MAPPING OF CONFINED AQUIFERS FOR MANUAL DRILLING IN HONG LOCAL GOVERNMENT AREA OF ADAMAWA STATE USING PROBABILITY KRIGING

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Abstract
Manual drilling offers a practical and affordable method of increasing access to groundwater supply in regions struggling with economic water scarcity. There were a lot of drilling activities that were carried out to find ground water in Hong Local Government Area of Adamawa State, but the results are not always positive, that is, sometimes drillers are not successful. Some of the areas with boreholes or wells use to experience drawdown during the dry season. This problem has led to high cost incurred for drilling activities, this can however, be due to poor knowledge of the geology of the area. Probability kriging is proposed as an interpolation method that builds upon previous efforts to identify suitable zones for manual drilling, particularly in weathered basement aquifers. This study focused on mapping confined aquifer for manual drilling using Probability Kriging. The studies produced map that show areas of confined and unconfined aquifer, the suitable areas for manual drilling are the confined aquifers. Places like Dzuma, kwakwa, ShuwaKala'a, Zum, ShuwaKala'a, Makera partly Mararaban Mubi and Gashala are more and has the potential for manual drilling. The results of the Kriging for the best model and suitable locations for manual drilling are produced and presented in the form of probability map using probability kriging interpolation. This study has improved the ability to understand the hydrogeology of the study area and recommended that further research should be conducted to assess the performance of probability kriging with other non-parametric Kriging methods in identifying suitable sites for manual drilling.

Keywords: Probability Kriging, Mean Error, Root Mean Squared Error, Mean Standadised Error, Root Mean Square Standard Error, Average Standard Error

Introduction

Manual drilling is a practical and affordable solution for wells less than 40 meters deep in alluvial soils such as clay and sand and soft weathered rock formations such as soft sandstone and limestone (Robert, 2010). There are many areas around the world where it can effectively provide water for drinking and for irrigation to un-served rural populations at a fraction of the cost of conventional drilling. Over the last 20 years, Nigeria has become increasingly dependent on groundwater, which is now estimated to provide drinking water for over 100 million people (from hand dug wells, boreholes/tube-wells and springs). Nigeria is witnessing a process whereby manual drilling (mainly jetting) for domestic water supplies is becoming a main-stream and accepted approach in the feasible areas of at least 25 of Nigeria's 36 states (Kerstin 2015). According to West and Sinha (2019), aquifers are underground layers of water-bearing rocks or sediments that collect and transport groundwater. These aquifers must be identified and characterized in order to ensure sustainable groundwater management. Aquifer depth, resistivity, and thickness are important factors for groundwater exploration because they determine the quality and amount of available groundwater resources (Shishaye 2016).

Amechi et. al. (2022), identifying the regional distribution of these factors is critical for efficient groundwater extraction and long-term conservation. Philip and David (2020) utilised Indicator Kriging to identify suitable zones for manual drilling in weathered crystalline basement aquifers. Robin et al (2021) applied Indicator Kriging to hydraulic head data to test alternative conceptual models for spring source aquifers and explained that the techniques Indicator Kriging can inform conceptual model uncertainties arising from the interpretation of sparsely distributed hydraulic head datasets, a major benefit over traditional interpolation methods. Partha and Jyotiprava (2017) Compared deterministic and stochastic methods to predict spatial variation of groundwater depth, among the kriging methods, UK performed better than OK to predict water table depth. Kalid et al (2024) assessed the optimal interpolation approach to groundwater depth estimation, the results demonstrated the superiority of the Radial Basis Functions (RBF) method, exhibiting the lowest RMSE, MAE, and the highest R^2 compared to IDW and OK. Khairul *et al.* (2021) studied groundwater table variability and trend using ordinary kriging: in Sylhet, Bangladesh and Kriging gave more accurate results in mapping the groundwater level across the study area.

Statement of Problem

There were a lot of drilling activities that were carried out to find ground water, but the results are not always positive, that is, sometimes drillings are not successful. Some of the areas with boreholes or wells use to experience drawdown during the dry season. This problem has led to high cost incurred for drilling activities, this can however, be due to poor knowledge of the geology of the area. Hence, the need for scientific identification aquifer that are confined for resources exploration, exploitation and management.

Aim of the Study

This research identified and map confined aquifers of Hong Local Government Area (LGA) through the following objectives.

Objectives of the Study

- I. Estimate aquifer depth and thickness using vertical electrical sounding.
- II. Estimate aquifer depth and thickness of the aquifer using stochastic interpolation technique and perform model cross validation (comparison) and obtaining the best model.
- III. Use the best fit estimation models for aquifer depths and thicknesses to produce the confined aquifer map of the study area.

Materials and Methods

Study Area

Hong Local Government Area (Figure 1.1) is located in Adamawa state Nigeria; it was created in 1987 with Hong town as the administrative headquarter. It is located on latitude 9^0 58' to 10^0 35'N and longitude 12^0 35' to 13^0 13' E. It has a land area of 2,662 Km^2 (Gundiri, 2024). The population of Hong Local Government Area from an exponential projection of 2016 to 2018, the study area has a population of 239,602. It borders Borno state to the North, Gombi Local Government Area to the West, Song Local Government Area to the South, Maiha Local Government Area to the Southeast and Mubi North and South Local Government Areas and Mubi to the East (Zemba *et al* 2020).

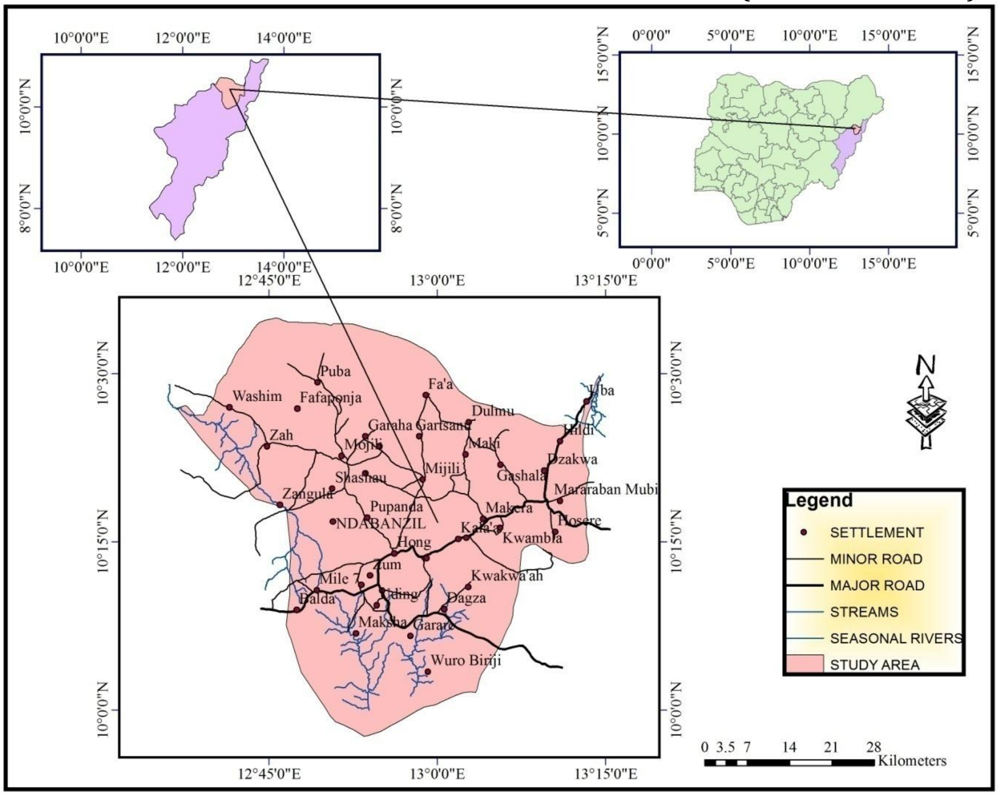

Figure 1.1: Vertical Electrical Sounding Sites of the Study Area
Source: Gundiri, 2024

Materials

The following materials were used for the study:
Terra-meter ABEM SAS 4000, Coiled wire, Tape, Hammer, GPS (Garmin 60), Current and potential electrodes, D.C Battery 12volts and Computer system

Software

Software used for the study are as follows:
i. ArcGIS 10.1 for geo-statistical analysis
ii. Interpex IX1Dv2 for plotting of obtained geo-electrical data.

Aquifer depth and thickness estimation using vertical electrical sounding

Estimation of aquifer depth and thickness was performed using Vertical Electrical Sounding (VES) a Schlumberger array (Figure 2). The data was obtained in the field where the study area is located. The obtained data was plotted in Interpex IX1Dv2 and estimated aquifer depth and thicknesses were obtained.

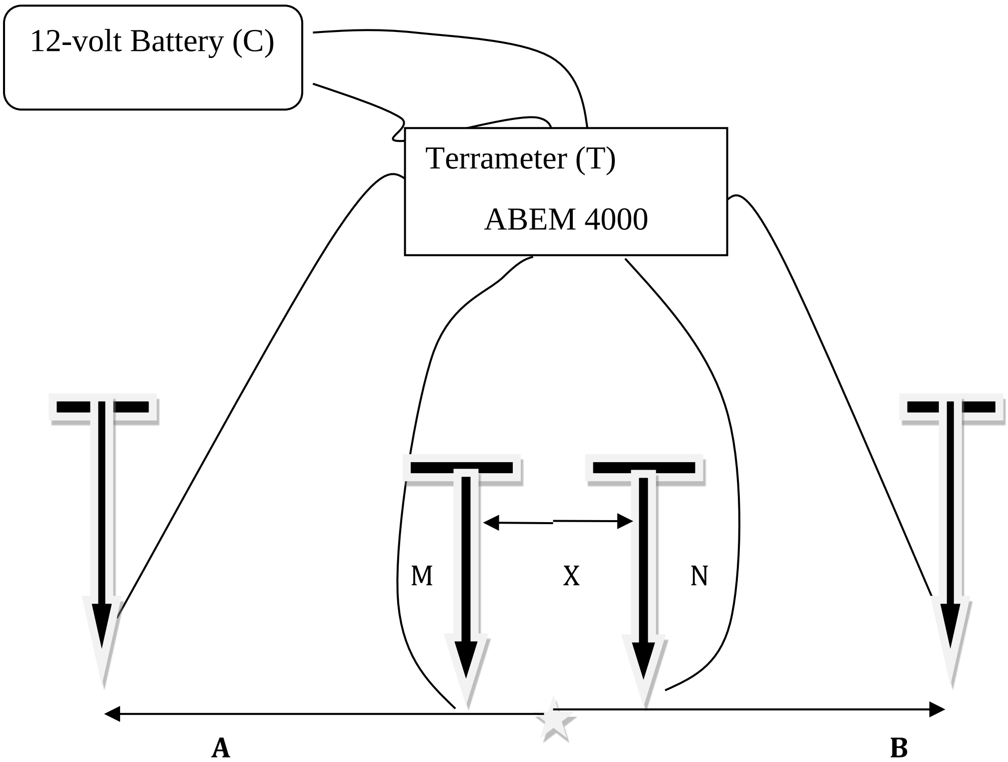

Figure 2: Configuration of Schlumberger Array for Vertical Electrical Sounding

In Mijili a sample point X (Figure 2) was identified on the ground and ground coordinates were obtained. At the first sounding measurement, the current electrodes A and B were placed at a distance of 1m at either side of point X, while the potential electrodes M and N were placed at a distance of 0.2m at either side of point X. For subsequent sounding measurements, the current electrodes (A and B) and potential electrodes (M and N) were moved further apart progressively, with A&B ranging from 1m to a maximum of 100m away from X; and M & N ranging from 0.2 to a maximum of 1.5m away from X. Steel rods were used to range the alignment thus making them perfectly straight. At both points M and N (potential electrodes) the steel rods were pegged. When the current electrode spacing is at a maximum of 10.0m, then the spacing of potential electrode XM and XN was changed to 1.5m. The reason for the separation of current electrode AB/2 is that the current penetrates continuously deeper with increasing separation of current electrodes.

The steel rods at point A, M, N, B were connected using cables to the terrameter (T), the terrameter was then powered by a 12-volt Battery (C). The connection was done in such a way that A and B receives current from the terrameter while MN emits current received from the ground into the terrameter. Therefore, while cables at TA and TB are emitting current to the ground, cables MT and NT are receiving the returned signal back to the terrameter. The readings were taken by the terrameter, and it was used to measure and record the resistance of the subsurface. The terrameter reads the signals from M and N and outputs a reading known as the resistance. The values of the resistance obtained in the field were multiplied by their respective Geometric factor (G) for each spacing of the electrodes. This gives the required apparent resistivity results. Geometric factor is a numerical multiplier defined by the geometrical spacing between electrodes. This becomes the reading for Mijili. The same procedure was adopted for the 40 sampling points in the study area.

Mapping of Estimated Aquifer Depths and Thicknesses using Geostatistics (Stochastic Interpolation)

Geo-statistic was used to produce the map of estimated aquifer depths and thicknesses. The data used for the geostatistical estimation are Aquifer depths and Thicknesses from the summary of table of Vertical Electrical Sounding (VES) parameters of the study area (Table 1). The aquifer depths data was explored to check for normality of the data using histogram from geostatistics wizard of ArcGIS 10.1, check for the presence of trend and decide the order of removal and finally produce the map of estimated aquifer depth and thickness.

Model cross validation (comparison)

After the geostatistical estimation, cross validation table generated the statistics that quantifies the errors for both aquifer depths and thicknesses. The comparison was assessed based on the Smallest Mean Square Error (RMSE) with a condition that the Average Standard Error (AVE) should be close to the Root Mean Squared prediction errors (RMSE); if these conditions are satisfied; you are correctly assessing the variability in prediction, hence accepted. This process was accomplished based on (Esri 2012) and Kalpana and Pramila (2011).

Mapping of confined aquifers for Manual Drilling

In order to determine the feasibility of manual drilling, the criteria utilized by Fussi (2017) was adopted, this includes aquifer depths threshold to a maximum of 40 meters for the feasibility of manual drilling and aquifer thickness between 0 to 50 meters. The parameters used in identifying the confined aquifer were the output from the best geostatistical methods for both aquifer depths and thicknesses. Probability Kriging, was used in producing the map of confined aquifer, using a threshold value above 30 meters for both aquifer depths and thicknesses because it is less vulnerable to pollution through infiltration. The output from this analysis was a binary map with 1 indicating areas of confined aquifers and 0 indicating unconfined aquifers areas. Raster calculator was then used to multiply the two binary maps (aquifer depths and aquifer thicknesses) to show areas of confined and unconfined aquifers.

Results

Estimated Aquifer Depths and Thicknesses from Vertical Electrical Sounding

After data collection of Vertical Electrical Sounding and plotting, the output from the plotting produced a graph that determines the number of layers, their depths, thicknesses, and respective resistivity. The geologic section for the sounding locations shows three to four geologic layers. Low resistivity values indicate presence of aquifer whereas, sharp increase in the resistivity values indicate absence of aquifer, thus making it a fresh basement. In extracting the layer information for aquifer in the study area, the resistivity values were carefully observed. Mijili, ShuwaKala'a, Uba, HildiDzakwa, MarabanMubi, Gashala, Makera, Gartsanu, Kubutava, Washim, Mojili, Zangula, Hosere, Puba, Shashau, WuroBoki, Zah, Pupanda, Fafaponja, Ndabanza, Garaha, Mugwalar and Kwambla indicated four (4) distinct geologic layers. The third layer is the aquifer unit with resistivity values that ranges from 10.0Ωm to 813.48Ωm, but a sharp increase was noticed in the fourth layer with resistivity that ranges from 208.01Ωm to 13018.0Ωm thus making it a fresh basement, therefore, the region between third and fourth layer is the aquifer unit.

Similarly, Dulmu, Fadama Rake, Kwakwah, Hildi, Kala'a, Hong, Dagza, Fachi, Garare, Mile 7, Ngalbi Pella, Uding, Zum, WuroBiriji, Maksha, Fa'a and Maki show three (3) distinct layers. The second layer is the aquifer unit of the area with low resistivity values that ranges from 22.097Ωm to 224.09Ωm, but a sharp increase was noticed in the third layer with resistivity that ranges from 174.97Ωm to 4202.4Ωm indicating absence of aquifer (fresh basement), therefore, the region between second and third layer is the aquifer unit. The areas that constitute optimum groundwater potential are Dulmu, FadamaRake, Kwakwa'ah, Hildi, Kala'a, Hong, Dagza, Fachi, Mile 7, Ngalbi, Uding, Zum and Fa'a with resistivity of 22.183Ωm to 94. 067Ωm.Garare Zum, Wuro Biriji and Maki constitute areas with medium aquifer condition with resistivity values of 113.03Ωm and 229.37Ωm.

Table 1: Summary of Measured Vertical Electrical Sounding (VES) Parameters of the Study Area

SN	Sample Location	Lat.	Long.	Res. 1	Res. 2	Res. 3	Res. 4	Aquifer Thickness (m)	Aquifer Depth (m)
1	Mijili	10.3425	12.9783	194.77	42.699	167.58	3131.7	40.374	53.603
2	ShuwaKala'a	10.2561	13.043	165.02	32.519	206.04	1679.4	46.964	53.481
3	Uba	10.4589	13.2219	50.396	120.25	39.751	208.42	39.94	43.855
4	Dzakwa	10.3562	13.159	79.727	40.226	97.409	6852.4	44.776	51.543
5	MararabanMubi	10.3112	13.1827	229.51	122.12	63.303	8928.9	16.67	22.111
6	Gashala	10.365	13.094	476.43	112.65	85.349	9093.3	32.655	39.12
7	Makera	10.284	13.068	370.26	101.86	83.253	4293.4	26.670	32.464
8	Gartsanu	10.407	12.973	144.7	41.918	128.94	12674.0	41.983	52.942
9	Kubutava	10.352	12.893	132.08	75.055	184.78	1147.3	20.634	27.166
10	Washim	10.45	12.691	17.492	57.487	532.81	954.58	37.695	48.953
11	Mojili	10.378	12.858	313.91	198.14	513.21	2907.8	21.706	28.153
12	Zangula	10.305	12.766	40.829	71.613	154.05	696.9	18.027	25.428
13	Hosere	10.265	13.175	482.22	156.03	127.53	13018	27.981	31.779
14	Puba	10.487	12.822	31.845	72.784	496.46	810.87	39.341	52.932
15	Shashau	10.329	12.844	36.167	69.758	414.7	794.19	42.712	54.68
16	WuroBoki	10.186	12.887	211.66	44.048	241.30	1677.7	56.446	69.791
17	Zah	10.392	12.747	39.528	79.632	471.16	762.67	39.899	53.958
18	Pupanda	10.286	12.896	7.19	12.612	10	7311.4	23.643	32.559
19	Fafaponja	10.448	12.792	392.00	328.10	849.31	4754.6	19.890	26.676
20	Ndabanza	10.28	12.845	206.77	172.47	794.55	3316.4	41.638	52.709
21	Garaha	10.407	12.893	446.77	229.71	566.32	3581.4	20.901	27.557
22	Mugwalar	10.392	12.914	298.07	133.03	329.02	2102.9	21.269	28.295
23	Kwambla	10.271	13.093	361.11	92.215	75.162	9003.3	25.630	31.117
24	Dulmu	10.428	13.047	130.02	66.336	706.56	-	14.457	15.838
25	Fadama Rake	10.226	12.984	88.796	29.972	2967.3	-	22.086	24.498
26	Kwakwa'ah	10.183	13.046	579.33	94.067	282.98	-	48.396	53.259
27	Hildi	10.3997	13.1827	216.12	57.839	555.58	-	19.119	21.199
28	Kala'a	10.2543	13.031	1208	71.935	5859.3	-	43.691	44.537
29	Hong	10.2329	12.9359	33.122	22.183	2196.1	-	20.747	21.961
30	Dagza	10.15	13.01	1191.2	70.340	5400.7	-	42.868	43.741
31	Fachi	10.149	12.791	84.084	30.248	1191.2	-	23.270	25.570
32	GarareZum	10.11	12.96	824.86	229.37	1373.6	-	28.236	32.659
33	Mile 7	10.1783	12.8211	239.88	61.249	175.1	-	30.104	31.11
34	Ngalbi	10.1775	12.9178	282.47	41.507	4202.4	-	27.038	30.629
35	Uding	10.1559	12.9101	59.21	73.797	667.05	-	17.358	20.365
36	Zum	10.2	12.9	262.5	31.304	3227.0	-	25.221	28.72
37	WuroBiriji	10.057	12.986	362.55	113.03	696.95	-	21.834	26.408
38	Maksha	10.114	12.879	492.04	170.92	1078.5	-	19.054	23.572
39	Fa'a	10.468	12.983	199.46	88.805	1007.3	-	15.451	16.56
40	Maki	10.38	13.042	365.54	123.23	1610.7	-	23.044	24.256

Comparison of statistical results of estimated aquifer depths and thicknesses

In this research, Universal Kriging circular model produced a map (Figure 4) and performed best for aquifer depth estimation because of the strong relationship between Root Mean Square Error and the Average Standard Errors as seen in the statistical table (Table 2) and graph of linear relationship (Figure 2), The result of the statistics for estimated aquifer depth estimation is in agreement with the work of Partha and Jyotiprava (2017) and Hassan (2018). While Ordinary Kriging exponential model produced a map for estimated aquifer depth (Figure 5) and it performed best because ASE and RMSE are closely related (table 3) and Figure (3). The statistics result for aquifer thickness is in agreement with Yao *et al.* (2014).

Table 2: Cross Validation Table (Statistics) for Estimated Aquifer Depths

Models	**Kriging Estimators**	**Mean Error**	**Root Mean Square Error**	**Mean Standardized Error**	**Root Mean Square Standardized**	**Average standard Error**
Circular	Simple	-0.007	13.755	-0.031	1.075	12.95
	Universal	**-1.509**	**14.397**	**-0.164**	**1.116**	**14.53**
	Ordinary	0.094	13.473	-0.017	0.988	14.06
Exponential	Simple	-0.007	13.755	-0.031	1.075	12.95
	Universal	-1.51	14.377	-0.163	1.11	14.6
	Ordinary	0.079	13.508	-0.019	0.996	14.02
Gaussian	Simple	-0.007	13.755	-0.031	1.075	12.95
	Universal	-1.516	14.386	-0.164	1.112	14.58
	Ordinary	0.092	13.477	-0.017	0.989	14.05
Spherical	Simple	0.228	13.73	-0.014	1.038	13.5
	Universal	-1.511	14.388	-0.164	1.113	14.58
	Ordinary	0.094	13.473	-0.017	0.988	14.06

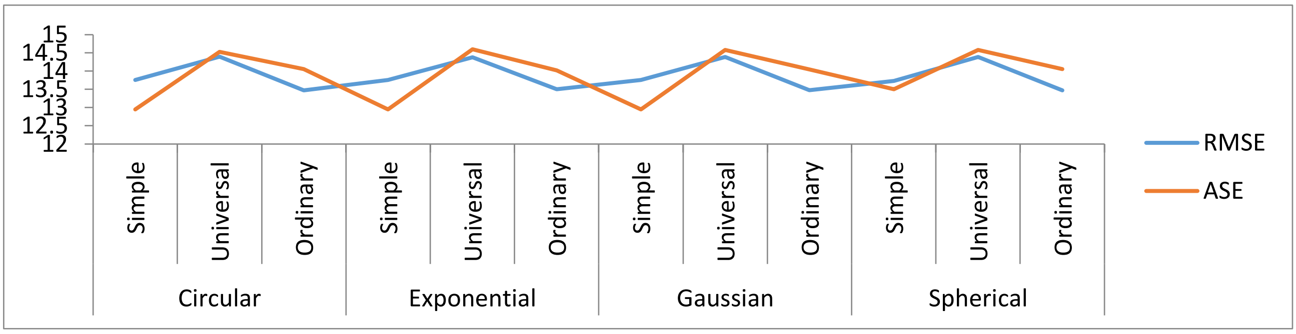

Figure 2: Relationship between Root Mean Square Error with Average Standard Error for Aquifer Depths

Table 5.2: Cross Validation Table (Statistics) for Estimated Aquifer Thicknesses

Models	Kriging Estimators	Mean Error	Root Mean Square Error	Mean Standardized Error	Root Mean Square Standardized	Average standard Error
Circular	Simple	0.045	11.28	-0.027	1.068	10.69
	Universal	-1.396	11.831	-0.172	1.103	11.54
	Ordinary	-0.093	11.153	-0.037	1.016	11.25
Exponential	Simple	0.122	11.223	-0.019	1.058	10.76
	Universal	-1.397	11.821	-0.172	1.097	11.59
	Ordinary	**-0.097**	**11.149**	**-0.037**	**1.018**	**11.24**
Gaussian	Simple	0.041	11.284	-0.027	1.069	10.69
	Universal	-1.405	11.832	-0.172	1.1	11.57
	Ordinary	-0.091	11.147	-0.036	1.014	11.26

Spherical	Simple	-1.396	11.831	-0.172	1.101	11.56
	Universal	0.095	11.219	-0.022	1.06	10.73
	Ordinary	-0.088	11.138	-0.036	1.012	11.27

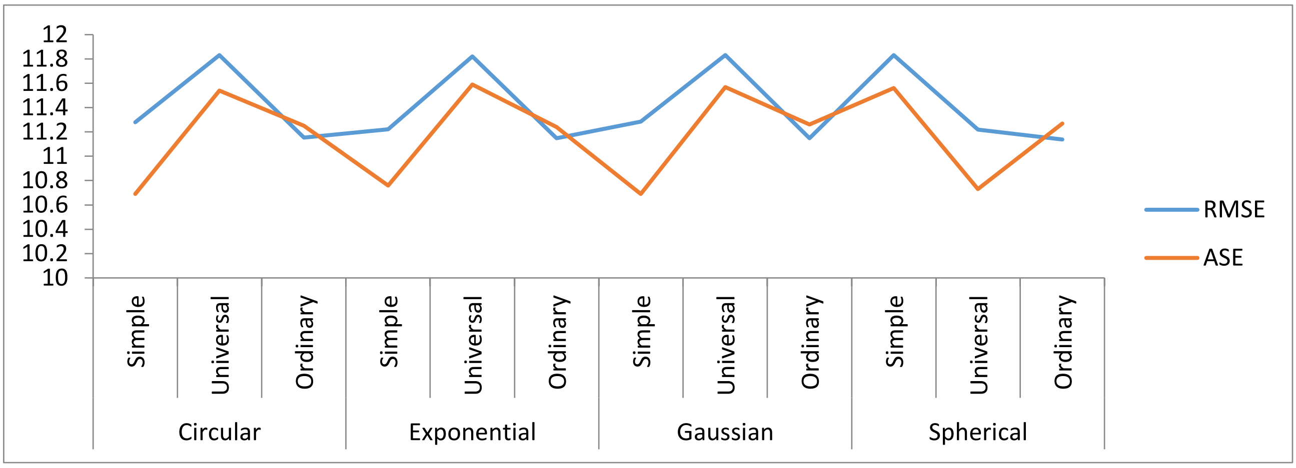

Figure 3: Relationship between Root Mean Square Error with Average Standard Error for Aquifer Thicknesses

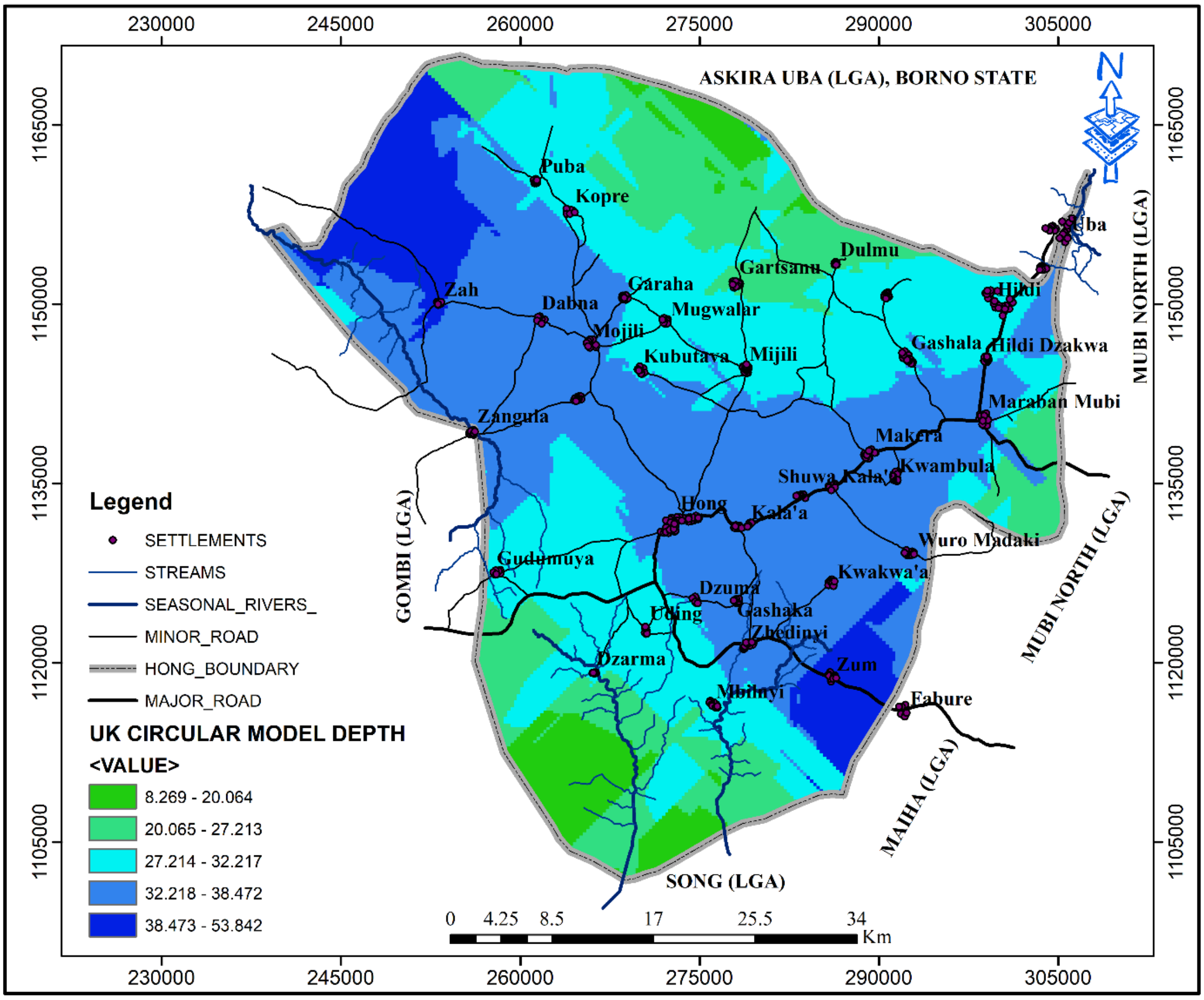

Figure 4: Universal Kriging Circular Model Map of Estimated Aquifer Depths

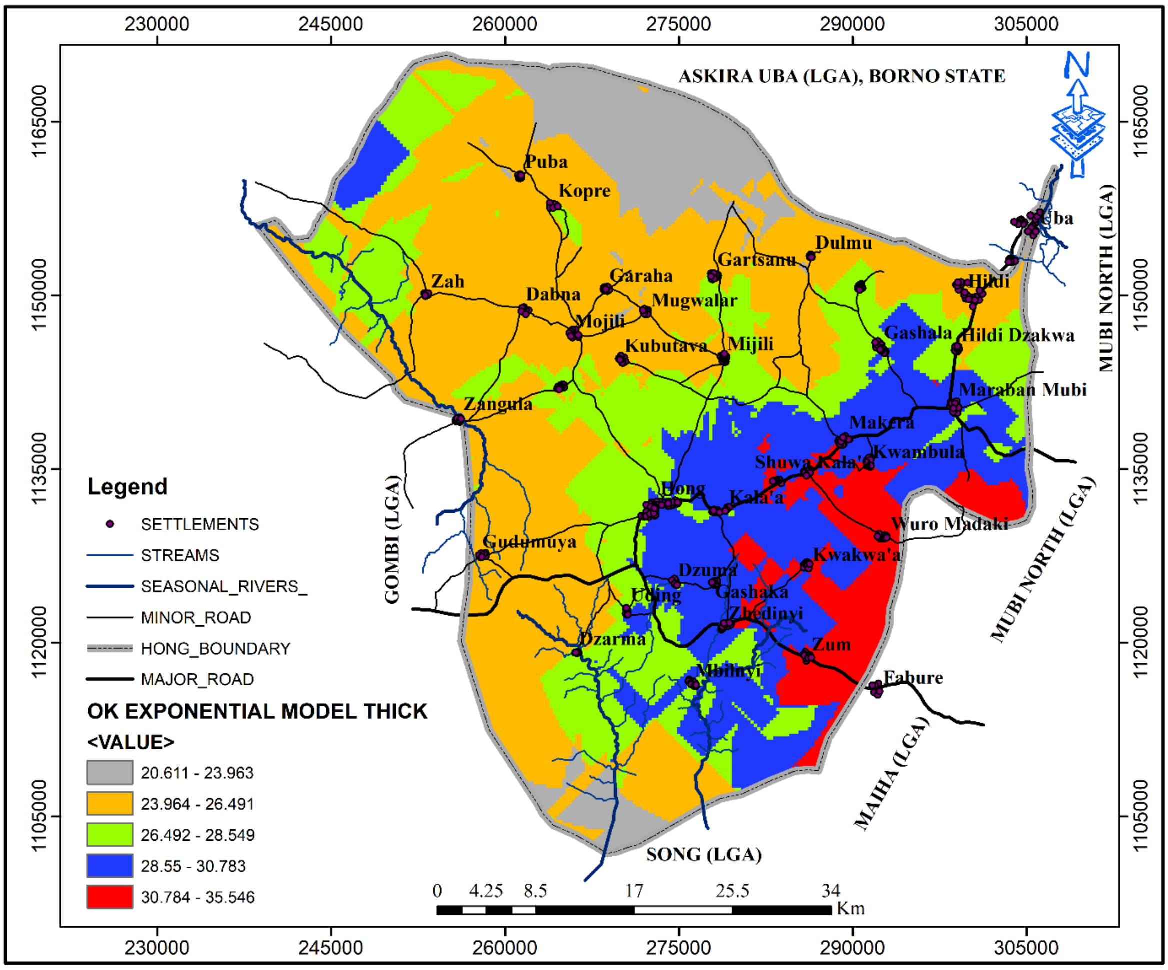

Figure 5: Ordinary Kriging Exponential Model Map of Estimated Aquifer Thicknesses

Confined Aquifers Mapping for Manual Drilling

The results of confined aquifer were obtained in the form of maps. The maps used for identifying area of confined aquifers are the results of the best estimation model for aquifer depths (Universal kriging circular model) and aquifer thickness (Ordinaty Kriging exponential model). Ordinary Kriging was used in identifying confined aquifers, these maps are binary map for aquifer depths (Figure 6) and aquifer thickness (Figure 7). The result of the confined aquifer as obtained from the multiplication of the two binary images is the map showing confined and unconfined aquifer areas (Figure 8).

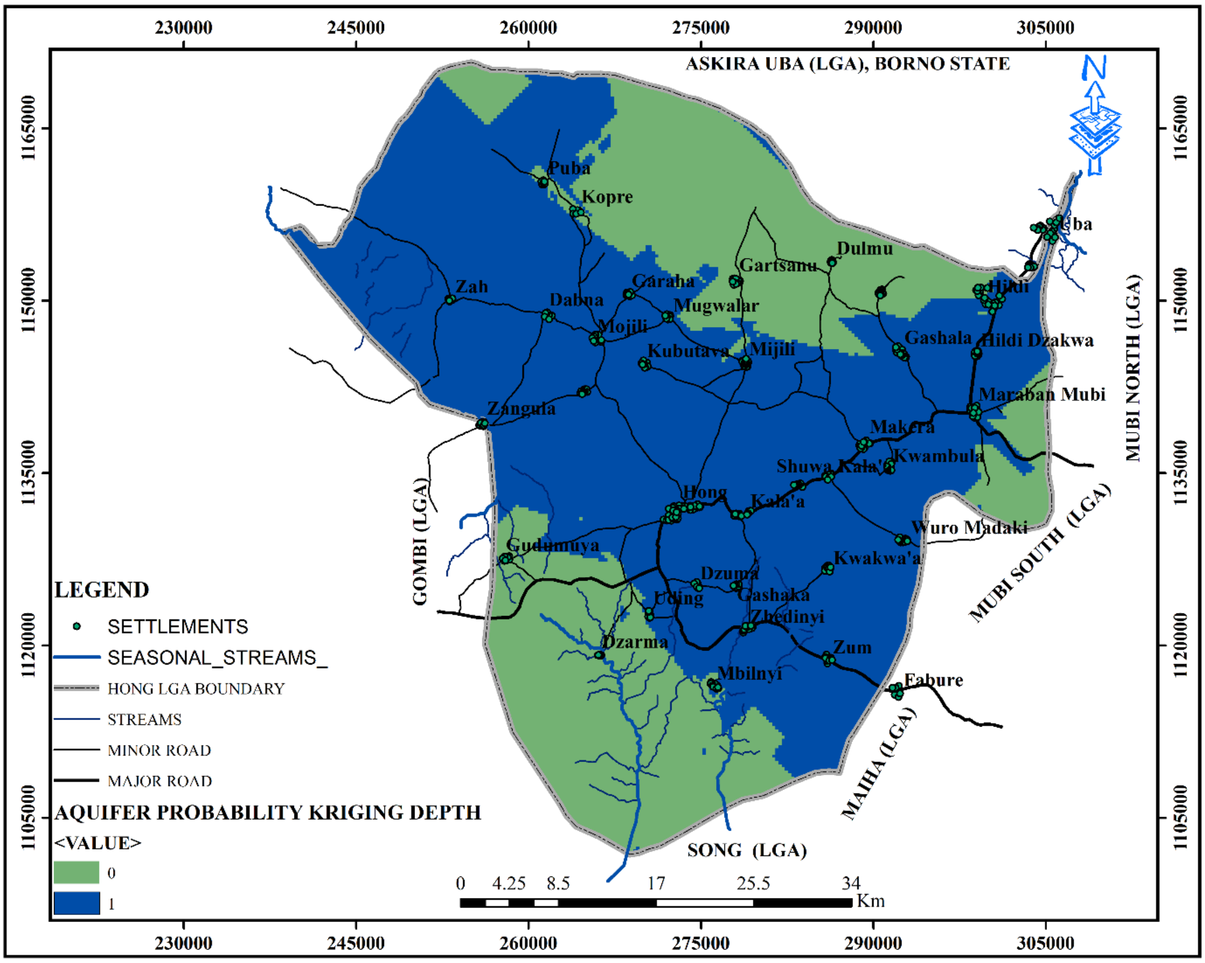

Figure 6: Probability Kriging Map For Aquifer Depths greater than 30 Meters

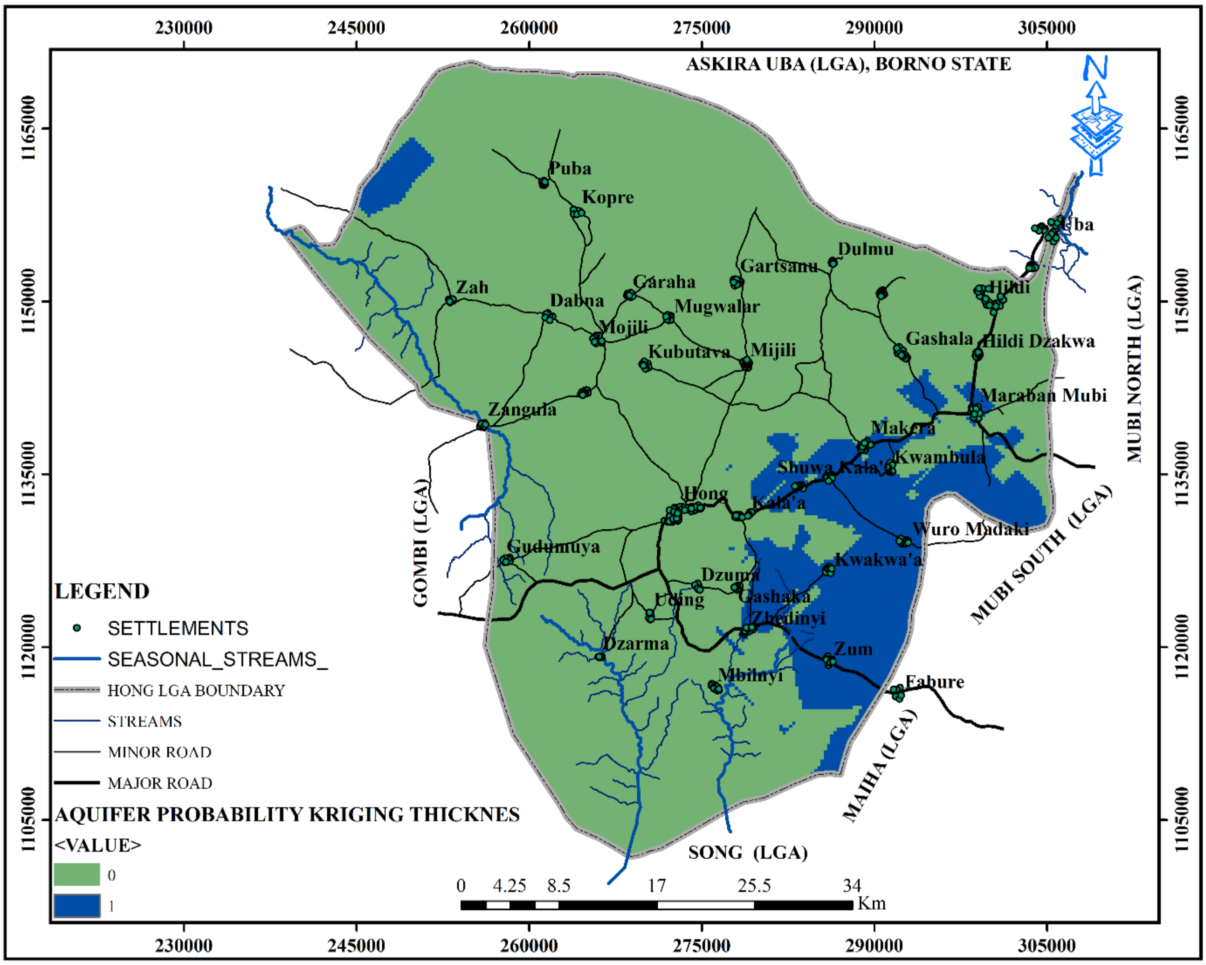

Figure 7: Probability Kriging Map for Aquifer Thicknesses greater than 30 Meters

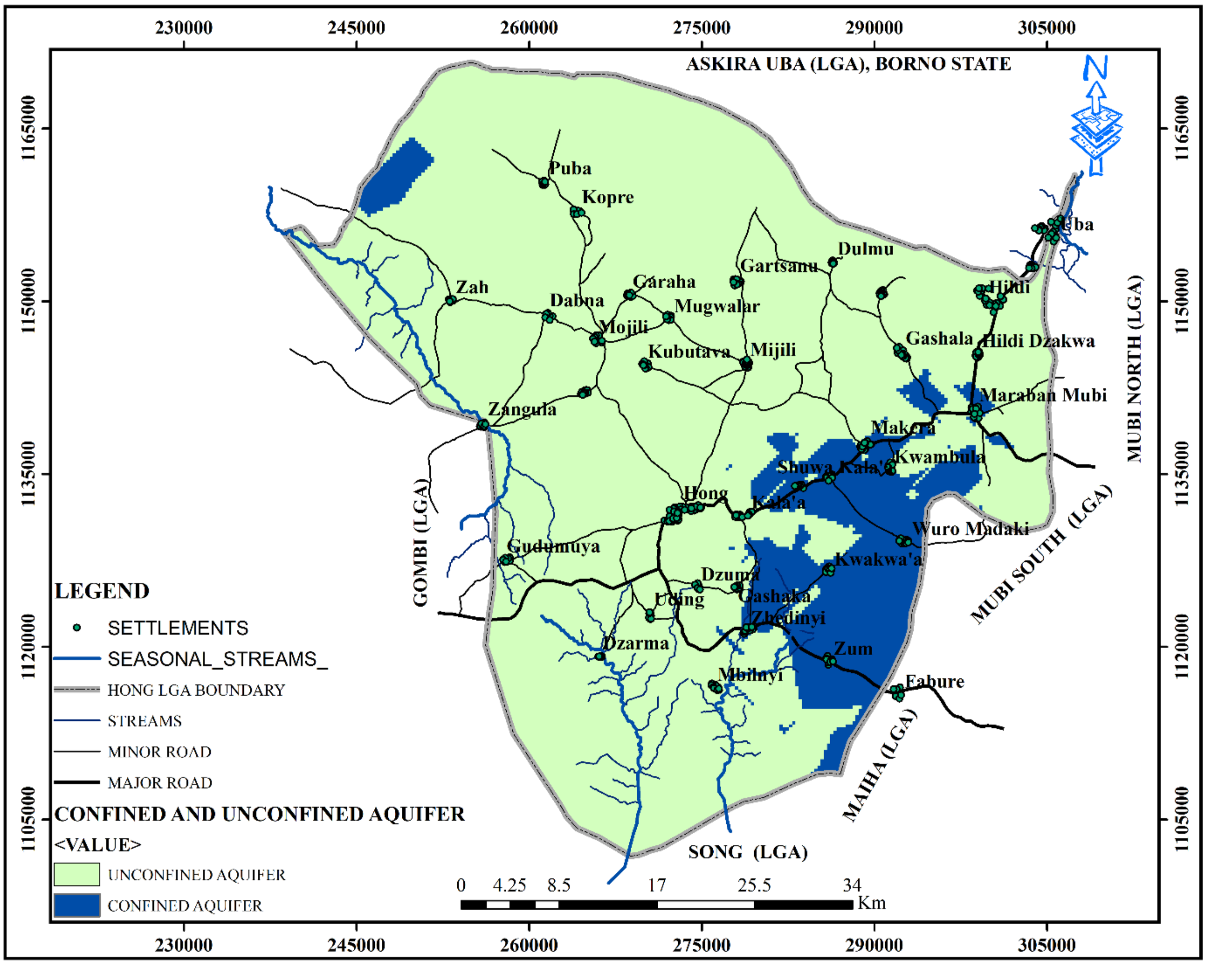

Figure 8: Map of Confined Aquifers for Manual Drilling

For confined aquifers map production for manual drilling, the output from the best Probability Kriging for aquifer depths greater than 30 meters (Figure 6), this indicated that the central part of the study area is deeper compared to other places as indicated in blue colour, the affected areas are villages around Zah, Dabna, Mojili, Zangula, Hong, Kwakwa, ShuwaKala'a, MrarabanMubi, Hildi, Uba, Gashala, Mijili, and Garaha making the area promising for manual drilling while the northern and southern part has a depth less than 30 meter, they are shallower. The affected areas are Dulmu, Gartsanu, Mugwalar, Kopre and Dzarma. The Probability Kriging map for aquifer thickness greater than 30 meters (Figure 7) indicated that it is the thickest and has the potential of manual drilling, these affect mostly the Eastern part of the study area, the areas affected are; Dzuma, kwakwa, ShuwaKala'a, Zum, ShuwaKala'a and Gashaka while areas that are un-confined based on the parameter used affect Puba, Kopre, Hildi, Uba, Mijili, Gartsanu, Mugwlar, Garaha, Mojili, Zangula, Zah and Dabna. The final map as obtained from the multiplication of the two probability maps (Probability Kriging) produces a map that shows areas of confined and unconfined aquifer, the confine areas are areas suitable for manual drilling. Places like Dzuma, kwakwa, ShuwaKala'a, Zum, ShuwaKala'a, Makera partly Mararaban Mubi and Gashaka are more confined (Figure 8) and has the potential for manual drilling.

Conclusion

This research estimated the aquifer depths and thicknesses using Vertical Electrical Sounding (VES) and produced the map of estimated aquifer depths and thicknesses using geostatistics methods. The villages around Dzuma, Kwakwa'a, Zum, Shuwa Kala'a, Gashala, Makera and partly Mararaban Mubi are identified as areas of confined aquifers and suitable for manual drilling. This knowledge has improved the ability to understand the hydrogeology of the study area.

Recommendations

Findings from this study revealed that aquifer mapping for water production is an important alternative in boosting water production in the area. It is on this basis that, other geophysical methods of data collection can be adopted in other research and compare results. The mapping approach and techniques used can be applied in other part of the globe. This approach can be used for the exploration of other mineral resources. Assess the performance of probability kriging with other non-parametric Kriging methods in identifying suitable sites for manual drilling.

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