

Figure 27: External hazard index of 5 water samples

(iv) Radium equivalent

Figure 28, shows that the radium equivalent was less than both the world average value of 58 Bq/kg [23] and 370 Bq/kg the recommended non-hazardous limit of activity set by ICRP [47].

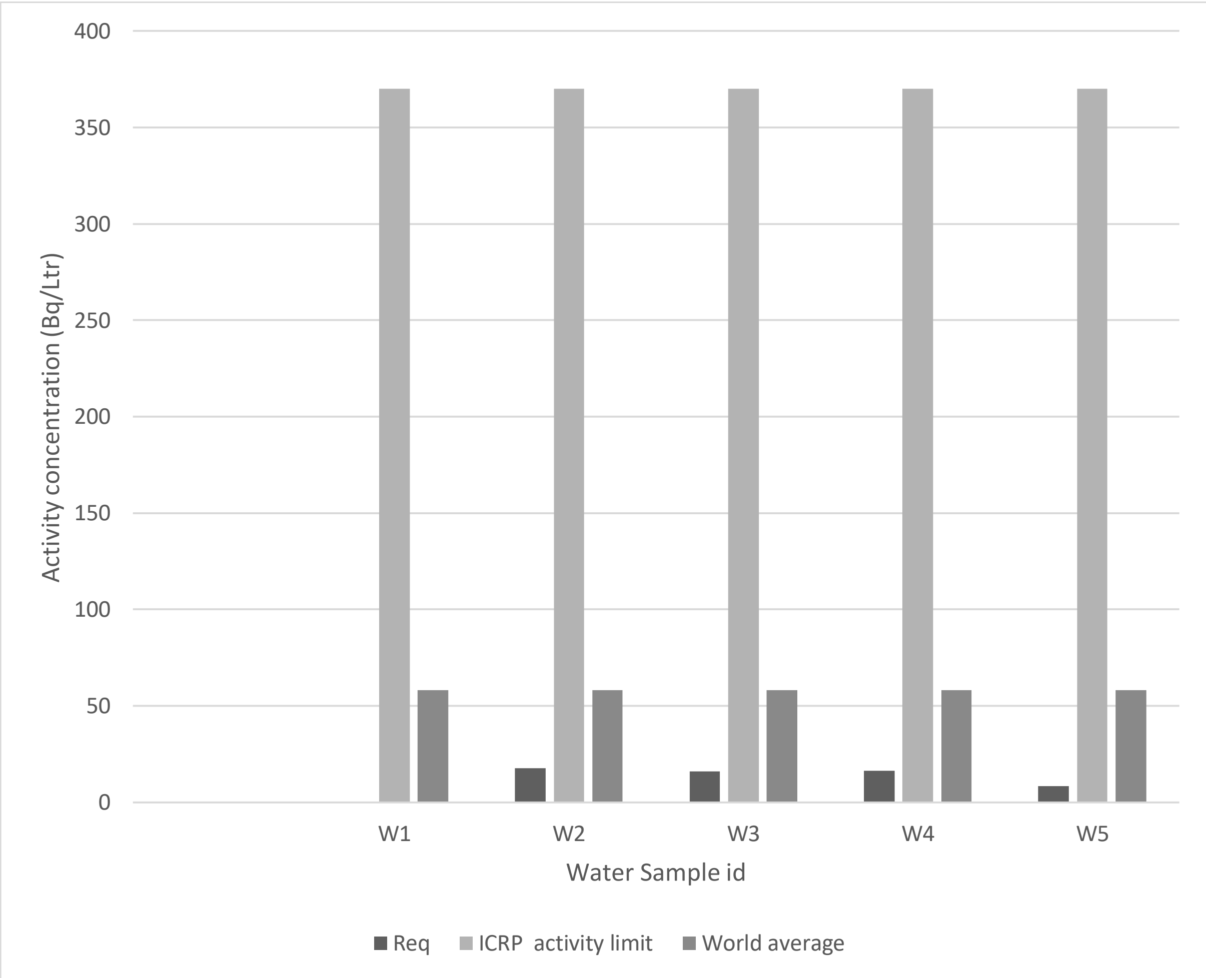

Figure 28: Radium equivalent of 5 water samples

CHAPTER FIVE

5.0 DISCUSSION

This Chapter discusses the findings in relation to the four objectives of the research study namely: to evaluate the activity concentrations of natural radionuclides ^{238}U, ^{232}Th and ^{40}K in soil samples, plant samples from the site where the CNST will be constructed and water samples from the dam nearby, to determine the ADR, AED, H_{ex} and Ra_{eq} from the measured activity concentrations, to create baseline data of activity concentration, ADR, AED, H_{ex} and Ra_{eq} for the site and to compare the obtained results with results of sites from other `countries were similar work was undertaken.

(a) Evaluated values of activity concentrations of ^{40}K, ^{238}U, ^{238}Th in soil, plant samples from the site and water samples from a nearby dam.

Radioactivity levels in soil samples were measured. The activity concentration values of ^{40}K ranged from 66.84 ± 3.30 Bq/kg to 150.45 ± 9.51 Bq/kg, with an average of 120.39 ± 5.37 Bq/kg. The activity concentration values of ^{238}U ranged from 2.36 ± 0.14 Bq/kg to 9.21 ± 0.65 Bq/kg, with an average value of 4.75 ± 0.23 Bq/kg and those of ^{232}Th ranged from 2.06 ± 0.22 Bq/kg to 12.13 ± 0.63 Bq/kg, with an average value of 9.63 ± 0.35 Bq/kg. Potassium-40 had the highest values of activity concentrations among the three radionuclides of interest. The values of activity concentration of ^{40}K varied greatly within the site with sample BH11 having the lowest activity while sample BH 2 had the highest activity. The high levels of ^{40}K might be attributed to the previous application of inorganic fertilizers rich in potassium to enhance crop production since the site was used for farming and is surrounded by land still being used for farming. The values of activity concentration for both ^{238}U and ^{232}Th did not vary much, they were almost in the same range. The activity concentrations of ^{40}K, ^{238}U, ^{238}Th in soil samples are below the reference levels values of activity concentration of 370 Bq/kg, 25 Bq/kg and 30 Bq/kg respectively [12]. It was observed that natural radioactivity in soil samples is normal as expected.

The levels of radioactivity in plant samples were also measured. The activity concentration values of ^{40}K ranged from below detectable limit to 296.76 ± 16.03 Bq/kg, with an average of 172 ± 5.34 Bq/kg. The activity concentration values of ^{238}U ranged from 3.53 ± 5.46 Bq/kg to 28.08 ± 3.25 Bq/kg, with an average of 9.91 ± 0.89 Bq/kg and ^{232}Th had a range of 3.93 ± 0.73 Bq/kg to 20.49 ± 0.40 Bq/kg, with an average of 9.81 ± 1.76 Bq/kg. The average activity concentration of ^{40}K was the highest among the three radionuclides and varies greatly, from below detectable limit for sample S3 and S6 to S8 having the highest activity concentration.

The high levels of ^{40}K in plant samples might be attributed to the non-specific element uptake process of essential nutrients by plants from soils [55]. Since ^{40}K and stable potassium are similar they are both up taken by plants and this may be the reason for the high values of ^{40}K which accumulated over a long period of time [55]. However stable potassium is one of the essential elements needed for proper plant growth and is added to soils to increase its fertility in the form of chemical fertilizers [55]. The obtained activities for both ^{238}U and ^{232}Th did not vary much and were almost in the same range. The activity concentrations of ^{40}K, ^{238}U, ^{238}Th in plant samples are below reference levels of activity concentration of 370 Bq/kg,25 Bq/kg and 30 Bq/kg respectively [12]. This shows that natural background radiation from plant samples is normal.

Water samples had their radioactivity levels measured. The minimum activity concentration value of ^{40}K was 36.67 ± 21.99 Bq/kg while the maximum was 54.60 ± 34.90 Bq/kg, with an average of 44.82 ± 0.05 Bq/kg. The activity concentration values of ^{238}U ranged from below detectable limit (BDL) to 11.53 ± 1.35 Bq/kg, with an average of 7.83 ± 0.32 Bq/kg while those for ^{232}Th ranged from BDL to 4.35 ± 4.65 Bq/kg with an average of 3.03 ± 0.22 Bq/kg. The high levels of ^{40}K in water in the dam are mostly due to inorganic fertilizers rich in potassium used on farms surrounding the dam. The fertilizer in soils from farm lands near the dam eventually end up in the dam especially during the rainy season when water from land is drained into the dam with a lot of dissolved solids which include chemical fertilizers. Though the average activity concentration of ^{40}K is high the water is still safe for domestic use since the level of ^{40}K in our bodies does not accumulate to hazardous levels because our bodies metabolism controls its levels [48]. The average activity concentration value of ^{232}Th was slightly above the guidance level of 1 Bq/kg, the radioactivity limit recommended for drinking water by the World Health Organisation (WHO) [48]. The average activity concentration value of ^{238}U was below the guidance level of 10 Bq/kg limit set for drinking water by (WHO) [48]. The levels detected in the dam water meet the exemption levels, hence can be deemed safe for domestic use.

(b) Determined values of ADR, AED, H_{ex} and Ra_{eq} in soil, plant samples from the site and water samples from a nearby dam.

The determined values of ADR in soil samples ranged from 10.85 nGy/h to 14.90 nGy/h with an average of 13.00 ± 1.32 nGy/h. The estimated values of AED ranged from 0.01 mSv/y to 0.02 mSv/y with an average of 0.02 ± 0.01 mSv/y was far below the annual dose limit of 1 mSv/y recommended by ICRP [52]. The H_{ex} values in soil samples ranged from 0.06 to 0.09 with an average of 0.07 ± 0.01 which was far below unity the non-hazardous radiation safety limit recommended by ICRP [46]. Radium equivalent values ranged from 21.80 Bq/kg to 31.70 Bq/kg with an average of 27.33 ± 3.09 Bq/kg. The values of Ra_{eq} at all sample points and the average were below the maximum non-hazardous activity concentration value recommended by ICRP of 370 Bq/kg [46]. This radiological data indicates that natural background radiation from soils at the site is normal.

In plant samples determined ADR values ranged from 7.23 nGy/h to 30.64 nGy/h with an average of 16.44 ± 6.71 nGy/h. The determined AED values ranged from 0.01 mSv/y to 0.04 mSv/y with an average of 0.019 ± 0.01 mSv/y which was below the annual exposure limit to radiation of 1 mSv/y as recommended by ICRP [52]. The determined H_{ex} had a range of 0.04 to 0.17 with an average of 0.09 ± 0.04 which was below unity the non-hazardous limit of radiation set by ICRP [46]. The Ra_{eq} values ranged from 16.41 Bq/kg to 63.11 Bq/kg with an average of 34.89 ± 13.41 Bq/kg which was below 370 Bq/kg the non-hazardous activity concentration limit set by ICRP [47]. The obtained radiological data shows that natural background radiation from plants at the site is non-hazardous.

For water samples the determined ADR, values ranged from 1.81 nGy/h to 8.32 nGy/h with an average of 5.90 ± 2.52 nGy/h. The determined AED values ranged from below detectable limit to 0.01 mSv/y with an average of 0.01 ± 0.00 mSv/y. The AED values at all sample points together with the average are far below the annual exposure limit of 1 mSv/y limit set by ICRP [52] and the individual dose criterion (IDC) set by WHO in Guidelines for drinking water quality (GDWQ) which is 0.1 mSv/y [48]. The natural background radiation in water from the dam near the proposed site for the Centre has no radiological hazards to people and environment at the present time.

(c) **Baseline data of activity concentration, ADR, AED, H_{ex} and Ra_{eq} for the area pre-operational**

The baseline data of the values of activity concentration, ADR, AED, H_{ex}, Ra_{eq} and the average values for all samples has been created in tables given in Chapter four of the study. The tables of activity concentration for the three types of samples are 9, 12.16,19,23 and 26. The tables of radiological hazards for the three types of samples are 12, 19 and 26.

(d) Comparison of obtained average results with average values from selected parts of the world were similar work has been undertaken and world average values

The average values of activity concentration, ADR, AED, H_{ex}, Ra_{eq} for soil, plant samples at the site and water samples from the dam near the proposed site for the Centre were compared with average values from sites from other countries. These are sites where studies were undertaken to create baseline data for future reference since the sites were earmarked for the construction of either research reactors or nuclear power plants. The average values of activity concentration, ADR, AED, H_{ex}, Ra_{eq} for soil, plant at the site and water samples from a dam near the site were also compared with world average values.

The average values of activity concentrations of ^{40}K, ^{238}U and ^{232}Th in soil samples were 120.39 ± 5.37 Bq/kg, 4.75 ± 0.23 Bq/kg and 9.63 ± 0.35 Bq/kg respectively. It can be seen that these activities are far below world average values of activity concentration for ^{40}K, ^{238}U, ^{232}Th, which are 420 Bq/kg, 33 Bq/kg and 45 Bq/kg respectively [12]. The average activity concentrations from the Centre were compared with those from sites from other countries. The observed average values of activity concentration in soil samples from the Centre were below those from sites from other countries.

The average values of ADR, AED, H_{ex}, Ra_{eq} in soil samples were 13.00 ± 1.32nGy/h, 0.02 ± 0.01mSv/y, $0.07 0.01 \pm$ and 27.33 ± 3.09 Bq/kg respectively. The average values of ADR, AED in soil samples are below world average values of 59 nGy/h and 2.40 mSv/y respectively according to UNSCEAR report of 2000 [12]. The world average value of H_{ex} is not available although the average H_{ex} in soils samples was below unity the non-hazardous index level of radioactivity. The average value of Ra_{eq} in soils was below the world average value of 58 Bq/kg [23]. The radiological hazards in the soils were also compared with those from other Countries. The radiological hazards at the Centre are below those from sites from other countries.

In Plant samples from the Centre all the three radionuclides were present with average values of activity concentration of ^{40}K, ^{238}U, ^{232}Th, being 172.71 ± 5.34 Bq/kg, 9.91 ± 0.89Bq/kg and 9.81 ± 1.76 Bq/kg respectively. These values of activity concentration of ^{40}K, ^{238}U, ^{232}Th in plant samples from the Centre were below the world average values of 420 Bq/kg, 33 Bq/kg and 45 Bq/kg as reported by UNSCEAR report of 2000 [12]. A comparison was made with measurements from other areas of the world. All three radionuclides were detected in Plant samples from the Centre with ^{40}K having the highest activity concentration, although it was far lower than the result at Kudankulam in India that was the highest.

The average values of ADR, AED, H_{ex}, Ra_{eq} in plant samples were 16.44 ± 6.71 nGy/h, 0.02 ± 0.01 mSv/y, 0.09 ± 0.04 and 34.89 ± 1.76 Bq/kg respectively. The average values of ADR, AED in plant samples were below world average values of 59 nGy/h and 2.40 mSv/y respectively [12]. The average value of H_{ex} is not available but it was below unity the non-hazardous index level of radioactivity. The average value of Ra_{eq} was below the world average value of 58 Bq/kg [23]. When radiological hazards were compared with those from other countries. It was observed that radiological hazards at the Centre in plant samples were almost in the same range as those from sites of other countries except for Brazil at Agra were all radiological hazards were below detectable limit.

The average values of activity concentration in water samples of ^{40}K, ^{238}U, ^{232}Th were 44.82 ± 0.05Bq/kg, 7.83 ± 0.32 Bq/kg and 3.03 ± 0.22 Bq/kg respectively. The average values of activity concentrations of ^{40}K,^{238}U ,^{232}Th in water samples were below world average values of 420 Bq/kg, 33 Bq/kg, 45 Bq/kg respectively [12]. The average values of activity concentration in water samples were compared with those from areas from other countries. The average values of activity concentration for water samples from the dam near the Centre had the second highest average activity while those from Bangladesh at Rooppur had the highest activity.

The average values of radiological hazards of ADR, AED, H_{ex}, Ra_{eq} in water samples were 5.90 ± 2.52 nGy/h, 0.01 ± 0.00 mSv/y, 0.01 ± 3.70 and $14.56 \pm$ Bq/kg respectively. The average values of ADR, AED in water samples were below world average value of 59 nGy/h and 2.40 mSv/y respectively, according to UNSCEAR report of 2000 [12]. The Ra_{eq} was below the world average value of 58 Bq/kg [23] while world average value of H_{ex} is not available. Radiological hazards at the Centre were even compared with those at sites from other countries. The water from the dam near the proposed site for the Centre had the second highest

ADR, AED, H_{ex}, and Ra_{eq}. It was observed that all radiological hazards were below the non-hazardous limits of radiation.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.0 Conclusion

The study obtained the activity concentrations of the three main radionuclides, ^{40}K, ^{238}U, ^{232}Th of concern together with their average activity concentrations for soil, plant and water samples from a dam near the proposed site for the Centre. The study has also obtained the ADR, AED, H_{ex} and Ra_{eq} for all the mentioned samples together with their average values.

The obtained activity concentrations of ^{40}K,^{238}U,^{232}Th in soil samples and were in the range of $(66.84 \pm 3.30 \text{ to } 150 \pm 9.51)$ Bq/kg, $(2.36 \pm 0.14 \text{ to } 9.21 \pm 0.65)$ Bq/kg and $(2.06 \pm 0.22 \text{ to } 12.13 \pm 0.63)$ Bq/kg respectively. The obtained average activity concentrations of ^{40}K ,^{238}U,^{232}Th which are 120.39 ± 5.37 Bq/kg, $4.750.23 \pm$ Bq/kg and 9.63 ± 0.35 Bq/kg respectively. The average values of activity concentrations of ^{40}K, ^{238}U and ^{232}Th are below both the reference values of 370 Bq/kg, 25 Bq/kg, 30 Bq/kg and world average values of 420 Bq/kg, 33 Bq/kg and 45 Bq/kg respectively [12]. The ADR values in the soil samples were found to be in the range of (10.85 to 14.90) nGy/h with an average of 13.00 ± 1.32 nGy/h which was below the world average of 59 nGy/h [12]. The AED values had a range of (0.01 to 0.02) mSv/y with an average of 0.02 ± 0.1 mSv/y. This was far below the world average value of 2.40 mSv/y and is minimal with respect to the annual dose limit of 1 mSv/y as recommended by ICRP [52]. The H_{ex} ranged between (0.06 to 0.09) with an average of 0.07 ± 0.01. The average H_{ex} was far less than unity indicating the site has normal background radiation [46]. The Ra_{eq} estimated for the soil samples ranged from (21.80 to 31.70) Bq/kg with an average value of 27.33 ± 3.09 Bq/kg. The estimated average value of Ra_{eq} is far lower than both world average value of 58 Bq/kg [23] and the recommended safe limit value of 370 Bq/kg , recommended by ICRP [47].

The measured activity concentrations for ^{40}K,^{238}U,^{232}Th in plant samples which were in the range of (BDL to 296 ± 16.03) Bq/kg, $(3.53 \pm 5.46 \text{ to } 28.05 \pm 3.25)$ Bq/kg and $(3.93 \pm 0.73 \text{ to } 20.49 \pm 0.40)$ Bq/kg respectively. The obtained average activity concentrations of ^{40}K ,^{238}U, ^{232}Th were found to be 172 ± 5.34 Bq/kg, 9.91 ± 3025Bq/kg and 9.81 ± 1.76 Bq/kg respectively. The average values of activity concentrations of ^{40}K, ^{238}U and ^{232}Th are below both reference values of 370 Bq/kg, 25 Bq/kg, 30 Bq/kg and the world average values of 420 Bq/kg, 33 Bq/kg and 45 Bq/kg respectively [12]. The ADR values in the plant samples were found to be in the range of $(7.23 \text{ to } 30.64)$ $\mathrm{nGy/h}$ with an average of 16.44 ± 6.71 $\mathrm{nGy/h}$ which is below the world average of 59 $\mathrm{nGy/h}$ [12]. The AED values had a range of $(0.01 \text{ to } 0.04)$ $\mathrm{mSv/y}$ with an average of 0.02 ± 0.01 $\mathrm{mSv/y}$. This is far below the world average value of 2.40 $\mathrm{mSv/y}$ and is below the annual dose limit of 1 $\mathrm{mSv/y}$ as recommended by ICRP [52]. The H_{ex} ranged between $(0.04 \text{ to } 0.17)$ with an average of 0.09 ± 0.01. The average H_{ex} was far less than unity indicating the site has normal background radiation [46]. The Ra_{eq} estimated for the collected plant samples ranged from $(16.41 \text{ to } 63.11)$ $\mathrm{Bq/kg}$ with an average value of 34.89 ± 13.41 $\mathrm{Bq/kg}$. The estimated average value of Ra_{eq} was far lower than the recommended safe limit value of 370 $\mathrm{Bq/kg}$ as recommended by ICRP [47] and world average value of 58 $\mathrm{Bq/kg}$ [23].

From the study the obtained activity concentrations of ^{40}K,^{238}U,^{232}Th in water samples from the dam near the site for the Centre and were observed to be in the range of $(36.67 \pm 21.99 \text{ to } 54.60 \pm 34.90)$ $\mathrm{Bq/kg}$,(below detectable limit to 11.53 ± 1.35) $\mathrm{Bq/kg}$ and (below detectable limit to 4.35 ± 4.65) $\mathrm{Bq/kg}$ respectively. The obtained average activity concentrations of ^{40}K ,^{238}U, ^{232}Th were found to be 44.82 ± 0.05 Bq/kg, 7.83 ± 0.32 $\mathrm{Bq/kg}$ and 3.03 ± 0.22 Bq/kg, respectively. The average values of activity concentrations of ^{40}K, ^{238}U and ^{232}Th are seen to be below both reference values levels of 370 $\mathrm{Bq/kg}$, 25 $\mathrm{Bq/kg}$, 30 $\mathrm{Bq/kg}$ and the world average values of 420 $\mathrm{Bq/kg}$, 33 $\mathrm{Bq/kg}$ and 45 $\mathrm{Bq/kg}$ respectively [12]. The ADR values in the water samples were found to be in the range of $(1.81 \text{ to } 8.32)$ $\mathrm{nGy/h}$ with an average of 5.90 ± 2.52 $\mathrm{nGy/h}$ which is below the world average of $59\mathrm{nGy/h}$[12].

The AED values had a range of (below detectable limit to 0.01) $\mathrm{mSv/y}$ with an average of 0.01 ± 0.00 $\mathrm{mSv/y}$. This is far below the world average value of 2.40 $\mathrm{mSv/y}$ and is minimal with respect to the annual dose limit of 1 $\mathrm{mSv/y}$ recommended by ICRP [52]. The H_{ex} were observed to range between $(0.01 \text{ to } 0.04)$ with an average of 0.03 ± 0.01. The average external H_{ex} was far less than unity indicating the site has normal background radiation [46]. The Ra_{eq} estimated for the water samples ranged from $(8.23 \text{ to } 17.63)$ $\mathrm{Bq/kg}$ with an average value of 14.56 ± 3.70 $\mathrm{Bq/kg}$. The estimated average value of Ra_{eq} was far lower than both world average of 58 $\mathrm{Bq/kg}$ [23] and the recommended safe limit value of 370 $\mathrm{Bq/kg}$ as recommended by ICRP [47].

From these results obtained, it can be concluded that the activity concentrations together with their associated radiological hazards at the site were the Centre would be constructed are minimal. The ionising radiation is below the public exposure limits of 1 mSv/year to pose any amount of health risk to the public and the environment at the moment.

6.2 Recommendations

The government of the Republic of Zambia through RPA, the agency mandated to regulate the use of ionising radiation in Zambia and ZEMA, the agency mandated to protect the environment and control pollution by industries may carry out the following recommendations.

(a) Design a plan for routine monitoring of radioactivity at the site, when construction starts, during operation and be continued until decommissioning of the installations and beyond for the protection of the public and environment.

(b) Install equipment for hydrological observations, weather observations and Seismometers for monitoring of the earth's crust movements and gravitational field at the Centre.

(c) This study has only dealt with surface water in a dam near the site. There is need to evaluate the level of natural radioactivity in water underground the site since some radionuclides are able to dissolve in underground water sources and accumulate.

(d) The results obtained in this study should be used by RPA as baseline data prior to any construction, commissioning and operation of any Nuclear Facility or Nuclear installation at the Centre.

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