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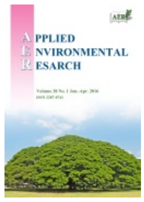

Modelling of Radiological Health Risk in Water from Abstraction Well Close to a Hypothetical Radioactive Waste Repository in the Accra Plains

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Abstract

This study evaluated the integrity of the geosphere of the Accra Plains to host a radioactive waste disposal facility for Ghana's radioactive waste materials. The study thus assessed the migration of radioactive contaminant from a hypothetical radioactive waste disposal facility through the geosphere to the biosphere in the Accra Plains. The Accra Plains is predominantly underlain by schist rocks, hence the hydrogeologic parameters of schist rock from literature were used as input data. AMBER software was used to develop a model to estimate the peak total annual effective dose from all the radionuclides at various receptor locations. The endpoint of interest was the dose received by a receptor for ingesting water from an abstraction well located at distance; 100 m, 200 m, 500 m, 1 km, 2 km, 3 km, 4 km and 5 km from the hypothetical repository. From the simulation, the annual effective dose values ranged from 2.07E-25 Sv/y to 6.45E-17 Sv/y which are all below the International Commission on Radiological Protection (ICRP) dose constraint of 0.3 mSv/y. The lifetime cancer risk for ingesting water from the abstraction wells were then calculated from the annual effective dose values. The resulting values ranged from 1.06E-24 to 3.30E-16 thus indicating that the potential cancer risk for ingesting water from the abstraction wells located within 100 m to 5 km from the hypothetical disposal facility is negligible. The model results demonstrate that, siting a disposal facility in the study area might not pose any significant risk to the sprawling population and the environment.

Keywords: Lifetime cancer risk; Annual effective dose; Accra Plains; Disposal facility

Introduction

Radioactive sources have been in use in the field of medicine, agriculture, industry, research and academics in Ghana since 1950 [1]. These radioactive sources have specifically been used in food irradiation to preserve and extend the shelf life of farm produce; medical centres for cancer treatment (radiotherapy and diagnostics), and in sterilization of medical equipment and products, as well as disinfestations. In addition,

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they have been used for research and teaching purposes; in smoke detectors, road construction, in exploration of oil and gas, as well as in R&D laboratories [2]. Application of radioactive materials normally generate radioactive waste materials. These waste materials are dangerous and potentially present risk to humans as well as the environment. There is the need to manage these waste materials safely to avoid any allied risks for the present and future generations. It is necessary in principle for societies or organizations that have benefited from use of radioactive materials to act responsibly to safely manage them to avoid undue burden on future generations [3]. Some of these radioactive waste materials can decay rapidly and safely, nonetheless, some long-lived radioactive waste will always remain. There is the need therefore to dispose them of in underground repositories.

The use of radioactive materials in Ghana has resulted in a stock of disused radioactive sources, which needs to be managed and dispose of prudently. These disused sources contain different radionuclides in varied amounts. Several of these radioactive sources, though small in size, have high radioactivity. These radioactive sources can present a substantial risk to human health and the environment if not managed properly. The need therefore for a disposal facility for both the existing and future radioactive waste materials cannot be overstated. Accra Plains is the prospective host site for such a radioactive waste disposal facility in Ghana. Glover [2] established that the hydrogeochemical environment for rocks at Okwenya and that of the bases of the Krobo Mountains in the Plains are conducive for siting a radioactive waste repository.

In order to establish the safety of a disposal system for the disposal of these long lived radioactive waste materials, the system must satisfy radiological safety criteria imposed by regulatory agencies. In this regard, mathematical modelling of the performance of the disposal system is essential to demonstrate that the system meets such quantitative criteria.

The geosphere as a natural barrier and its long-term stability capable of isolating radionuclides from the environment are the prime benefits of geological disposal of radioactive waste [4]. For the geosphere to serve as an effective natural barrier it should be able to protect the disposal system physically for millions of years by providing suitable environment to elongate the life span of the engineered barriers. Furthermore, the geosphere should also restrict the movement of radionuclides in event of potential release from the repository through sorption and matrix diffusion within the host rock [4]. Geosphere features such as fractures and pores may facilitate radionuclides migration in the environment. In this regard, there is the need to examine the geosphere, which will lead to informed decision making to mitigate any potential effects of the disposal system on humans and the environment.

The main objective of the study was to assess the migration of radioactive contaminants from a hypothetical radioactive waste disposal facility sited in the Accra Plains. This was to affirm the integrity of the geosphere of the Accra Plains to host a disposal facility for Ghana’s radioactive waste materials that can neither be decay stored nor return to the country of origin. The study considered potential escape of radionuclides from the disposal facility to abstraction wells down the hydraulic gradient located 100 m, 200 m, 500 m, 1 km, 2 km, 3 km, 4 km and 5 km from the disposal facility. Additionally, radiological health risk assessment was undertaken to ascertain the consequence on the population within the vicinity in the event of ingesting water from the abstraction well. The study applied AMBER software modelling to achieve this aim.

Materials and methods

1) Description of the Accra Plains

Accra Plains is situated on the east of the Akwapim Range. The plains slopes marginally to the ocean with gentle, mature topography lying beneath [5]. The Akwapim Mountains are along the northwest and west of the plains, on the north towards the east is the River Volta and Gulf of Guinea along the south (Figure 1). Direction of rivers are known as lineaments in aerial photographs. This is based on the steeply dipping faults as well as directions of dike intrusions in addition to joint or shears exhibiting likely weak zones in the rocks [6]. The plains is positioned southeast of Ghana, between latitude $0^{o}\ 20^{1}$ W and $0^{o}\ 40^{1}$ E, and latitudes $5^{o}\ 30^{1}$ N and $6^{o}\ 15^{1}$ N. The area of the plains is around 7000 km^2 [2].

The rainfall pattern of the northern part of the plains is very much considerably higher and better distributed and uniform. The lowest mean monthly temperature of about 26 ºC occurs in August with the highest of about 30 ºC occurring between March and April. The maximum mean monthly relative humidity is at most 75%, and the lowest is about 60% [8]. The Accra Plains is largely flat forming a low-lying area with limited isolated inselbergs and ridges such as the Krobo, Shai and Osudoku hills that rise above 100 m. Generally, the elevation of the plains is less than 40 m. The Akwapim Togo Mountain rises to a height of 365 m above sea level attaining a width of approximately 3 to 6 km. This mountain is made-up of stratified rocks that slope to the southeast [9].

Geologically, the Accra Plains is mostly underlain by acidic Dahomeyan and Togo rocks [10]. The acidic Dahomeyan group of rocks generally consists of muscovite-biotitic gneiss, quart-feldspar gneiss, augen gneiss and minor amphibolites. These rocks slightly weather to permeable calcareous clay. Togo rocks are mainly metamorphic and highly folded arenaceous group of rocks consisting of quartzite, quartz schist, sandstone, shale, sericite schist and phyllite. Jasper and hematite quartz schist are common [10]. Many fractures and joints characterize rocks of Togo formation, with an average density of 80 joints per cubic metre [2]. The Togo Structural Unit consists of rocks such as quartzites, phyllites and schists. The geology consists of the very low Dahomeyan and Togo permeable rocks. Secondary porosities, for example, fractures, faults, joints etc. and the associated weathered zone develop in the rocks. These control groundwater occurrence in these rocks [11].

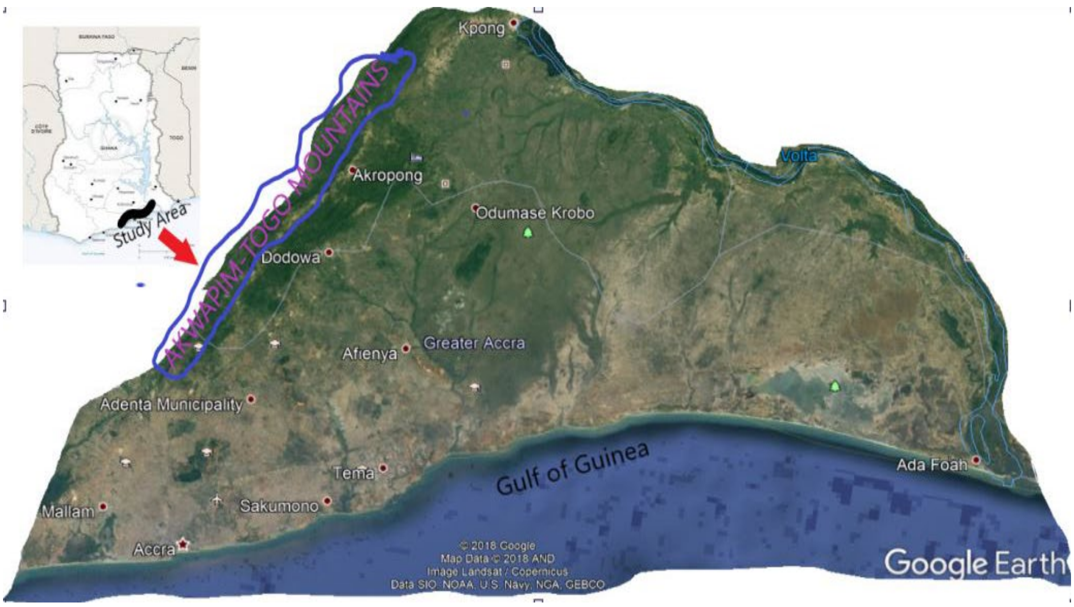

Figure 1 Location map of the Accra Plains (adapted from Essel et al. [7]).

The crystalline basement rocks dominate the hydrogeological setting of the Accra Plains with aquifer systems occurring beneath water table, confined and semi-confined conditions. The weathered zone is generally impervious and the rocks are massive crystalline in structure. This limits the yields obtainable from boreholes or hand-dug wells [2]. There are three aquifers with good groundwater potentials in these rock formations. The borehole yields of both the confined and unconfined aquifers range between 0.41 – 29.8 m^3 h^{-1} [6]. Agbevanu [6] maintains that, nine out of ten borehole yields of the study area considered were all below 12.4 m^3 d^{-1}, revealing that the boreholes can at least serve domestic purpose hence the need to protect them. That work further revealed that, pumping test data collected on the study area indicated that boreholes with depths and yield vary between 55 – 90 m and 5 – 60 L min^{-1} (i.e., 0.3 – 3.6 m^3 h^{-1}) respectively, indicating low yield. Darko et al. 1995 [10] estimated the mean potential yield of the Dahomenyan aquifer to be 5.9 m^3 d^{-1}. The potential of the Dahomeyan formation as a source of drinking water is poor. However, several boreholes of moderate to good yield are located in the Adenta and Oyarifa areas along the northern border closer to the Akwapim Togo Mountain. Even though the produced water is brackish or saline, it is suitable for alternative uses such as washing. The rocks are characteristically impermeable with groundwater in the geologic formation governed primarily by secondary porosity, i.e. fractures, faults, joints and the associated weathered zone [12].

2) Disposal facility considered

The hypothetical radioactive waste repository is based on the Borehole Disposal System (BDS). This is a narrow diameter (0.26 m) borehole design established under the International Atomic Energy Agency (IAEA) / African Regional Cooperative Agreement for Research, Development and Training related to Nuclear Science and Technology (AFRA) Regional project. The BDS is a multi-barrier disposal system that is capable of safely confining conditioned Disused Sealed Radioactive Source (DSRS) with an inner high integrity stainless-steel capsule containing the DSRS; an inner cement containment barrier, and an outer high integrity stainless-steel container and backfill cement, as well as the surrounding geosphere as exhibited in Figure 2.

The disused radioactive sources to be disposed, Table 1, conditioned inside a high integrity stainless steel capsule that is placed inside the high integrity stainless steel container, separated by cement grout containment barrier. The disposal package expected to last for thousands of years when the package emplaced within a depth of 30 to 100 metres in an engineered borehole located in a suitable host geological media.

3) Parameters used as input data

The values of the hydrogeological parameters used, obtained from literature for schist rock has been presented in Table 1.

Table 2 shows the inventory of radionuclides considered with initial activities and their corresponding half-lives.

4) Conceptual and mathematical model

The method of matrix interaction consistent with the requirements of the assessment with AMBER computer code was applied for the development of the conceptual model. The geosphere in-between the hypothetical disposal facility and an abstraction well was discretised into sixty (60) compartments. The compartments consist of rock matrix with a single fracture in water saturated porous rock (Figure 3). The assumption was that, transport in the fracture obeyed the advection-diffusion equation. Molecular diffusion was the dominant mechanism for transport in the porous matrix. Transfers between the compartments were the processes with the potential to move contaminants around the system.

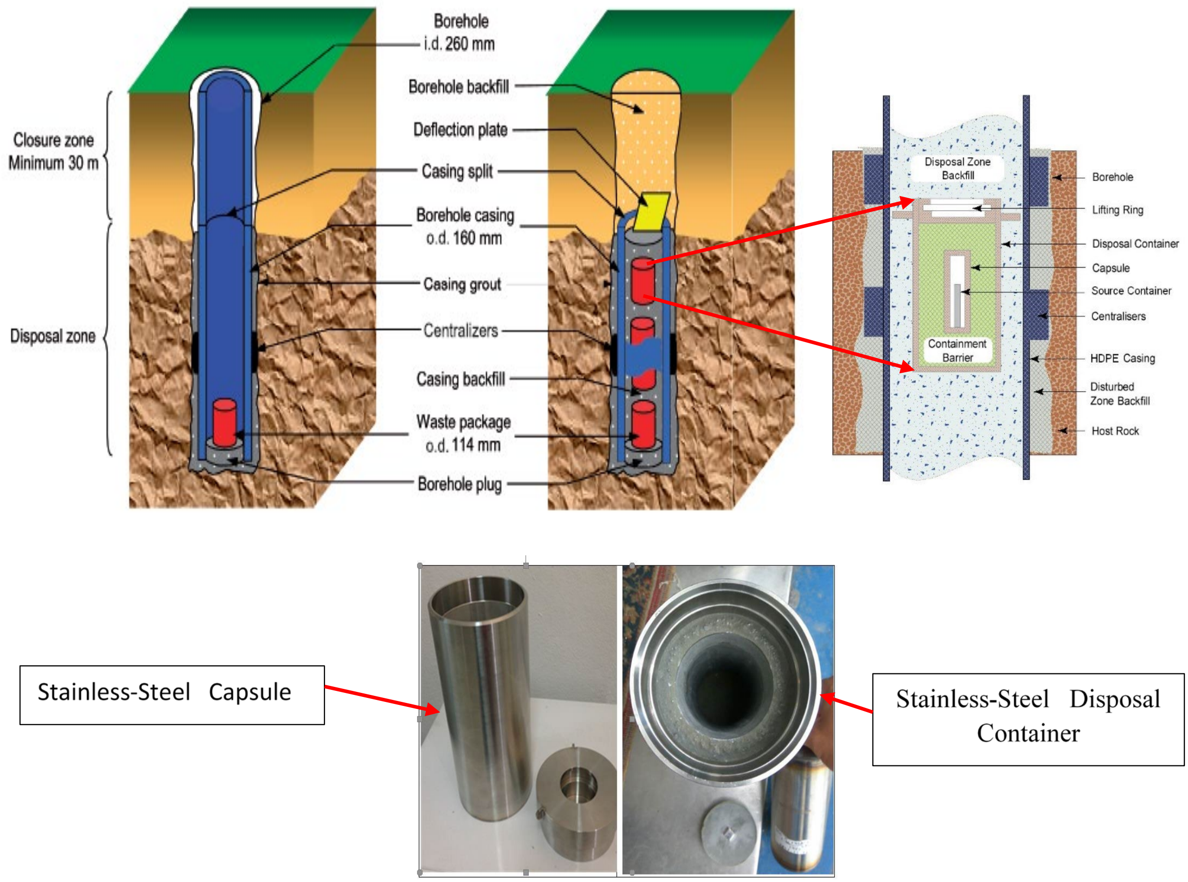

Figure 2 A schematic representation of the borehole disposal system (Source: Jan-Marie [13]).

Table 1 Parameters used as input data in the model

Hydrogeology parameters for Schist Rock		
Parameter	**Value**	**Source**
Hydraulic conductivity _Matrix	3.65e-4m y^{-1}	[14]
Hydraulic conductivity _Fracture	3.65e-2m y^{-1}	[14]
Hydraulic gradient	0.05	[15]
Water-filled porosity _Matrix	1e-6	[16]
Water-filled porosity -Fracture	1e-2	[16]

Table 2 Inventory of radionuclides used in the study

Radionuclide	Activity (Bq)	Half life (years)
Co-60	2.5e+14	5.27
Cs-137	2.1e+11	30
Sr-90	7.2 e+9	29.1
Am-241	8.0 e+10	432
Ra-226	10.0e+9	1600

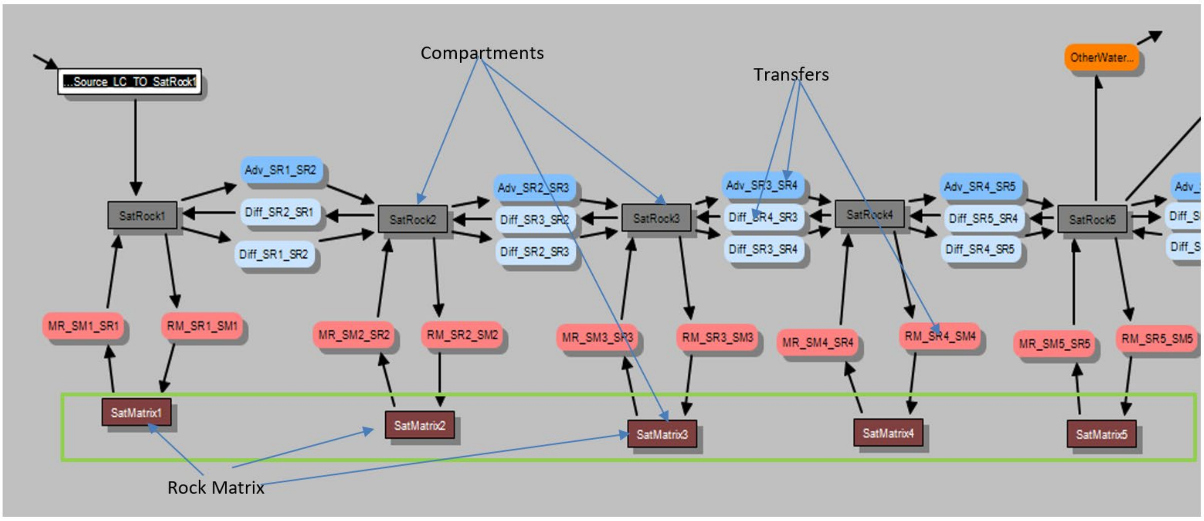

Figure 3 Screenshot of portion of the developed AMBER model.

For the calculation of endpoint of interest, the model was implemented in AMBER software. The endpoint of interest included the fluxes of radionuclides around the disposal facility and potential dose rates that may arise to inhabitants within the vicinity. Exposure of humans to radiation was projected effective dose to an adult on consumption of water from an abstraction well down the hydraulic gradient from the disposal facility. Shown in Figure 4 is an abstraction well located 5 km away from the disposal facility considered in this study. In addition, abstraction wells sited 100 m, 200 m, 500 m, 1 km, 2 km, 3 km and 4 km from the disposal facility were also considered.

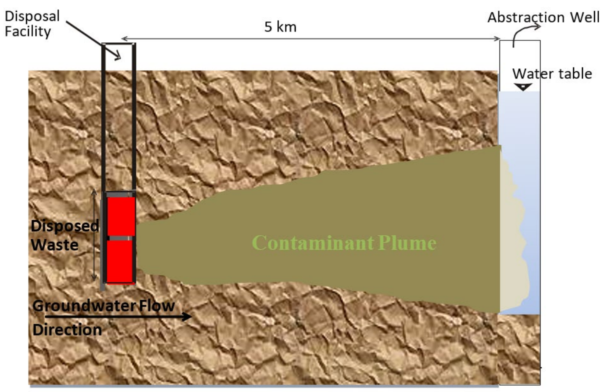

Figure 4 Schematic representation of liquid releases.

Results and discussion

The study used the AMBER model to estimate the potential exposure of the population in the study area. This was done by estimating the peak total annual effective dose from all the radionuclides at various receptor locations (abstraction well location), i.e., 100 m, 200 m, 500 m, 1 km, 2 km, 3 km, 4 km and 5 km from the hypothetical repository. The results are as shown in Figure 5 for purposes of comparison with recommended dose limits.

From Figure 5, the peak annual effective dose values ranged from 2.07E-25 Sv/y to 6.45E-17 Sv/y with mean peak annual effective dose of 8.32E-18 Sv/y which is lower than the ICRP limit of 0.3 mSv/y. Furthermore, the dose profile around the disposal facility has been plotted for the various receptor locations resulting in Figure 6. As can be seen from the graph, the highest peak dose from the shortest receptor location, 100 m is 6.45e-17 Sv/y which is 14 times less than the ICRP limit of 0.3 mSv/y.

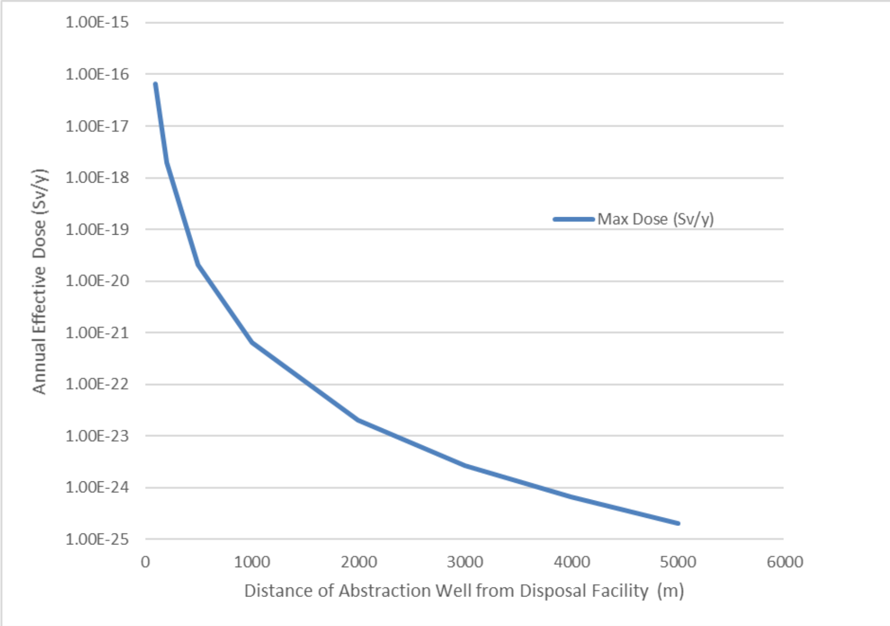

Figure 5 Estimated annual effective dose for ingestion of water from the abstraction well.

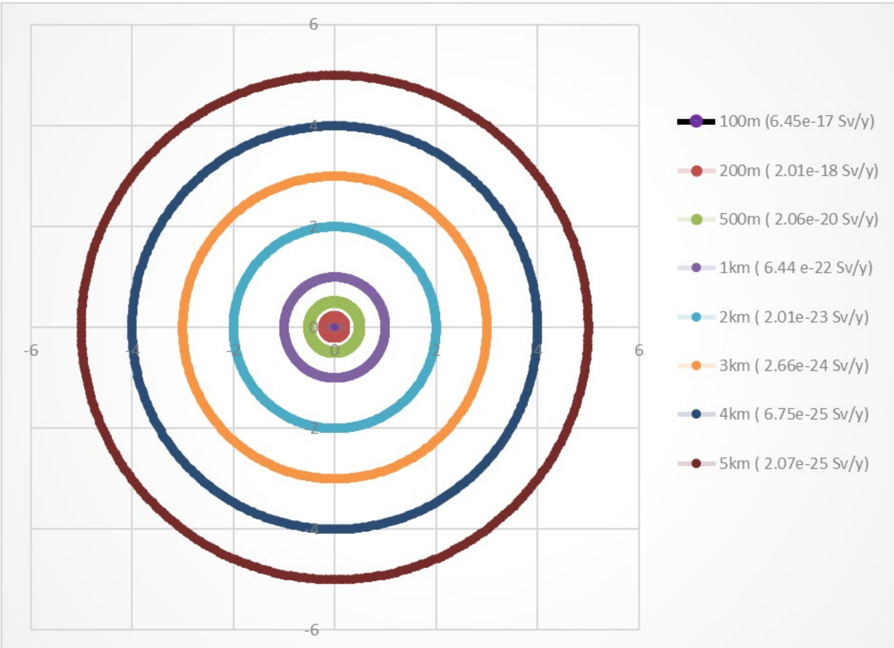

Figure 6 Dose profile at various distance around the disposal facility.

1) Lifetime cancer risk assessment

The Eq. 1 used to calculate the lifetime cancer risk [18].

$$\text{Lifetime Risk} = DR_w \times DL \times RF \qquad \text{(Eq. 1)}$$

Where DR_W is the annual effective dose equivalent (Sv/year) as estimated above using the AMBER model, DL is duration of life (70 years), and RF is risk factor (Sv^{-1}).

For the Risk factor (RF), the ICRP (1991) [19] recommended nominal probability coefficient of 7.3×10-2 Sv^{-1} was adopted. As can be seen from Figure 7, the risk values ranged from 1.06E-24 to 3.30E-16 with a mean value of 4.25 E-17. The result shows that the risk in ingestion of water from the abstraction well for the radionuclides considered in negligible in the study area.

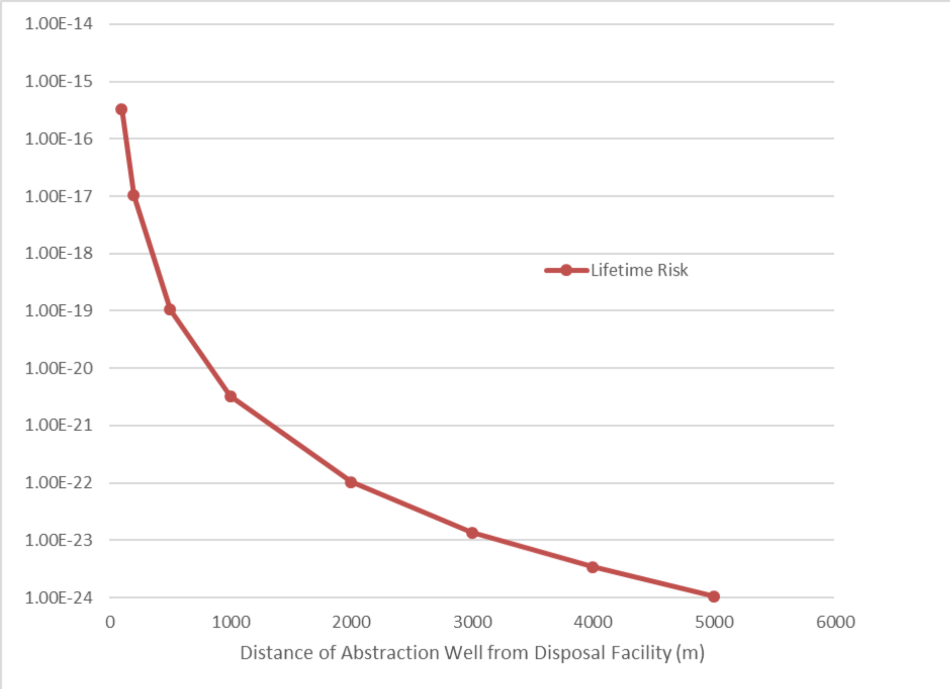

Figure 7 Estimated cancer risk for ingestion of water from the abstraction well.

Conclusion

The study assessed the possibility of the geosphere of the Accra Plains to host a disposal facility for Ghana's radioactive waste materials, which cannot be decay stored or repatriated to the country of origin. This was done by simulating the doses that a receptor will be exposed to by ingesting water from an abstraction well within the proximity of the hypothetical disposal facility. The study further assessed the radiological health risk due to ingestion of water from the abstraction well. The excess lifetime cancer risks were calculated, using values of the annual effective dose equivalent for the abstraction well, and this was then used to estimate the lifetime cancer risk for the general population of the study area. The results indicated insignificant levels of the radionuclides, in the abstraction well. The results indicated negligible cancer risk with the ingestion of water from the abstraction wells located at distances ranging from 100 m to 5 km from the hypothetical disposal facility. This implies that siting of the disposal facility in the Accra Plains may not pose any significant radiological hazard to the communities in the area in the future. As there is the need to manage the radioactive waste accrued from the peaceful application of nuclear technology in the Ghanaian economy, the outcome of this study is thus relevant to the greater protection of human health and the environment. This study is a guide for detailed safety assessment for siting high-level radioactive waste repository in the study area. Regulatory Authorities as well can use the findings of the study as a guide to regulate future radioactive waste disposal program in the study area.

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