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Investigation of Groundwater Quality with Borehole Depth in the Basin Granitoids of the Ashanti Region of Ghana

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Abstract

The dependence of groundwater quality on borehole depth is usually debatable in groundwater studies, especially in complex geological formations where aquifer characteristics vary spatially with depth. This study therefore seeks to investigate the relationship between borehole depth and groundwater quality across the granitoid aquifers within the Birimian Supergroup in the Ashanti Region. Physicochemical analysis records of groundwater quality data were collected from 23 boreholes of public and private institutions in the Ashanti Region of Ghana, and the parametric values of iron, fluoride, total hardness, pH, nitrate, and nitrite were used to study the groundwater quality-depth relationship. The results showed that the depth-to-groundwater quality indicated a marginal increase in water quality in the range of 30 to 50 m, which is mathematically represented by the low-value correlation coefficient ($r^2 = 0.026$). A relatively significant increase occurs in the depth range of 50 to 80 m, which is given by a correlation coefficient of $r^2 = 0.298$. The mean percent parameter compatibility was 74%, 82%, 89%, and 97% at 50, 60, 70, and 80 m depths, respectively. The variations in groundwater quality per depth ratio ranged from 1.48, 1.37, 1.27, and 1.21 for 50, 60, 70, and 80 m depth, respectively. The recommended minimum borehole depth for excellent groundwater quality is suggested with a compatibility per meter depth ratio of 1.37. This results in a range between 50 and 70 m as the most desirable drilling depth for excellent groundwater quality within the granitoids of the Birimian Supergroup of the Ashanti Region in Ghana.

Keywords

Groundwater Quality, Borehole Depth, Birimian Supergroup, Granitoid Aquifers, Ashanti Region

1. Introduction

The Ashanti Region of Ghana is located approximately between latitude 5.50˚N to 7.46˚N and longitude 0.15˚W to 2.25˚W [1] [2], with a population of about 5,440,463 inhabitants in 2021, according to the Ghana Statistical Service [3] [4]. Two main lithostratigraphic complexes underlie the region [1]: the Paleoproterozoic supracrustal and intrusive rocks; and the Neoproterozoic to early Cambrian lithologically diverse platform sediments. The Paleoproterozoic rocks consist of the Birimian Supergroup (Birimian sediments and volcanics, which include phyllites, schists, migmatites, granites, granite gneiss, and quartzites and occur mainly in the northwest and southwest of the region) [5] [6] [7], the Tarkwaian Group (composed of quartzites, phyllites, grits, and conglomerates intruded by laccoliths and sills of epidorite), and the Eburnean Plutonic Suite (consisting of undifferentiated granitoids such as granites, granodiorites, and gneiss). Rocks of the Birimian Supergroup constitute about 54% of the study area [8] [9].

The Tarkwaian Group and the Eburnean Plutonic Suite constitute 2% of the region's underlying rocks [10]. According to [11], the Neoproterozoic to early Cambrian rocks comprise the Voltaian Supergroup consisting of the Kwahu-Morago, Oti-Pendjari, and Obosum Groups, underlain by basal sandstones, consisting mainly of quartz-sandstone, pebbly grits, shale, mudstone, siltstone, sandstone, arkose, and conglomerate. The Voltaian Supergroup underlies approximately 44% of the study area and is located predominantly in the northeastern parts of the region. The Birimian Supergroup and the overlying Tarkwaian Group cover extensive, well-populated, and economically active areas in the region, and are of significant geological importance owing largely to the huge mineral deposits and rich agricultural soil cover [12] [13] [14]. Groundwater, also a major water supply resource, has been modestly exploited over the last two decades to meet water supply needs in many rural communities in Ghana, where over 95% is used for domestic purposes [8] [15] [16] [17]. Three main factors appear to control the occurrence of groundwater in the basin granitoids: the extent and effect of rock decomposition, the presence of quartz aplite and pegmatite veins, and the presence of fracture openings [18] [19] [20] [21]. According to [20], the most important factor affecting groundwater accumulation in the Birimian Province is rock decomposition. However, the extent of rock decomposition in the Birimian Province is often determined by the presence of veins, fractures, and shear zones, as these provide conduits for water circulation and promote the decomposition process. The result is that areas of fractures and veined rock coincide with areas of deep decomposition, although a rock without these structures may be deeply decomposed [22].

Groundwater flow is mostly restricted to joints and fractures within the crystalline rock formations. Borehole yields are therefore often limited. In some areas, a thick layer of weathered, friable material ("regolith") overlies the crystalline basement and provides potential for increased groundwater storage. This weathered layer can be over 100 m thick in some places but is typically in the range of 1 - 70 m thick [23]. According to [24], successful boreholes drilled through the Birimian and Tarkwaian rocks range from 35 to 55 m with a mean depth of 42 m. Due to interactions with the atmosphere, the surficial environment, soil, and bedrock, a wide range of different elements can become dissolved in the groundwater [25]. Therefore, groundwater tends to have much higher concentrations of most constituents than surface water, and deep groundwater that has been in contact with rock for an extended time tends to have higher concentrations than shallow boreholes.

In the literature, extensive groundwater quality assessments in Ghana have been carried out by [7] [18] [26]-[35] and several others, but these have mainly emphasized spatial variations in quality and pollution, the determination of chemical constituents of the groundwater, and the constituent's concentration levels in conformity to local and international acceptable limits.

The influence of borehole depth on groundwater quality has not received much attention, probably due to the argument that the deeper the borehole, the better. However, it was found that this assumption does not reflect the general trend in borehole drilling for potable water in the underlying geology [36]. Statistical analysis by [37] identified minimal decreases in groundwater quality in terms of calcium and pH with depth in some borehole samples collected from locations in Port Harcourt Metropolis, Nigeria. [38] further investigated the nitrate concentration of boreholes in Cumbria and found that the nitrate concentration in some relatively deep boreholes was more than 20 mg/L. Using simple numerical modeling, the study suggested that the proportion of groundwater pumped is sensitive to the presence of fissures near the boreholes and the location of the boreholes relative to "superficial deposit-free windows." [39], while investigating groundwater problems in the Upper East Region of Ghana, observed significant variations in fluoride concentration with depth of groundwater from the Bongo granitoids in the Bolgatanga area. Shallow, hand-dug wells were found to have much lower fluoride concentrations compared to groundwater from deep boreholes due to dilution from recent recharge. High fluoride concentrations in the range of 1.5 - 5.0 mg/L have been found in boreholes in granitic formations in the Upper East and West Regions of Ghana [40] [41] [42] [43].

This study uses statistical analysis to investigate the influence of borehole depths on groundwater quality for some parameters such as iron, fluoride, nitrate, nitrite, pH, and total dissolved solids. The objective is to provide baseline information that will enable geophysicists and hydrogeologists to establish a minimum depth for boreholes drilled in the basin granitoids of the Ashanti Region in Ghana.

2. Methodology

A borehole dataset was collected from the records of public institutions and private borehole owners for a decade (2012-2022). The records comprised of single measurements, usually undertaken on the completion of the boreholes. The groundwater quality analysis was performed by the Water and Sanitation Laboratory, Civil Engineering Department, Kwame Nkrumah University of Science and Technology, Kumasi following international standard drinking water practices [44]. The groundwater quality results are shown in **Table 1**. The IBM SPSS Statistics 27 software package was used to determine the descriptive statistics of the parametric values, such as mean and standard deviation, to reflect the spatial variability of the values obtained from the 23 representative boreholes. The Microsoft Excel spreadsheet was also used to create the correlation diagrams. **Figure 1** shows the geological formations in the study area.

The procedure proposed by [36] to conduct similar investigations was used to compute the percent parameter compatibility, as shown in Equations 1 and 2. The average parameter percentages were also calculated (**Table 2**) and regressed with depth to determine the relationship between borehole depths and water quality.

$$\text{Percentage Compatibility} = 1 - \frac{\text{Sample Value}}{\text{WHO Value}} \times 100\% \tag{1}$$

If the value of a parameter is 0, the compatibility with the World Health Organization (WHO) value is 100%; if the value of a parameter is equal to the WHO value, the compatibility is 0%. However, Equation (2) applies to the pH of the groundwater samples:

$$\text{Percentage Compatibility of pH} = \frac{\text{Sample pH Value}}{6.5} \times 100\% \tag{2}$$

The deviation in the formula for calculating the pH value is because the WHO value for it is a range between two limits (6.5 and 8.5), while other parameters have maximum values only. Therefore, the pH limit used depends on the sample's average pH value: acidic, basic, or neutral level in drinking water. It was observed that the borehole water in the study area was generally; hence, 6.5, being the maximum permissible acidic or pH level by WHO, was substituted into Equation. (2) to evaluate the compatibility of the samples with the safe acidity level for drinking water.

3. Results and Analysis

3.1. Groundwater Sample Analysis

The results of the physicochemical analysis of the groundwater samples are shown in **Table 1**. **Table 1** shows that the borehole data did not exhibit homogeneity in all properties. A borehole at a single location in the study area may not have common groundwater quality point estimates for all other locations. This indicates spatial variability in all boreholes. Therefore, groundwater quality monitoring must be observed spatially and not by a lumped estimate.

Table 1 also showed that the mean concentrations of iron, fluoride, total hardness, pH, nitrate, and nitrite were within the WHO permissible limits for drinking water. For instance, mean concentrations of 0.05 mg/L and 0.38 mg/L

Table 1. Water quality results of the selected chemical parameters in the study.

Borehole Location	**Sample ID**	**Parameter**	**Fe**	**Fl**	**Total Hardness**	**pH**	**nitrate NO_3**	**nitrite NO_2**	**Depth of Borehole**
		WHO Standards	**0 - 0.3 (mg/L)**	**0 - 1.5 (mg/L)**	**0 - 500 (mg/L)**	**6.5 - 8.5 pH units**	**0 - 10 (mg/L)**	**0 - 0.1 (mg/L)**	**(m)**
Anhwiafotu	S1		0.001	0.25	41	6.08	5.3	0.013	64
Nweneso	S2		0	0	0	5.48	0	0.006	65
Dwease	S3		0	0.54	28	6	1	0.002	60
Saabo	S4		0.5	0.13	67	6.4	1	0.009	58
Fenaso 3	S6		0.001	0.16	0	5.78	3	0.003	69
Atonsuagya	S9		0.001	1.85	8	5.46	4	0.007	61
Maase Brofeyedu	S12		0	0.2	36	6.42	0	0.009	79
Bonkwaso	S13		0.006	0.21	70	6.22	0.2	0.008	69
Asamang	S14		0	0.91	0	5.38	2	0.003	76
Boamag Maase	S15		0.008	0.03	0	5.3	0	0.005	67
Woramponso	S16		0.001	0.3	73	6.26	2.5	0.001	60
Konkori	S17		0.001	0.26	101	6.33	6.5	0.021	58
Tanoso 1	K18		0.14	0.2	64	6.5	6.02	0.017	40
Tanoso 2	K19		0.05	0.89	63	6.24	6.5	0.016	55
Tanoso 3	K20		0.03	0.32	54	6.01	5.18	0.013	60
Tanoso 4	K21		0.15	0.18	94	6.02	0.8	0.006	50
Domeabra	K22		0.04	0.47	20	5.23	0.02	0.001	40
Apemso	K23		0.01	0.21	16	4.5	0.73	0.004	35
Kotei	K24		0.14	0.26	78	6.17	0.66	0.002	40
Kwamo	K25		0.07	0.7	153	6.96	1.9	0.008	35
Ekyem 1	K26		0.01	0.1	32	3.84	0.13	0.003	35
Ekyem 2	K27		0.01	0.07	0	5.65	0.08	0.006	35
Tikrom	K28		0.06	0.47	20	4.38	1.2	0.006	35
Mean			0.05	0.38	44.26	5.77	2.12	0.01	54.2
Standard Deviation			0.11	0.40	39.05	0.73	2.25	0.01	14.4

K18-28: Records obtained from private borehole owners within the Kumasi District.

were recorded for iron and fluoride, respectively, which is between the range concentrations of 0.003 - 1.14 mg/L and 0.154 - 0.427 mg/L, respectively for iron and fluoride reported by [19] and [45] within the study area. However, the value of 0.5 mg/L recorded for iron at S4 was above the recommended WHO limit. However, this was an isolated case and may not reflect the general trend in iron concentration within the basin granitoids in the study area. However, iron concentrations above the mean value of 0.05 mg/L were observed in seven boreholes, representing approximately 30% of the total number of samples.

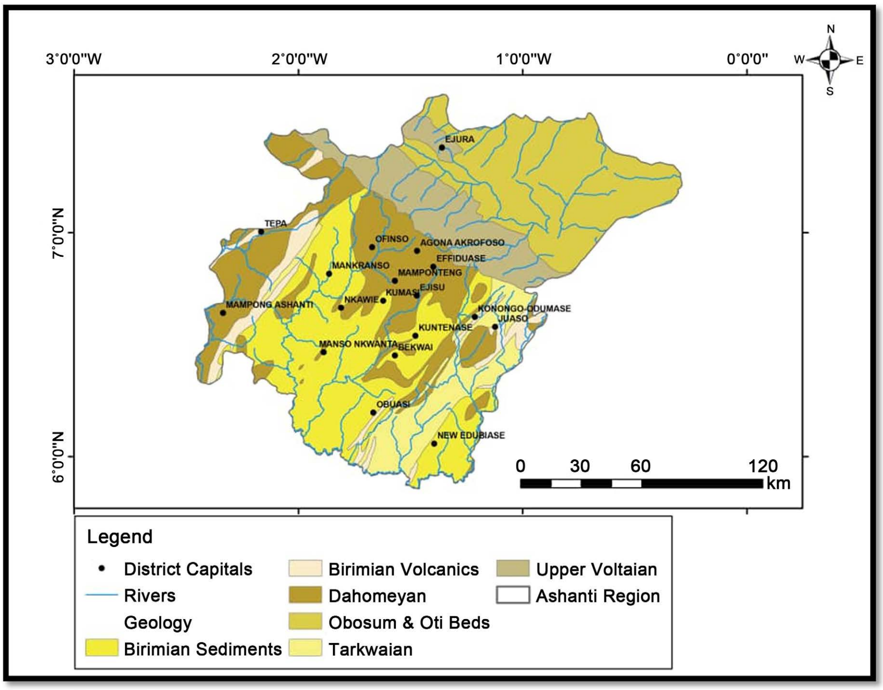

Figure 1. Simplified geological map of the Ashanti region of Ghana.

This suggests that iron in the groundwater of the basin granitoids in the study area could cause significant problems. High iron concentrations in groundwater can lead to brownish discoloration of cooking utensils and fabrics, an unpleasant taste, and often, rejection of the water by users [46] [47] [48]. Only sample S9 had fluoride concentrations above the WHO limit of 1.5 mg/L, suggesting minimal fluoride contamination in the region. High concentrations of fluoride in drinking water have been reported to cause both dental and skeletal fluorosis [42] [49] [50].

3.2. Borehole Depth and Quality Determination

The percent compatibility of each parameter was calculated using Equations 1 and 2. A summary of the results is presented in **Table 2**. The results show the percent parameter compatibility of the groundwater samples with the WHO values for each of the borehole samples.

With regards to pH, the mean value was 5.77, but in general, 95% of the total number of samples had pH values below the lower limit of 6.5, indicating the slightly acidic nature of groundwater abstracted from the granitoids of the Birimian Supergroup. Highly acidic drinking water tastes sour [51] and can lead to corrosion in distribution pipes and fittings as well as household plumbing as well as eye irritation, whereas alkaline water leads to the deposition of salts in distribution pipes [52] [53] [54]. Treatment to minimize acid concentration should be considered as part of groundwater development in the study area.

Total hardness, nitrate, and nitrite had mean values of 44.26, 2.12, and 0.01 mg/L, respectively which were within the acceptable WHO limits. According to

Table 2. Parameter percentage compatibility of the results.

Sample ID	Parameter Percentage Compatibility (PPC)						Average Parameter Percentage Compatibility (APPC)	Depth of Borehole
	Fe (mg/L)	Fl (mg/L)	Total Hardness (mg/L)	pH (mg/L)	nitrate NO_3 (mg/L)	nitrite NO_2 (mg/L)		(m)
S1	99.7	83.3	91.8	93.5	47.0	87.0	84	64
S2	100.0	100.0	100.0	84.3	100.0	94.0	96	65
S3	100.0	64.0	94.4	92.3	90.0	98.0	90	60
S4	0.0	91.3	86.6	98.5	90.0	91.0	76	58
S6	99.7	89.3	100.0	88.9	70.0	97.0	91	69
S9	99.7	0.0	98.4	84.0	60.0	93.0	73	61
S12	100.0	86.7	92.8	98.8	100.0	91.0	95	79
S13	98.0	86.0	86.0	95.7	98.0	92.0	93	69
S14	100.0	39.3	100.0	82.8	80.0	97.0	83	76
S15	97.3	98.0	100.0	81.5	100.0	95.0	95	67
S16	99.7	80.0	85.4	96.3	75.0	99.0	89	60
S17	99.7	82.7	79.8	97.4	35.0	79.0	79	58
K18	53.3	86.7	87.2	100.0	39.8	83.0	75	40
K19	83.3	40.7	87.4	96.0	35.0	84.0	71	55
K20	90.0	78.7	89.2	92.5	48.2	87.0	81	60
K21	50.0	88.0	81.2	92.6	92.0	94.0	83	50
K22	86.7	68.7	96.0	80.5	99.8	99.0	88	40
K23	96.7	86.0	96.8	69.2	92.7	96.0	90	35
K24	53.3	82.7	84.4	94.9	93.4	98.0	84	40
K25	76.7	53.3	69.4	0.0	81.0	92.0	62	35
K26	96.7	93.3	93.6	59.1	98.7	97.0	90	35
K27	96.7	95.3	100.0	86.9	99.2	94.0	95	35
K28	80.0	68.7	96.0	67.4	88.0	94.0	82	35

Parameter percentage compatibility = 100% implies the parameter is below detection (BD) or 0, Parameter percentage compatibility = 0% implies parameter is equal to or above the WHO value.

[51] total hardness is a measure of the suitability of water for domestic, drinking, and many industrial purposes. Since all total hardness concentrations of the groundwater samples were within the acceptable WHO limits, the quality of the groundwater in the study area is suitable for drinking water consumption.

The minimal nitrate and nitric concentrations could be due to the boreholes being located far from possible sources of pollution such as refuse dumps, septic tanks, and agricultural lands where organic and inorganic fertilizers are used. The mean concentrations of the observed parameters except pH, were within WHO acceptable limits. About 95% of the pH values recorded were below 6.5, the lower limit recommended by the WHO. For iron, about 30% of the values recorded were above the average value of 0.05 mg/L. Iron and pH concentrations in drinking water could be problematic in boreholes drilled over the granitoids and should therefore be considered in groundwater development in the region. **Table 1** also shows spatial variations in parametric values from borehole to borehole, indicating that a single measurement could not be used as representative of all boreholes in the project area.

Figure 2 and **Figure 2** present the regression of the average percent parameter compatibility for moderately deep (30 - 50 m) and deep (50 - 80 m) borehole depths. From **Figure 2** it can be seen that that the correlation between borehole depth and groundwater quality at depths between 30 and 50 m was not significant. The correlation coefficient, r^2, was 0.026. The value of r^2 approaching zero confirms a very weak relationship between the depth of the boreholes and the groundwater quality from a depth of 30 - 50 m in the study area. The weak correlation could indicate that groundwater was abstracted from the weathered zone aquifers overlying the parent rock. typically, aquifers in weathered zones are characterized by a few meters of thick sandy clay or clayey sand, often concretionary beneath a collapsible zone, and an overlying massive accumulation of secondary minerals (clays), in which some stable primary minerals may be present in their native form. this layer, in turn, was highly weathered, resulting in fractured bedrock. chemical composition is not expected to vary significantly within the same aquifer, and therefore the effect on groundwater quality may be marginal.

Figure 3 shows the correlation between deep boreholes (50 - 80 m depth) and groundwater quality. From the graph, the average percentage compatibility of the parameters was approximately 74%, 82%, 89%, and 97% at 50, 60, 70, and 80 m depth, respectively. This suggests that quality increases with depth. Deep boreholes are less likely to be contaminated by pollutants because the surface pollutants slowly percolate to reach the underground aquifer through the overlying moderately to highly impervious weathered rocks. Occasionally, the conduits within the fractured rocks become obstructed with sandy-clayey materials, which enhance the filtration process of contaminants into groundwater but reduce percolation. The mean quality/depth ratio was 74% compatibility per meter of borehole depth, giving a value of r^2 of 0.298, determined from the regression of depth versus groundwater quality and mathematically stated as

$$y = 0.741x + 37.32$$

$$r^2 = 0.298$$

where, y = average parameter percent compatibility with WHO limits.

x = depth of borehole (m).

r^2 = correlation coefficient.

The variation in groundwater quality per depth ratio ranged from 1.48 for the 50 m depth to 1.37, 1.27, and 1.21 for the 60, 70, and 80 m depths. This suggests that there is a minimum threshold depth for high-groundwater quality and a

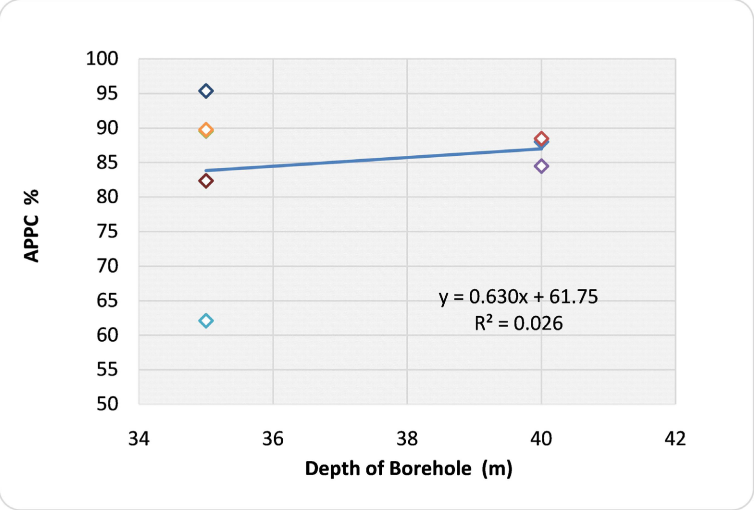

Figure 2. Average percentage compactibility at 30 - 50 m depth.

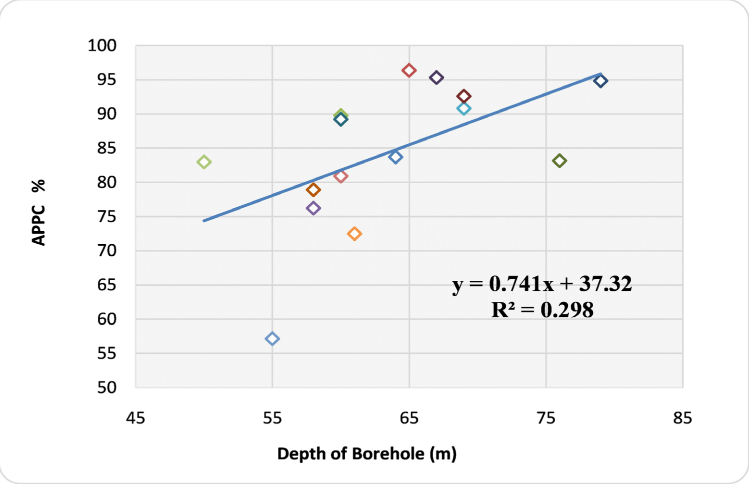

Figure 3. Average percentage compactibility at 50 - 80 m depth.

maximum water quality depth ratio that has a reducing or marginal effect on water quality. The mean value of quality per depth ratios was calculated to be 1.3%. Above this value, the groundwater quality-depth ratio increases, but at values below it decreases. This suggests that the minimum threshold depth for high quality (high compatibility) is 1.3% compatibility per meter of depth ratio. The depth range of the assumed threshold is estimated to be 50 - 70 m drilling depth, which could indicate the depth range for obtaining quality water extraction within the granitoids of the Birimian Supergroup of the Ashanti Region.

4. Conclusion

The concentration of iron, fluoride, total hardness, pH, nitrate, and nitrite in groundwater in the Birimian Supergroup granitoids of the Ashanti Region are spatially distributed, and groundwater quality standards vary from borehole to borehole and also depending on different borehole depths. Groundwater quality increases with depth, marginally from 30 to 50 m for moderately deep boreholes and significantly between the depth ranges of 50 and 80 m for deep boreholes. This observation is statistically represented by the correlation coefficients $r^2 = 0.026$ and $r^2 = 0.298$, respectively of the analyzed groundwater samples. The recommended minimum threshold depth for high groundwater quality is suggested within the ranges of 50 - 70 m, which sets the limit of groundwater quality compatibility per meter of depth ratio for high groundwater quality. The results from this study could serve as a guide to groundwater exploration in the Basin Granitoids in the Ashanti Region of Ghana and similar geological formations.

Conflicts of Interest

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

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