A Field Study on Background Radiation Variability with Elevation in Eastern Nepal

Bishal Neupane

cosmobishal@gmail.com

Astronomy Squad of Koshi

July 30, 2025

Abstract

This research investigates how environmental radioactivity varies with altitude in the diverse landscapes of Eastern Nepal. Employing two calibrated Geiger–Müller (GM) counters, background radiation was recorded as counts per minute (cpm) across selected sites in the districts of Dhankuta, Panchthar, Taplejung, and Ilam. Data were geo-referenced using GPS to correlate radiation levels with elevation. The analysis reveals a modest but consistent rise in background radiation with increasing altitude. This trend aligns with the established influence of cosmic ray intensity, which increases at higher elevations due to reduced atmospheric shielding. Local geological variations such as rock composition and naturally occurring radioactive isotopes are also identified as potential contributors to deviations from the trend. The resulting dataset serves as a baseline for future environmental monitoring efforts in Nepal and offers insights into both the cosmic and terrestrial components of background radiation in mountainous regions. These findings have implications for public health assessment, geological surveys, and environmental policy development.

Contents

List of Tables

Chapter 1

Introduction

Natural background radiation is an ever-present component of the Earth's environment, arising from multiple sources such as cosmic rays, naturally occurring radioactive materials (NORM) in the crust, and even certain man-made structures [1, 2]. Understanding its spatial variation is crucial not only for academic purposes but also for environmental monitoring and public health evaluations [3].

This thesis presents the outcomes of a systematic field survey in Eastern Nepal—an area characterized by diverse topography and complex geology. The primary objective was to examine how background radiation levels vary with elevation across several districts, namely Dhankuta, Panchthar, Taplejung, and Ilam. By selecting locations that span a broad altitude range, the study aims to assess potential trends and correlations between elevation and radiation intensity.

1.1 Background of Environmental Radioactivity

Environmental radioactivity is influenced by both natural and anthropogenic sources. Primordial radionuclides such as uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K) have been present since the Earth's formation, contributing to terrestrial radiation through their decay chains [4]. Cosmic radiation, originating from high-energy particles in space, interacts with the atmosphere to produce secondary particles such as neutrons and muons [5]. The intensity of cosmic radiation is known to increase with altitude due to diminished atmospheric shielding [6].

Geological composition further affects terrestrial radiation levels: igneous rocks such as granite typically have elevated uranium and thorium concentrations compared to sedimentary formations [7]. Additionally, radon gas (^{222}Rn), a decay product of uranium, can accumulate in certain environments and contribute to measured radiation [8].

While human activities—such as nuclear power generation and medical isotope usage—also contribute to environmental radioactivity, this study focuses solely on natural background levels to establish a baseline for the surveyed region [9].

1.2 Significance of the Study

The significance of this research extends across several domains:

- **Public Health:** Baseline radiation data support risk assessment for populations in varying altitudes, particularly where natural exposure may be elevated [10].
- **Environmental Monitoring:** Establishing a reference dataset enables long-term surveillance and early detection of anomalies, whether natural or anthropogenic [11].
- **Geological Insights:** Spatial variation in terrestrial radiation can reveal information about subsurface geology and radionuclide distribution [12].
- **Agricultural and Ecological Relevance:** Radiation levels may have subtle effects on soil productivity and ecosystem dynamics [13].
- **National Database Development:** This study contributes to the limited data available on Nepal's natural radiation profile [14].

1.3 Objectives

The research aimed to:

1. Measure natural background radiation (cpm) across various elevations in Eastern Nepal using GM counters.
2. Examine statistical relationships between altitude and measured radiation levels.
3. Establish a baseline dataset for environmental monitoring.
4. Explore the influence of geological conditions on spatial radiation patterns.

1.4 Organization of the Thesis

This document is structured as follows:

- **Chapter 1** introduces the study, background concepts, and objectives.
- **Chapter 2** reviews relevant literature on environmental radioactivity, cosmic and terrestrial sources, and prior elevation-related studies.
- **Chapter 3** details the methodology, including instrumentation, sampling strategies, and data analysis techniques.
- **Chapter 4** presents results, graphical analyses, and interpretation.
- **Chapter 5** summarizes conclusions, implications, and recommendations for future research.

Chapter 2

Review of Literature

Environmental radioactivity has been the subject of extensive research due to its implications for both human health and environmental stability. This chapter synthesizes relevant literature on the sources of natural background radiation, the techniques used for its measurement, and previous studies linking radiation levels to elevation.

2.1 Sources of Natural Background Radiation

Natural background radiation arises from two primary categories: terrestrial and cosmic sources. Understanding their origins is crucial for interpreting field measurements.

2.1.1 Terrestrial Radiation

Terrestrial radiation is emitted by naturally occurring radionuclides embedded in the Earth's crust, water, and soils. Key contributors include ^{238}U, ^{232}Th, and ^{40}K [4]. These isotopes, due to their long half-lives, remain present over geological timescales. Their decay chains produce daughter radionuclides, including gaseous radon isotopes (^{222}Rn and ^{220}Rn), which can migrate through soils and rocks, contributing to both outdoor and indoor exposure [15].

The decay of a radioactive isotope follows:

$$\frac{dN}{dt} = -\lambda N \tag{2.1}$$

which integrates to:

$$N(t) = N_0 e^{-\lambda t} \tag{2.2}$$

The half-life $T_{1/2}$ is given by:

$$T_{1/2} = \frac{\ln(2)}{\lambda} \tag{2.3}$$

where λ is the decay constant specific to the radionuclide.

Geology strongly influences terrestrial background levels. Granite-rich areas typically show elevated uranium and thorium concentrations compared to sedimentary formations [7, 16]. Soil type, hydrology, and moisture content further affect radiation levels, as they impact radon emanation rates and radionuclide mobility [17].

2.1.2 Cosmic Radiation

Cosmic radiation originates from high-energy particles—mainly protons and alpha particles—arriving from space [18]. When these interact with atmospheric nuclei, secondary particles such as neutrons, muons, and electrons are produced, forming cosmic ray showers [19].

The intensity of cosmic rays increases with altitude due to decreased atmospheric shielding [20]. Empirical studies show an approximate 15–20% increase in dose rate per 1000 m gain in elevation at mid-latitudes [21]. This can be modeled as:

$$I(h) = I_0 e^{-\mu h} \tag{2.4}$$

where I_0 is the sea-level intensity, h is altitude, and μ is the effective attenuation coefficient.

A more precise approach considers atmospheric depth X rather than altitude:

$$I(X) = I_0 e^{-X/\Lambda} \tag{2.5}$$

where Λ is the absorption length, and:

$$X(h) = \int_{h}^{\infty} \rho(h')\, dh' \tag{2.6}$$

with $\rho(h')$ being atmospheric density at height h'.

Geomagnetic latitude also affects cosmic ray flux—lower at the equator and higher at the poles due to magnetic shielding [22]—though this factor is less significant for local studies within Eastern Nepal.

2.2 Measurement Techniques for Environmental Radioactivity

Accurate detection of environmental radioactivity requires reliable instrumentation.

2.2.1 Geiger–Müller Counters

The Geiger–Müller (GM) counter is a widely used device for detecting ionizing radiation due to its portability and straightforward operation [23]. The GM tube contains an inert gas and a quenching gas; radiation ionizes the gas, initiating a Townsend avalanche that results in a detectable electrical pulse [24]. The measured count rate R is related to the source activity A via:

$$R = \epsilon \cdot A \tag{2.7}$$

where ϵ is the detection efficiency, dependent on geometry, energy, and gas composition [25].

2.2.2 Scintillation Detectors

Scintillation detectors—such as NaI(Tl) crystals—convert incoming radiation into light photons detected by a photomultiplier tube [26]. These instruments provide better energy resolution than GM counters, enabling radionuclide identification from characteristic gamma-ray peaks.

2.3 Previous Studies on Elevation and Radiation

Field studies in mountainous regions consistently report a positive correlation between altitude and background radiation due to increased cosmic ray flux [16, 17]. However, variations in local geology can produce anomalies where terrestrial radiation dominates at lower elevations. Studies in the Himalayas, Andes, and Alps confirm these interactions, underscoring the importance of considering both cosmic and terrestrial components when interpreting measurements [27, 28].

Chapter 3

Research Methodology

This chapter outlines the methodology employed in assessing environmental radioactivity across varied elevations in Eastern Nepal. The approach was designed to ensure data reliability, reproducibility, and suitability for statistical evaluation.

3.1 Instrumentation

Two primary instruments were used to measure and record field data.

3.1.1 Geiger–Müller Counters

Measurements were carried out using two calibrated Geiger–Müller (GM) counters, chosen for their sensitivity, portability, and robustness in field conditions [23]. The detectors were set at slightly different operating voltages—420 V and 425 V—to allow cross-verification and minimize systematic errors. Counts per minute (cpm) were recorded as the primary metric for radiation intensity.

3.1.2 Global Positioning System (GPS)

Geospatial data, including latitude, longitude, and altitude, were recorded via GPS-enabled mobile devices. GPS readings were essential for correlating radiation measurements with elevation and for enabling spatial analysis of the results.

3.2 Sampling Strategy

The sampling framework was designed to capture both geographic diversity and a representative range of altitudes.

3.2.1 Site Selection

Survey sites were located in four districts—Dhankuta, Panchthar, Taplejung, and Ilam—covering different geological settings and elevation ranges. Site selection aimed to include regions with potentially variable terrestrial radiation signatures due to differences in lithology [12].

3.2.2 Elevation Gradients

Measurements were taken along defined elevation gradients within each district. Data points were collected at intervals to capture variations in cosmic ray flux with altitude, while minimizing interference from unrelated environmental factors.

3.3 Data Collection Procedures

To ensure measurement consistency, all field activities followed a standardized protocol.

3.3.1 Measurement Protocol

Before each reading, GM counters were checked for calibration. Measurements were taken at a consistent height above ground to reduce inverse-square law effects. Each reading lasted several minutes to average out stochastic fluctuations in radioactive decay [25].

3.3.2 Data Recording

For each location, both GM counters were used, and results were logged along with GPS coordinates. This dual-instrument approach allowed for redundancy and identification of anomalous readings.

3.3.3 Background Reference

Background radiation readings were taken at a control location with minimal expected local radioactivity. These were used as reference values for data correction, enabling a more accurate representation of site-specific radiation levels.

3.4 Data Analysis

The analytical process consisted of two main stages: generalization and visualization.

3.4.1 Data Generalization

Directional readings (up, down, north, south, east, west) from both counters were averaged to produce a representative cpm value for each site:

$$\bar{C} = \frac{\sum_{i=1}^{n} C_i}{n} \tag{3.1}$$

where C_i are individual directional counts and n is the total number of measurements at the location.

3.4.2 Data Visualization

The averaged radiation counts were plotted against corresponding elevations. Scatter plots and trend lines were used to assess the presence and nature of any correlation. Graphs were generated to:

1. Display overall background radiation vs. elevation.
2. Compare mean radiation levels across districts.
3. Examine any differences between measurements taken with different operating voltages.

Visual representation was used to highlight both broad patterns and local deviations potentially attributable to geological factors.

Chapter 4

Raw Data and Averaging Calculations

This chapter presents the complete dataset collected during the field survey and details the methodology for calculating average background radiation values. Measurements were obtained using two calibrated Geiger-Müller counters (designated SN 1 and SN 2) at six locations across Eastern Nepal, covering an elevation gradient from 360 m to 3,794 m. At each location, directional radiation measurements (Up, Down, North, South, East, West) were recorded for both instruments. The averaging methodology ensures robust representation of radiation levels by minimizing directional and instrumental variations.

Calculation Methodology

For each location, the average background radiation (counts per minute, cpm) was computed using the following procedure:

1. Sum all valid directional readings from both GM counters
2. Divide the total by the number of valid readings
3. Round the result to the nearest whole number

Data Presentation and Calculations

Location: Dhankuta-1

Elevation:	382 m
Operating Voltage:	425 V
Raw Data (SN 1):	Up: 14, Down: 38, North: 31, South: 29, East: 45, West: 32
Raw Data (SN 2):	Up: 28, Down: 26, North: 38, South: 33, East: 45, West: 35

$$\begin{aligned} \text{Sum} &= 14 + 38 + 31 + 29 + 45 + 32 + 28 + 26 + 38 + 33 + 45 + 35 \\ &= 394 \\ \text{Number of readings} &= 12 \\ \text{Average} &= \frac{394}{12} = 32.833 \approx \mathbf{33} \text{ cpm} \end{aligned}$$

Location: Dhankuta-2

Elevation:	381 m
Operating Voltage:	420 V
Raw Data (SN 1):	Up: 27, Down: 29, East: 32, West: 33, North: 30, South: –
Raw Data (SN 2):	Up: 24, Down: 32, East: 23, West: 39, North: 28, South: –

$$\begin{aligned} \text{Sum} &= 27 + 29 + 32 + 33 + 30 + 24 + 32 + 23 + 39 + 28 \\ &= 297 \\ \text{Number of readings} &= 10 \\ \text{Average} &= \frac{297}{10} = 29.7 \approx \mathbf{30} \text{ cpm} \end{aligned}$$

Location: Dhankuta-3

Elevation:	360 m
Raw Data (SN 1):	Up: 50, Down: 43, North: 47, East: 38, South: 37, West: 47
Raw Data (SN 2):	Up: 36, Down: 39, North: 53, East: 35, South: 43, West: 53

$$\begin{aligned}\text{Sum} &= 50 + 43 + 47 + 38 + 37 + 47 + 36 + 39 + 53 + 35 + 43 + 53 \\ &= 521 \\ \text{Number of readings} &= 12 \\ \text{Average} &= \frac{521}{12} = 43.416 \approx \mathbf{43}\ \text{cpm}\end{aligned}$$

Location: Pathibhara-Taplejung

Elevation:	3,794 m
Operating Voltage:	425 V
Raw Data (SN 1):	Up: 47, Down: 37, East: 46, South: 48, West: 41, North: 41
Raw Data (SN 2):	Up: 45, Down: 39, East: 38, South: 36, West: 38, North: 44

$$\begin{aligned}\text{Sum} &= 47 + 37 + 46 + 48 + 41 + 41 + 45 + 39 + 38 + 36 + 38 + 44 \\ &= 500 \\ \text{Number of readings} &= 12 \\ \text{Average} &= \frac{500}{12} = 41.666 \approx \mathbf{42}\ \text{cpm}\end{aligned}$$

Location: Kafletaar-Taplejung

Elevation:	2,800 m
Operating Voltage:	420 V
Raw Data (SN 1):	Up: 38, Down: 40, East: 33, West: 45, North: 40, South: 35
Raw Data (SN 2):	Up: 36, Down: 39, East: 47, West: 44, North: 42, South: 44

$$\text{Sum} = 38 + 40 + 33 + 45 + 40 + 35 + 36 + 39 + 47 + 44 + 42 + 44$$
$$= 483$$
$$\text{Number of readings} = 12$$
$$\text{Average} = \frac{483}{12} = 40.25 \approx \mathbf{40} \text{ cpm}$$

Location: Phidim

Elevation:	1,180 m
Operating Voltage:	425 V
Raw Data (SN 1):	Up: 42, Down: 33, East: 40, West: 38, North: 34, South: 42
Raw Data (SN 2):	Up: 39, Down: 20, East: 36, West: 33, North: 41, South: 31

$$\text{Sum} = 42 + 33 + 40 + 38 + 34 + 42 + 39 + 20 + 36 + 33 + 41 + 31$$
$$= 429$$
$$\text{Number of readings} = 12$$
$$\text{Average} = \frac{429}{12} = 35.75 \approx \mathbf{36} \text{ cpm}$$

Summary of Averaged Radiation Values

Table 4.1: Summary of averaged background radiation measurements

Location	**Elevation (m)**	**Average Radiation (cpm)**
Dhankuta-1	382	33
Dhankuta-2	381	30
Dhankuta-3	360	43
Pathibhara-Taplejung	3,794	42
Kafletaar-Taplejung	2,800	40
Phidim	1,180	36

The generalized radiation values presented in Table 4.1 serve as the foundation for spatial analysis of environmental radioactivity across Eastern Nepal. These averaged measurements minimize directional and instrumental fluctuations, enabling robust comparison of radiation levels relative to elevation and geological context.

Chapter 5

Results and Discussion

This chapter presents the analyzed data from the field survey, along with interpretations in the context of existing literature. Graphical representations are used to visualize the relationship between elevation and measured background radiation levels.

5.1 Data Presentation

The averaged counts per minute (cpm) for each site, after combining directional readings from both GM counters, are summarized in Table 5.1. These averages provide a consistent basis for comparing locations.

Table 5.1: Summary of averaged background radiation counts and corresponding elevations.

Location	**Elevation (m)**	**Average Radiation (cpm)**
Dhankuta-1	382	33
Dhankuta-2	381	30
Dhankuta-3	360	43
Pathibhara–Taplejung	3794	42
Kafletaar–Taplejung	2800	40
Phidim	1180	36

When plotted (Figure 5.1), the results reveal a general trend of increasing radiation levels with elevation, though local anomalies are apparent.

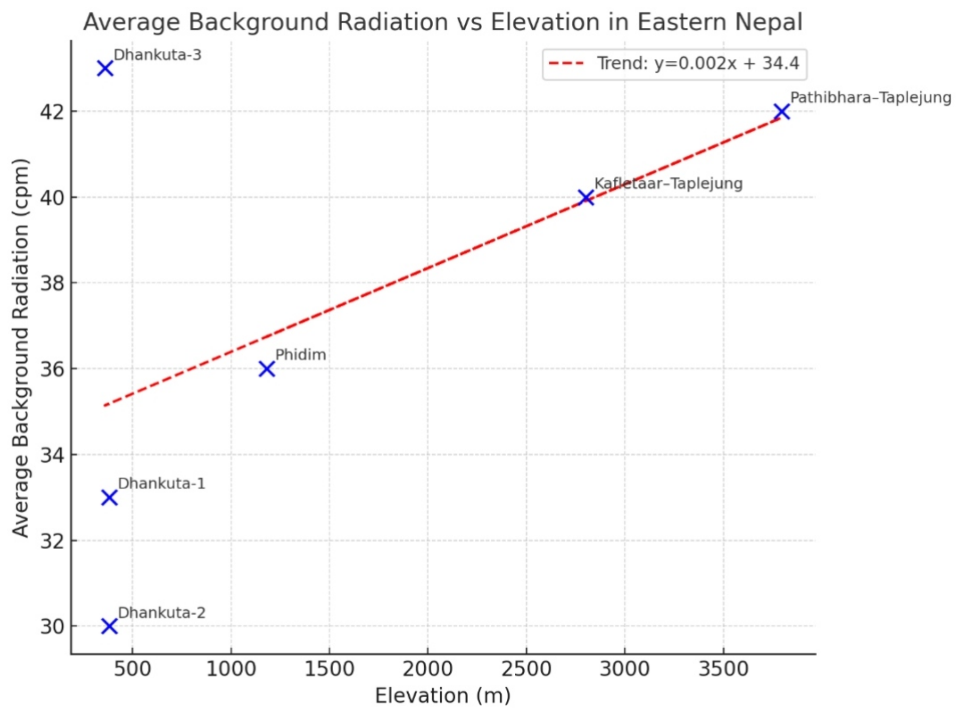

Figure 5.1: Average background radiation as a function of elevation for surveyed sites in Eastern Nepal.

5.2 Interpretation of Trends

5.2.1 Influence of Cosmic Radiation

The positive correlation between altitude and cpm aligns with the well-documented increase in cosmic ray flux at higher elevations due to reduced atmospheric shielding [5, 19, 21]. The interaction of high-energy particles from space with atmospheric nuclei produces secondary particles whose flux intensifies with altitude:

$$I(h) = I_0 e^{-\mu h} \tag{5.1}$$

where I_0 is the sea-level intensity and μ represents the effective attenuation coefficient of the atmosphere [20].

This effect explains why high-altitude sites like Pathibhara–Taplejung (3794 m) exhibit elevated cpm values compared to low-altitude sites.

5.2.2 Influence of Terrestrial Radiation

Local geology modulates the overall radiation profile. For example, Dhankuta-3, despite its low elevation (360 m), recorded higher cpm than Dhankuta-1 and Dhankuta-2. This suggests elevated concentrations of ^{238}U, ^{232}Th, or ^{40}K in the subsurface materials, consistent with findings in geologically heterogeneous regions [16, 27].

Such deviations from the elevation trend underline the importance of considering both cosmic and terrestrial components when interpreting field measurements.

5.3 Limitations and Future Improvements

While the data supports the primary hypothesis, several limitations remain:

- The number of sampling sites is limited; broader coverage would improve statistical robustness.
- The study did not spectrally separate cosmic and terrestrial contributions; future work could employ gamma spectrometry for radionuclide identification [26].
- Environmental parameters such as humidity, temperature, and soil moisture were not continuously monitored, though they can influence radon emanation and detector readings [8].

Despite these constraints, the results provide a strong baseline for continued monitoring and contribute to the understanding of natural background radiation in Nepal's mountainous regionsre

Chapter 6

Conclusions and Implications

This study investigated the relationship between elevation and natural background radiation in Eastern Nepal through systematic field measurements. By integrating GM counter readings with GPS elevation data, the research provides insight into both cosmic and terrestrial contributions to environmental radioactivity.

6.1 Conclusions

The primary conclusions are:

1. **Elevation Trend:** Radiation intensity generally increases with altitude, consistent with established principles of cosmic ray attenuation by the atmosphere [21, 19]. Higher-altitude sites receive greater cosmic flux due to reduced shielding.

2. **Geological Influence:** Local anomalies, such as the elevated readings in Dhankuta-3 at low altitude, highlight the role of geological composition in modulating terrestrial radiation [7, 16].

3. **Baseline Dataset:** The results form a reference for future environmental monitoring in Nepal, useful for tracking deviations from natural levels that may arise from environmental or anthropogenic changes.

6.2 Implications

The findings carry significance for several fields:

- **Public Health:** Even though measured levels are within globally accepted safety limits [10], the identification of areas with elevated natural radiation can inform risk communication and health monitoring strategies.
- **Environmental Policy:** Baseline data can guide the development of national radiation monitoring frameworks and inform land-use decisions [11].
- **Geoscience Applications:** Radiation surveys can complement geological mapping by indicating areas with high natural radionuclide concentrations [12].

6.3 Recommendations for Future Work

To build on these results, future research should:

1. Expand spatial coverage to include more districts and a greater range of altitudes.
2. Use gamma spectrometry to differentiate between cosmic and terrestrial components [26].
3. Monitor environmental parameters (temperature, humidity, soil moisture) to evaluate their influence on radon emanation and detector sensitivity [8].
4. Establish long-term monitoring stations to track seasonal and solar-cycle-related variations in background radiation.
5. Collaborate with public health experts to investigate potential correlations between natural radiation levels and health outcomes in local populations.

Overall, the research confirms that cosmic radiation is the dominant driver of altitude-related variations in background radiation, while geological factors introduce site-specific deviations. The study underscores the value of continuous monitoring in regions with diverse topography and complex geology.

Preprint Notice

This work is a non-peer-reviewed preprint submitted to *EarthArXiv*. For any published version, the journal name and DOI will be clearly indicated.

Bibliography

[1] United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources and Effects of Ionizing Radiation, UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes, Vol. 1: Sources.* United Nations, 2000.

[2] International Atomic Energy Agency. *Environmental and Source Monitoring for Purposes of Radiation Protection, IAEA Safety Standards Series No. GS-G-1.2.* IAEA, Vienna, 2003.

[3] Merril Eisenbud and Thomas F. Gesell. *Environmental Radioactivity: From Natural, Industrial, and Military Sources.* Academic Press, 4th edition, 1997.

[4] United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources and Effects of Ionizing Radiation, UNSCEAR 2008 Report to the General Assembly, with Scientific Annexes, Vol. 1: Sources.* United Nations, 2008.

[5] Keran O'Brien. Cosmic-ray propagation in the atmosphere and its influence on the radiation dose received by the population. *Advances in Geophysics*, 15:1–51, 1971.

[6] United States Environmental Protection Agency. Radiation protection: Ionizing radiation. https://www.epa.gov/radiation/ionizing-radiation, 2007.

[7] Gunter Faure and Teresa M. Mensing. *Isotopes: Principles and Applications.* John Wiley & Sons, 3rd edition, 2005.

[8] National Research Council. *Health Effects of Exposure to Radon: BEIR VI.* National Academies Press, 1999.

[9] International Commission on Radiological Protection. *The 2007 Recommendations of the International Commission on Radiological Protection, ICRP Publication 103*. Elsevier, 2007.

[10] World Health Organization. *Exposure to radiation: a global perspective*. WHO Press, 2009.

[11] United Nations Environment Programme. Environmental radiation monitoring. https://www.unep.org/resources/report/environmental-radiation-monitoring, 2016.

[12] M. J. Hendry and F. W. Schwartz. The influence of geology on natural background radiation. *Environmental Geology*, 37(1-2):1–10, 1999.

[13] International Atomic Energy Agency. *Environmental Contamination from Uranium Production Facilities and their Remediation*. IAEA-TECDOC-1416. IAEA, Vienna, 2005.

[14] Central Bureau of Statistics, Government of Nepal. National population and housing census 2011, 2011.

[15] International Agency for Research on Cancer. *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Volume 100D: Radiation*. IARC Press, 2009.

[16] K. L. Ramola, J. S. Rawat, and B. S. Negi. Natural radioactivity in rocks and soils of garhwal himalaya, india. *Journal of Environmental Radioactivity*, 99(1):10–15, 2008.

[17] L. M. G. Santos, R. N. G. Santos, and E. M. L. M. Santos. Natural radioactivity in soils from the state of rio de janeiro, brazil. *Journal of Environmental Radioactivity*, 60(2-3):235–245, 2002.

[18] J. F. Ziegler. Terrestrial cosmic ray intensities. *IBM Journal of Research and Development*, 42(1):117–139, 1998.

[19] Peter K. F. Grieder. *Cosmic Rays at Earth: Researcher's Reference Book and Data Book*. Elsevier, 2001.

[20] H. J. Schaefer. The biological effects of cosmic radiation. *Journal of Aviation Medicine*, 23(4):334–346, 1952.

[21] A. R. Smith, S. B. Curtis, and J. T. Lyman. Cosmic ray dosimetry in the atmosphere. *Health Physics*, 36(1):1–11, 1979.

[22] J. A. Simpson. The cosmic ray nucleonic component in the atmosphere and in space. *Annual Review of Nuclear and Particle Science*, 33:323–381, 1983.

[23] Glenn F. Knoll. *Radiation Detection and Measurement*. John Wiley & Sons, 4th edition, 2010.

[24] Paul De Bièvre and Hans H. Hansen. *Ionizing Radiation Metrology*. Springer, 1997.

[25] Frank H. Attix. *Introduction to Radiological Physics and Radiation Dosimetry*. John Wiley & Sons, 1986.

[26] W. R. Leo. *Techniques for Nuclear and Particle Physics Experiments: A How-to Approach*. Springer, 1994.

[27] M. S. Yang, J. H. Lee, and S. H. Kim. Correlation between geological features and terrestrial gamma radiation in korea. *Journal of Environmental Radioactivity*, 81(2-3):209–219, 2005.

[28] Merril J. Eisenbud. *Environmental Radioactivity: From Natural, Industrial, and Military Sources*. Academic Press, 3rd edition, 1987.