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Gamma Ray Logging as a New Approach for In-situ Measurement of Radionuclide Concentrations and Determination of Groundwater Contamination

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Abstract

Analysis of in-situ activity concentrations of natural radionuclides in a groundwater borehole measured using the geophysical Gamma Ray (GR) log has been carried out in this study as a new approach in the determination of groundwater contamination. The measurement was carried out in the Niger Delta of Nigeria as our study area. The use of the in-situ borehole GR logging as a new approach attracts a fresh attention and opens another phase when compared with the conventional method of groundwater sample collection and testing in the laboratory. This new GR logging method eliminates any risk associated with the exposure of such samples to other sources of radiation other than the geologic source. The data available from the GR log covers a depth range of between 35m and 108m, through which three distinct geologic formations namely the gravelly sand, clayey shale and deeper shale zones were identified. From the log measurements, the contamination of the groundwater was investigated by the analysis of the lithology radionuclide concentration levels and comparison with the world permissible limits. The results obtained show that the gravelly sand water aquifer has a minimum GR value of 16.5 API, maximum value of 25.4 API, and mean value of 20.4 API. The minimum value of the in-situ concentration is 2.05ppm, maximum value is 3.15ppm and mean value is 2.53 ppm. This is equal to a minimum value of 2.05 x 10^{-9}µg/kg, maximum value of 3.15 x 10^{-9}µg/kg and mean value of 2.53 x 10^{-9}µg/kg. The aquifer lithologyis further characterized by in-situ activity concentration of minimum value of 25.32Bq/kg, maximum value of 38.90 Bq/kg, and a mean value of 31.25 Bq/kg. These values represent the uranium equivalence of the natural radionuclides in the borehole and are clearly below the world permissible limits recommended for water quality. The values also compare well with the values reported in the literature for the Niger Delta region of Nigeria.

Keywords

In-situ, Gamma, Ray, Log, Borehole, Groundwater, Radionuclides

1. Introduction

Groundwater – the major source of drinking water in Nigeria - is characterized by the presence of natural radionuclides in various concentrations. These include mainly uranium-238, thorium-232 and potassium-40 as well as their progeny (daughter nuclides). Both ^{238}U and ^{232}Th have long decay series with members ^{226}Ra, ^{222}Rn, ^{214}Bi, etc, all of which are radioactive. There exist three main decay series of natural radionuclides starting from the radionuclides uranium-238 (^{238}U), thorium-232 (^{232}Th) and uranium-235 (^{235}U). The ^{238}U decay chain produces several radionuclides, which are of radiological concern. These are ^{238}U, ^{234}U, ^{226}Ra, ^{222}Rn, ^{210}Pb and ^{210}Po. The chain ends at the stable lead isotope ^{206}Pb. The ^{232}Th-decay chain comprises ^{232}Th, ^{228}Ra, ^{228}Th, ^{224}Ra and ^{220}Rn, which also have radiological relevance. The chain stops at the stable lead isotope ^{208}Pb. The Uranium-235 decay chain produces the following relevant radionuclides: ^{235}U, ^{231}Pa, ^{227}Ac, ^{227}Th and ^{223}Ra. The chain stops at the stable lead isotope ^{207}Pb. Natural potassium, an ubiquitous element in the soil with a half-life of 1.3 x 10^{9} years, contains 0.0119% natural radioactive ^{40}K [1]. This isotope decays to ^{40}Ar with the emission of gamma ray with energy 1.46 MeV. Since potassium-40 occurs in a fixed

proportion in the natural environment, the gamma rays can be used to estimate the total amount of potassium present.

In a closed system, starting with a specified amount of a mother element, the number of atoms of daughter elements and their activity grows gradually until radioactive equilibrium of the disintegration series is reached. At this point, the activities of all the radionuclides of the series are identical. Thus the measurement of the concentration of any daughter element can be used to estimate the concentration of any other element in the decay series. A parent nuclide is hence identified by its daughter nuclides via their characteristic emissions in their decay chain.

When an atom of a radioactive element undergoes a disintegration, either an alpha- (α-) or beta-(β-) particle is emitted; each disintegration is, however, usually accompanied by a gamma (γ-) ray emission because the product nucleus after a decay is left in an excited state, and the surplus energy is irradiated as a γ-ray [2]. Owing to this phenomenon, a plausible approach in the determination of radioelement concentrations of ^{238}U, ^{232}Th and ^{40}K, which are the most naturally abundant radionuclides in the rock lithology, may involve counting the gamma-emissions in preference to gross-alpha and gross beta emitters. This is because the emission of alpha and beta radiations in an atomic decay occurs exclusively of each other, while the gamma-emission independently accompanies the alpha and beta decays.

Radionuclides accumulate in the earth in detectable amounts in clays, shales and sandstones that contain micas, alkali feldspar, clay minerals, glauconite, or uranium-rich waters [3-5]. Although the nuclides accumulate more in clays and shales, making these layers more easily identifiable in a gamma ray (GR) log, sand and gravelly sand lithologies can also be identified in the GR-log but with lower GR-responses as their radionuclide contents are not as comparably high as those of clays and shales [5, 6]. Due to the detectable presence of uranium-238, thorium-232 and potassium-40 in the earth with half-lives which are comparable to the age of the earth, they are known as primordial elements which have been present in the earth since its existence and therefore account for its radioactivity [1]. It is reported that in addition to the existence of natural radionuclides within the rocks, anthropogenic activities such as chemical processing, manufacturing, oil drilling and production also lead to accumulation of chemical wastes and contaminants on soil surface that add significantly to the radioactive contents of soils and rocks through seepage mechanism [7-9]. The radioactive substances that are trapped in the rocks eventually migrate into the groundwater formation due to the spontaneous rock-water interactions and processes that occur in the lithology of the earth's crust.

The variations in the concentrations of radionuclides in geological formations with depth have been reported by various researchers and authors. Nevas et al. [10] assert that radioactivity variation in lithologies is a function of soil type and mineral contents of the environment. Nevas et al. [11] determined the distributions of natural gamma-emitting radionuclide in three soil profiles developed on tertiary sedimentary materials in mountain landscapes of the Central Spanish Pyrenees and reported a depletion of radioactivity concentration with depth. Avwiri et al. [12] evaluated the radiological effects of soil profile samples of Udi and Ezeagu areas of Enugu State, Nigeria, and reported a contrast in behaviour of the radionuclide concentrations down the soil lithology depths. Vukasinovic et al. [13] assessed the radionuclide variation from a series of soil cores between 13 and 40cm depth collected in different lithologies and reported that radionuclide concentration shows variations in the depth profile as well as in the different morphedaphic environments studied.

The health effects/relevance of ingested radionuclides through drinking water are equally well documented in the literature. Due to granitoid bedrock and groundwater characteristics, concentrations of several natural radionuclides in groundwater are sometimes exceptionally high and exposure through drinking water from wells drilled in such bedrocks is encountered. Ajayi et al. [14] report that groundwater radionuclides when ingested into the body at levels exceeding normal levels tend to damage radiosensitive tissues and organs of the body; while Canu et al. [15] show that radiation exposure through drinking water results from naturally occurring radionuclides in drinking water sources, in particular alpha-radiation emitting uranium, radium, and their progeny. They report, according to the World Health Organization (WHO), that when activity concentration in drinking water exceeds the recommended level of 1 Bq/L for simultaneously measured gross activity of a mixture of natural alpha-emitters [^{238}U, ^{234}U, ^{232}Th, ^{226}Ra, and ^{210}Po] and beta emitters [^{228}Ra and ^{210}Pb], radionuclides-specific concentration should be brought in compliance with WHO guidance levels: 0.1Bq/L for ^{228}Ra; 1 Bq/L for $^{223\text{-}226}Ra$, ^{234}U and ^{235}U; 10Bq/L for ^{238}U; 100Bq/L for ^{222}Rn; and 15μg/L for total uranium [16].

Avwiri [8] reports that natural radionuclides in the soil and water of an environment are present as daughters of uranium (^{238}U), and thorium (^{234Th}) isotopes distributed by natural geologic and geochemical processes in addition to potassium (^{40}K) (4%) and small quantities of fission-product residues from atmospheric weapon tests. Exposure to excess level of the ionizing radiation from the disintegration of these radionuclides causes somatic and genetic effects that tend to damage critical organs of the body, which ultimately can lead to death. A study to measure and determine the radionuclide concentration levels in soil and water around three cement companies using the gamma ray spectrometry was carried out. The objective of the study was fundamentally to measure the concentration levels and determine whether they were above the International Commission on Radiological Protection (ICRP) maximum permissible limits which could have significant health implications. The values obtained were, however, below the ICRP limits and no health risks were associated with the measured concentration levels.

Ogundare and Adekoya [9] citing the work of Patel [17] define radioactive contamination of the environment as any increase in the natural background radiation arising out of human activities involving the use of naturally occurring or artificially produced radioactive substances. They report that the hazards to people and the environment from radioactive

contamination depend upon the nature of the radioactive contaminant and the level of contamination. To determine possible contamination of drinking water by radionuclides, they concentrated their study on measurement of mean gross alpha and gross beta activities in surface soil and drinkable water in the surrounding communities of a steel processing company. They used a low background gasless counting system with a solid state silicon PIPS detector to detect and count the emissions. The results they obtained show that the mean activities in the water ranged between 0.0064 ± 0.00001 and 0.0182 ± 0.0001Bq/l for gross alpha and between 0.046 ± 0.001 and 0.126 ± 0.001Bq/l for gross beta. These values were found to be lower than the recommended permissible levels for drinking water, implying that the water is not radionuclide-contaminated and drinking such water therefore has no significant health risks.

Agbalagba et al [7] carried out a study to determine the groundwater aquifer potential and radioactivity levels of the soil lithology depths at Agbor in Delta State, South-South, Nigeria and their associated health risk. The activity concentrations of ^{40}K, ^{226}Ra, and ^{232}Th in the lithology were assessed using sodium iodide NaTi detector and counter. The health implications arising from the measured radiological parameters were analysed. They obtained the mean activity concentrations as 254.0 ± 62.7Bq/kg for ^{40}K, 17.0 ± 5.7Bq/kg for ^{226}Ra and 14.2 ± 5.0Bq/kg for ^{232}Th. These values obtained are all below the world permissible limits and compare well with values reported in the literature for some parts of the world. The estimated radiological risk parameters examined are radium equivalent (Ra_{eq}), annual gonadal equivalent dose (AGED), external hazard index (H_{ex}), internal hazard index (H_{in}), absorbed dose rate (D), annual effective dose equivalent (AEDE), excess lifetime cancer risk (ELCR), and the mean values obtained are 56.9mSv/y, 189.3mSv/y, 0.2Bq/kg, 0.2Bq/kg, 27.6ηGy/h, 135.3mSV/y, and 0.12×10^{-3} respectively, which are all below their recommended permissible limits with no associated health hazards.

Furthermore, it is globally reported that an association of various types of cancer with radionuclide concentrations in drinking water occurs. Four case control epidemiological studies estimated associations between ingestion of radium via drinking water and bone cancer. Two studies were conducted in Wisconsin based on the same cancer registry over the periods 1979-1989 [18] and 1980-1997 [19]. Moss et al. [18] report a positive but non-significant association between osteosarcoma incidence and gross-activity exceeding 330Bq/l in county water supplies, whereas Guse et al. [19] report no association with radium levels in drinking water supplies. Two case-control studies were conducted on bone cancer and ^{226}Ra in water supplies at birthplace residences in Ontario, Canada based on mortality [20] and incidence data [21]. The first study reports a significant association between mortality for each subtype of bone cancers combined and ^{226}Ra concentration in community water supplies or birthplace private wells. Both studies also report associations between Osteosarcoma and ^{226}Ra concentration, and a significant association is reported based on a combined statistical analysis of the two studies. Furthermore, three case-cohort studies were conducted on 107 stomach cancer cases by Auvinen et al [22], 112 urinary cancer cases by Kurttio et al [23] and 35 leukemia cases by Auvinen et al. [24]. The authors found no significant associations with radionuclide concentrations (uranium, radium and radon) in well water. However, each study included a relatively small number of cases and therefore had only modest statistical power.

Wrenne et al. [25] report that ingested radionuclides are absorbed into the blood and accumulate in specific tissues that they may damage. Of absorbed uranium, 66% is rapidly eliminated via urine, while the rest is distributed and stored in the kidney (12-25%), bone (10-15%) and soft tissue. Radium is deposited mostly in the bone, while ingested radon gas diffuses into the stomach wall, making the stomach wall the tissue most irradiated by ingested radon because of its short half-life (3.8 days) [26]. In groundwater, uranium-238 and uranium-234 are in disequilibrium and occur in largely varying activity ratios with the activity of uranium-234 higher than uranium-238. Hence, the chemical toxicity of ingested uranium is almost solely due to ingested uranium-238. Uranium is deposited in the soft tissue of the body with the highest organ doses to the bone [22].

Avwiri et al. [27] in their study reveal the cancer-effect of soil-borne radiation. They show that the ingestion of food crops obtained from radionuclide-contaminated soil can lead to internal radiation doses which can cause cancer fatality. The estimated effective dose due to ingestion of food crops ranges from 26.82μSv/y (rice) to 283.39μSv/y (banana). The radiation doses obtained in banana, yam, cassava, and plantain were higher than the reference level of 70μSv/y and some literature values. Cancer risk and non-cancer risk components were evaluated from the estimated annual effective doses. The results they obtained show that in terms of the lifetime fatality cancer risk to adult, approximately 15 out of 1,000,000 may suffer from some form of cancer fatality and for the lifetime hereditary effect, approximately 39 out of 1,000,000 may suffer some hereditary effects. Besides, Alsaffar et al. [28] report that the human populations can be exposed to radiation from the soil. The uptake of radionuclides by plant roots constitutes the main pathway for the migration of radionuclides from the soil to humans via the food chain. Their results show that Transfer Factor (TF) is an important parameter that encompasses influence of physicochemical properties of soil, environmental conditions and types of radionuclides.

Due to the potential adverse effects of ingestion of radionuclides through drinking water, global standard has been set in order to protect members of public from radiation exposure above permissible levels. The World Health Organization (WHO) recommends that activity concentration in drinking water must not exceed 1Bq/l for gross activities [simultaneously measured activity from a mixture of natural alpha- and beta-emitters] [16]. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [29] recommends 400Bq/l for ^{40}K, 35Bq/kg for ^{226}Ra, and 30μg/kg for ^{232}Th in soils and water.

To determine activity concentrations in drinking water from drilled wells and ensure compliance with recommended limits,

the method conventionally used involves collection of water samples in containers and transport of such samples to the laboratory for testing [e.g. 7, 8, 9, 14, 22, 27]. Furthermore, recent studies around the world show that the transport of water samples to the laboratory for testing remains the norm in measurements of radionuclide concentrations for determination of groundwater quality. Prasad et al [30] used the laboratory sampling method in their study to measure and assess the radiological impact of natural radionuclides in groundwater of Himalayan regions in Uttarakhand, India. They report that the average concentrations of radon ($35\ \mathrm{Bq\,l^{-1}}$) and uranium ($1.3\ \mu\mathrm{g\,l^{-1}}$) in the groundwater sample were found well within the safe limits recommended by the World Health Organization. In another recent study, Alomari et al [31] measured the activity concentrations of ^{226}Ra, ^{228}Ra and ^{222}Rn in relation to their public health impacts in 87 groundwater samples using the conventional laboratory testing processes and astonishingly found that their mean annual effective dose was 0.481 mSv with mean lifetime risk of 24.599×10^{-4}, exceeding the admissible limit of 10^{-4}. Furthermore, Adegunwa et al [32] conducted a recent radiological study in which they measured the activity concentrations of the natural radionuclides (^{238}U, ^{232}Th and ^{40}K) in groundwater samples taken from areas surrounding the Transmission Company of Nigeria, Osogbo, using the conventional laboratory HPGe detector to test the water samples. They found that the concentrations were at levels that do not pose any health risk.

However, the conventional laboratory testing method is beset with risk of exposure of groundwater samples to other sources of radiation other than the geologic source, which is one of the major concerns of this paper. Aweto et al [33] report that this same uncertainty scenario occurs during assessment of total dissolved solids (TDS) in groundwater using the conductivity method. They assert that the conductivity method which depends on measurement of temperature-dependent conductance results in erroneous assessment of TDS if temperatures of collected water samples are used, because the temperatures are altered between the period of collection and testing. In-situ temperatures of aquifers are thus preferred in TDS evaluation.

Till date, there is no known geophysical method that has been used in the Niger Delta region and Nigeria as a whole, involving in-situ measurement of activity concentration by borehole logging. This study adopts a different approach from the conventional method and entails the use of in-situ Gamma-Ray (GR) sonde to log the depths of the borehole through the geologic formations down to the aquifer. Cosmic effects are virtually nil as is the contribution of radiation from the air if the hole is logged.

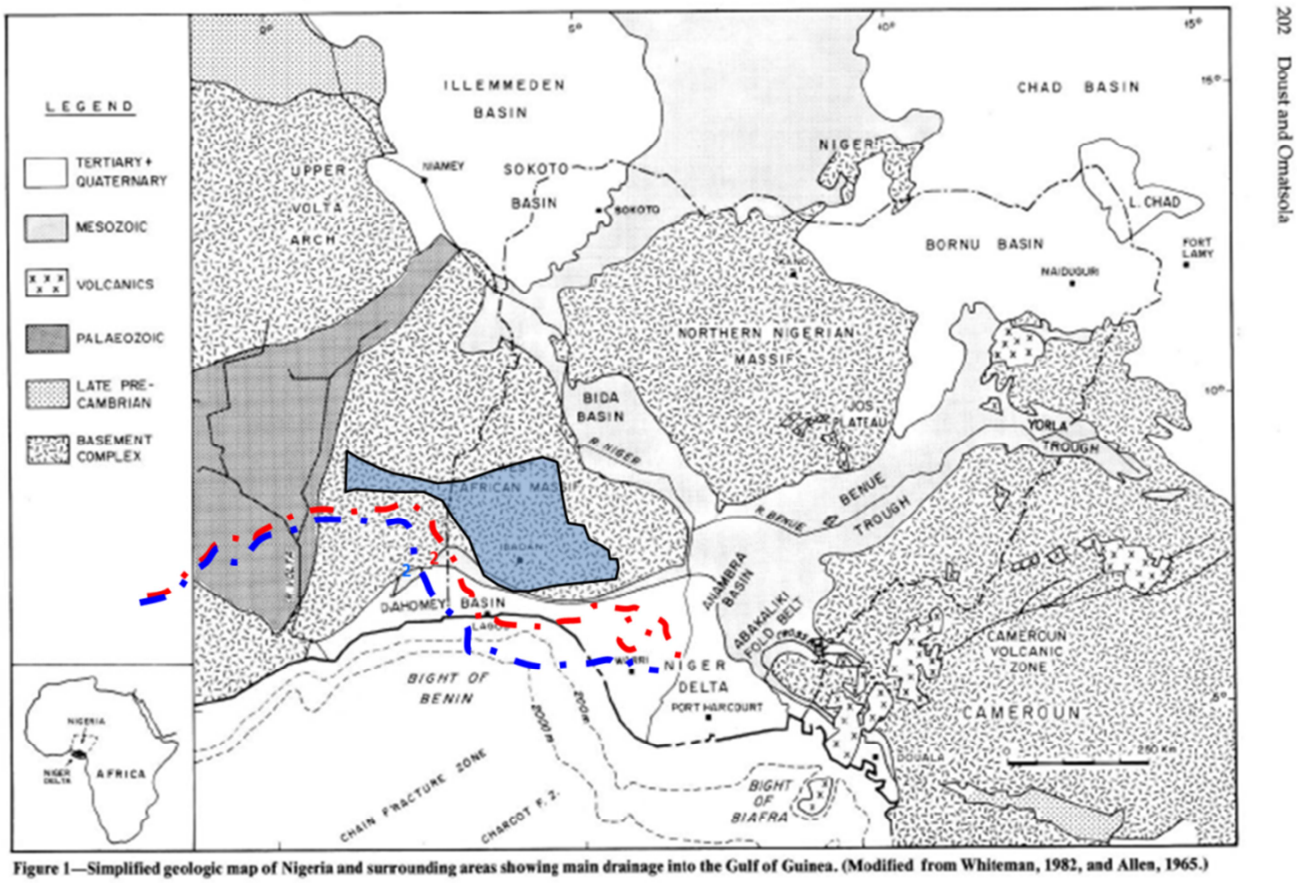

Figure 1—Simplified geologic map of Nigeria and surrounding areas showing main drainage into the Gulf of Guinea. (Modified from Whiteman, 1982, and Allen, 1965.)

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Figure 1. *Location Map of the Niger Delta (Modified from Whiteman [34] and Allen [35]).*

2. Materials and Methods

2.1. Study Area- The Niger Delta

The Niger Delta is basically a sedimentary basin and tertiary delta situated in equatorial West Africa in the Gulf of Guinea (Figure 1). The development of the Niger Delta began, on a geologic time scale, with the formation of the delta at the site of a rift triple junction associated with the opening of the southern Atlantic. This event started in the late Jurassic and continued into the Cretaceous. The delta proper began developing in the Eocene, accumulating sediments that are now over 10km thick. The coastal sedimentary basin of Nigeria had been the scene of three depositional cycles. The first began with a marine incursion in the middle Cretaceous and was terminated by a mild folding phase in Santonian time. The second included the growth of a proto-Niger Delta during the late Cretaceous and ended in a major Paleocene marine transgression. The third cycle, from Eocene to Recent, marked the continuous growth and development of the main Niger Delta.

The delta extends throughout the Niger Delta Province and borders the Atlantic Ocean at the Southern end of Nigeria between latitudes 3^0 and 6° and longitudes 5° and 8° [36]. The onshore portion of the province is delineated by the geology of southern Nigeria and southwestern Cameroon. The northern boundary is the Benin flank — an east northeast trending hinge line south of the West African basement massif. The northern eastern boundary is defined by outcrops of the Cretaceous on the Abakaliki High. The offshore delineation of the province is defined by the Cameroon volcanic line to the east, the eastern boundary of the Dahomey basin to the west and a sediment contour of thickness 2km. The province covers 300,000 square kilometers of area and includes the geologic extent of the tertiary delta that habours only one identified petroleum system. This system is referred to as the tertiary Niger Delta (Akata- Agbada) petroleum system [37].

The stratigraphy of the Niger Delta shows that the Niger Delta subsurface comprises an upper sandy Benin Formation, an intervening unit of alternating sandstone and shale known as the Agbada Formation and a lower shaly formation called the Akata Formation. These three delta facies extend across the whole delta and each ranges in age from early Tertiary to Recent and is related to the present outcrops and environments of depositions. Drinking water obtained from drilled boreholes in the Niger Delta is sometimes characterized by heterogeneous lithology at various aquifer depths, which range from about 20m to 60m as reported by Agbalagba et al. [7], Aweto et al. [33], and Bello et al. [38].

2.2. Instrumentation and Methodology

Borehole Gamma Ray (GR) log measures the natural radioactivity of a formation as well as reveals the lithology. The GR spectrometry forms one of many techniques used to acquire measurements in boreholes after drilling, to characterize the physical properties of the intersected geology. It is part of a broader range of nuclear techniques used in borehole logging, particularly for petroleum exploration but can be adopted for hydro-geological purposes. A gamma-ray logging system uses a gamma ray source (e.g. 137Cs) to generate back-scattered gamma rays, which provides measured values of activity of radioisotopes domiciled in formations as well as the bulk density of the surrounding rock. The GR logging system typically comprises a probe (tool) incorporating sources and detectors (for an active system) and depth counter, which is lowered down the borehole. The probe is attached to a recording system on surface by a cable that is used to transmit power to the probe unless batteries are installed in the probe and data to the surface unless recorded in memory in the probe. A winch and pulley assembly is used to lower or raise the probe for continuous logging, and because of the statistical nature of gamma emissions, a recording time of several seconds (an appropriate time constant) and a proper predetermined speed are necessary to obtain a reasonable count. Hence, the sensitivity of the tool depends on the count time and speed with which the borehole is logged [4]. The lateral penetration of the tool adjacent the borehole is 10-30 cm, depending on the density of the rock. The gamma ray spectral probe measures the full gamma ray spectrum from which the total count, K, U and Th windows are extracted.

Figure 2. *A Typical Spectral Gamma Ray Tool/Probe.*

The GR log response, after appropriate corrections for borehole, is proportional to the weight concentrations of the radioactive material in the formation and is given by

$$\mathrm{GR} = \frac{\sum \rho_i V_i A_i}{\rho_b} \quad (1)$$

where ρ_i are the densities of the radioactive materials

V_i are the bulk volume factors of the materials

A_i are proportionality factors corresponding to the radioactivity of the mineral

ρ_b is the bulk density of the formation

Clays have an activity between 100 and 200 API and sands below 50API. The measured values of radioactive concentrations in this study are presented relative to the borehole depth ranges of investigation and associated lithologies. The results obtained are compared to reports of previous works documented in the literature for the Niger Delta region of Nigeria to help in further validating the

results. All analyses are based on borehole GR data obtained from a drilled well in the Niger Delta.

The conversion of concentrations in API to ppm (parts per million) is given by:

$$A_{total}(ppm) = N \times \lambda \quad (2)$$

where A_{total} is the total concentration of the formation, N is the measured or logged GR value and λ is a conversion factor = 0.124 [U_{eq}]. The equivalent U defines the uranium equivalence of 1 ppm of Th or uranium equivalence of 1% K [39].

The spectral gamma ray instrument computes A_{total} (in ppm) in Equation (2) by the arithmetic combination of the concentrations of the natural nuclides (^{238}U, ^{232}Th and ^{40}K). The spectral gamma ray (SGR) is thus the total or sum of the concentrations of U, Th and K in the formation (after converting the concentrations of Th and K to their uranium equivalence). This is then given by

$$SGR(ppm) = A_{total} = A(^{238}U) + A(^{232}Th)_{Ueq} + A(^{40}K)_{Ueq}$$
$$= A(^{238}U) + A\lambda_{TH(Ueq)} + A\lambda_{K(Ueq)} \quad (3)$$

where A is concentration (in ppm) of the individual natural nuclides, λ_{TH} is a factor for conversion of thorium concentration in ppm to its uranium equivalence ($\lambda_{TH} = 0.49$) and λ_K is a factor for conversion of potassium concentration in ppm for 1% K to its uranium equivalence ($\lambda_K = 2.43$) [39]. Hence, Equation (3) may be re-written as

$$SGR(ppm) = A(^{238}U) + 0.49A(^{232}Th)_{Ueq} + 2.43A(^{40}K)_{Ueq} \quad (4)$$

The total concentration of the formation in μg/kg is given by

$$A_{total}(\mu g/kg) = A_{total} \times c.f \quad (5)$$

where c.f is a conversion factor equal to 1.0×10^{-9} and A_{total} is in ppm.

In the same vein, the total activity concentration of the formation in Bq/kg is

$$C_{total}(Bq/kg) = A_{total} \times c.f \quad (6)$$

where c.f is a conversion factor = 12.35 and A_{total} is in ppm.

3. Results

Figure 3 represents the GR log for a borehole drilled in the Niger Delta. The borehole was logged through a depth range of about 35m to 108m. The soil profiles/lithology identified from the log from the top of the logged zone comprises gravelly sandstones with depths ranging from 35m to about 70m, clayey shale with the depths ranging from 71.5m to 93m and shale with depths ranging from 93m to 108m. The gravelly sand zone represents the aquifer zone. This aquiferous zone is the zone of clean drinkable water, with low GR values ranging from 16.5 API at the 63m depth to 25.4API at the 35.5m depth. The clayey shale zone has GR values ranging from 55.2API at the 71.5m depth to 88.4API at the 77.5m depth, while the shale zone has GR values ranging from about 90.1API at the 94m depth to 132.6API at the 100.8m depth. The depth range from 71 to 108m which consists of clayey shale and shaly formations considering their relatively higher activity concentrations is non-aquiferous.

Table 1 shows the various values of radionuclide concentrations in API, ppm, Bq/kg and μg/kg for the gravelly sand groundwater aquifer, the clayey shale and shale zones. These results facilitate the comparison of the concentration levels of radionuclides in the groundwater aquifer with the world permissible limits, which helps to ascertain whether or not the groundwater has been contaminated with the presence of the radionuclides in the aquifer.

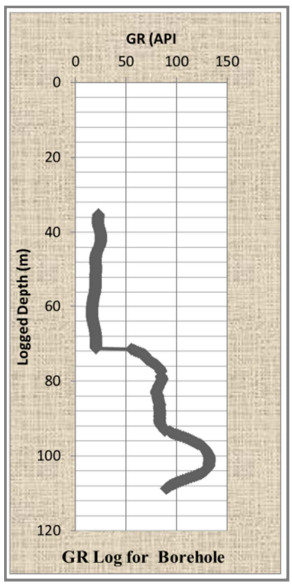

Figure 3. *The GR Log Obtained for the Drilled Groundwater Borehole.*

Table 1. *Values of Concentrations for the Groundwater Aquifer Depths, Clayey Shale and Shale Zones.*

Logged Depth (m)	Lithology		Concentrations (Ueq)			
			API	ppm	Bq/kg	μg/kg
35 - 70	Gravelly Sand	Min	16.5	2.05	25.32	2.05×10^{-9}
		Max	25.4	3.15	38.90	3.15×10^{-9}
		Mean	20.4	2.53	31.25	2.53×10^{-9}
71.5 - 93	Clayey shale	Min	55.2	6.85	84.60	6.85×10^{-9}
		Max	88.4	10.96	135.36	10.96×10^{-9}
		Mean	80.9	10.03	123.87	10.03×10^{-9}
93-108	Shale	Min	90.1	11.17	137.95	11.17×10^{-9}
		Max	132.6	16.44	203.06	16.44×10^{-9}
		Mean	117.7	14.60	180.25	14.60×10^{-9}

4. Discussion of Results

Table 1 shows the various values of radionuclide activity concentrations in API, ppm, Bq/kg and µg/kg for three clear lithologies that have been identified from the top of logged depths namely gravelly sand, clayey shale and shale zones. The depths ranging from 35m to 70m represent the gravelly sand zone, the depth range from 71.5m to 93m represents the clayey shale formation, while the depth range from 93m to 108m represents the shale zone. The gravelly sand formation is the aquiferous zone that transmits clean drinkable water into the borehole. The other two shaly formations are non-aquiferous considering their higher GR values as measured using the GR log.

The gravelly sand aquifer has minimum GR value of 16.5API, maximum GR value of 25.4API, and mean GR value of 20.4 API. It has minimum, maximum and mean concentrations of 2.050, 3.150, and 2.530ppm respectively or minimum value of 2.05 x 10^{-9}µg/kg, maximum value of 3.15 x 10^{-9}µg/kg, and mean value of 2.53 x 10^{-9}µg/kg. It is further characterized by activity concentrations of minimum value 25.32Bq/kg, maximum value 38.90 Bq/kg, and a mean value of 31.25Bq/kg. These values represent the uranium equivalence of the natural radionuclides and are clearly below the world permissible limits [29]. These values also compare well with the values obtained by Agbalagba et al. [7] during their study of the radioactivity levels of soil depth lithology for determination of drinking water quality conducted at Agbor Community in the Niger Delta of Nigeria.

The clayey shale zone has minimum GR value of 55.2 API, maximum value of 88.4 API, and mean of 80.9 API. The minimum, maximum and mean concentrations of radionuclides in this zone are 6.85, 10.96, and 10.03 ppm respectively or minimum value of 6.85 x 10^{-9}µg/kg, maximum value of 10.96 x 10^{-9}µg/kg, and mean value of 10.03 x 10^{-9}µg/kg. This same zone has minimum activity concentration of 84.60Bq/kg, maximum value of 135.36 Bq/kg, and a mean value of 123.87Bq/kg. The concentration level of this formation is therefore comparatively higher than that of the aquifer.

The deeper shaly lithology has a minimum GR value of 90.1API, maximum GR value of 132.6 API, and mean value of 117.7API. The minimum, maximum and mean radionuclide concentrations in this zone are 11.170, 16.442, 14.595ppm respectively, while the minimum activity concentration is 137.95Bq/kg, maximum value is 203.06Bq/kg, and mean value is 180.25Bq/kg. It is thus clear that the deeper shaly formation is characterized by relatively higher levels of radionuclide concentration than the overlying shallower formations.

The results obtained in this study clearly reveal the aquifer as having radionuclide concentration levels well below the world permissible limits and groundwater drilled from it therefore has no associated radionuclide contamination.

5. Conclusion

Analysis of in-situ activity concentrations in groundwater borehole measured using the gamma ray log has been carried out in this study. Values obtained are consistent and compare well with literature values. The results obtained also successfully reveal the non-radionuclide contamination of the groundwater. Over the years, measurements of concentration levels of radionuclides in borehole water have always relied on collection of water samples from boreholes and transport of the samples to the laboratory for testing, with the associated risk of exposing such samples to other sources of radiation other than the geologic source. This study has therefore provided the in-situ borehole logging method as an effective alternative option for measurement of activity concentrations in groundwater aquifer. In addition to the convenience it offers, this method serves to eliminate any uncertainty associated with the measurement of activity concentrations in the determination of groundwater quality.

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