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Assessment of Radioactivity in Borehole Waters of the North Riviera Sodeci Catchment Field in Abidjan, Côte d'Ivoire

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Abstract

The radioactive isotopes of the decay series of uranium-238 (^{238}U), thorium-232 (^{232}Th) and potassium-40 (^{40}K) occur naturally in varying amounts in groundwater. They are the subject of many measures, mainly because of the risk they represent from a public health point of view. The purpose of this study is to measure the radioisotope content of borehole waters from the north riviera (NR) catchment field of the Ivorian drinking water distribution company (SODECI). These measurements will make it possible to assess the absolute levels of radioisotopes in the water from SODECI's boreholes used directly for drinking or swimming, and possibly the associated risk from a public health point of view. To achieve this, a sampling campaign from the seven functional boreholes and the control or treatment tower took place in July 2018 at the NR well field. The analysis of radionuclides by gamma spectrometry was carried out in the laboratory of the Radiation Protection Institute (RPI) of the Ghana Atomic Energy Commission (GAEC). The naturally occurring radionuclides identified during the borehole water samples analysis are ^{238}U, ^{232}Th, and ^{40}K. The results reveal that the specific activities of uranium vary from 0.45 ± 0.18 Bq/L to 0.55 ± 0.17 Bq/L with an average of 0.49 ± 0.15 Bq/L. Those of thorium vary from 0.66 ± 0.14 Bq/L to 0.78 ± 0.18 Bq/L with an average of 0.72 ± 0.16 Bq/L and potassium of 4.14 ± 0.53 Bq/L at 5.87 ± 0.60 Bq/L with an average of 5.32 ± 0.58 Bq/L.

Keywords

North Rivera (NR) Catchment Field, Drilling Water, Natural Radionuclides, Uranium, Thorium, Potassium

1. Introduction

In developing countries like Côte d'Ivoire, groundwater is an important source of drinking water supply and is therefore vital for the development of these countries. Indeed, a water resource of good quality and in sufficient quantity is necessary for the economic development and the well-being of the populations [1]. However, the quality of water is defined by physical, chemical, biological and radiological parameters.

The presence of natural radionuclides in drinking water is most often associated in particular with the origins of groundwater. Indeed, the radioisotopes contents are higher for waters circulating in the crystalline rocks than those coming from the sedimentary rocks [2].

In Abidjan, SODECI's north riviera (NR) catchment field allows the exploitation of groundwater to supply drinking water to part of the population in the city of Abidjan. This field is located about 5 km from the former Akouedo landfill. This landfill was uncontrolled and received all types of waste. In addition, the government has decided to close this landfill in view of the nuisance and its situation on 04 July 2019.

The main objective of this study is to measure the radioactivity of groundwater, in particular the drilling water of the NR catchment field of SODECI. To date, no data is available concerning the radiological state of this source of water supply to the population of Abidjan. It also makes it possible to assess the risk associated with absolute levels of radioisotopes in water, from a public health point of view.

2. Materials and Methods

2.1. Study Area

The samples were taken at the NR catchment field of SODECI, in the commune of Cocody, precisely in the Akouedo zone. This catchment field is located in the north of the former Akouedo landfill, about 5 km away. It includes 10 boreholes, 7 of which operated continuously at an average flow rate of 250 m^3/hour/borehole.

The geological profile of the area consists from top to bottom of sandy clay, medium sands and coarse sands resting on a granite and schist base (**Figure 1**).

The aquifer that develops in the Akouedo zone is the aquifer of the terminal continental aquifer. It is operated by SODECI through the NR catchment field to supply drinking water to part of the city of Abidjan.

The Mio-Pliocene Age Continental Terminal is made up of discontinuous lateritic crusts, coarse fluvial sands, black clays and clayey sands, and gravelly to variegated clay levels. Its power (0 to 160 m maximum) depends on the depth of the substratum and the state of erosion of the soil surface [3] [4].

The master plan for integrated water resources management in Côte d'Ivoire shows that this aquifer is essentially made up of sandy clay and sands (**Figure 2**) [3].

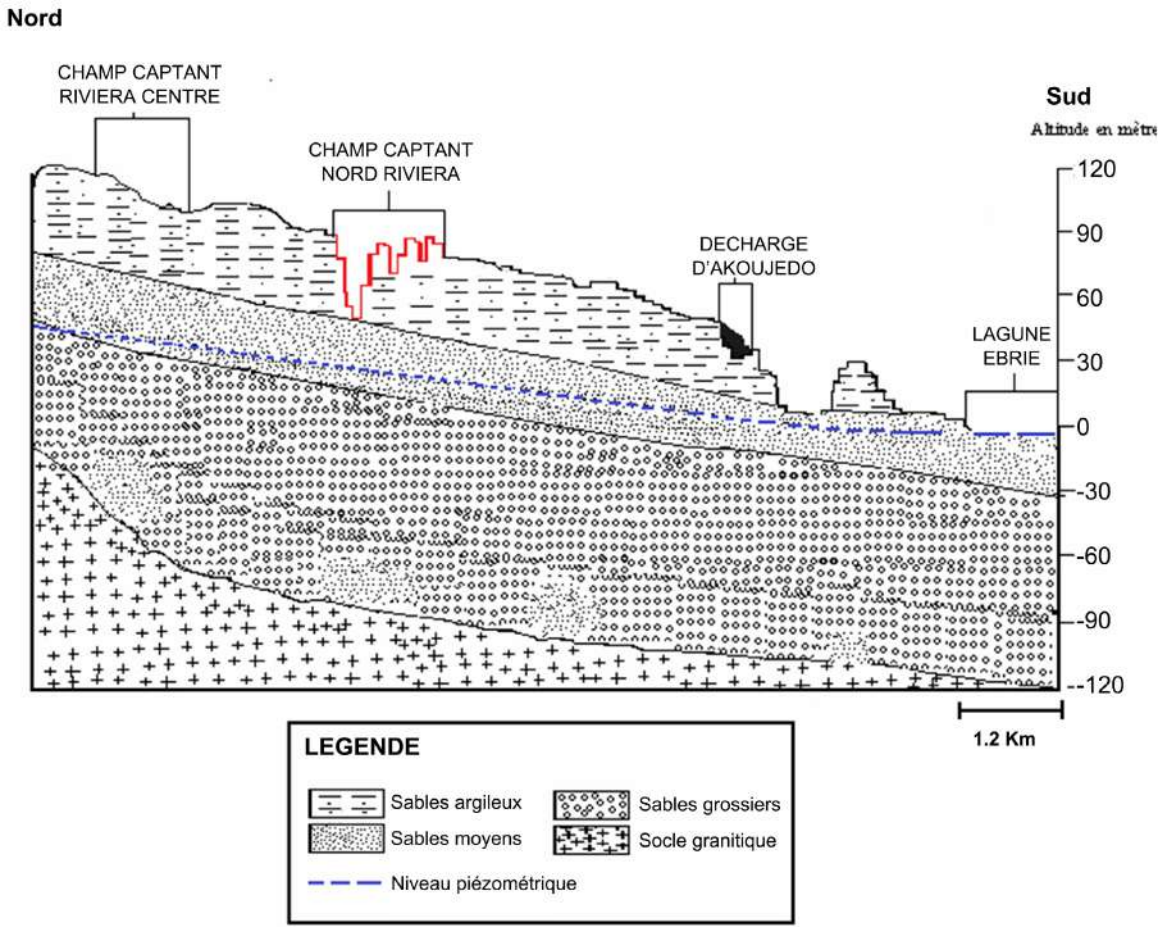

Figure 1. Geological profile of the Akouedo zone [3].

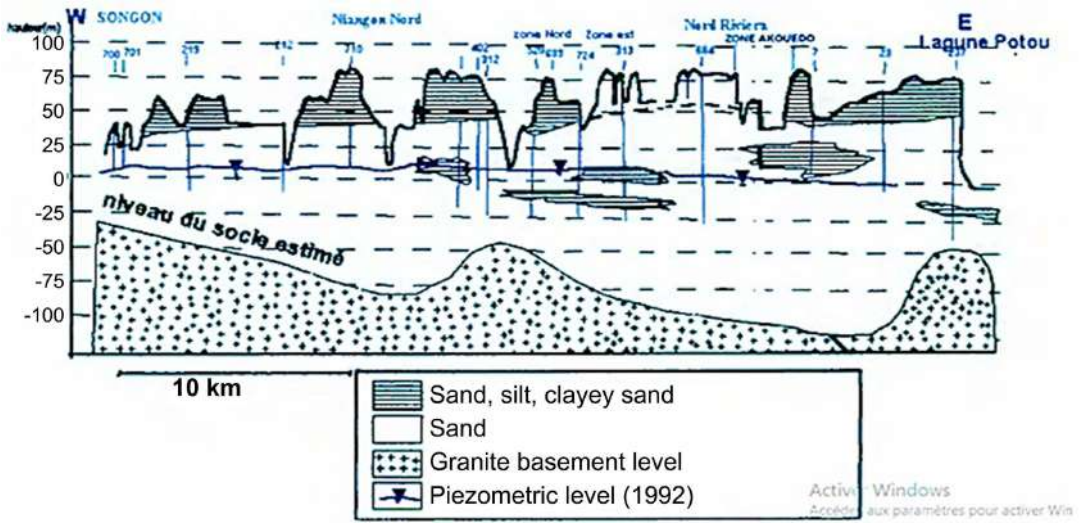

Figure 2. West-east geological profile of the aquifer of the Abidjan sedimentary basin [3].

2.2. Sampling Sites

Groundwater samples were taken from all functional boreholes in the NR well-field (F02, F03, F09, F10, F16, F18, F20) and from the control (TC) or mixing

tower (Figure 3). This is the place where all the groundwater from the working boreholes meets and is treated with lime and chlorine and then distributed for household consumption. All the boreholes have a minimum depth of 120 m (source SODECI).

2.3. Sampling Method

As the boreholes were fitted with pumps, the water was sampled directly in 1.5 L polyethylene bottles previously washed with nitric acid then with distilled water and finally three times with the sample to be taken. The bottles were filled to the brim then the cap screwed on to avoid any gas exchange with the atmosphere. The labeled water samples were transported in a cooler, allowing the temperature to be stored at a value below 6˚C for 48 hours, to the GAEC laboratory. The *in-situ* parameters were measured using a pH instrument and HI 98127 Conductivity. These are conductivity, pH, and temperature (T). For the pH measurement,

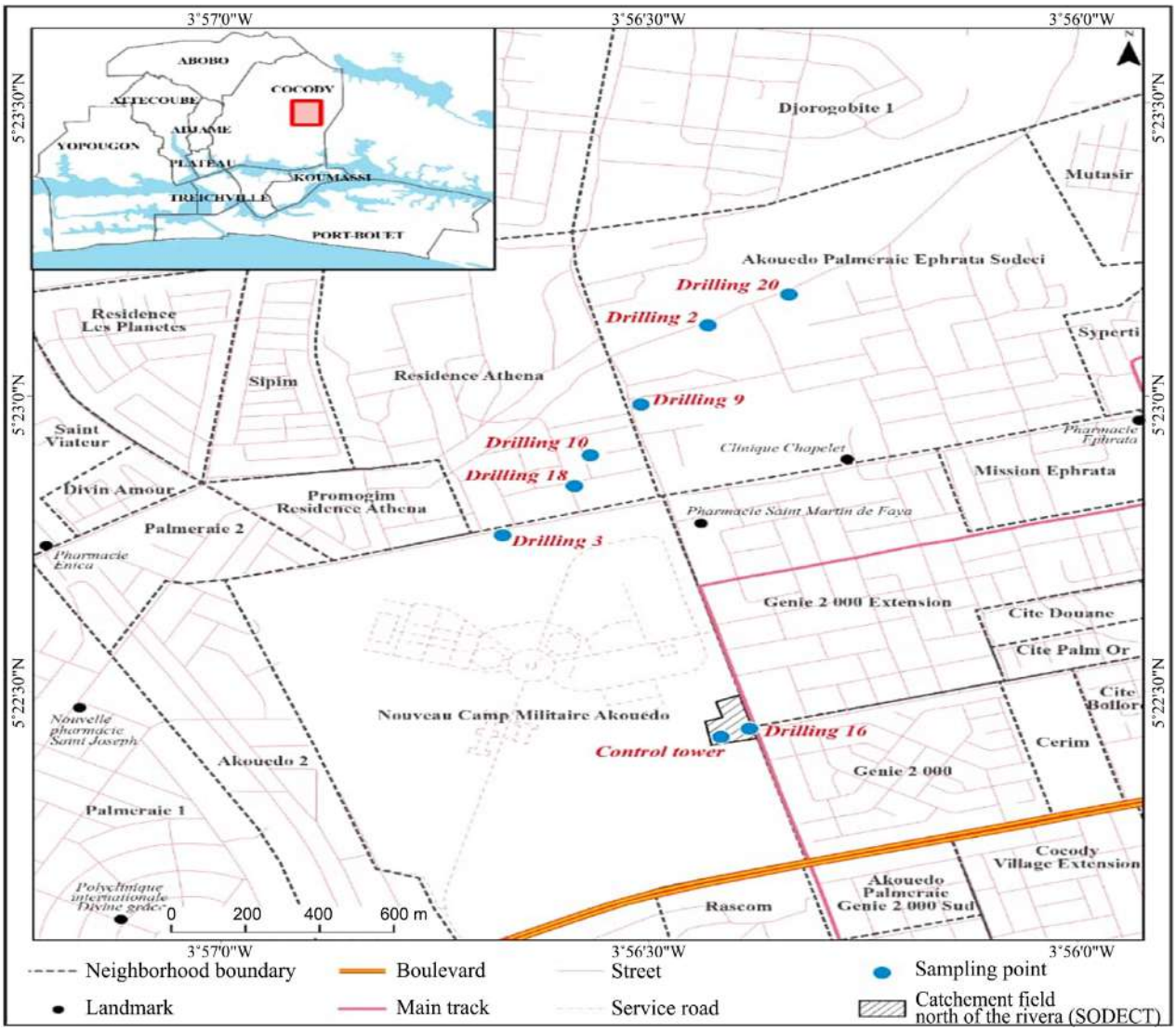

Figure 3. Drilling water sampling points.

the device was calibrated with buffer solutions pH = 7.01 then pH = 4.01. For conductivity, the device was calibrated by immersing the probe in the clean calibration solution of 1413 µS/cm. The temperature is displayed directly when measuring pH or conductivity.

2.4. Method of Analysis

The method used is gamma spectrometry analysis in which the concentrations of radionuclides present in water are directly evaluated.

The radiological preparation and analysis of the eight samples was carried out in the laboratory of the Radiation Protection Institute (RPI) of the Ghana Atomic Energy Commission (GAEC).

The samples were homogenized and transferred to one-liter marinelli beakers without filtration. The marinelli were pre-washed with distilled water, dried and rinsed with acetone to avoid contamination. In order to maintain the radioactive balance between parents and short-lived progenies, the homogenized samples were hermetically sealed. Then they were stored for 1 month, weighed and analyzed using a high purity germanium detector.

But before the activity measurements, the detector was calibrated for energy and efficiency with a standard source of radionuclides of well-known and uniformly distinguished concentrations. These known energies are defined in the energy range from 122 keV to 1836.063 keV thus covering the low, medium high energy range of the spectrum.

Background were measured and subtracted to obtain clear counts for the samples (Table 1).

The minimum detectable activity (AMD) of each radionuclide is calculated by the gamma spectrum analysis software, GENIE 2000. The minimum detectable activity is the smallest quantifiable radioactive activity value that a radionuclide can have.

The AMD was calculated by the following formula:

$$\mathrm{AMD} = \frac{2.706 + 4.66X\sqrt{N}}{\varepsilon\left(E_\gamma\right) XP_E XT_C} \quad [4] \tag{1}$$

N: Number of strokes of the background noise spectrum;

2.706 and 4.66: Constants linked to the geometry of the detector;

Table 1. Radionuclides contained in the standard source used for the calibrations and their energies.

Radionuclides	Energies (keV)
Cobalt-57	122
Cerium-139	165.864
Pewter-113	391.69
Cesium-137	661.66
Yttrium-88	898.042 and 1836.063
Cobalt-60	1173.237 and 1332.501

$\varepsilon(\gamma)$: Detector efficiency (HPGe);

P_E : Gamma ray emission probability;

T_C : Counting time.

The specific activities of radionuclides, expressed in Bq/L were determined by the following equation:

$$A = \frac{N_{net}(E)}{\varepsilon(E) \cdot t \cdot I_{\lambda} \cdot M \cdot C_i} \quad (2)$$

$N_{net}(E)$: the net area of the peak or the number of net strokes in the energy peak E;

$\varepsilon(E)$: metering efficiency for energy E;

I_γ: the probability of emission of gamma radiation of energy E;

t: counting time in seconds;

M: mass of the sample in kg or volume (L);

C_i: product of different corrective factors inherent to the measurement conditions.

3. Results and Discussion

3.1. *In Situ* Parameters

Table 2 presents the parameters values measured in the field which are the pH, the temperature and the distribution of the electrical conductivity in this aquifer.

➢ **Temperature**

The temperatures of the samples recorded during the July campaign, the period corresponding to the rainy season in Côte d'Ivoire, are almost constant (between 26.0˚C and 26.6˚C) (Figure 4),with an average of 26.36˚C. This average temperature of the water leaving the boreholes corresponds to the average monthly temperature for July, one of the coldest months of the year [5].

➢ **pH**

All groundwater samples have a pH < 7 (Figure 5). Our borehole water samples are therefore acidic. However, the TC water sample of pH 6.9 is within the WHO recommended pH range (6.5 - 8.5) for consumption [4]. It can be noted that the pH of acidic groundwater is therefore regulated by adding lime and chlorine to the TC.

Table 2. Physico-chemical parameters of borehole water samples.

Samples	Temperature (˚C)	Ph	Conductivity (µS/cm)
F02	26.2	4.6	27
F03	26.4	4.7	26
F09	26.0	4.5	29
F10	26.6	4.6	31
F16	26.5	4.5	43
F18	26.5	4.7	31
F20	26.2	4.5	30
TC	26.5	6.9	139

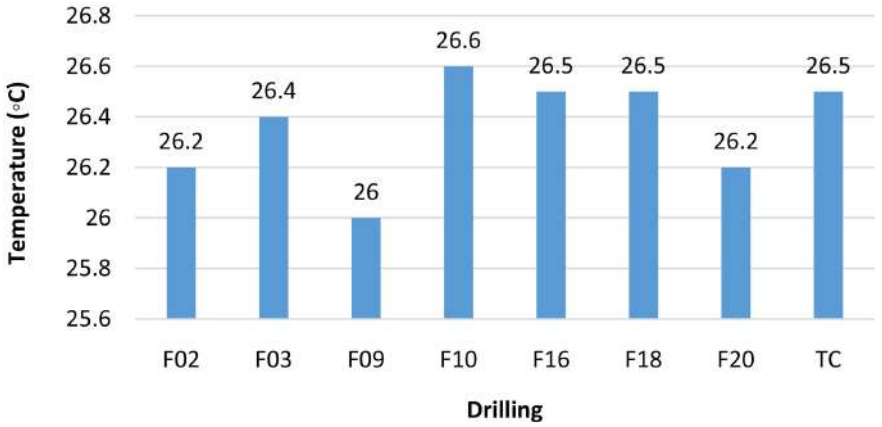

Figure 4. Drilling water temperatures.

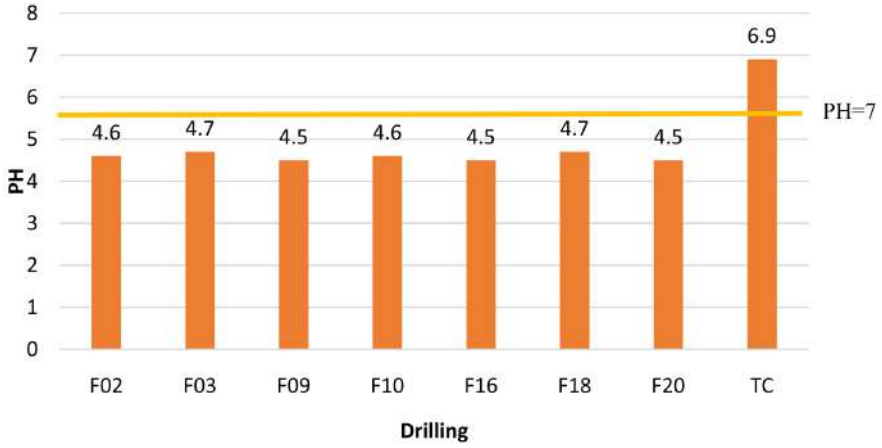

Figure 5. Drilling pH.

➢ **Conductivity**

Electrical conductivity reflects the degree of overall mineralization and provides information on the level of salinity. It allows the overall assessment of all the products in solution in water. The conductivities measured in the drilling water vary from 26 µS/cm to 43 µS/cm. The value of the conductivity in the TC is 139 µS/cm. The measured electrical conductivity values are much lower than 700 µS/cm (Figure 6), the limit value given by the WHO [4].

The low conductivity of drilling water may be due either to the nature of the geological layers (absence of limestone) or to the presence of a low level of mineral elements. The increase in conductivity at the TC level may be due to the treatment provided for the consumption of water from boreholes.

The drill water samples are acidic and weakly mineralized. These results agree with those of several authors including Yéï Marie-Solange Oga [6]. Indeed, the waters of the terminal continental are acidic ($3.50 < PH < 5.36$) and very little mineralized (from 20 to 55 µS/cm) [6].

3.2. Radiological Parameters

The results of the analyzes carried out in the laboratory of the Radiation Protec-

tion Institute at GAEC are shown in Table 3. The natural radionuclides detected during the analysis of the samples are: ^{238}U, ^{232}Th and ^{40}K.

The values illustrated in Table 3 show that in all samples (Figure 7):

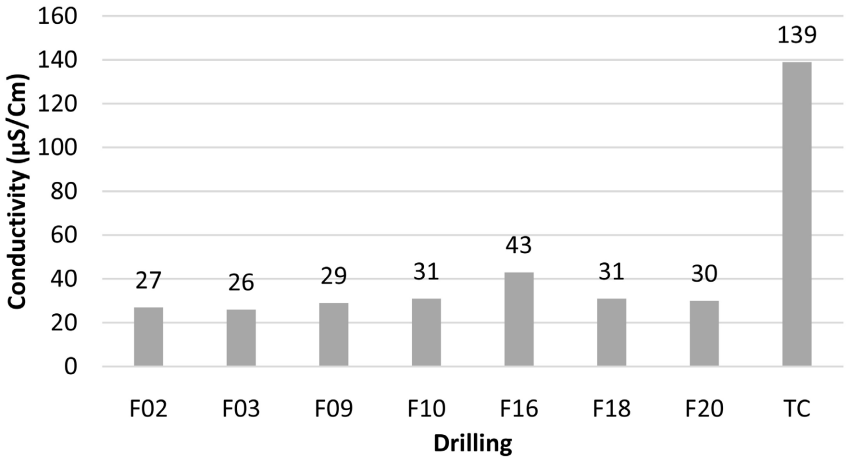

Figure 6. Conductivities of drilling water.

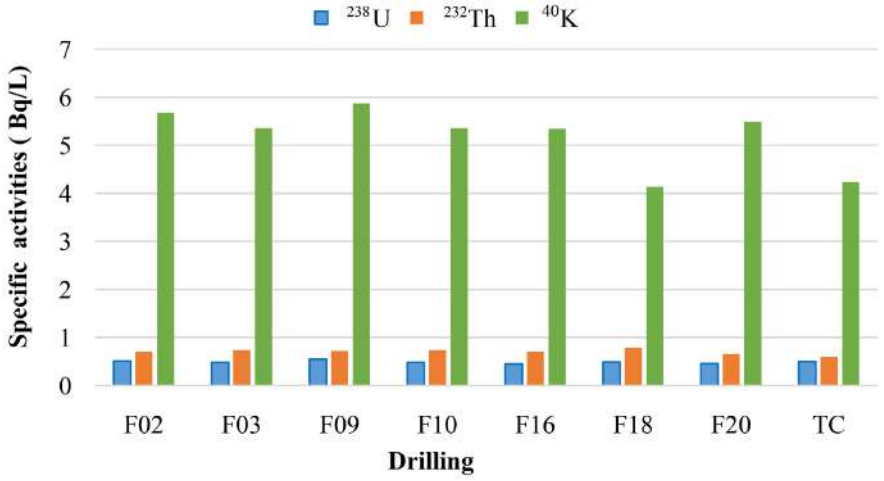

Figure 7. Specific activities of ^{238}U, ^{232}Th and ^{40}K in drilling water samples.

Table 3. Concentration of ^{238}U, ^{232}Th, ^{40}K in borehole water samples.

Sample code	Activity in Bq/L		
	^{238}U	^{232}Th	^{40}K
F02	0.51 ± 0.14	0.70 ± 0.16	5.68 ± 0.59
F03	0.48 ± 0.15	0.74 ± 0.16	5.36 ± 0.56
F09	0.55± 0.17	0.72 ± 0.19	5.87 ± 0.60
F10	0.48 ± 0.15	0.74 ± 0.16	5.36 ± 0.56
F16	0.45 ± 0.18	0.70 ± 0.14	5.35 ± 0.66
F18	0.49 ± 0.17	0.78 ± 0.18	4.14 ± 0.53
F20	0.46 ± 0.12	0.66 ± 0.13	5.49 ± 0.56
TC	0.50 ± 0.15	0.60 ± 0.14	4.24 ± 0.40

- The concentration of ^{40}K radionuclide is very higher than that of ^{232}Th and ^{238}U.
- The concentration of ^{232}Th is higher than that of ^{238}U.

➢ **Uranium 238**

The concentrations of ^{238}U in the well water vary from 0.45 to 0.55 Bq/L with an average of 0.49 ± 0.15 Bq/L. This average value is roughly equal to the value of uranium for TC 0.50 ± 0.15. Dual toxicity is attributed to uranium, chemical toxicity and radiological toxicity. Regarding chemical toxicity, the guide value for the maximum uranium content in drinking water is 15 µg/L, or 0.186 Bq/L [7].

The guideline value for radiological toxicity is 10 Bq/L or 120 µg/L considering only ^{238}U. The chemical toxicity of this radionuclide being the most penalizing, it will be considered as a reference value [7]. In our samples the reference concentration is largely exceeded, approximately 2.7 times the concentration recommended by the WHO (**Figure 8**). The high values of ^{238}U in drilling water could be due to their acidic character (pH = 4.5 - 4.7) because uranium is particularly soluble in this range of pH [2].

➢ **Thorium 232**

The concentration of thorium in borehole water varies from 0.66 to 0.78 Bq/L (**Figure 9**) with an average of 0.72 ± 0.16 Bq/L. While TC exhibits an activity of 0.60 ± 0.14 Bq/L. The ^{232}Th concentrations for all borehole water samples are significantly higher than the low concentrations typically found in groundwater. Indeed, groundwater has low concentrations of between 3×10^{-3} and 2.9 µg/L, *i.e.* 372×10^{-7} and 3.596×10^{-2} Bq/L [8]. The same observation is made by Laurence Böhm according to whom the content of thorium in water does not exceed 1 µg/L or 0.0124 Bq/L.

However, thorium, having a strong affinity with the particulate phases, strong activities of these radionuclides in the groundwater samples may be due to the non-filtration of the samples analyzed [9].

One can also notice that the concentration of ^{232}Th is higher compared to ^{238}U. This can be explained by the fact that it is more abundant in terms of mass than ^{238}U in rocks by a factor of 2 to 3 [2] [8].

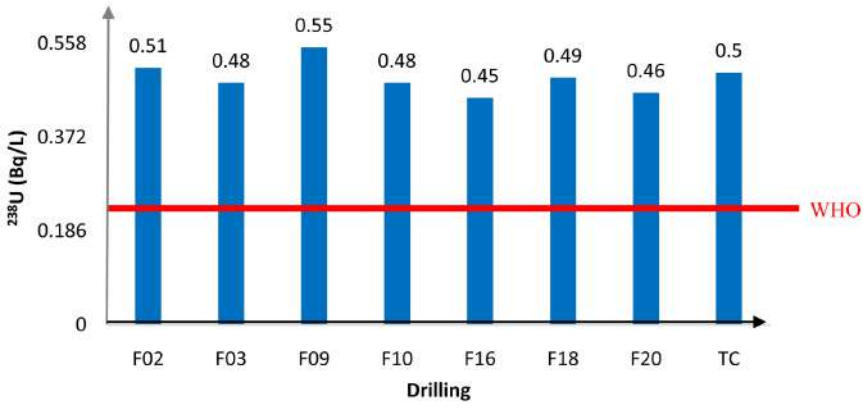

Figure 8. Specific activities of ^{238}U in borehole water samples.

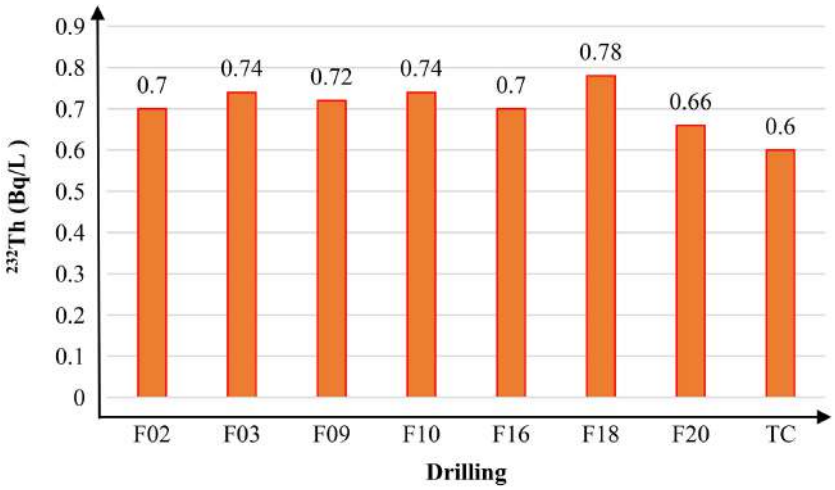

Figure 9. Specific activities of ^{232}Th in drilling water samples.

➢ **Potassium 40**

The ^{40}K concentrations in drilling water vary from 4.14 to 5.87 Bq/L (**Figure 10**) with an average of 5.32 ± 0.58 Bq/L. This average value is greater than the ^{40}K value of the TC.

The higher concentration values for ^{40}K could also be explained by the fact that natural potassium is quite abundant in the earth's crust (23 g/Kg) [10].

From all of the above, we therefore generally observe that our samples show high concentrations of the natural radionuclides ^{238}U, ^{232}Th and ^{40}K.

This could be due to the bedrock composition of the area. The geological profile of the Akouedo zone rests on a schistose granite basement. The radioisotope contents are higher for circulating water in crystalline rocks than those from sedimentary rocks [2]. Indeed, rocks such as granites, schists are crystalline rocks.

Also, a low pH leads to a dissolution of trace metals but also increases the concentrations of natural radionuclides in groundwater [4].

➢ **Discussion at the control tower (TC)**

At the TC level, we notice that ^{238}U has a concentration of 0.50 ± 0.15 Bq/L which is higher than the concentration of most of the drilling water samples. However, this concentration is approximately equal to the mean value 0.49 ± 0.15 Bq/L (**Figure 11**). The high concentration of uranium in the water at the TC could be related to the fact that the groundwater is found on the surface, oxidized medium. Indeed, the low uranium contents in deep water are partly linked to the oxygen-poor environment [2]. Also, the high concentration of uranium at the TC level could be explained by the fact that uranium is much more mobile than thorium [11]. This mobility could be accentuated by the complexation of uranium by humic substances. Indeed, the acidity of groundwater is linked to the presence of a high content of free CO_2. This high content is due to the constant presence of organic matter linked to the infiltration of humic acids [12]. And the complexation of uranium by a strong complexing agent (eg humic substances) can inhibit retention and thus promote mobility of uranium in the aqueous medium [13].

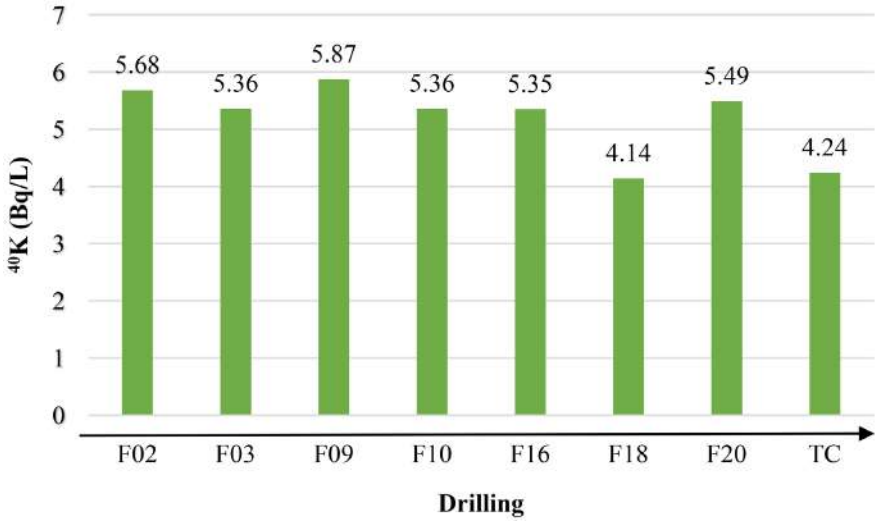

Figure 10. Specific activities of potassium in borehole water samples.

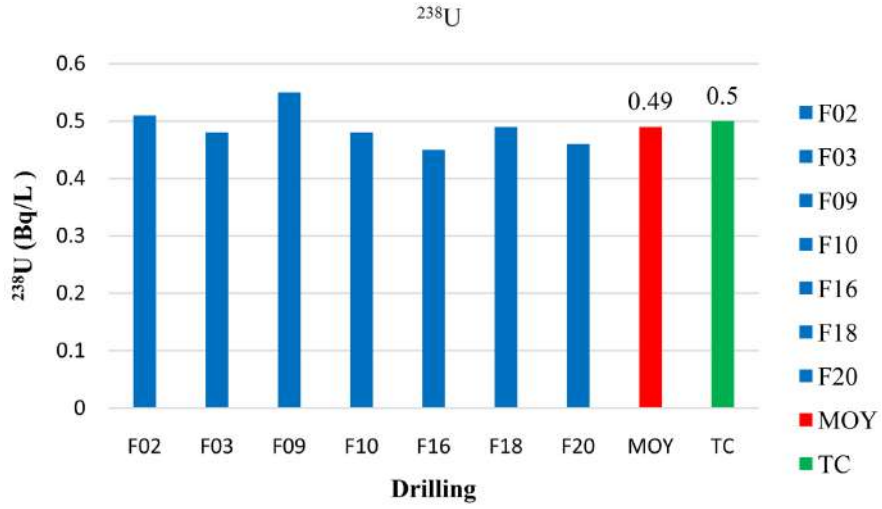

Figure 11. Comparison of the mean value of ^{238}U in drilling water and TC.

Note that the waters collected from all the functional boreholes are grouped in the TC for treatment. The presence of uranium in an amount equal to the average borehole water could be explained by the chemical composition of the lime. From a chemical point of view, the lime material manufactured by the industry is a calcium oxide with more or less magnesium oxide and carbonate-based impurities in particular. The dissolution of carbonates can cause uranium to increase. Indeed, the dissolution of carbonates leads to the formation of bicarbonate ions, which can complex uranyl ions, increasing the mobility of uranium and therefore contamination problems [2] [11].

Also, the NR lime treatment process may not be effective for uranium removal [14]. However, an ex-factory sample gives a result of the maximum level of radioactivity in the water which can then only decrease in the networks [15].

Concerning the ^{232}Th and the ^{40}K at the TC level, they respectively present concentrations of 0.60 ± 0.14 Bq/L and 4.24 ± 0.40 Bq/L well below the calculated

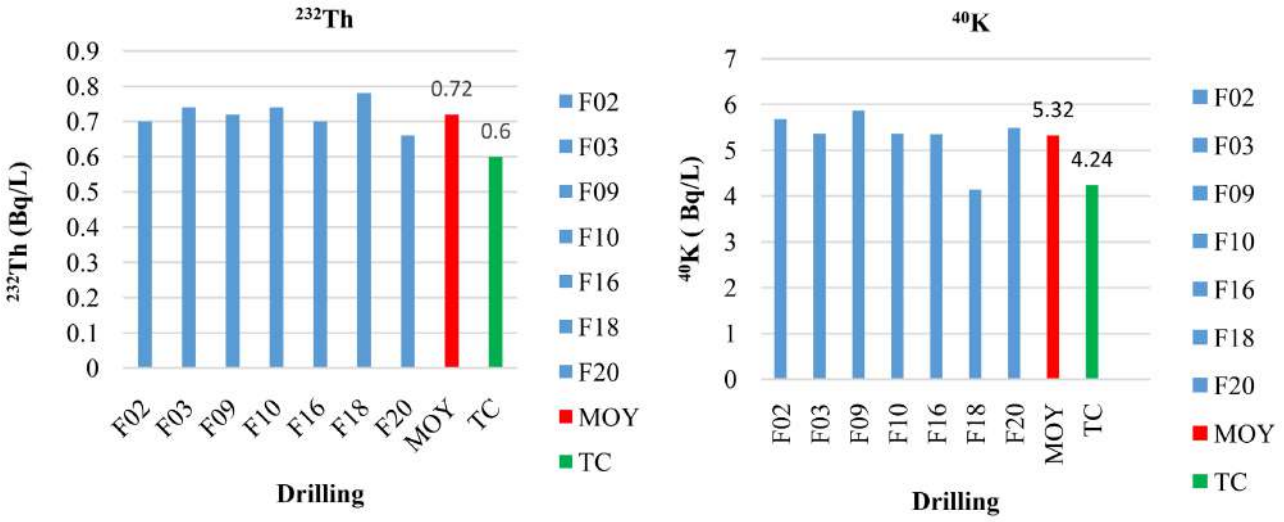

Figure 12. Comparison of the average value of ^{232}Th and ^{40}K of drilling water with that of TC.

mean values of groundwater in thorium 0.72 ± 0.16 Bq/L and potassium 5.32 ± 0.58 Bq/L (**Figure 12**).

The drop in ^{232}Th and ^{40}K activities could be due to the physicochemical treatments provided to the drilling water. Indeed, most radionuclides including uranium can be effectively removed in water treatment facilities. Proven radionuclide removal technologies commonly used there include ion exchange, reverse osmosis and lime softening [16]. Water softeners use the principle of ion exchange which removes radionuclides [16].

As thorium has an affinity with the particulate phases in water, the decrease in its content at TC level could be due to processing. Only physico-chemical treatments in a treatment plant are likely to modify their content (reduction of radionuclides adsorbed on suspended matter) [15]. This is also explained by Health Canada (2009) according to which, the water supply generally undergoes a treatment which has the effect of eliminating the substances in suspension in the water because the suspended matter retains the majority of the contamination. This also makes it possible to reduce dissolved substances and therefore, the radioelements which are present.

Although the high values of radionuclide concentrations of ^{238}U, ^{232}Th and ^{40}K measured in borehole water have a natural origin, we cannot rule out an anthropogenic contribution. These high concentrations of radionuclides could also be linked to human activities close to the NR field, in particular the former Akouedo landfill and the dwellings located nearby which could artificially or technologically increase the concentrations of natural radionuclides in the water by infiltration industrial and domestic waste in drilling water.

4. Conclusions

The radioactive analysis of the samples of borehole water from the NR catchment field enabled us to assess the radiological risk due to exposure to the natu-

ral radioactivity present in these waters. This study allowed us to have an idea on the distribution of ^{238}U, ^{232}Th and ^{40}K activities in the well water exploited by SODECI to supply drinking water to part of Abidjan's population. To this end, the analysis results show for the drilling water a level of ^{238}U activity varying from 0.45 to 0.55 Bq/L with an average of 0.49 ± 0.15 Bq/L greater than the guideline value recommended by the WHO in drinking water with regard to toxicity which is the penalizing value.

The thorium concentrations vary from 0.66 to 0.78 Bq/L with an average of 0.72 ± 0.16 Bq/L. These concentrations are much higher than the concentrations of thorium generally present in drilling water with a concentration between 3×10^{-3} and 2.9 µg/L (*i.e.* between 372×10^{-7} and 3.596×10^{-2} Bq/L) according to several authors. Finally, potassium 40 varies from 4.14 to 5.87 Bq/L with an average of 5.32 ± 0.58 Bq/L.

This high natural isotopic concentration does not make it possible to rule out an artificial origin for the high values of uranium and thorium concentrations in the drilling water. Indeed, these high concentrations of radionuclides could also be linked to the presence of the former Akouedo landfill and the dwellings located near the NR catchment field.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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