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Modeling Depth as a Constraining Factor for Optimum Groundwater Yield - A case Study

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Abstract

This research work focused on the contribution of depth to the yield of boreholes for water supply project in parts of Fadama Floodplain West Chad Basin, Northeastern Nigeria. An integrated method involving geoelectric and borehole lithological analysis and record of yields and aquifer hydraulic properties from boreholes was employed. Four distinct subsurface geologic layers and corresponding depths were delineated. These included the topsoil, alluvial sand, Chad Formation/weathered column and the bedrock. The thicknesses of the upper three layers were 0.4 – 6.7; 1.6 - 32.2 and 15.9 -168.6 m respectively. The depth to rockheads varied from 18.4 to 175.5 m. The second layer presumably alluvium layer constitutes the main aquifer unit with optimum depth not greater than 30 m. However, within the upper 25 - 30 m, high groundwater yield of between 9 – 13.4 l/s (779.3 – 1163.8 m3/day) with hydraulic conductivity and transmissivity values of 6.7 to 1329.4 m/day and 122.7 to 10427.5 m3/day respectively were obtained. Beyond this depth, yields were wholly retarded between 2.0 l/s (172.8 m3/day) and 6.9 l/s (602.2 m3/day) arising from the significant contribution of the poor hydrogeological materials . It is, therefore, concluded that borehole depth model (25 - 30 m) and not those terminated at rock heads or within bedrock depression zones as in general case gave an optimum groundwater yield with a cumulative discharge capacity greater than 420 l/s (36,288 m3/day) expected from a battery of maximum of 42 boreholes in this part of the Chad Basin.

Keywords: Depth, Contribution, Yield, Borehole, Transmissivity, Permeable, Floodplain.

1. Introduction

In the light of the River Jama'are floodplain water supply project initiated by the Federal Government of Nigeria, a cumulative discharge capacity of 420 l/s (36,288 m^3/day) is required from a field of maximum of 42 boreholes. This requires an average groundwater discharge of 10 l/s (864 m^3/day), but not less than 7.5 l/s (648 m^3/day) for the servicing of the two major towns of Azare and Jama'are, and sub-rural communities in Katagum Local Government Area of Bauchi State, Northeastern Nigeria (Fig. 1). The statistics of the population figure of these communities is very important for the design of water supply scheme since the projected/expected yields are dependent on the population to be serviced. The population growth rate of 2.83% per year per urban area reported by the Central Bank of Nigeria (in its 1999 annual economic report), was adopted for a trial population projection to a period up to year 2015. This enables assumed growth rates of 2% and 1.5% for the period of 2016-2020 and 2021-2030 respectively for the projected population figures of Azare and Jama'are towns and the communities along the pipeline route (Table 1). The floodplain is located between Azare and Jama'are towns, 30 kilometres west of Azare (Figs. 1). The groundwater potential of the floodplain has been recognized for a long time following the initiatives of the FGN, 1978; GSN (1978) and Bauchi State Agriculture Development Project (1988) on Bauchi State Hydrogeology-Hydrogeological unit descriptions by Wardrop Engineering Inc. Winnipeg, Canada based on 1205 boreholes and 234 boreholes constructed under Contract BSADP-6 and BSADP-19 respectively. Site investigation with multiple techniques is key to the construction of depth model. Geophysical methods with borehole lithological investigation are commonly applied (Matheis, 1989; Olayinka and Olorunfemi, 1992; Olorunfemi and Fasuyi, 1991; Mohammed, 2007). Correlation of the geophysical data with the lithological data allows identification of relevant layers of hydrogeological interest and yield compliant. The optimum yield potential of an area can be mapped by using the depth model and knowledge of geological setting.

This paper presents borehole depth model from the outcomes of the two time-variant geophysical investigations and borehole lithological investigation analysis. The earlier geophysical investigation of the study area (Belmont, 2003) delineated seven geoelectrical layers and two aquifer units: upper alluvium and lower weathered/fractured basement aquifers. The result of the geophysical investigation was used to determine borehole optimum drill depths and the

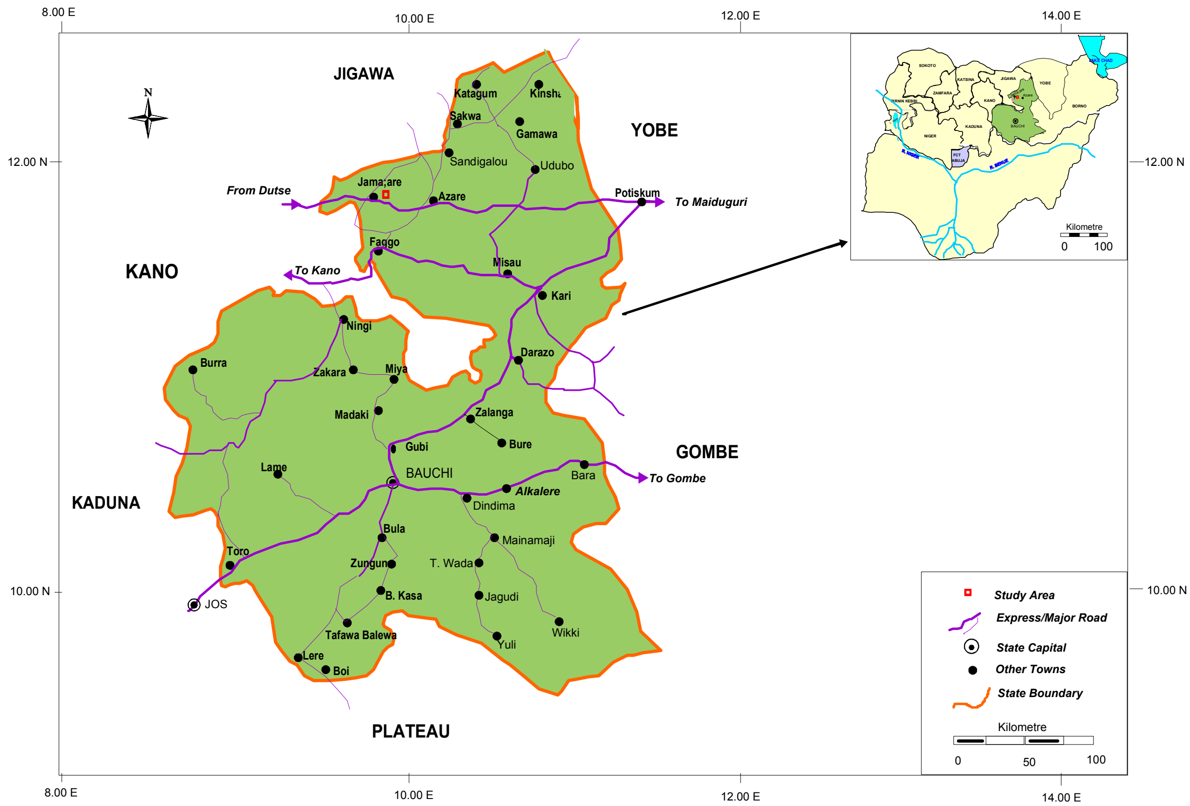

Fig. 1. Map of Bauchi State showing the Study Area

Table 1: Projected population figures of Azare, Jama'are and their regional communities

Year	Azare township	Azare regional communities	Jama'are township	Jama'are regional communities
2000	110, 295	7, 578	39, 042	4, 017
2010	145, 798	10, 018	51, 608	5, 310
2020	185, 077	12, 717	65, 512	6, 740
2030	214, 789	14, 758	76, 029	7, 823

Source: Hadejia Jama'are River Basin Development Authority (2001)

choice of borehole sites (Table 2). A test hole was drilled to depth of 62 m with sustained groundwater yield of 3 l/s (259.2 m^3/day). Eight additional boreholes were drilled, to rock heads or within the basement rock to take advantage of the two aquifer units predicted from the geophysical survey. Discharges from these wells (Table 2), vary from 2 l/s (172.8 m^3/day) to a moderate yield of 6.97 l/s (602.2 m^3/day). These groundwater yield values were considered much less than the expected average of 10 l/s (864 m^3/day) or acceptable minimum of 7.5 l/s (648 m^3/day). The lithological logs obtained from the drilled well in show a sequence of clayey topsoil, silty/fine medium/coarse/gravelly sands and the underlying basement bedrock in most cases, with the sandy columns intercalated with lenses of reddish/pinkish clay as well as plastic clay in most places.

Table 2: Characteristics of Boreholes Completion at Depths

Borehole Code	Borehole location	Geoelectric Depth to Rockhead (m) Belmont (2003)	Static Water Level (m)	Yield (l/s)	: (m^3/day)
Obs.B/H	19	130	3.5	10.0	864
Test B/H	62	130	5.3	3.0	259.2
BH-3	50	120	3.7	5.82	502.85
BH-5	42.8	110	2.7	6.75	583.2
BH-10	45.1	30	3.9	6.97	602.21
BH-32	60	100	2.8	2.4	207.36
BH-41	53.4	125	3.8	2.7	233.28
BH-43	47.4	50	2.2	2.0	172.8
BH-46	53.8	50	2.8	2.5	216
BH-48	57	95	4.9	5.0	432

A correlation of the borehole depths with the groundwater yields for the boreholes shows that groundwater yields in the basin generally decrease with increase in borehole depth (Fig. 2). This observation goes contrary to productivity of aquifers of between 6.7 and 16.7 litres/second recorded in the floodplain area (BSADP, 1988).

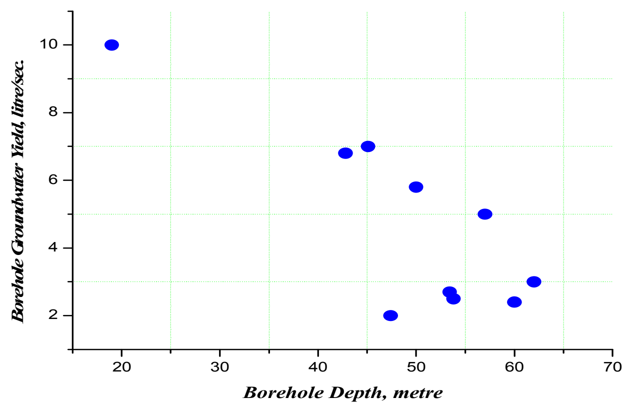

Fig. 2: Borehole Groundwater Yield versus Borehole Depth for Preliminary (trial) Boreholes

2. Geology and Hydrogeology

The study area is underlain by Cretaceous-Tertiary Chad Formation and Recent alluvial Formation of Pleistocene age (BSADP, 1988; Matheis, 1989). The two formations directly rest on the basement bedrock rock. However, rocky hills and inselbergs of the basement rock occur around Geidam, Gumel and Shira, about 30 km southwest of the study area. This suggests that the study area is located within a transitional sedimentary/basement terrain. The major geological features in the area include approximately NW-SE trending geophysically identified suspected deeply buried regional parallel faults/fractured zones in the basement bedrock.

The alluvium deposits with the flood plain consist of silts, clays, and sands, while the Chad Formation is composed of Quaternary sediments of lacustrine origin (Carter et al., 1963). The basis of gravels constitute the main aquifer with which the silts clays the aquitard (GSN, 1978; BSADP, 1988; Matheis, 1989; Offodile, 1992, 2002).

3. Materials and Methods of Study

The data acquisition involved the records of the interpretation results of Schlumberger resistivity soundings, borehole lithological logs, GPS geographic information and record of yields from 41 boreholes and their aquifer hydraulic properties. Apparent resistivity data were collected at 106 stations at selected points and at the vicinity of the existing boreholes (Mohammed 2007). The geographic co-ordinates of each of the sounding/borehole stations were recorded with a GARMIN 12 Channel Personal Navigator (GPS). The geoelectric interpretation results containing the resistivity and thickness and depth to bedrock extracted to aid the characterization of the aquifer system were acquired and used for the analysis. Groundwater yield is often a complex function of aquifer thickness and resistivity thresholds and usually form the basis a rational choice of drill sites may be made as in Table 3 (Mohammed 2007). Forty one boreholes were subsequently drilled via the use of the direct hydraulic rotary drilling technique following the recommendation (Table 3/Figure 3). As the drilling progressed, a careful record or logging (i.e. sampling of bailed out cuttings of the boreholes was kept for various geologic formations encountered at depths. The record of the penetration rate coupled with the physical properties of each formation encountered as drilling progressed enabled proper positioning of the sequence of occurrence of the lithology. This constitutes the borehole lithological log or simply the drillers' log (Fig. 4) that were further used for analysis.

4. Results and Discussion

4.1 Results

Table 3 and Appendix I show the results of the geoelectric survey interpretation recorded from 69 borehole sites. These sites were considered drillable for the overall success of the water supply scheme. The record contains among others the geoelectric parameters (i.e the layer thickness and resistivity) of the two saturated columns- alluvium and clayey Chad Formation and the depth to bedrock.

Figure 4 shows the lithological logs for some of the boreholes drilled.

4.2 Discussion of Results

The lithological logs are characterized by a series of brown to grey fine grained/clayey texture as the topsoil, alluvium, sandy clay/ clay and the basement unit. The observation borehole that gave the maximum yield of 10 l/s (864 m^3/day) was terminated at a shallow depth of 19 m within the upper alluvium aquifer. Borehole (BH 48), 57 m deep gave a yield of 5 l/s (432 m^3/day), transmissivity of 158.1 m^2/day, hydraulic conductivity of 11.1 m^2/day/m and specific capacity of 91.5 m^3/day/m as against a yield of 12.2 l/s (1054.1 m^3/day), transmissivity of 385.8 m^2/day, hydraulic conductivity of 27.2 m^2/day/m and specific capacity of 223.2 m^3/day/m for the same borehole BH-48 which was later backfilled to 32 m deep.

The sustained appreciable groundwater yield (3.0-5.0 litres/seconds or more) of the numerous shallow (not deeper than 7.0 m) tube-wells located within the upper alluvial sand aquifer in the study area over the years indicates that the alluvial sands have potentials for moderate to high groundwater yield. Thus, efforts are concentrated on the thickness of the alluvium and its immediate underlying strata in characterizing the groundwater potential of the site. The yield of boreholes in the present study area probably depends to some extent on the saturated thickness of the alluvium aquifer, its storage and discharge capabilities. Alluvium deposit is generally known for its great storage potential, particularly its gravelly horizons.

Table 3. The selected borehole sites and their geoelectric parameters

S/N	VES Points	Resistivity (ohm-m)		Thickness (m)			Remark/Order of Sites' Priority
		ALV	CCF	ALV	CCF	DTB	
1	5	286	34	9.6	59.6	71	First order
2	6	790/248	33	12.2	76.1	86.8	First order
3	7	297	25	9.3	64.8	77.8	First order
4	10	840	62	9.2	38	48	First order
5	12	460	50	13.7	136.9	152.8	First order
6	26	1168/264	34	11	75	87.4	First order
7	27	280	27	9.9	42.2	52.9	First order
8	30	379	73	11.3	124.4	141.4	First order
9	34	469	27	9.1	59.9	70.2	First order
10	37	2763/84	13	21.8	45.9	74.1	First order
11	51	4067/374	22	12.1	82.1	95.2	First order
12	53	2398/344	17	21.4	37.8	60	First order
13	55	312	24	12.1	61.9	80.2	First order
14	56	441	55	10.1	120.4	133.8	First order
15	57	295	140	13.6	31.4	47.4	First order
16	77	842/312	15	21.8	24	46.5	First order
17	78	475	18	12	33.8	47.1	First order
18	81	252	29	10.5	59.9	72.8	First order
19	87	2106/566	58	15	87.4	103	First order
20	102	335	45	9.1	24.4	38.8	First order
21	104	602	31	28.8	53.4	85.9	First order
22	105	456/257	64	20.6	59	81	First order
23	4	272	27	8.4	76.7	86.4	Second order
24	24	295	51	7.5	44.2	56.4	Second order
25	35	5706/421	56	7.9	101.3	109.7	Second order
26	59	471	33	8.1	39.4	51.6	Second order
27	67	268	55	8	75.4	84.9	Second order
28	3	173	34	14.7	62.5	80.6	Third order
29	8	207	39	14.2	53.8	71.1	Third order
30	9	959/178	41	15.9	45.9	62.4	Third order
31	13	141	40	26.7	63.3	93.4	Third order
32	14	108	36	21	151.6	175	Third order
33	15	119	33	11.7	80.8	95.9	Third order
34	16	95	40	20.1	57.5	79.4	Third order
35	18	110	42	20.5	86.8	108.4	Third order

ALV - Alluvium Layer

CCF - Clayey Chad Formation/Weathered Basement

DTB - Depth to Basement

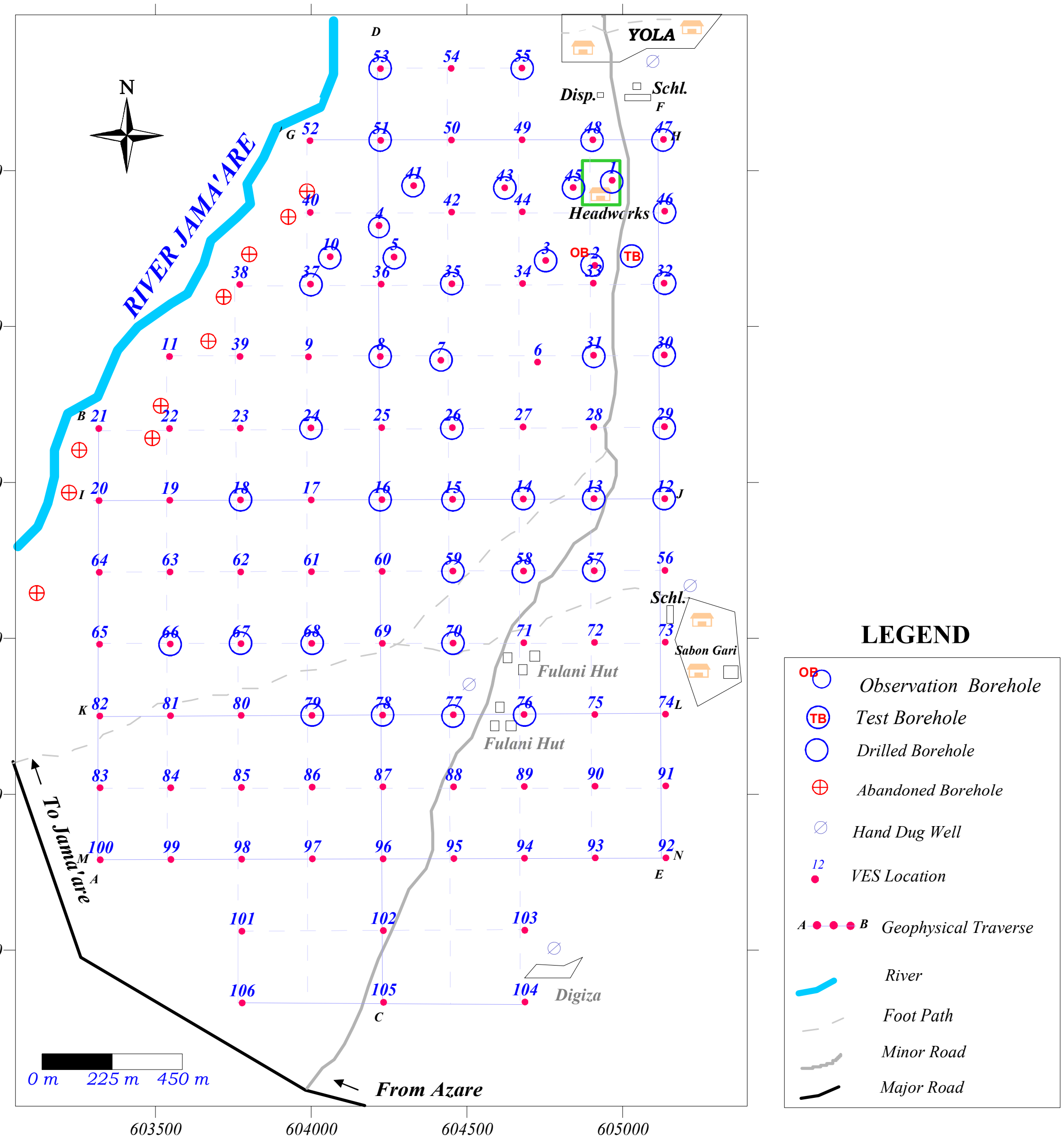

Fig. 3. Map showing locations of the boreholes drilled and completed

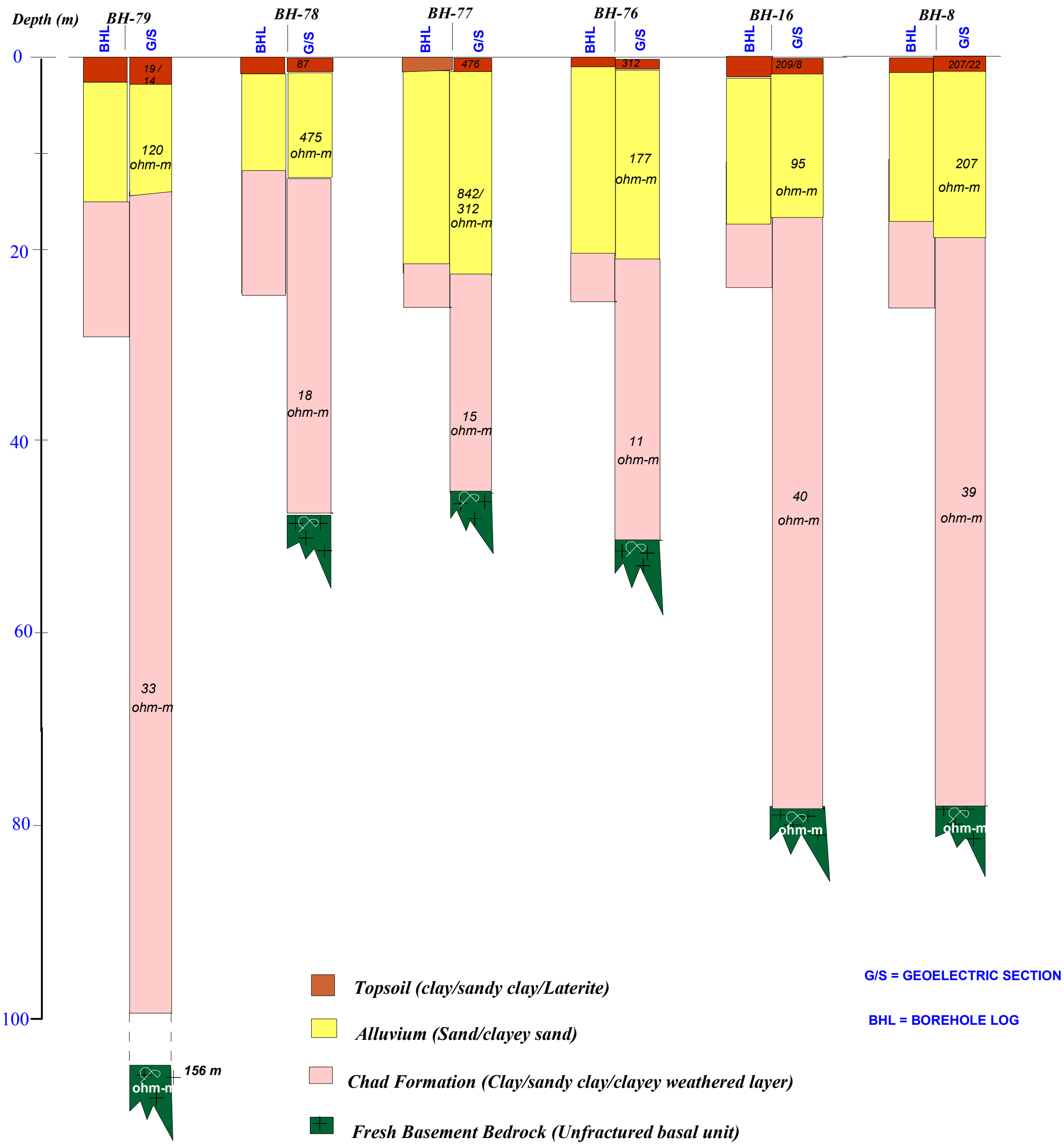

Fig. 4. Lithological logs and geoelectric parameters of some of the boreholes

The clay/sandy clay second layer belongs to the mainly argillaceous clayey Chad Formation. The formation grades into the basal clayey weathered basement layer (Fig. 4/Table 3) with relatively low resistivity values that averaged about 40 ohm-m. The layer matrix is appreciably clayey constituting an impermeable block with tendency for limited or low groundwater yielding capacity, in spite of its significant thicknesses (up to 175 m) within deep basement depressions, in some few areas. This unit as the second aquifer (sometimes interbedded with sand lenses) is a poor aquifer and hence contributes minimally to the overall yield of wells and boreholes in the area.

In the light of the above considerations, the second layer (alluvium) remains the most important aquifer unit with a groundwater potential of medium to high rating based on yields of several shallow tubewells and few test boreholes in the study area. Discharge capacities of between 7.5 and 10.0 l/s have been achieved.

The alluvium unit covers the mean interval of about 3 to 14 m depth. The unit is marked with about 60 – 70 % quartz and is fine-medium grained in most places. The clay/sandy clay unit is found within the interval of about 14 to 78 m which corresponds to the clayey Chad formation/weathered basement column in the basin. The unit consists of interbedding series of thin gravels, sands silts and clays which constitutes. The observation borehole that gave the maximum yield of 10 l/s (864 m^3/day) was terminated at shallow depth (19 m) within the upper alluvium aquifer. It is, therefore, suspected that the upper alluvial deposit may have constituted the major aquifer and the lower clayey Chad Formation / weathered basement aquifer, an aquitard. The field transmissivity values range between 122.7 and 10427.5 m^3/day with the exception of BH-55 with a value of 18783.7 m^2/day. The field hydraulic conductivity (K) values range from 6.7 to 1329.4 m/day. The observation is in agreement with the range of known values of hydraulic conductivity of 2 - 295 gpd/$ft^{2,}$ (8.3 x 10^{-4} - 1.22 x 10^{-3} m/day) and transmissivity of between 12.4 and 12400 m^3/day for unconsolidated sediments as earlier observed by Driscol (1986). The entrance velocities vary between 0.0017 and 0.0075 m/s. These values lie within the recommended value of not greater than 0.03 m/s (Driscol, 1986; Roscoe, 1990). This provides a good measure of the effect of screen slot size on the yield. The results of the study reveal the presence of an extremely poor clay/sandy clay/clayey Chad Formation/weathered aquifer with little transmissive capacity across the study area, which signified a relatively low effective porosity and low permeable environment. No indication of fracturing tendency was observed from the VES curves/results, and hence no fractures occurred through the depths of wells. The permeable (alluvium) zone was found to occur at the top of the clayey Chad Formation/weathered strata, just below the clayey topsoil. This unit may have formed from the meandering stream flow deposition and has constituted the primary sustainable upper aquifer in the area, while directly below is the Chad Formation/weathered aquifer which contributes minimally to the overall success of well yields. The resistivity response of the subsurface geologic units in the area may have depended on the sand to clay ratio and the degree of saturation. The alluvium unit with about 70 % quartz enhances the resistivity values and perhaps hydraulic conductivity and transmissivity better than its immediate underlying clay Chad Formation/weathered unit. Where alluvial sand materials predominate, is characterized by good hydraulic properties. Transmissivity and hydraulic conductivity values obtained from deeper wells were significantly less than those from shallow depths (backfilled). For example, in BH- 48, 57 metres deep, has a yield of 5 l/s (432 m^3/day), transmissivity of 158.1 m^2/day, hydraulic conductivity of 11.1 m^2/day/m and specific capacity of 91.5 m^3/day/m as against a yield of 12.2 l/s (1054.1 m^3/day), transmissivity of 385.8 m^2/day, hydraulic conductivity of 27.2 m^2/day/m and specific capacity of 223.2 m^3/day/m for the shallow (about 32 m deep) backfilled equivalent (Figs. 5 a and b). Information from the results, therefore, showed that the hydraulic conductivity and transmissivity values within the upper 25 - 30 m are enhanced and thus suggest zone of good infiltration coefficient and hydraulic conductivity. However, beyond this depth, the deposits become more clayey matrixed and yields are wholly retarded arising from the significant contribution of the thick clay matrix. However, no sand more permeable than alluvium was found beyond a depth of 25 - 30 m. It is, therefore, suggested that an optimum borehole depth of 25 - 30 m below ground level is recommended for this part of the Chad Basin.

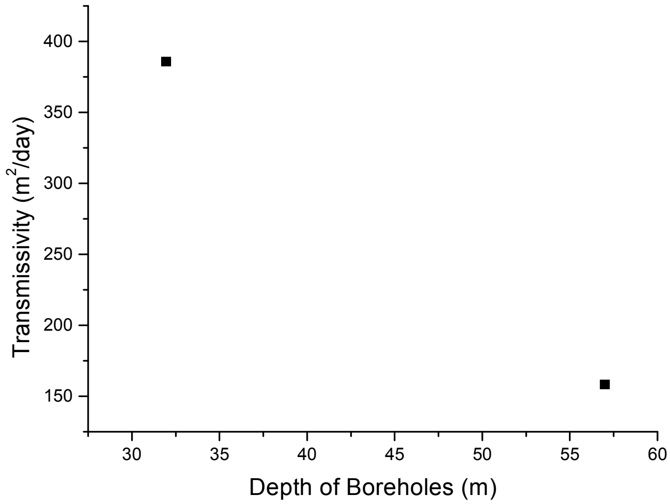

Fig. 5.a: Variation of Transmissivity with Borehole Depth for Borehole BH-48

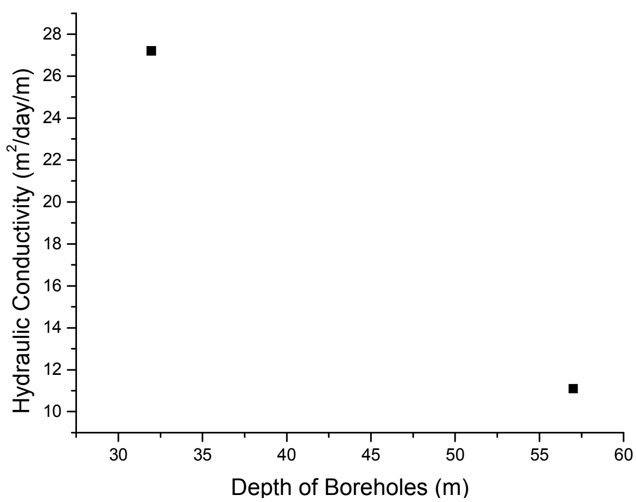

Fig. 5 b: Variation of Hydraulic Conductivity with Borehole Depth for Borehole BH-48

5. Conclusion and Recommedation

5.1 Conclusion

It can thus be concluded that groundwater yield is generally high when the depth of the abstraction boreholes is kept within the upper alluvial deposit or generally not deeper than 25 – 30 m. Deeper boreholes give characteristically lower groundwater yield due to low transmissivity and hydraulic conductivity of the basal clayey Chad Formation/weathered basement.

5.2 Recommendation

The challenges of long-term safe rate of abstraction vis-à-vis ever changing climatic factors are important considerations in groundwater development in any parts of the basin. The quantity of water available from an aquifer depends on the amount of natural recharge, the rate of abstraction and the underground storage available. It is, therefore, recommended that further study be carried out to assess the prospectivity of the interbedded thin sandy layers or lenses within the clayey Chad Formation/weathered basement layer at depth greater than 35 m for any contribution to the volume of the underground storage. Geophysical borehole (resistivity) logging tool can be used in such a study. Moreover, the degree of hydraulic connectivity between the aquifer and the underlying aquitard may further be investigated since few shallow wells seemed to have intersected the underlying aquitard even at depth model 25 – 30 m and or beyond. The long-term safe rate of abstraction should be determined from a combination of hydro meteorological (water budget studies/river hydrographic analysis) and modeling techniques to assess annual volume of groundwater recharge and perennial yield of aquifers/wells and/or the average value of long-term yield. Finally, the methodology employed in this study has proven to enhance our understanding of the area and the methodology be routinely employed to other parts of the basin and areas with similar geological settings.

Acknowledgements

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Acknowledgements

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Appendix I. The selected borehole sites and their geoelectric parameters

S/N	VES Points	Resistivity (ohm-m)		Thickness (m)			Remark/Order of Sites' Priority
		ALV	CCF	ALV	CCF	DTB	
36	19	125	50	21.3	112.9	136.3	Third order
37	21	1313/172	33	19.2	71.8	91.4	Third order
38	29	242	44	15	117.4	134.7	Third order
39	43	180	12	16.4	30.9	50.1	Third order
40	44	113	40	11.7	70.4	87.1	Third order
41	47	156	29	23.9	43.9	71	Third order
42	52	105	24	13.6	116	133.1	Third order
43	58	136	46	32.2	100.4	137.4	Third order
44	65	150	27	16.9	33.9	60	Third order
45	68	127	44	10	68.7	83.3	Third order
46	70	189	30	13.4	61.5	77.6	Third order
47	76	1436/177	11	14.7	27.3	45	Third order
48	79	120	33	14.1	138.9	156.3	Third order
49	84	128	15	11.5	29.4	44.6	Third order
50	85	122	38	15.4	48.7	67.6	Third order
51	90	673/153	35	29.9	74.9	106.5	Third order
52	93	106	25	10.1	79.7	96.5	Third order
53	95	223/232	75	16.2	138.2	154.8	Third order
54	96	293/175	16	23.8	34.1	58.7	Third order
55	98	216	47	10.8	95.4	108	Third order
56	99	74	12	12.5	29.9	60.8	Third order
57	103	92	33	14	36	56	Third order
58	106	145	37	17	39.2	58.5	Third order
59	31	779	34	3.5	168.6	174.1	Wildcat
60	40	614	74	5.3	87.2	94.4	Wildcat
61	46	430	19	4.2	44.7	53.8	Wildcat
62	48	437	50	4.2	39.6	46	Wildcat
63	49	312	31	5.7	47.8	56	Wildcat
64	62	228	46	8.9	34.2	44.5	Wildcat
65	66	415	21	3.7	32.4	38.5	Wildcat
66	69	212	43	8.1	57.9	70.9	Wildcat
67	82	822	60	5.1	95.8	101.9	Wildcat
68	88	724	32	7.3	43.1	52	Wildcat
69	89	304	28	5.4	61.7	70.1	Wildcat

ALV - Alluvium Layer

CCF - Clayey Chad Formation/Weathered Basement

DTB - Depth to Basement