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Baseline Measurements of Natural Radioactivity Around the Manyoni Uranium Deposit (Tanzania): Selection of Sampling Points

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ABSTRACT

In order to acquire baseline data for prospective uranium mines, environmental radioactivity measurements are usually performed over large areas. This leads to a huge number of sampling points with a time-consuming and expensive data-acquisition process. For this study, probabilistic and non-probabilistic sampling strategies were used to determine the fewest possible sampling points needed to establish baseline data around the prospective uranium mine of Manyoni (Tanzania). The probabilistic approach used stratified and systematic grid sampling to obtain 32 sampling points at a 27.96 km^2 site prone to pollution from the prospective mining activities. These points were proportionally distributed based on pre-determined strata, geological areas, and administrative wards. Non-probabilistic sampling used judgmental sampling to allocate 8 sampling points in a region expected to receive higher levels of mining dust pollution than the WHO guidelines. We present a more representative and less expensive sampling approach with fewer sampling points around the prospective mine.

Keywords: Sampling strategy, Natural radioactivity, Uranium mining, Baseline data

INTRODUCTION

Uranium mining activities, if not well managed, may enhance the levels of natural radioactivity in the environment, especially from radionuclides such as potassium-40 (^{40}K) and progenies of uranium-238 (^{238}U) and thorium-232 (^{232}Th) (US EPA, 2022). Depending on the levels and exposure pathways, this may lead to an increase in external and internal exposures of the human body to ionizing radiation, causing various harmful effects, including cancer (Brugge et al., 2005). To minimize the effects of radiation exposures resulting from these radionuclides and ensure compliance with environmental regulatory limits, the establishment of baseline data is essential. When mining begins, deviations in radiation exposure levels above the baseline levels will be attributed to uranium mining.

Several attempts have been made to measure natural radioactivity levels in the environment for the establishment of baseline data for potential uranium mining areas in Tanzania (Lolila, 2011; Mazunga, 2011; Mwalongo, 2011; Kimaro and Mohammed, 2015; Elisadiki and Makundi, 2015; Kasoga et al., 2016). These attempts were motivated by the need for baseline data following the establishment of radiation safety regulations for the mining and processing of radioactive ores in 2011 (Tanzania Atomic Energy Commission, 2011). In these attempts, several types of random sampling methods were used to choose the samples, and the selection of sampling points (and sampling area) was either based on the proximity and accessibility of the sampling point to the proposed uranium mine or detector security. Although these studies were beneficial in terms of establishing baseline data, they all shared a common drawback: the sampling points were chosen without considering factors that will influence pollution in the study area when uranium mining begins. To overcome this drawback, Banzi et al. (2015) used the **A**merican Meteorological Society-**E**nvironmental Protection Agency **R**egulatory **Mod**el (AERMOD), an atmospheric dispersion model that uses pollution inventories of the source, meteorological and topographical parameters as inputs to produce ground level concentrations of air pollutants at different drift distances as an output. The model predicted a pollution-prone area of about 1300 km^2 around the proposed Mkuju River uranium mine in Tanzania, which included populated settlements. Implicit in the attempt to select sampling points using the recommended 10 m x 10 m grid (United States Nuclear Regulatory Commission [US NRC], 1992) for each sampling point is that the baseline data for the predicted area would require a huge number (2 x 10^8) of sampling points (Banzi et al., 2015). In the same way, in our present study, we tried to allocate sampling points in a pollution-prone area of 27.96 km^2 near a prospective uranium mine in the Manyoni Project area (detailed in the next section). We realized that using the 10 m x 10 m grid recommended by the US NRC (1992) would also require a huge number (~2.8 x 10^5) of sampling points. Furthermore, using the 100 m x 100 m grid recommended by the Department of Mines and Petroleum (2010) in the area would significantly reduce the number (~2.8 x 10^3) of sampling points. However, in a normal situation of data collection and analysis of radioactivity in environmental samples (e.g., by using gamma ray spectrometry, which takes ~24 hours per sample), this number of sampling points would require more than 7 years to provide the required baseline data. This time is unrealistic for the establishment of baseline data needed before the commencement of uranium mining. To overcome this problem, the present study aims to design a sampling methodology with the fewest possible sampling points for establishing natural radioactivity baseline data around the prospective uranium mine at Manyoni in Tanzania.

METHODOLOGY

The Sampling Area

The sampling area of 27.96 km^2, modelled by AERMOD and bordered in red in Figure 1, has a high probability of being polluted by dust particles from future open-pit uranium mining activities at Playa C1 (a uranium deposit) in the Manyoni district in central Tanzania (Lolila et al., 2022). The area requires sampling points for the establishment of baseline data on natural radioactivity in the environment. About 70% of this area lies within the Manyoni Mjini administrative ward, and 30% falls under the Mkwese administrative ward.

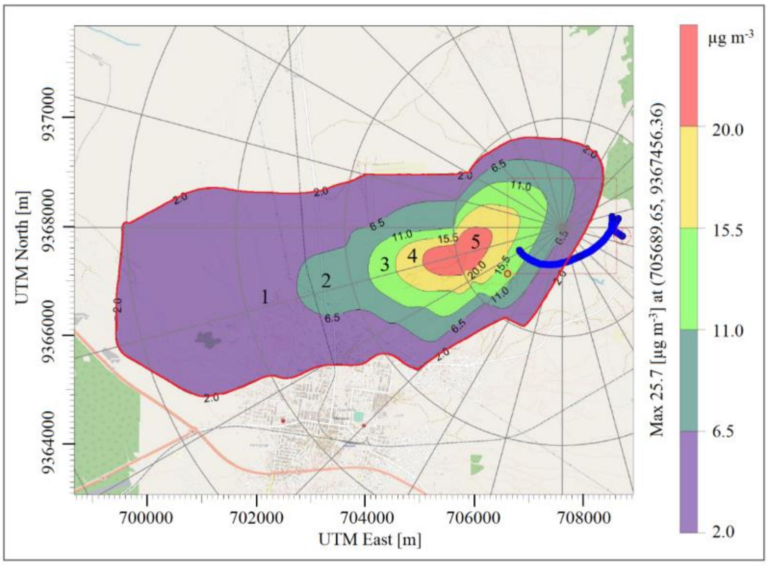


Figure 1: Map showing the sampling area with five zones

The sampling area has five non-overlapping and contiguous zones (marked by numbers 1, 2, 3, 4, and 5 in Figure 1), which were obtained based on the modelled mean annual ground level concentration (AGLC) of dust particulates with an aerodynamic diameter of ≤ 10 µm (PM$_{10}$) in ambient air (Lolila et al., 2022). These zones were designated using PM_{10} because it is one of the major air pollutants produced by open-pit mining activities such as blasting, drilling, bulldozing, loading, unloading, and truck transportation (Sinha and Banerjee, 1997; Trivedi et al., 2010). Furthermore, the PM_{10} released by uranium mining activities may contain naturally occurring radioactive elements such as daughters of ^{238}U and ^{232}Th as well as ^{40}K, which can change their baseline levels in the sampling area.

Selection of the Sampling Strategy

In this study, the selection of sampling points in the sampling area was done in two ways. In the first way, stratified sampling followed by systematic grid sampling was used. For stratified sampling, pre-existing information from the previous section (Figure 1) was utilized to partition the sampling area into five non-overlapping strata (zones) that were expected to be more homogeneous internally than the whole area. Additional information on regions within the sampling area that have similar geological settings or are within similar local administrative wards was also considered. In the second way, judgmental sampling was used to allocate sampling points in the area expected to experience higher mean AGLCs of PM_{10} than the WHO (2006) guideline of 20.0 µg m^{-3} (zone 5 in Figure 1). The next sections explain how the two sampling strategies were used to determine the number of sampling points in the sampling area.

Stratified Sampling Strategy

Determination of the number of total samples for all strata

Since the total number of sampling points equals the total number of samples required at the sampling area, the total number of samples was first calculated. With estimated values of variability within each stratum, S_h, a pre-specified fixed total cost of collecting and analyzing samples (in dollars), $C - c_0$, and stratum weights, W_h, the total number of samples for all strata combined, n, was calculated using the values given in Table 1 and Equation 1 from Gilbert (1987), which is given as follows:

$$n = \frac{\left(C - c_0\right)\sum_{h=1}^{L} \frac{W_h S_h}{\sqrt{c_h}}}{\sum_{h=1}^{L} W_h S_h \sqrt{c_h}} \tag{1}$$

where L denotes the number of strata ($h=1, 2, ..., L$); S_h is the estimated standard deviation of the measured values in stratum h; $W_h = N_h / N$ is the weight associated with stratum h; N_h is the total number of possible sampling locations (units) in stratum h; and $N = \sum_{h=1}^{L} N_h$ is the total number of possible units in all strata combined. Likewise, $C = \left(c_0 + \sum_{h=1}^{L} c_h n_h\right)$ is the total sampling budget; c_0 is the fixed overhead cost; c_h is the cost of collecting and measuring (analyzing) a sample in stratum h; and n_h is the number of samples collected in stratum h. The cost of analyzing samples in this study is the pricing associated with having environmental samples analyzed by gamma ray spectrometry at the Tanzania Atomic Energy Commission Laboratory.

Table 1: Input values for calculating the total number of sampling points in all strata

Parameter	**Stratum**				
	1	**2**	**3**	**4**	**5**
h	1	2	3	4	5
S_h	1	1	1	1	1
c_h (US \$) (collection, analytical)	30.89 (9.21, 21.68)	30.89 (9.21, 21.68)	30.89 (9.21, 21.68)	30.89 (9.21, 21.68)	30.89 (9.21, 21.68)
N_h (m^2)*	1.82561×10^7	4.91935×10^6	2.49457×10^6	1.57298×10^6	7.13395×10^5
$W_h = N_h / N$	0.653	0.176	0.089	0.056	0.026
C (US \$)	2,000.00				
c_0 (US \$)	1,000.00				

*Area of the stratum *h*

Distribution of samples to individual stratum

To optimally assign the total number of samples in each individual stratum *h*, Equation 2 by Cochran (1977) was used:

$$n_h = n\frac{N_h\sigma_h/\sqrt{c_h}}{\sum_{h=1}^{L} N_h\sigma_h/\sqrt{c_h}} \tag{2}$$

where σ_h is the true population standard deviation for stratum *h*; other symbols have the same meanings as described after Equation 1. In practice, σ_h is replaced with an estimate, S_h, obtained from prior data as proposed by Gilbert (1987). From Equation 2, two observations are made: (i) the number of samples is directly proportional to N_h and σ_h, therefore more samples should be allocated to the more variable and larger stratum; (ii) the number of samples is inversely proportional to $\sqrt{c_h}$, therefore fewer samples should be allocated to the more expensive stratum. If the cost per population unit is the same for all strata, Equation 2 reduces to Equation 3 (Cochran, 1977) as follows:

$$n_h = n\frac{N_h\sigma_h}{\sum_{h=1}^{L} N_h\sigma_h} \tag{3}$$

Equations 2 and 3 can be used if an accurate estimate of the population mean and eventually σ_h is available. Alternatively, when this information is not readily available, as was the case in this study, proportional allocation of the number of samples in a stratum can be done using Equation 4 (Gilbert, 1987). For this reason, the number of samples for each stratum in this study was allocated using Equation 4 as follows:

$$n_h = nW_h = n\frac{N_h}{N} \tag{4}$$

Determination of the sampling locations

After distributing the samples to the individual strata, a method for determining where those samples should be collected inside each stratum was required. To establish this method, Visual Sample Plan (VSP) software version 7.16 was used. This software provides several sampling mechanisms for determining sampling locations, including simple random sampling, stratified sampling, systematic grid sampling with a random start or with a fixed start, and adaptive cluster sampling (Matzke et al., 2014). In this study, sampling points were allocated in each stratum using systematic grid sampling with a random start. The use of a systematic grid ensures uniform spatial coverage of the sampling points in each stratum and the entire site. After allocating the samples on the grids, a list of coordinates for each sampling point was generated by the VSP software, and each sampling point was displayed on a map.

Additional considerations for allocating the sampling locations in stratum h

When sampling captures the full range of variability in the radionuclide distribution in a survey unit, it is said to be representative. It is well known that natural background radiation varies with local geology (UNSCEAR, 1993). To capture the extent of this variability, a geological map of the sampling area was also considered when allocating the sampling points. Two geological settings, displayed in grey and brown in Figure 2 and marked by GW (geology on the west) and GE (geology on the east), respectively, exist in the area. The grey area's geology is described as terrestrial coarse clastic sediments, higher coastal terrace, laterite, and alterite, whereas the brown area's geology is defined as a gneiss-granite-migmatite complex (Dodoman and Isangan Group) (Geological Survey of Tanzania, 2021).

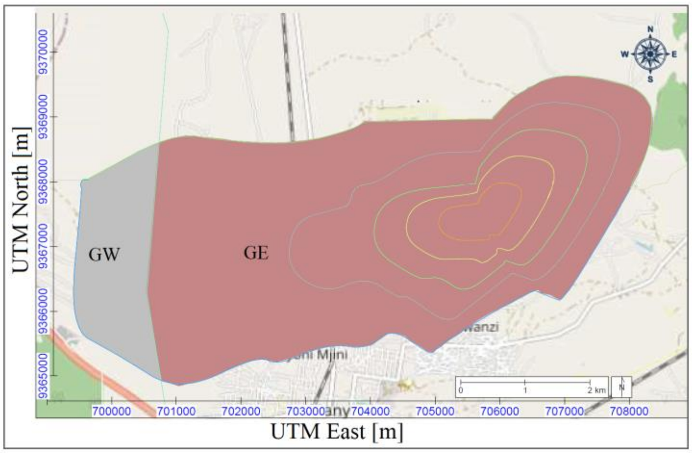


Figure 2: A map showing the geological regions in the demarcated area

The regions GW and GE roughly occupy 3.45 km^2 and 24.50 km^2, which encompass 12.34% and 87.66% of the sampling area, respectively. This information about proportionality was used to distribute the n samples, which were previously calculated using the stratified sampling approach. The obtained geological regions overlay the five strata previously obtained in the sampling area. As a result, rather than distributing the n sampling points separately, the previously allocated points in the five strata were redistributed on the sampling area by running the VSP software several times until the proportional number of sampling points in each stratum (n_h) and geological setting were reached.

Moreover, since future management of environmental pollution may differ in different local administrative areas, the distribution of the administrative wards in the sampling area was also considered when allocating the sampling points in the sampling area. Figure 3 shows that the Mkwese and Manyoni Mjini wards, respectively, occupy 29.3% and 70.7% of the sampling area. In these wards, the same proportion was used to determine the number of sampling points. Since the wards overlay the five previously acquired strata as well as the geological areas GW and GE, the previously obtained n points were reallocated numerous times using VSP software until the proportional number of sampling points in each stratum, geological region, and ward were achieved.

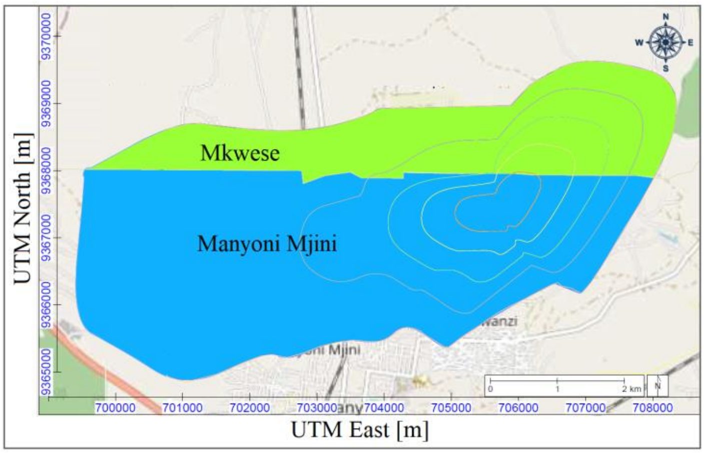


Figure 3: A map showing the administrative wards of Mkwese and Manyoni Mjini

Judgmental Sampling Strategy

Another consideration when selecting a site for environmental baseline monitoring was done by using the statement: "Samples should be drawn from areas expected to experience maximum deposition" (IAEA, 2010). In this regard, an area of about 713395.32 m^2 with an expected PM_{10} deposition with a mean AGLC greater or equal to the recommended WHO (2006) annual limit of 20 $\mu g\ m^{-3}$ for PM_{10} (i.e., region 5 in Figure 1) was chosen for sampling. In this area, 8 sampling points, each inside a grid with a spacing of 300 m × 300 m, were selected based on professional judgment: 1 sample point, H1, was selected from a location expected to receive the highest mean AGLC of PM_{10}, and 7 sampling points were allocated near H1. While a few sampling points can be allocated using judgmental sampling, the sampling design is biased and does not support any statistical interpretations (IAEA, 2019). Therefore, in this study, the selection of sampling points for the establishment of baseline data based on judgmental sampling will yield data that can only be used as a reference for future checks of compliance with environmental protection regulatory limits and not for any statistical inferences about the entire area that could be polluted by the prospective uranium mining activities.

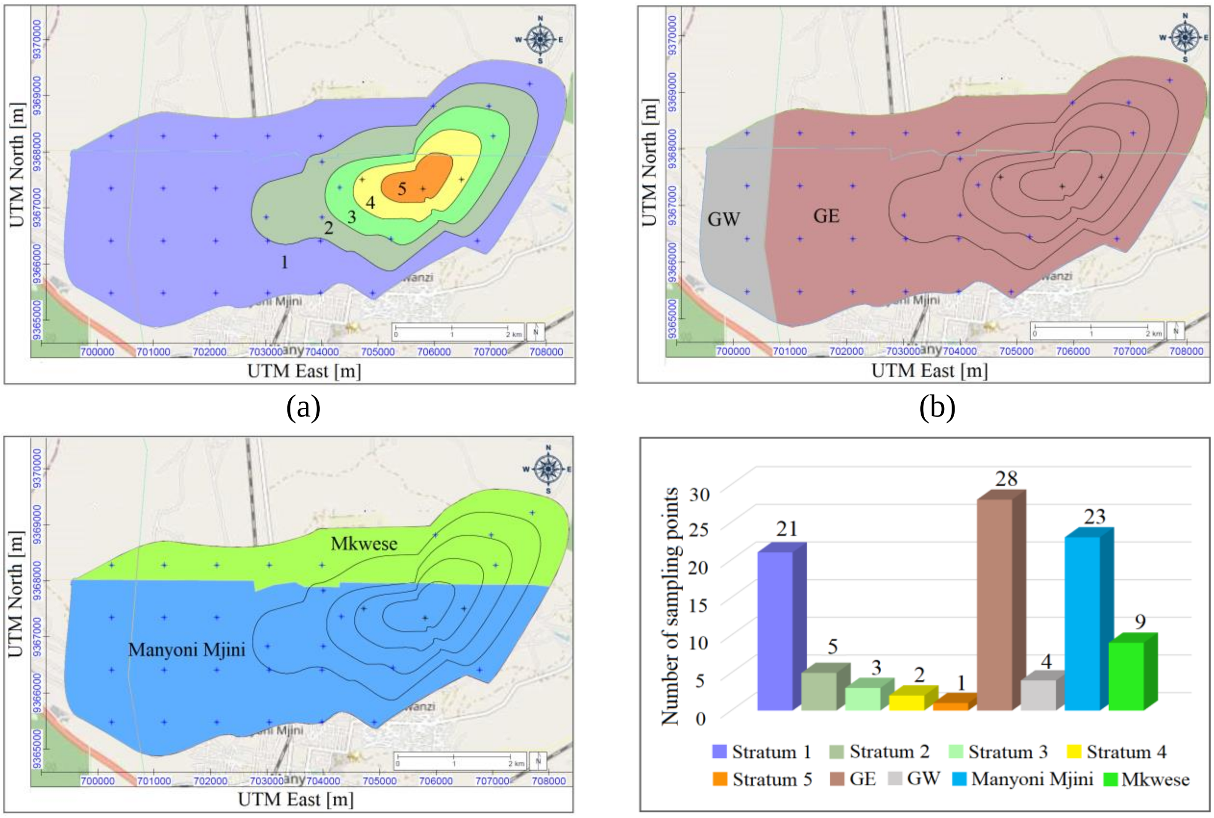
RESULTS AND DISCUSSION

The Total Number of Samples for All Strata and Their Distribution in Individual Strata

Based on Equation 1 and its inputs in Table 1, the total number of samples, n, for the combined strata in the sampling area was 32. Using Equation 4 and stratum weights W_h from Table 1, these samples were allocated in each stratum for the available 5 strata. Figure 4(a) shows the number of samples (i.e., the sampling points) allocated in strata 1, 2, 3, 4, and 5, which are 21, 5, 3, 2, and 1, respectively. From Figure 4, it can be observed that the stratum with the largest W_h was allocated many sampling points and vice versa (Figure 4(a)).

Moreover, Figures 4(b) and 4(c) show the distribution of sampling points in each geological region and administrative ward, respectively. It can be noted that the proportional distribution provided 4 sampling points in the GW region (12.34%) and 28 in the GE region (87.66%). In the same manner, 9 sampling points were distributed in the Mkwese ward (29.3%) and 23 in the Manyoni Mjini ward (70.7%). The overall distribution of the sampling points according to strata, geological regions, and administrative wards is summarized in Figure 4(d). In general, the square-grid size allocated for each distribution in Figure 4 was 932.4 m × 932.4 m. However, due to stratum shape effects, the actual grid size in the stratum may appear to differ from the allotted one

(Figure 4). Despite this variation, when shape effects were eliminated (i.e., when using a real grid size), the number of sampling points allocated in the sampling area remained the same.



(a) (b)

(c) (d)

Figure 4: Proportional distribution of the sampling points

The obtained 32 sampling locations were labeled as S1, S2 up to S32, and their distribution, based on the random start, is shown in Figure 5.

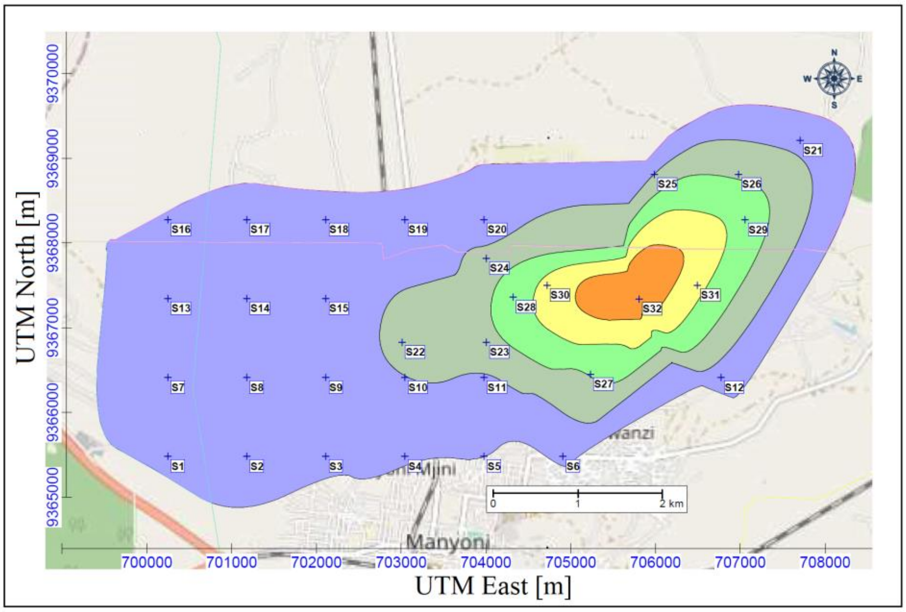


Figure 5: A map showing the distribution of sampling points with labels

A list of geographical coordinates for each sampling point as located in UTM zone 36M is given in Table 2. With the help of a global positioning system (GPS) receiver, this list is very useful for accessing sampling points during baseline monitoring as well as during operational monitoring of uranium mining activities.

Table 2: The geographical coordinates of the sampling points from S1 to S32

Label	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**
Easting (m)	700245.0	701177.3	702109.7	703042.1	703974.5	704906.9	700245.0	701177.3
Northing (m)	9365480	9365480	9365480	9365480	9365480	9365480	9366412	9366412
Label	**S9**	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**
Easting (m)	702109.7	703042.1	703974.5	706771.6	700245.0	701177.3	702109.7	700245.0
Northing (m)	9366412.4	9366412.4	9366412	9366412	9367345	9367345	9367345	9368277
Label	**S17**	**S18**	**S19**	**S20**	**S21**	**S22**	**S23**	**S24**
Easting (m)	701177.3	702109.7	703042.1	703974.5	707704.0	703009.9	704001.8	704001.8
Northing (m)	9368277.2	9368277.2	9368277	9368277	9369210	9366829	9366829	9367821
Label	**S25**	**S26**	**S27**	**S28**	**S29**	**S30**	**S31**	**S32**
Easting (m)	705985.6	706977.5	705230.7	704318.8	707054.4	704718.6	706492.3	705805.2
Northing (m)	9368813.2	9368813.2	9366451	9367363	9368274	9367503	9367503	9367340

The Total Number of Sampling Points for the Area with the Highest Pollution Potential

The 8 gridded sampling points, labeled H1 to H8, and their distribution in the area with the highest pollution potential are shown in Figure 6. A list of geographical coordinates for each sampling point in UTM zone 36M is given in Table 3. Since they were obtained based on judgmental sampling, samples obtained using these points cannot be used to make statistical inferences about the entire site as they are not representative of the entire site. However, the points can be used to collect samples for both baseline and operational monitoring of uranium mining operations. When uranium mining commences, the baseline monitoring data can be compared with the operational monitoring data. This will help to ensure that environmental protection regulations are followed during and after mining.

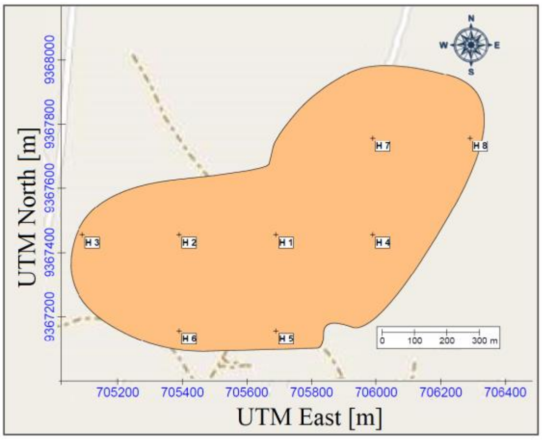


Figure 6: A map showing the distribution of sampling points based on judgmental sampling

Table 3: The geographical coordinates of the sampling points H1 to H8

Label	**H1**	**H2**	**H3**	**H4**	**H5**	**H6**	**H7**	**H8**
Easting (m)	705690	705390	705090	705990	705690	705390	705990	706290
Northing (m)	9367456	9367456	9367456	9367456	9367156	9367156	9367756	9367756

Comparison with Previous Studies

Table 4 summarizes several studies conducted to establish baseline data on natural radioactivity near uranium deposits in Tanzania, primarily at the Manyoni, Bahi, and Mkuju River. According to this summary, the sampling strategies used in the baseline studies conducted by Banzi et al. (2017), Elisadiki and Makundi (2015), Kimaro and Mohammed (2015), and Mohammed and Mazunga (2013) seem to be stratified random sampling with relatively few sampling points. In these studies, the selection of the sampling points was based mainly on the proximity and accessibility of the sampling points to the prospective uranium mine or detector security. Except for Banzi et al. (2017), for which the sampling area was obtained by modeling with AERMOD (Banzi et al., 2015), the sampling points were chosen without considering factors that affect pollution in the sampling areas when uranium mining begins.

Table 4: Comparison of the selection of sampling points with previous studies

Research	**Study area**	**Strategy for selecting sampling points**	**Number of sampling points**	**Criteria for selection of sampling areas or sampling points**
Banzi et al. (2017)	Mkuju River (1300 km^2 simulated by Banzi et al. (2015))	Random sampling	52 from 42 sampling blocks: 42 in the vicinity of the Mkuju River uranium project and 10 in the concession area	The sampling blocks were created based on ambient gamma dose rate measurements The sampling points were selected from areas in the vicinity of the Mkuju River Uranium Project and in the concession area of the project
Elisadiki and Makundi (2015)	Manyoni District (28620 km^2)	Random sampling	20 from 7 villages: 3 points in six villages and 2 points in one village	The selected villages were near the uranium-mineralized zones The sampling points were chosen at locations where the radiation detector was considered to be secure
Kimaro and Mohammed (2015)	Bahi Wetlands (2000 km^2)	Random sampling	25 from 3 geographic zones: 7 points from Northern zone, 8 from the Central zone, and 10 from the Southern zone	The sampling points were selected based on their proximity and accessibility to the exploration areas surrounding the uranium deposits
Mohammed and Mazunga (2013)	Likuyuseka ward (5,919 km^2)	Random sampling	30 from 3 geographic zones: 10 points from Northern zone, 10 from the Central zone, and 10 from the Southern zone	The sampling points were selected from areas near the Mkuju River uranium deposit

This study	Manyoni ($27.96\ km^2$ simulated by AERMOD)	Stratified and systematic sampling	40 from the modelled area: 32 in the entire sampling area and	The sampling area and strata were chosen based on pollution dispersion modeling
		Judgmental sampling	8 in the area expected to receive mean AGLC of $PM_{10} \geq 20\ \mu g\ m^{-3}$	The sampling points were selected and distributed in proportion to the sampling budget, strata sizes, geological setting, and administrative wards

When compared to these previous studies, the stratified sampling strategy developed in this study resulted in a relatively small number of sampling points (32) with several improvements. The first improvement was that the sampling points were chosen from the site (strata) selected based on meteorological, topographical, and source (of pollution) parameters, which in principle influence the dispersion of pollutants in the area requiring baseline data. In this way, a significantly smaller area ($27.96\ km^2$) with a higher potential for pollution was obtained, and the selection of sampling points was only focused on this site. Secondly, the use of Equation 1 offered a criterion for getting the total number of sampling points in all strata within the available budget, a criterion that was lacking or not specified in previous studies. Thirdly, the use of Equation 4 provided a proportionate number of sampling points in each stratum, which will eventually yield baseline samples with features that are proportional to the entire population. Fourthly, the blending of systematic grid sampling with stratified sampling, as applied in this study, ensures uniform spatial coverage of sampling points in each stratum and the entire site. Fifthly, the systematic approach with sampling points chosen at the grid intersections eliminates clustered selection, a phenomenon in which randomly selected sampling points (or samples) are unusually close together in a population (Ross, 2022). Moreover, the sampling points in this study are more representative, as their choice captured the variation of natural radioactivity with the local geology of the site under study. Furthermore, when the area under study is in more than one administrative ward, this study distributed the sampling points in each ward to make environmental monitoring easier to manage.

CONCLUSION

This work was undertaken to design a sampling methodology with a minimum number of sampling points for the establishment of baseline data on natural radioactivity in the prospective uranium mine of Manyoni. Using a blend of stratified sampling and systematic grid sampling has resulted in 32 sampling points for the entire sampling site. These points can be used to estimate the mean for the whole site under the condition that sampling and analytical expenses do not exceed a certain limit (Table 1). In addition, using judgmental sampling, 8 sampling points were allocated to a small subset of the entire site. The area covered by this subset is expected to experience high dust pollution (PM_{10}) from the prospective mine. Since the 8 points were obtained through bias, they can only be used to establish baseline data and for future reference without making any statistical inferences. Considering a normal situation of collecting environmental samples and analyzing their radioactivity, the number of sampling points allocated to the site under this study is suitable for the establishment of baseline data on environmental radioactivity around the proposed uranium mine at Manyoni.

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