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Determination of Aquifer Hydraulic and Statistical Parameters Using Granulometric Method in Yenagoa, Southern Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors. Author GCG designed the study, performed the statistical analysis, wrote the protocol and first draft of the manuscript. Author OAO managed the analyses of the study and the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

Grain-size analysis of aquifer sand samples from Yenagoa was carried out by the mechanical sieving technique. Using the grain-size analysis curves, mean representative grain diameters d_{10} and d_{60} were determined and porosity was derived from the empirical relationship between porosity and grain uniformity (η). From determined porosity values, hydraulic conductivity was computed using Kozeny-Carman and Hazen equations. The result showed that porosity ranged between 0.41 - 0.45, while the hydraulic conductivity (k) values ranged from 8×10^{-4} m/s to 4×10^{-3} m/s and 6×10^{-4} m/s to 4×10^{-3} m/s respectively in the area. The high porosity and hydraulic conductivity values were consistent with aquifer characteristics of unconsolidated fine to medium coarse coastal sands.

Keywords: Grain size analysis; porosity; hydraulic conductivity; kozeny-carman; Hazen; Yenagoa.

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1. INTRODUCTION

Potable water is a basic necessity of life, mans continued existence depends to a large extent on its availability. Increased economic activities in Yenagoa the capital city of Bayelsa State has caused a geometric increase in population over the past two decades, the inability of government to develop new water infrastructure has led to shortages in supply of potable water to the populace. The healthy alternative to surface water bodies which are mostly contaminated by poor waste management practices and other environmental vices in the area is underground water, sourced by swallow boreholes. Groundwater quality depends on factors like the local geology, degree of chemical weathering of rocks, chemistry of recharge water, rock water interactions amongst other geochemical processes. Indiscriminate boreholes have been drilled across the city of Yenagoa to meet domestic and industrial needs for water, also several hydrochemical investigations have been carried out by researchers to ascertain the potability of groundwater in the Niger Delta [1,2,3,4], despite all these, there has been no detailed study of the aquifer system in terms of its hydraulic characteristics. Effective planning and management of groundwater resource requires fore knowledge of the aquifer properties like transmissivity (T), storativity (S), porosity (ϕ) and hydraulic conductivity (K) which controls groundwater flow and transport [5]. The conventional methods for determining aquifer parameters is by Pumping Test [6,7] and more recently by geoelectric investigation [8,9], which is non-unique and represent macroscopic averages over large volumes of the pore medium. It is difficult to accurately characterize subsurface aquifer properties using only information obtained from widely spaced boreholes. A more complete and accurate characterization of aquifer parameters can be achieved using integrated borehole, geologic and geophysical data.

This research investigates the aquifer properties (porosity and hydraulic conductivity) of unconsolidated soils obtained from boreholes in Yenagoa and environs using grain size analysis. This technique is cost-effective and reliable, results obtained can be used to improve the quality of groundwater flow simulation models in the area.

1.1 Geology and Description of Study Area

The study area falls into the coastal sedimentary Niger Delta Basin. It lies within Latitudes 04°23.3′ and 04°38.2′North and Longitudes 006°05′ and 006°40′East. It is a typical deltaic plain with flat topography. It is accessed by a network of major and minor roads and drained by tributaries of the River Nun and several creeks including the Kolo and Epie. The low lying alluvial plains are characterised by a rain forest vegetation, the economic activities of the locals in the area is primarily farming and fishing. The Niger Delta is a complex prolific basin formed by an extensional rift system in the Niger Delta and Gulf of Guinea, on a passive continental margin near the west coast of Nigeria between latitudes 3°N and 6°N and longitudes 5°E and 8°E [10], It is one of the largest sub areal basins in Africa with an expanse of about 75,000 km, a total area of 300,000 sqkm, sediment fill of up to 500,000 cubic km and a sediment fill of 9–12 km [11]. The Niger Delta is bound on the Northwest by a subsurface continuation of the Benin flank, on the East by the Calabar flank and to the South by the Oban Masif [12]. The major lithostratigraphic units observed on a well section through the Niger Delta consist of an upper delta top facies, a middle delta front lithofacies and a lower pro-delta lithofacies [10].The lithostratigraphic units correspond respectively with the uppermost Benin Formation aged Oligocene to recent, the Agbada Formation which lies beneath the Benin Formation aged Eocene to recent and the lowest lying Akata Formation aged Paleocene to recent [13]. The Akata Formation is composed mainly of marine shales with sandy and silty beds which are believed to have been laid down as turbidites and continental slope fills with an estimated thickness of 7,000 m. The Agbada Formation which the petroleum bearing unit in the Niger Delta, consists mostly of shore face and channel sands with minor shales in the upper parts and an intercalation of sands and shales in equal proportion in the lower parts, with a thickness of over 3,700 m [14]. The Benin Formation consisting of continental sands and gravels is about 280 m thick and maybe up to 2,100 m in the region of maximum subsidence [15]. This is the aquiferous unit in the Niger Delta.

2. MATERIALS AND METHODS

Grain size analysis which involves the study of the sizes of aquifer soil samples, was used

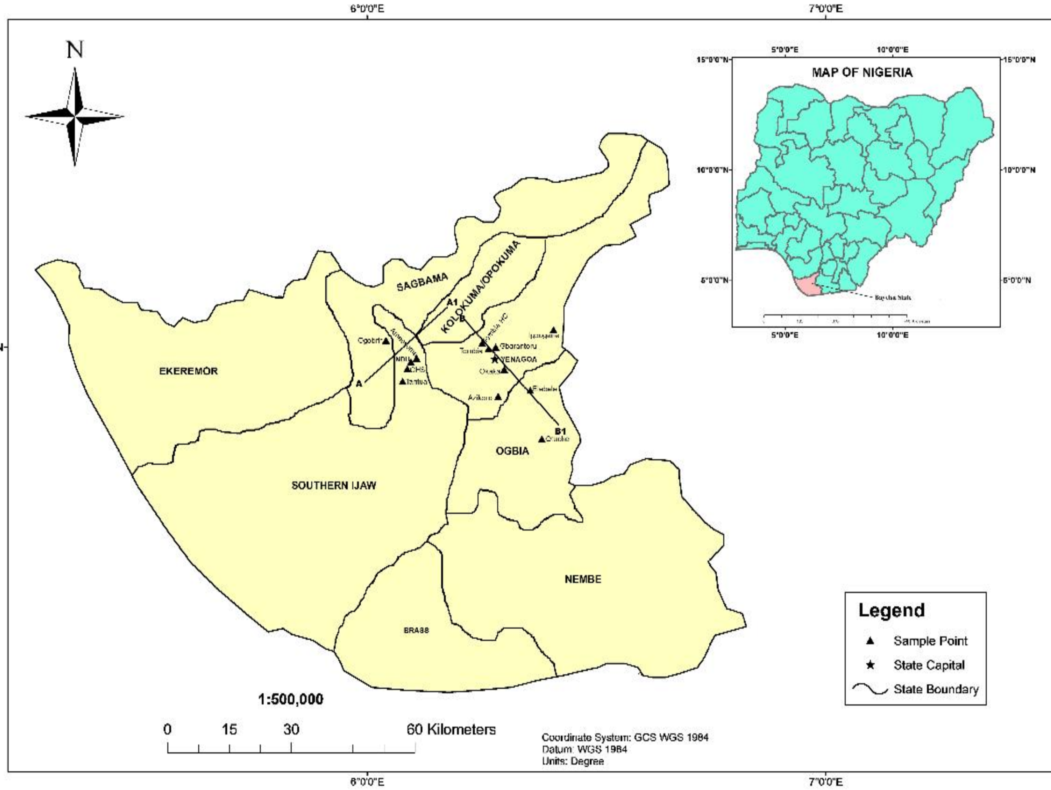

Fig. 1. Map of the study area

in also determining aquifer hydraulic parameter at some wells. The aquifer hydraulic parameters include; porosity and hydraulic conductivity.

2.1 Sample Collection

Soil samples from the aquifer layer were collected from nine (9) wells during drilling, each located within the study area. The samples were dried, and analysed for grain-size distribution, this was done to determine the percentage of different sizes of grains contained in each sample. Mechanical sieving analysis was done to determine the variation of grains with respect to specific diameters of mesh. The apparatus used included a scale balance, set of sieves, cleaning brush, sieve shaker, mixer, control cylinder, thermometer, beaker and timer.

2.2 Dry Sieve Technique

1 The weight of each sieve as well as the bottom plate used in the analysis was recorded
2 The weight of the dry sample was recorded.
3 The sieves were cleaned and assembled in ascending order (sieve #4 top and sieve #200 below) and the pan beneath sieve #200.
4 The sample was carefully poured into the top sieve and the cap placed over it.
5 The sieve stack was placed in the mechanical shaker for 10 minutes.
6 The stack was removed from the shaker and weight of each sieve was recorded. The weight of the bottom pan containing retained fine soil was also recorded.

2.3 Data Analysis

1 The mass of soil retained on each sieve was obtained by subtracting the weight of the empty sieve from the mass of the sieve + retained soil and this was recorded as the weight retained. The sum of the retained masses equalled the initial mass of the soil sample.
2 The percentage retained on each sieve was then computed.
3 A semi-logarithmic plot of grain size against percent fines was then made (Fig. 2).

2.4 Determination of Porosity Using Grain Size Analysis

Porosity represents the non-solid fraction of geologic materials where fluids can be held, the percentage of the volume of pore space to the total volume of rocks include; grains- solids – sediments of sedimentary rocks, fractures, faulty vesicles in volcanic rocks. The porosity of a sedimentary rock depends on the size, shape and arrangement of the material of the composing rock.

Porosity (ϕ) was determined using the [16] relationship.

$$\phi = 0.225 * \left(1 + 0.83^{u}\right) \quad (1)$$

Where u = $\frac{d_{60}}{d_{10}}$ (d_{60} *and* d_{10} the grain diameter in which 60% and 10% of the soil samples are finer, respectively)

2.5 Determination of Hydraulic Conductivity from Grain Size Analysis

Hydraulic conductivity (K) from the grain size analysis was determined using two relations; Kozeny-Carman and Hazen equations, they are two of the most widely accepted and used derivation of hydraulic conductivity as a function of the characteristics of the soil medium. Also the Kozeny-Carman and Hazen equations are employed where the effective grainsize is between 0.1 mm to 3 mm, as such is the case in this research.

Kozeny- Carman equation;

$$K = \left(\frac{g}{v}\right) \times \left(8.3 \times 10^{-3}\right) \times \left[\frac{\phi^3}{(1-\phi)^2}\right] \times d_{10} \quad (2)$$

Hazen equation;

$$K = \left(\frac{g}{v}\right) \times 6 \times 10^{-4} \left(1 + 10\left[\phi - 0.26\right]\right) \times d_{10}^{2} \quad (3)$$

Where g = acceleration due to gravity (9.8 m/s^2), v = kinematic viscosity (0.087m^2/day), d_{10} = grain size diameter of 10%, ϕ = porosity

2.6 Determination of Statistical Parameters

The statistical parameters from the grain size analysis include the mean, sorting, skewness, and kurtosis. These parameters are derived based on the 5th, 16th, 25th, 50th, 75th, 84th and 95th percent from the grainsize curve (Fig. 2).

a) **Graphic mean (*GMz*):** The mean which is the measure of the overall average size giving the optimal value, was determined using the [17] equation as shown below. This method gives appropriate and accurate results.

$$GMz = \frac{\phi 16 + \phi 50 + \phi 84}{3} \quad (4)$$

b) **Graphic sorting (standard deviation) (*GSD*):** This is the measure of the sediment distribution (spread grain distribution). Sorting has been used as one of the most important and useful parameters for grain size distribution because it gives indication of the effectiveness of the depositional medium in separating grains of different classes. The sorting was determined using [17] equation as shown below;

$$GSD = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6} \quad (5)$$

c) **Graphic skewness (*GSK*):** This is the measures of the distribution of the grain size on a cumulative curve. To determine the skewnesss, [17] equation which is displayed below, was applied.

$$GSK = \frac{\phi 84 + \phi 16 - 2\phi 50}{4(\phi 84 - \phi 16)} + \frac{\phi 95 - \phi 5 - 2\phi 50}{2(\phi 95 - \phi 5)} \quad (6)$$

d) **Graphic kurtosis (*KG*):** This measures the ratio of sorting at different parts of the distribution by comparing sorting in the central part of the curve with sorting in the tail. [17] relation was used to achieve this task;

$$KG = \frac{\phi 95 - \phi 5}{2.44\left(\phi 75 - \phi 5\right)} \quad (7)$$

3. RESULTS AND DISCUSSION

3.1 Grain Size Analysis

From the results of the grain size analysis (Table 1), the frequency curve showing a semi-logarithmic plot of Grainsize against Percent fines (Fig. 2a - i) was plotted. From the frequency curve, the percentile values necessary for determining the aquifer hydraulic and statistical parameters were obtained and presented in Table 2.

3.2 Aquifer Hydraulic Parameters Using Grain Size Analysis

The results of the aquifer hydraulic parameters which comprises of porosity (ϕ) determined using Vukovic & Soro relation (Equation 1), hydraulic conductivity (K) using Kozeny-Carman equation (Equation 2) and Hazen equation (Equation 3) respectively, are shown in Table 3.

4. DISCUSSION OF RESULTS

4.1 Statistical Parameters

The statistical parameters which include graphic mean (GMn), graphic sorting or standard deviation (GSD), graphic skewness (GSk) and graphic kurtosis (GKt) were computed and the results are presented in Table 3.

Graphic Mean (*GMn*): The mean size is a function of the size range of available materials and amount of energy impacted to the sediment which depends on current velocity or turbulence of the transporting medium [18]. The average mean value for the grain size distribution within the analysed sediments is 2.24. Graphic mean distribution for these sediments ranges from 0.47 to 3.20 in which, three (3) of the samples are very fine sands (samples 2, 6 and 9), four (4) of the samples are fine sands (samples 1, 3, 7 and 8) and the remaining two (2) are coarse sands (samples 4 and 5). This is indicative of fine sand,

Table 1. Summary result for grain size analysis

Sample-1							
Particle size (mm)	2.00	1.70	1.40	1.00	0.60	0.30	0.15
Percentage passing (%)	92.80	88.92	83.66	71.80	46.75	5.26	0.18
Sample-2							
Particle size (mm)	2.00	1.70	1.40	1.00	0.60	0.30	0.15
Percentage passing (%)	99.62	99.28	99.01	98.31	93.18	23.05	0.32
Sample-3							
Particle size (mm)	2.00	1.70	1.40	1.00	0.60	0.30	0.15
Percentage passing (%)	92.50	83.80	83.60	71.00	44.40	5.60	0.66
Sample-4							
Particle size (mm)	2.00	1.70	1.40	1.00	0.60	0.30	0.15
Percentage passing (%)	86.50	77.30	63.70	39.80	12.50	1.20	0.20
Sample-5							
Particle size (mm)	2.00	1.70	1.40	1.00	0.60	0.30	0.15
Percentage passing (%)	79.20	71.40	61.10	41.40	14.00	0.40	0.06
Sample-6							
Particle size (mm)	2.00	1.70	1.40	1.00	0.60	0.30	0.15
Percentage passing (%)	99.40	98.80	98.10	96.40	90.80	8.80	1.70
Sample-7							
Particle size (mm)	2.00	1.70	1.40	1.00	0.60	0.30	0.15
Percentage passing (%)	98.50	97.50	96.70	92.70	74.90	7.40	0.60
Sample-8							
Particle size (mm)	2.00	1.70	1.40	1.00	0.60	0.30	0.15
Percentage passing (%)	96.50	94.60	91.80	85.10	72.10	20.30	1.10
Sample-9							
Particle size (mm)	2.00	1.70	1.40	1.00	0.60	0.30	0.15
Percentage passing (%)	98.30	97.30	96.00	92.10	80.00	38.80	6.90

thus suggesting that the sediments were deposited under low energy condition, as sediments usually becomes finer with decrease in energy of transporting medium [19].

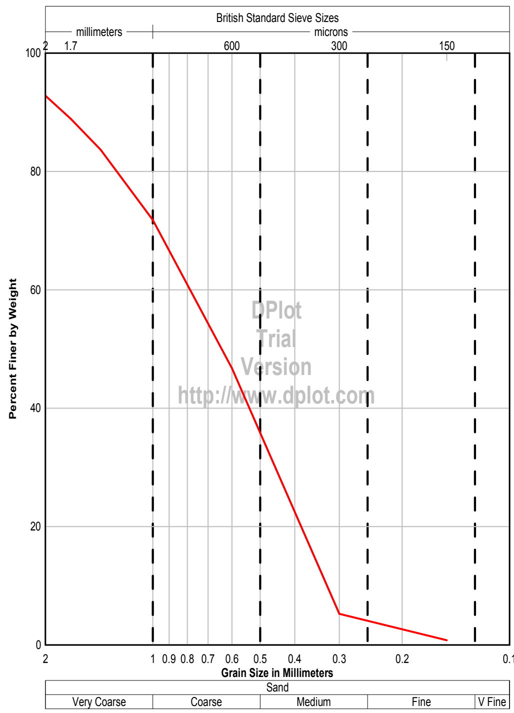

Fig. 2a. Sample 1

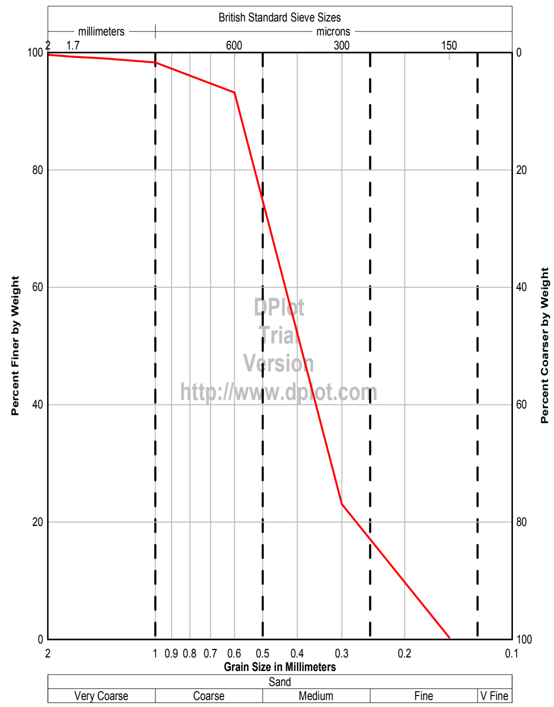

Fig. 2b. Sample 2

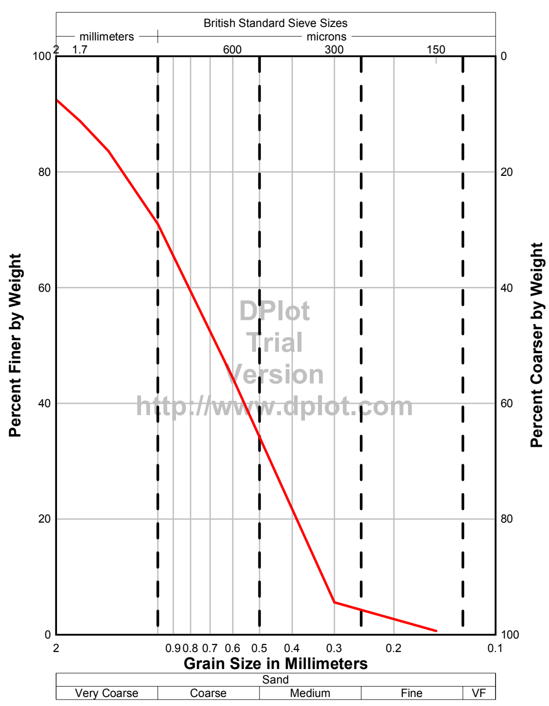

Fig. 2c. Sample 3

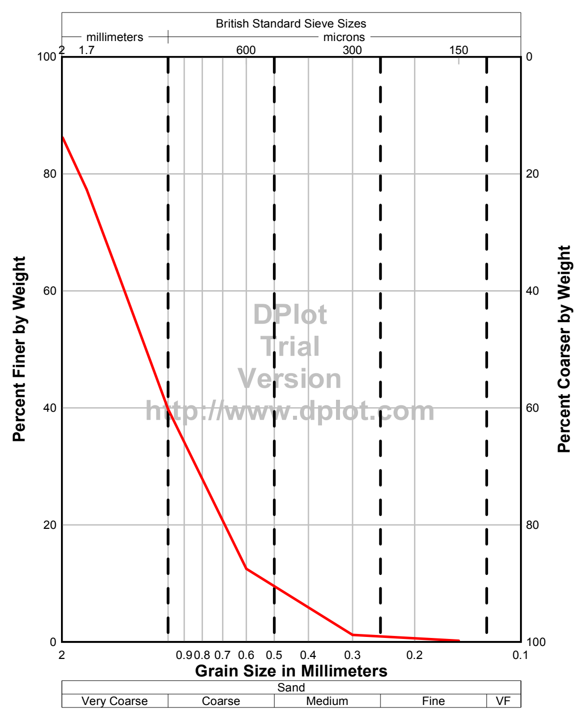

Fig. 2d. Sample 4

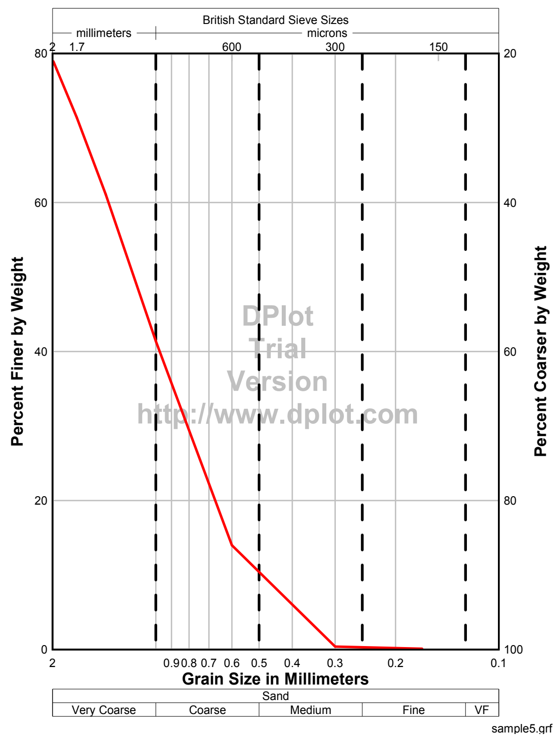

Fig. 2e. Sample 5

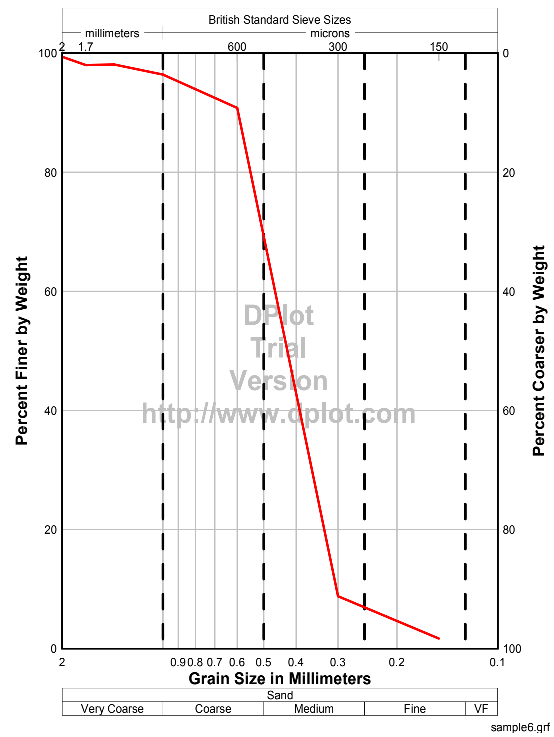

Fig. 2f. Sample 6

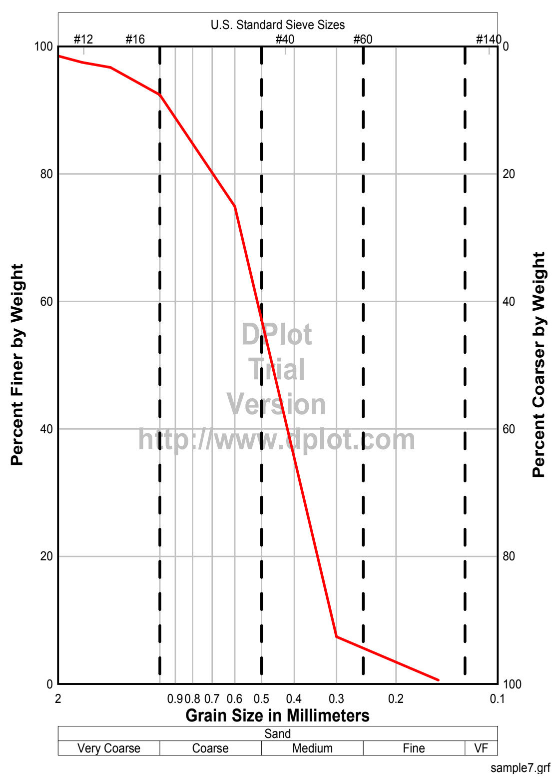

Fig. 2g. Sample 7

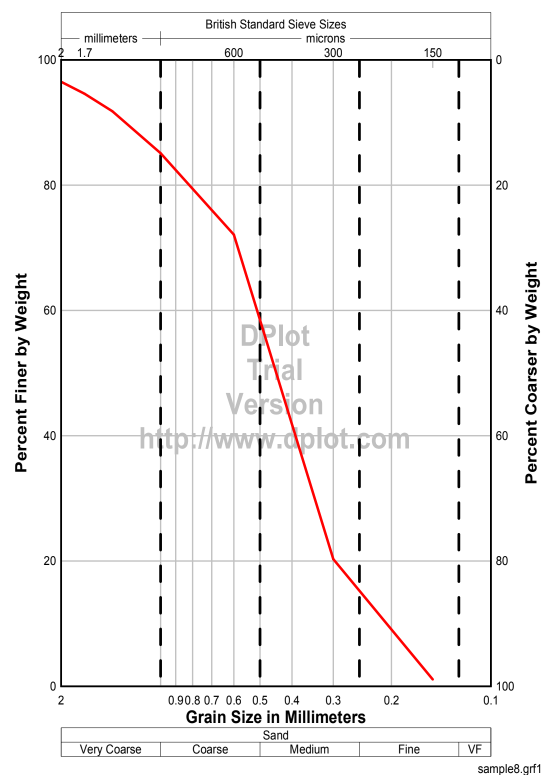

Fig. 2h. Sample 8

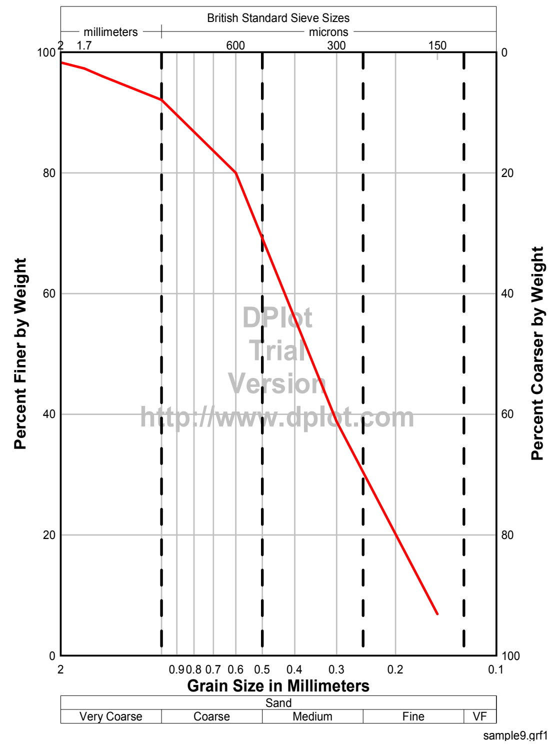

Fig. 2i. Sample 9

Fig. 2(a – i). Semi-logarithmic plot of grain size vs. percent fines for samples 1 to 9

Table 2. Percentile values of grain size analysis and statistical parameters

Samples	5%	16%	25%	50%	75%	84%	95%	GMn	GSD	GSk	GKt
1	-1.90	0.40	1.25	2.40	3.05	3.25	3.50	2.02	1.53	-0.50	1.23
2	2.05	2.65	2.75	3.15	3.50	3.80	4.30	3.20	0.63	0.08	1.23
3	-2.30	0.50	1.20	2.30	3.00	3.25	3.70	2.02	1.60	-0.42	1.37
4	-2.30	-1.10	-0.30	1.10	2.10	2.40	3.30	0.80	1.72	-0.24	0.96
5	-3.60	-2.10	-1.00	1.10	2.10	2.40	3.20	0.47	2.16	-0.40	0.90
6	1.70	2.60	2.70	3.00	3.30	3.40	3.95	3.00	0.54	-0.10	1.54
7	0.75	2.00	2.50	2.85	3.20	3.35	3.80	2.73	0.80	-0.30	1.79
8	-1.50	1.60	2.30	2.90	3.40	3.70	4.30	2.73	1.40	-0.40	2.16
9	0.72	2.15	2.60	3.22	3.80	4.10	4.40	3.16	1.05	-0.20	1.26

Table 3. Showing aquifer hydraulic parameters from grain size analysis

Sample	Porosity ϕ	Hydraulic conductivity, K (m/s), kozeny-carman	Hydraulic conductivity, K (m/day), kozeny-carman	Hydraulic conductivity, K (m/s), Hazen	Hydraulic conductivity, K (m/day). Hazen
1	0.42	0.002	165.20	0.002	141.80
2	0.43	8E-04	65.12	6E-04	53.43
3	0.41	0.002	147.30	0.002	130.80
4	0.41	0.004	343.20	0.004	313.80
5	0.41	0.004	336.90	0.004	311.60
6	0.45	0.002	182.00	0.002	129.60
7	0.44	0.002	186.60	0.002	136.50
8	0.42	8E-04	65.53	7E-04	56.99
9	0.41	4E-04	35.06	4E-04	32.10

Table 4. Summary of interpretation

Samples	Interpretations
1	Fine sand, poorly sorted, very coarsely skewed & leptokurtic
2	Very fine sand, moderately well sorted, near symmetrical and leptokurtic
3	Fine sand, poorly sorted, very coarsely skewed and leptokurtic
4	Coarse sand, poorly sorted, coarsely or negatively skewed and mesorkurtic
5	Coarse sand, very poorly sorted, very coarsely skewed and mesorkurtic
6	Very fine sand, moderately well sorted, coarsely or negatively skewed and very leptokurtic
7	Fine sand, moderately sorted, very coarsely skewed and very leptokurtic
8	Fine sand, poorly sorted, very coarsely skewed, and very leptokurtic.
9	Very fine sand, poorly sorted, coarsely or negatively skewed and leptokurtic

Graphic Sorting or Standard Deviation (*GSD*): This is a measure of the standard deviation which is the grain size distribution with respect to the mean. Sorting is a useful grain size data/ parameter because it gives an indication of the effectiveness of the depositional medium in separating grains of different classes. The analysed sediments show a standard deviation of 0.5 to 2.15 and a mean value of 1.3**.** Most of the samples are poorly sorted (Table 3, sample 1, 3, 4, 8 and 9), sample 5 is very poorly sorted while others are moderately well sorted (samples 2, 6, and 7). This is indicative of low to fair energy environment of deposition [20,21].

Graphic Skewness (*GSk*): This is a reflection of the depositional process. It is simply a measure of the symmetry of the distribution. Skewness is useful in environmental diagnosis because it is directly related to the fine and coarse tails of the size distribution and hence, suggestive of energy of deposition, [18]. The skewness values of the samples ranges from -0.076 to -0.421, thus indicating the presence of fine fraction and coarse fraction in population of particles. The positive values indicate skewness towards the finer grain sizes and the coarser grain sizes. The analysed samples are skewed towards the coarser grain sizes, typical of inland sediments.

Graphic Kurtosis (*GKt*): This is the measure of the peakness of the curves towards the coarser grain sizes. The samples are predominantly leptokurtic, that is, the central portions are better sorted at the tails. From Table 3, the range of kurtosis is from 0.899 to 2.161, where four (4) sample are leptokurtic, three (3) sample are very leptokurtic and two (2) are mesokurtic.

5. SUMMARY AND CONCLUSION

The results of the aquifer hydraulic parameters which comprised of porosity determined using Vukovic & Soro relation showed porosity of samples ranged from 0.41 to 0.45, with an average porosity of 0.42. The Hydraulic Conductivities obtained using Kozeny-Carman and Hazen equations ranged from $7.6\times10^{-4}\,m/s$ to $4\times10^{-3}\,m/s$ and $6.18\times10^{-4}\,m/s$ to $3.6\times10^{-3}\,m/s$ respectively. Hydraulic conductivity values obtained from Hazen equation correlate better with the observed hydraulic conductivity values in the area obtained by Pumping Test [8]. Statistical parameters such as the graphic mean, graphic sorting, graphic skewness and graphic kurtosis were also determined. The high porosity and hydraulic conductivity values were consistent with aquifer characteristics of unconsolidated fine to medium coarse coastal sands. Results obtained by grain size analysis are usually more accurate because it involves direct measurements from soils as against estimations by geophysical methods, the set back using this method is that it does not cover a wide perspective of hydraulic parameters.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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