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Radiological Risk Assessment For The Population Of Antsiranana Ii District, Madagascar, Due To External Exposure To Natural Radioactivity In Soil

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Abstract: The assessment of public exposure to natural radiation sources is a fundamental component of public health protection. This study evaluates the radiological hazards associated with soils in the Antsiranana II district, Madagascar, a region where the population has significant daily contact with soil for agriculture and as a building material. Activity concentrations of ^{40}K, ^{238}U, and ^{232}Th in 23 soil samples were used to calculate key radiological risk parameters. The radium equivalent activity (Raeq) ranged from 87 to 196 Bq.kg^{-1}, with a mean of 147 Bq.kg^{-1}, a value well below the international safety limit of 370 Bq.kg^{-1} for building materials. The absorbed gamma dose rate in air (Da) was calculated to have a mean of 67 ± 14 nGy.h^{-1}, which is slightly above the world average of 57 nGy.h^{-1}. Consequently, the mean annual effective dose (AED) received by the population from external exposure to soil was estimated at 0.21 ± 0.04 mSv.h^{-1}, significantly lower than the 1 mSv.h^{-1} public dose limit recommended by the ICRP. The associated lifetime excess cancer risk was also found to be negligible. Despite the observed geological enrichment in uranium and thorium, this study concludes that the overall radiological risk to the population from external terrestrial radiation in the district is low and does not pose a significant public health threat.

Keywords: Radiological Risk; Annual Effective Dose; Radium Equivalent; Soil Radioactivity; Public Health; Radioprotection; Madagascar.

1. Introduction

Soil is the primary source of external gamma radiation exposure for the human population, contributing significantly to the total natural background radiation dose (UNSCEAR, 2000). The level of this exposure is directly related to the concentrations of natural radionuclides, primarily ^{40}K, and the decay series of ^{238}U and ^{232}Th, in the local soil. Therefore, assessing the dose from these sources is a critical task in radiation protection and public health management. This is particularly important in rural areas where people spend considerable time outdoors for agriculture and often use soil-based materials for constructing their dwellings.

In the Antsiranana II district of Madagascar, such conditions are prevalent. While a companion study has established that the soils are naturally enriched in uranium and thorium, the direct impact on human health has not yet been quantified. It is essential to translate these activity concentrations into tangible risk parameters and dose estimates to determine if any protective measures are warranted.

This study aims to provide a comprehensive radiological risk assessment for the population of the Antsiranana II district. The specific objectives are: (1) to calculate the radium equivalent activity (Raeq) to assess the suitability of soils as a building material; (2) to estimate the absorbed gamma dose rate in air (Da); (3) to calculate the annual effective dose (AED) received by the population; and (4) to compare these values with established international safety limits and guidelines to evaluate the overall public health risk.

2. Materials and Methods

2.1. Geological Description of the Study Area

The study was conducted in the District of Antsiranana II, located at the northern tip of Madagascar (Fig. 1). The district covers an area of 5,645 km² and surrounds the Amber Mountain massif. As detailed in our previous work (Tsilailay *et al.,* 2025), the geological context is dominated by this vast stratovolcano, composed mainly of mafic rocks (basalts, basanites) and pyroclastic deposits formed from the Miocene to the Quaternary. These volcanic formations rest on a sedimentary basement of Jurassic to Eocene age (marls, limestones, sandstones) (Besairie, 1970; Lemoine, 1906, Ségalen, 1956, Barat, 1958, Cucciniello *et al*., 2011; Donné *et al*., 2021). The resulting pedology is a complex mosaic of ferralitic and volcanic soils, which directly influences the distribution of natural radionuclides.

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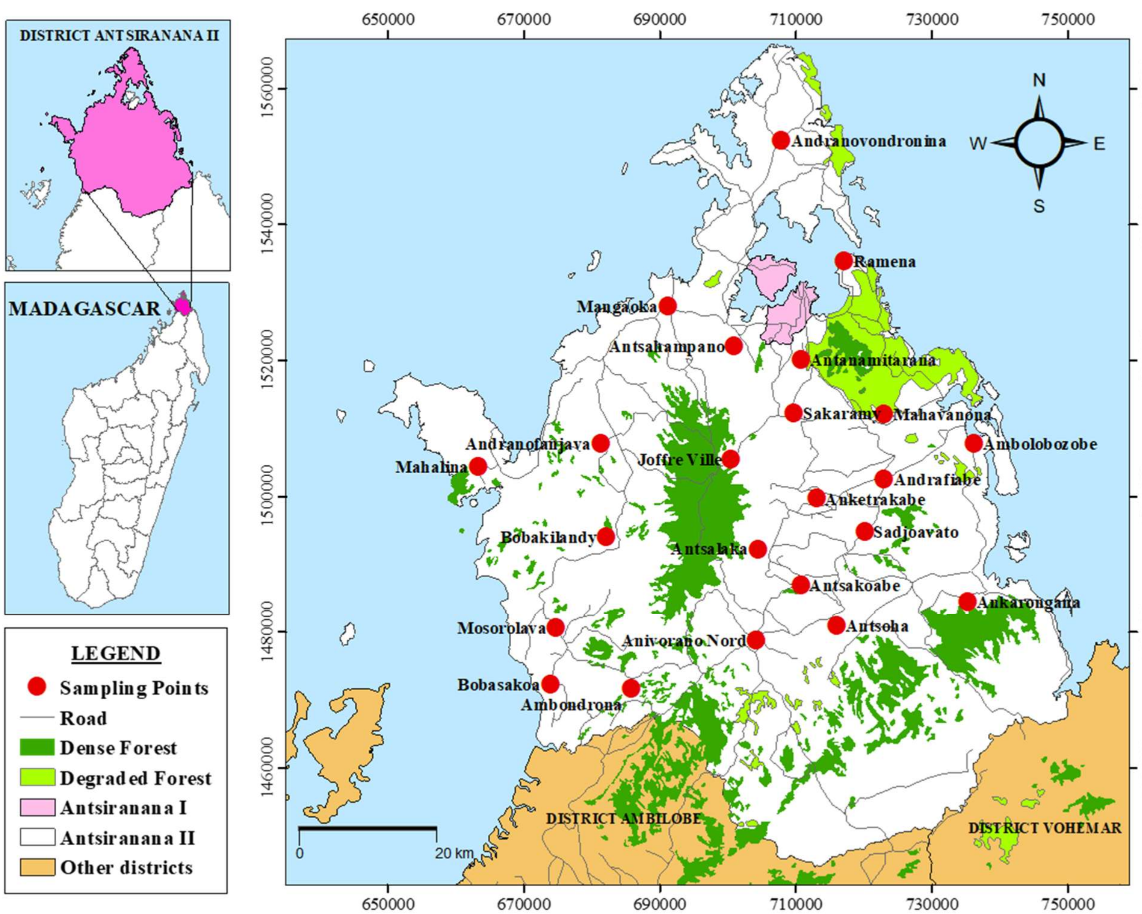

Fig. 1. Location of samplin

2.2. Sample Collection and Preparation

This study utilizes the radiological data obtained from 23 soil samples collected in July 2024, representative of the 23 rural communes of the district. The sampling methodology, geolocation, and preparation protocols are described in depth in Tsilailay *et al*. (2025). Briefly, composite samples were taken from a depth of 30 cm in undisturbed areas, dried at 105°C, ground, and sealed in standard containers for gamma spectrometry analysis at the National Institute of Nuclear Sciences and Techniques (INSTN) in Antananarivo. The specific activities of ^{40}K, ^{238}U series and ^{232}Th series utilized for the risk calculations in this paper were determined using a NaI(Tl) detector after a secular equilibrium period of four weeks.

Table I lists the 23 sampling points that cover all rural communes in the district. It confirms the study's wide geographical coverage, ensuring that the calculated risks are representative of the entire population of Antsiranana II.

Table I. Geographic coordinates (Laborde system) of the soil sampling locations

Sample ID	Locality	Longitude (m)	Latitude (m)
ANT-II1	Andrafiabe	723011.77	1502484.69
ANT-II2	Antsakoabe	710761.02	1486885.07
ANT-II3	Antsoha	716044.48	1480847.21
ANT-II4	Anivorano Nord	704240.35	1478671.06
ANT-II5	Bobasakoa	673923.98	1472230.68
ANT-II6	Mosorolava	674765.56	1480475.39
ANT-II7	Bobakilandy	682121.92	1493984.84
ANT-II8	Ambondrona	685847.52	1471631.25
ANT-II9	Ramena	717154.61	1534582.05
ANT-II10	Mahavanona	719181.83	1512612.84
ANT-II11	Antanamitarana	710750.21	1520064.04
ANT-II12	Sakaramy	709769.79	1512220.67
ANT-II13	Joffre Ville	700478.86	1505335.17
ANT-II14	Antsahampano	700946.00	1522024.88
ANT-II15	Sadjoavato	720184.90	1494724.01
ANT-II16	Ankarongana	735260.73	1484376.72
ANT-II17	Ambolobozobe	736629.65	1502500.17
ANT-II18	Anketrakabe	713103.22	1499671.28
ANT-II19	Andranofanjava	681337.59	1507710.73
ANT-II20	Mangaoka	691141.79	1527907.40
ANT-II21	Antsalaka	704475.52	1492220.09
ANT-II22	Andranovondronina	707220.69	1553790.51
ANT-II23	Mahalina	663297.85	1504377.30

2.3. Specific activity concentrations of ^{40}K, ^{238}U and ^{232}Th in soil

The activity concentrations of ^{40}K, ^{238}U series, and ^{232}Th series used in this study were determined from 23 soil samples collected in the Antsiranana II district. Measurements were performed using gamma-ray spectrometry, as detailed in our companion paper (Tsilailay *et al.,* 2025). These results are summarized in Table II.

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SCHOLAR AI Be Smart
Vol. 59 No. 1 September 2026, pp. 895-908

Table II. Specific activity concentrations of natural radionuclides (^{40}K, ^{238}U series, ^{232}Th series) in soil samples from Antsiranana II

Sample ID	**Specific activities (Bq/kg)**		
	^{40}K	**^{238}U series**	**^{232}Th series**
ANT-II1	115 ± 8	32 ± 4	58 ± 6
ANT-II2	127 ± 8	21 ± 3	20 ± 3
ANT-II3	162 ± 8	51 ± 5	24 ± 3
ANT-II4	189 ± 8	34 ± 4	59 ± 6
ANT-II5	390 ± 15	21 ± 3	47± 4
ANT-II6	249 ± 12	31 ± 4	9 ± 2
ANT-II7	294 ± 12	38 ± 4	67 ± 6
ANT-II8	159 ± 8	16 ± 2	21 ± 3
ANT-II9	174 ± 8	21 ± 3	24 ± 3
ANT-II10	310 ± 13	10 ± 2	40 ± 4
ANT-II11	155 ± 8	47 ± 4	37± 4
ANT-II12	186 ± 8	27 ± 3	27± 3
ANT-II13	107 ± 8	8 ± 2	46 ± 4
ANT-II14	341 ± 14	75 ± 5	38 ± 4
ANT-II15	168 ± 8	15 ± 2	38 ± 4
ANT-II16	100 ± 8	8 ± 2	49 ± 4
ANT-II17	350 ± 11	33 ± 4	10 ± 2
ANT-II18	63 ± 5	20 ± 3	5 ± 2
ANT-II19	170± 8	7 ± 2	34 ± 4
ANT-II20	113 ± 7	25 ± 3	12 ± 2
ANT-II21	137 ± 8	5 ± 2	51± 4
ANT-II22	94 ± 6	77 ± 5	22 ± 3
ANT-II23	155 ± 8	3± 2	35 ± 4
Mean value ± SD	**187 ± 91**	**27± 20**	**34± 17**
(Min – Max)	**[63– 390]**	**[3– 77]**	**[5–67]**

SD: Standard Deviation

2.3.1. Radium Equivalent Activity (Ra_{eq})

The radium equivalent activity (Ra_{eq}) is a calculated sum of the hazards associated with ^{238}U, ^{232}Th and ^{40}K in a sample. It is crucial for evaluating the overall radiation hazards posed by various radionuclides present in the sample. It was calculated using the formula proposed by Beretka et Mathew (1985) (Eke *et al.,* 2024; Shi *et al.,* 2024; Mwimanzi *et al.,* 2025):

$$Ra_{eq} = A_U + 1.43 \times A_{Th} + 0.077 \times A_K \qquad (1)$$

Where A_U, A_{Th}, and A_K are the activity concentrations in Bq.kg^{-1} of ^{238}U, ^{232}Th and ^{40}K, respectively. The accepted safety threshold of Ra_{eq} is 370 Bq kg^{-1} (UNSCEAR, 2020).

2.3.2. Absorbed Gamma Dose Rate (AGDR)

The absorbed gamma dose rate at 1 m above the ground surface from the concentration of radionuclides in samples was computed using equation (2) (Eke *et al.,* 2024; Shi *et al.,* 2024; Mwimanzi *et al.,* 2025):

$$AGDR = 0.462 \times A_U + 0.604 \times A_{Th} + 0.0417 \times A_K \qquad (2)$$

Where A_U, A_{Th} and A_K are defined as the activity concentrations in Bq.kg^{-1} of ^{238}U, ^{232}Th and ^{40}K, respectively.

2.3.3. Annual effective dose rate (AEDR)

The annual effective dose rate (AEDR) was calculated using equation (3) (Eke *et al.,* 2024; Shi *et al.,* 2024; Mwimanzi *et al.,* 2025):

$$AEDR = AGDR \times T \times Q \times \tau \times 10^{-6} \qquad (3)$$

Where Q is the conversion coefficient from absorbed dose to effective dose, with $Q = 0.7\ Sv \cdot Gy^{-1}$. τ represents the average occupancy factor, equal to 0.5. For this study, it is assumed that the individual spends approximately 50% of their time outside of a dwelling (Stolerie *et al.,* 2022). The annual exposure duration (T) is estimated at 8766 hours. An annual effective dose equivalent (*AEDE*) limit of 1 $mSv \cdot y^{-1}$ is considered acceptable for the general public (UNSCEAR, 2000).

2.3.4. Excess lifetime cancer risk (ELCR)

The *ELCR* was estimated using the formula (Eke *et al.,* 2024; Shi *et al.,* 2024; Mwimanzi *et al.,* 2025):

$$ELCR = AEDR \times DL \times RF \qquad (4)$$

Where DL is the average life expectancy (70 years), and RF is the risk factor (0.05 Sv^{-1}) for the general public (UNSCEAR, 2020).

2.4. Spatial mapping method

Surfer ® Version 30.1.218 and MS Excel 2019 software for Windows were used for making the spatial maps. In addition, the Kriging interpolation technique, a geostatistical method, was applied to create spatial distribution maps for radiological indices. This method provided a reliable estimation of values in unmeasured locations by considering both the distance and the degree of variation between measured data points, enhancing the accuracy of spatial analysis.

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SCHOLAR AI Be Smart
Vol. 59 No. 1 September 2026, pp. 895-908

3. Results and Discussion

Table III. Summary of radiological dose parameters for the population of Antsiranana II

Sample ID	**Raeq** ($Bq.kg^{-1}$)	**Da** ($nGy.h^{-1}$)	**AED** ($mSv.h^{-1}$)	**ELCR** ($x10^{-3}$)
ANT-II1	124 ± 5	55 ± 4	0.17 ± 0.02	0.51 ± 0.06
ANT-II2	59 ± 3	27 ± 2	0.08 ± 0.01	0.25 ± 0.04
ANT-II3	98 ± 4	45 ± 3	0.14 ± 0.02	0.41 ± 0.05
ANT-II4	133 ± 5	59 ± 4	0.18 ± 0.02	0.54 ± 0.06
ANT-II5	118 ± 5	54 ± 4	0.17 ± 0.02	0.50 ± 0.06
ANT-II6	63 ± 3	30 ± 3	0.09 ± 0.01	0.28 ± 0.04
ANT-II7	156 ± 7	70 ± 6	0.21 ± 0.02	0.64 ± 0.06
ANT-II8	58 ± 3	27 ± 2	0.08 ± 0.01	0.25 ± 0.03
ANT-II9	212 ± 9	98 ± 6	0.30 ± 0.02	0.90 ± 0.06
ANT-II10	91 ± 4	42 ± 3	0.13 ± 0.02	0.39 ± 0.05
ANT-II11	112 ± 5	51 ± 4	0.16 ± 0.02	0.47 ± 0.05
ANT-II12	80 ± 4	37 ± 3	0.11 ± 0.01	0.34 ± 0.04
ANT-II13	82 ± 4	36 ± 3	0.11 ± 0.01	0.33 ± 0.04
ANT-II14	156 ± 7	72 ± 6	0.22 ± 0.02	0.66 ± 0.06
ANT-II15	82 ± 4	37 ± 3	0.11 ± 0.01	0.34 ± 0.04
ANT-II16	86 ± 4	37 ± 3	0.11 ± 0.01	0.34 ± 0.04
ANT-II17	74 ± 4	36 ± 3	0.11 ± 0.01	0.33 ± 0.04
ANT-II18	32 ± 2	15 ± 2	0.05 ± 0.01	0.14 ± 0.02
ANT-II19	69 ± 3	31 ± 3	0.10 ± 0.01	0.29 ± 0.03
ANT-II20	51 ± 3	24 ± 2	0.07 ± 0.01	0.22 ± 0.03
ANT-II21	88 ± 4	39 ± 3	0.12 ± 0.02	0.36 ± 0.04
ANT-II22	116 ± 5	53 ± 4	0.16 ± 0.02	0.49 ± 0.05
ANT-II23	65 ± 3	29 ± 2	0.09 ± 0.01	0.27 ± 0.04
Min	**32**	**15**	**0.05**	**0.14**
Max	**212**	**98**	**0.30**	**0.90**
Mean ± SD	**96 ± 41**	**44 ± 19**	**0.13 ± 0.06**	**0.40 ± 0.17**
Reference Value	**< 370[1]**	**57[2]**	**< 1.0[3]**	**N/A**

[1] OECD-NEA (1979) for building materials. [2] UNSCEAR (2000) world average D_a. [3] ICRP (2007) public dose

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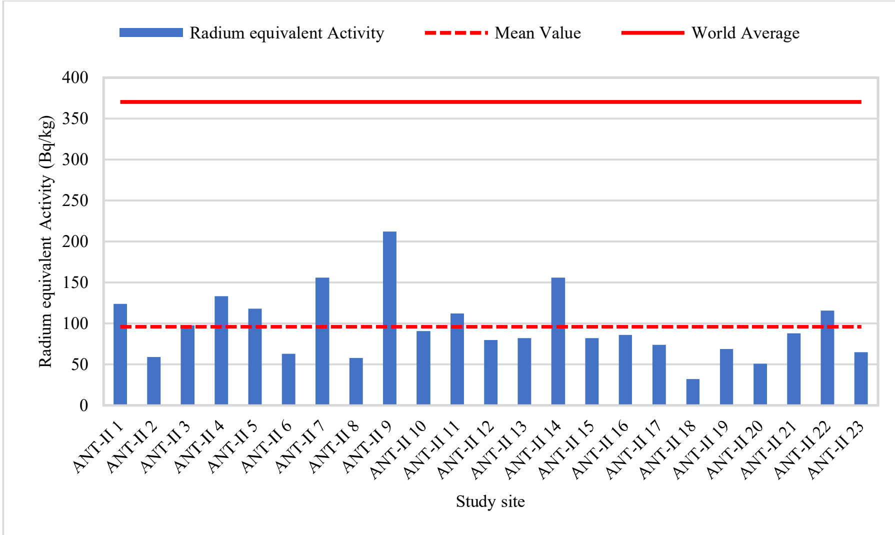

Fig. 2. Radium Equivalent Activity (Ra_{eq}) in soil samples compared to the world recommended maximum value (370 Bq.kg^{-1})

The Ra_{eq} values range from (32 ± 2) to (212 ± 9) Bq.kg^{-1}, with a mean of (96 ± 41) Bq.kg^{-1}. Crucially, all samples are well below the safety limit of 370 Bq.kg^{-1} set by the OECD for building materials (UNSCEAR, 2000). This indicates that soils from Antsiranana II can be safely used for construction without posing a radiological hazard.

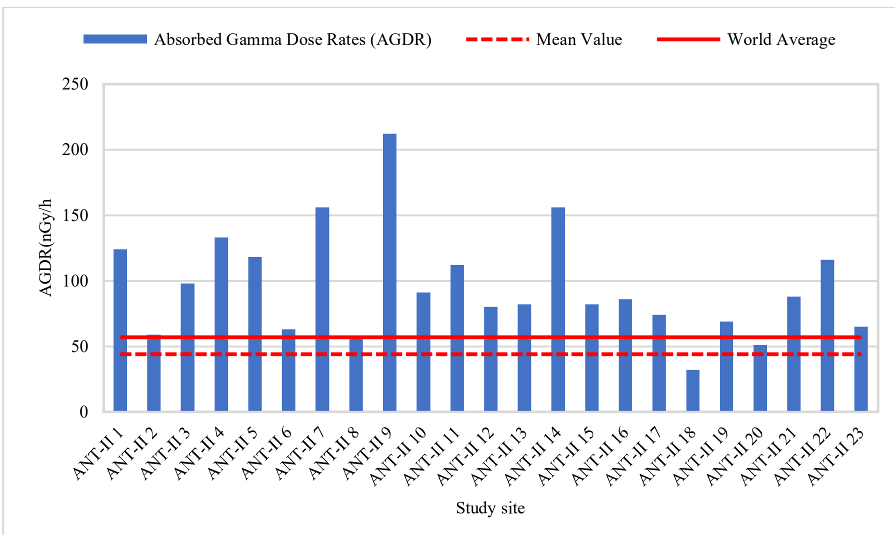

Fig. 3. Absorbed Gamma Dose Rates (*AGDR*) contributed by ^{40}K, ^{238}U, and ^{232}Th compared to the world average

FortheAbsorbedGammaDoseRateisrangesfrom (15 ± 2) to (98 ± 6) nGy.h^{-1}, with a mean of (44 ± 19) nGy.h^{-1}. This mean value is low than the world population-weighted average of 57 nGy.h^{-1} (UNSCEAR, 2000). This diminution is primarily driven by the higher thorium content in the volcanic soil (Tsilailay *et al.,* 2025).

Fig 3 and 4 demonstrate that while ^{40}K contributions are low, the combined dose from U and Th pushes the total *AGDR* above the world average for most samples. However, the excess is moderate and does not reach extreme values found in high

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https://ijpsat.org/
Vol. 59 No. 1 September 2026, pp. 895-908

background radiation areas, such as those reported in certain volcanic regions globally (Tzortzis *et al.,* 2003; López-Pérez *et al.,* 2021).

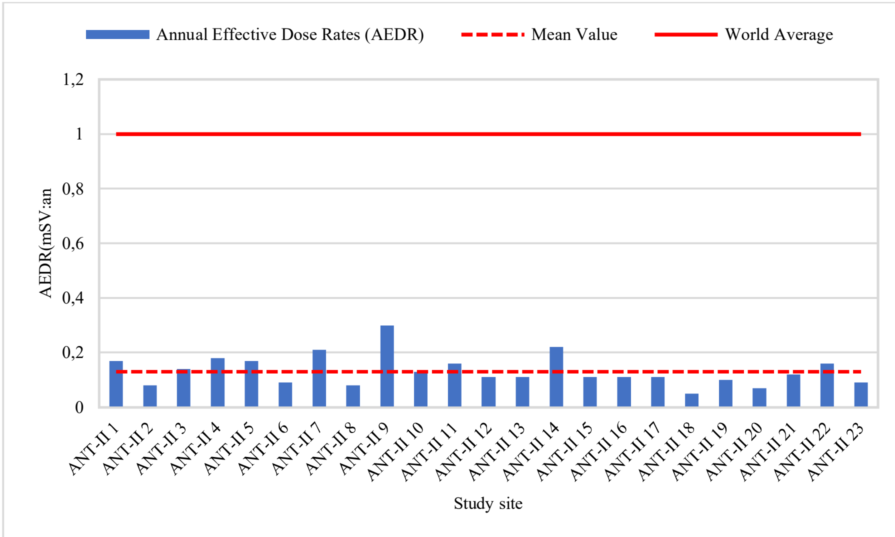

Fig. 4. Annual Effective Dose Rate (*AEDR*) for each commune compared to the public exposure limit (1 mSv.y⁻¹)

The Annual Effective Dose Rate varies between (0.05± 0.01 and (0.30± 0.02) mSv.an^{-1}, with a mean of (0.013± 0.06) mSv.an^{-1}. This is the most critical finding: despite the higher *AGDR*, the effective dose is drastically lower than the recommended public dose limit of 1 mSv.y^{-1} (UNSCEAR, 2000).

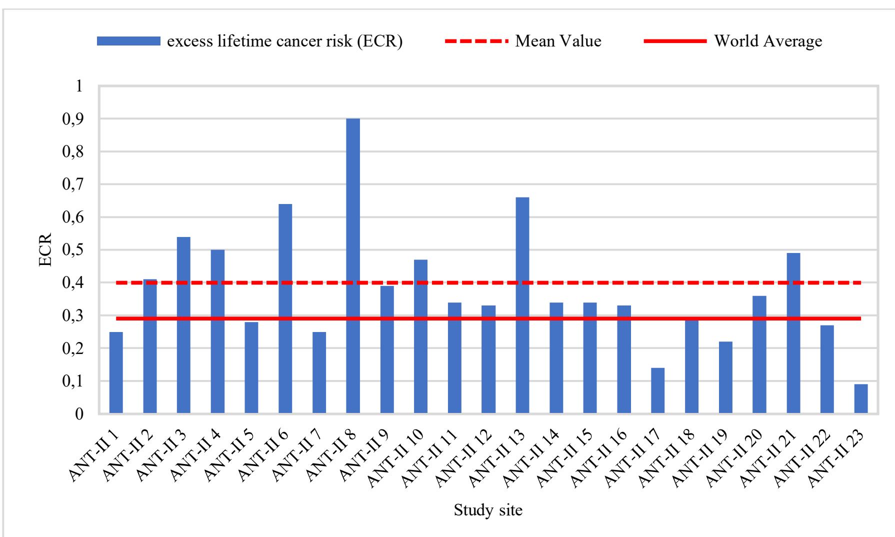

Fig. 5. Excess Lifetime Cancer Risk (*ECR*) for each commune compared to the public exposure limit (0.29 × 10^{-3}.)

The Excess Lifetime Cancer Risk averages 0.40 × 10^{-3}. This value is above to the world average of 0.29 × 10^{-3}. This suggests that the probability of developing cancer due to natural soil radiation in this district is not negligible .

The interpolation maps (Fig. 6, 7 and 8) reveal a distinct spatial pattern. The highest risks (red zones) are concentrated in specific areas (likely corresponding to specific volcanic flows or older pedological formations rich in Th/U), while the coastal sedimentary areas generally show lower risks. These maps are valuable tools for local authorities to identify zones of slightly elevated exposure, although all remain within safe limits.

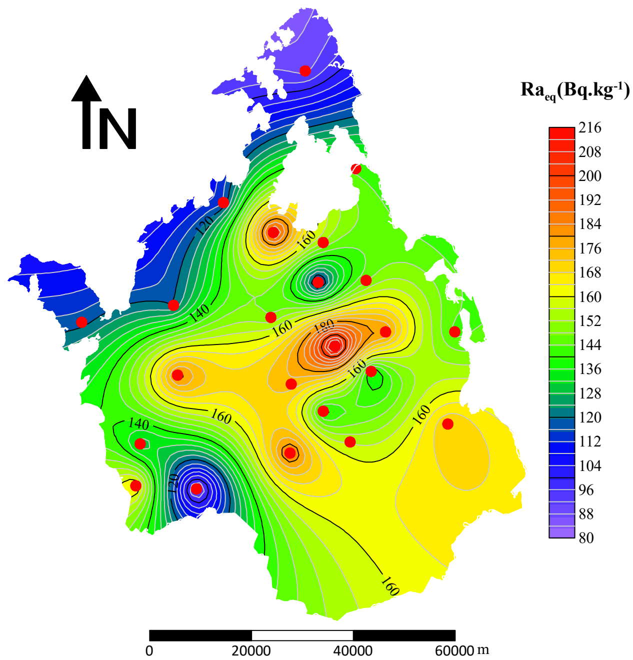

Fig. 6. Spatial distribution map of Radium Equivalent Activity (Ra_{eq}) in Antsiranana II

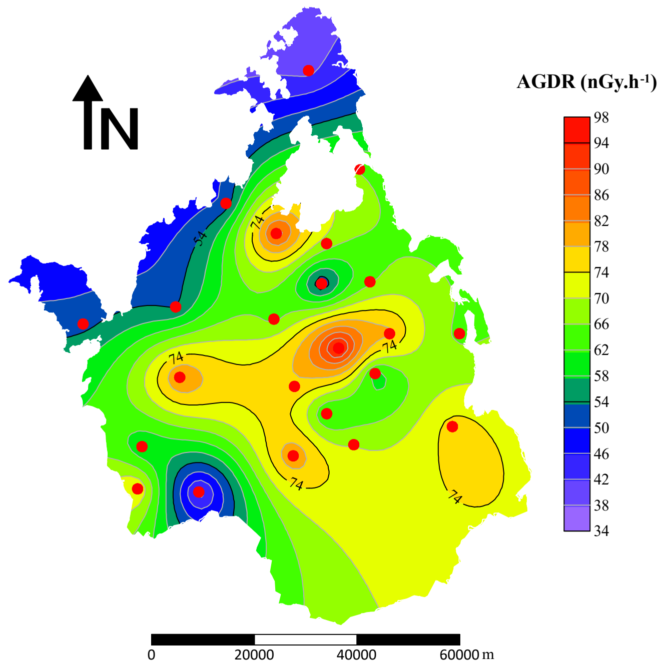

Fig. 7. Spatial distribution map of Absorbed Gamma Dose Rates (*AGDR*) in Antsiranana II

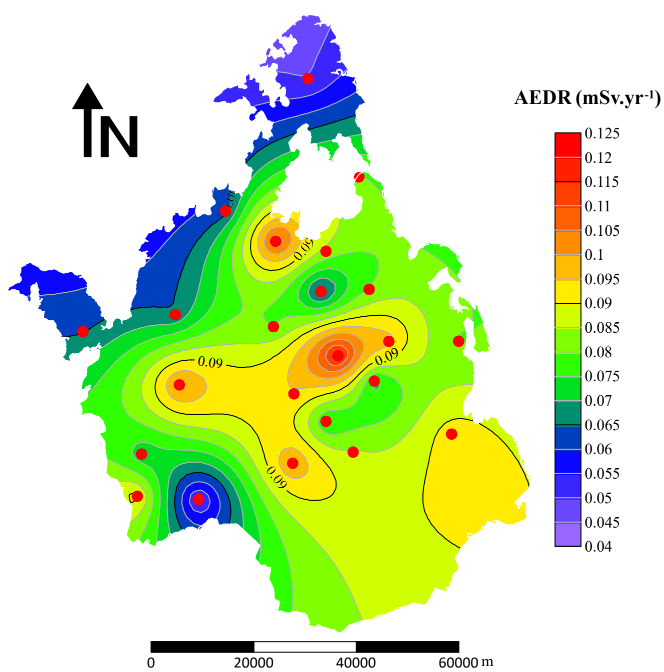

Fig. 8. Spatial distribution map of Annual Effective Dose Rates (*AEDR*) in Antsiranana II

Table IV. Comparison of radiological hazard indices with other districts in the DIANA and SAVA regions

District	Ra_{eq} (Bq.kg^{-1})	AGDR (nGy/h)	AEDR (mSv/yr)	ELCR (x10^{-3})
Antsiranana II (Present study)	96,00	44,00	0,13	0,40
Ambilobe (Stolerie *et al.*,2022)	120,00	58,00	0,18	0,50
Ambanja (Rahelivao *et al.*2023)	277,00	125,00	0,15	-
Antalaha (Ngoko *et al.* 2024 & 2025	133,00	58,00	0,18	0,53

Comparing the results with other districts in Northern Madagascar reveals the influence of regional geology on radiological risk (Table V).

The mean Ra_{eq} in Antsiranana II (96 Bq.kg^{-1}) is significantly lower than in Ambilobe (120 Bq.kg^{-1}), inAntalaha (133 Bq.kg^{-1}), in Ambanja (277 Bq.kg^{-1}). This disparity is explained by the geological substrate. Ambilobe is largely sedimentary and resulting in lower radioactivity. Ambanja, specifically the Ampasindava peninsula, contains granitic intrusions and specific mineralization (monazite) rich in Thorium, leading to much higher exposure levels (High Background Radiation Area). Antsiranana II occupies an intermediate position: its volcanic nature provides a moderate enrichment in actinides (Th) relative to sedimentary areas, but it lacks the heavy mineral accumulation found in Ambanja.

3.3. Limitations of the Study

This assessment focuses exclusively on the external radiation pathway. It does not account for internal exposure from the inhalation of radon (^{222}Rn and ^{220}Rn) and its progeny, or the ingestion of radionuclides through food and water. As radon inhalation is often the largest contributor to the total natural radiation dose, a complete radiological assessment of the region would require further investigation into these pathways.

4. Conclusion

This study provides the first radiological risk assessment for the population of the Antsiranana II district based on external exposure to terrestrial radiation. The results of the hazard indices calculation are conclusive. The radium equivalent activities are well below the safety limit, indicating that local soils are safe for construction purposes. Most importantly, the estimated annual effective dose is 0.21 mSv, which is significantly lower than the international public dose limit of 1 mSv. This study provides strong evidence that, from the perspective of external gamma radiation, the soils in the Antsiranana II district do not pose a significant radiological risk to public health. These findings are vital for local health authorities and provide a scientific basis for public reassurance.

In summary, while the volcanic geology of Antsiranana II creates a distinct radiological signature higher than neighboring sedimentary districts (like Ambilobe), it does not pose a significant radiological health risk to the population. No specific radiation protection measures or restrictions on soil use are required in this district. These findings provide a reassuring scientific baseline for local land management and public health monitoring and contribute to a better understanding of natural radioactivity in volcanically active regions of Madagascar and beyond.

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