



**HYDRO-SEDIMENTOLOGICAL EVALUATION OF AQUIFER PROPERTIES IN
PARTS OF SOUTHERN ANAMBRA BASIN**

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ABSTRACT

Nigeria's cities lack potable water supply due to failed municipal water supply systems, leading to groundwater reliance. Understanding hydrogeological settings of some basins like Anambra Basin is tough due to its complex geological heterogeneity and varying sedimentary structures. The commonly used electrical resistivity method has ambiguity issues because it often struggles to distinguish between different lithological units with similar resistivity values, leading to misinterpretation of subsurface geology. The alternative hydro-sedimentological approach estimates aquifer properties from grain size. In this study, twenty-five (25) sand samples were collected from boreholes cuttings; this is because sands are the primary aquifer-hosting materials in southern Anambra Basin. Ten empirical relationships were used to estimate hydraulic conductivities from the grain size data. Porosity, specific yield (SY), and specific retention (SR) were also empirically determined. Pumping data were available for ten (10) locations. For the remaining fifteen (15) locations, where pumping tests were not conducted, permeameter tests were performed on well cuttings to estimate hydraulic conductivity. The graphic mean of the sands ranges from 0.071 to 1.533phi, indicating that the sands are mainly medium-sized. Fractional porosity values, Specific yield and Specific retention range from 0.260 to 0.392, 0.274 to 0.039, and 0.125 to 0.322, respectively. Hydraulic conductivity ranges estimated from Hazen Simplified, Slichter, Terzaghi, Beyer, Sauerbrei, USBR, Barr, Alyamani & Sen, Chapuis, and Uma models are between 1.31-22.37m/day, 0.31-6.85m/day, 0.5-12m/day, 1.4-19m/day, 1.22-16.71m/day, 1.42-13.37m/day, 0.36-9.3m/day, 0.01-8.72m/day, 0.17-11.3m/day, and 0.02-10.64m/day respectively. Hydraulic conductivity obtained from pumping test ranges from 0.89 to 7.06m/day, while the values are 0.0864 to 25.488m/day from permeameter test, classifying the aquifers as having medium to high groundwater potential according to Terzaghi, Barr, Chapuis and Uma estimates. In conclusion, this study was able to map out the groundwater potential of the area and revealed the most suitable empirical relation for estimating groundwater potentials within the area.



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Keywords: Specific yield, Specific retention, Hydraulic conductivity.

INTRODUCTION

The growth in population, along with its associated increase in urbanization, has resulted in fierce competition for the limited freshwater resources among humans and other life forms. This situation is so dire that it is predicted that by 2025, about 1.8 billion people will be living in regions with absolute water scarcity, and two-thirds of the world's population could be under water-stressed conditions (Hanasakiet *al.*, 2013). The situation is not different in Nigeria, where more than half of the population resides in urban and semi-urban regions, with less than 50% having access to dependable sources of water for basic domestic needs (Federal Republic of Nigeria [FRN], 2000; Abubakar *et al.*, 2023), largely attributed to general breakdown in government-controlled municipal water supply. Furthermore, the problem is exacerbated during the dry season when surface water sources dry up (Adiat *et al.*, 2012).

In order to address the current situation of a lack of sustainable sources of potable water supply in many urban centers in Nigeria, individuals and communities, including those within the southern Anambra Basin, have resorted to exploiting groundwater to meet their domestic and other water needs because of its reliability and has less pollution concerns compared to surface water. However, since groundwater resources are often hidden from sight and held within underground aquifers in often complex geological and hydrogeological settings such as the Pre-Santonian rock units of the Anambra Basin (Nwajide, 1990; Anyanwu and Oguntade, 2021), several methods have been developed to understand the hydrogeological properties of aquifers within a given area in order to denote the groundwater potentials. The geophysical method of electrical resistivity is one of the most prominent methods often used in the exploration of groundwater. This method has been used extensively by several researchers to provide valuable information about the characteristics and potentials of groundwater resources within the Anambra Basin (Amadi, 2008; Okoro *et al.*, 2010; Anakwuba *et al.*, 2014; Usman *et al.*, 2015; Anomohanran, 2015; Omali *et al.*, 2018; Nwosu and Ledogo, 2020). However, while this method is cost-effective, it is important to note that it suffers from issues of non-uniqueness and ambiguity. This means



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that the same set of data can be interpreted in multiple ways, leading to different conclusions about the groundwater resources in a particular area (Yin, 2000).

The hydro-sedimentological approach, which estimates aquifer properties such as porosity, specific yield, specific retention, and hydraulic conductivity from grain size parameters of aquifer sands, is indeed a cost-effective alternative. This method is particularly economical when samples of aquifer-related sands/sediments are collected from near-surface areas. For instance, this approach was used by Detmer (1995) to study the permeability and porosity estimates of Pliocene and Quaternary sediments in the northern Albuquerque Basin. This methodology has also been employed by several researchers to estimate the hydraulic properties of aquifer sands within other parts of the Anambra and Niger-Delta Basin (Oborie *et al.*, 2018; Ozoko and Ezeugwu, 2022). Numerous empirical relationships have been developed to estimate the hydraulic conductivities of aquifers from grain size data (Sauerbrey, 1932; Kozeny-Carmen, 1953; Uma *et al.*, 1989; Barr, 2000; Chapuis, 2004). However, these empirical relations have limited conditions of application. They cannot be universally applied and only apply to specific regions. Therefore, it is often imperative to use several empirical relationships of hydraulic conductivities and compare them with hydraulic conductivity from either a permeameter or a pumping test to select the one that best applies in a given area (Detmer, 1995; Oborie *et al.*, 2018). Despite its usefulness, very few publications have focused on the hydro-sedimentological approach within the Anambra Basin. Among the few who have done so are Uma *et al.* (1989), Ozoko and Ezeugwu (2022). A more regional study that covered a large area, providing a more generalized perspective, was by Uma *et al.* (1989). Therefore, this study aims to use hydro-sedimentology to assess the groundwater potential of Orlu and its environs which is part of Southern Anambra Basin.

MATERIALS AND METHOD

Location of the study area

The research area, as shown in Figure 1, is situated within the Southern Anambra Basin and covers a span of 230 km². This area is defined by latitudes 5°41' to 5° 49'N and longitude 6°57' to 7°011'E. The boundaries were established to provide a comprehensive understanding of the hydrogeology/groundwater system of the part of southern Anambra Basin (Figure 1).



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The area is characterized by a gently undulating topography, with numerous river channels dissecting it. The Anambra Basin (Figure 2) is a triangular sedimentary basin that spans an area of 3000km². It contains about 9000m thick sedimentary deposits from the Cretaceous to Tertiary periods. The basin is situated west of the Lower Benue Trough and north of the Niger-Delta Basin, with its eastern and western margins defined by the Abakaliki Anticlinorium and Ibadan Basement massif respectively (Babatunde, 2010; Odunze *et al.*, 2013). The stratigraphic succession (Figure 3) within the basin reveals that the pre-Santonian members, which include the Asu-River Group, Ezeaku Group, and Awgu Shale, are strongly folded. In contrast, the post-Santonian formations such as the Nkporo Shale, Ajali Formation, Imo Formation., Ameki Formation., and Ogwashi-Asaba Formation exhibit nearly flat sedimentary successions (Nwajide, 1990). The aquifer sands in the study area originate from the Ameki and Ogwashi-Asaba Formations (Figure 2). These formations date back to the Eocene to Miocene periods. Within the study area, they constitute part of upland with high groundwater potential (Onu and Ibezim, 2004).

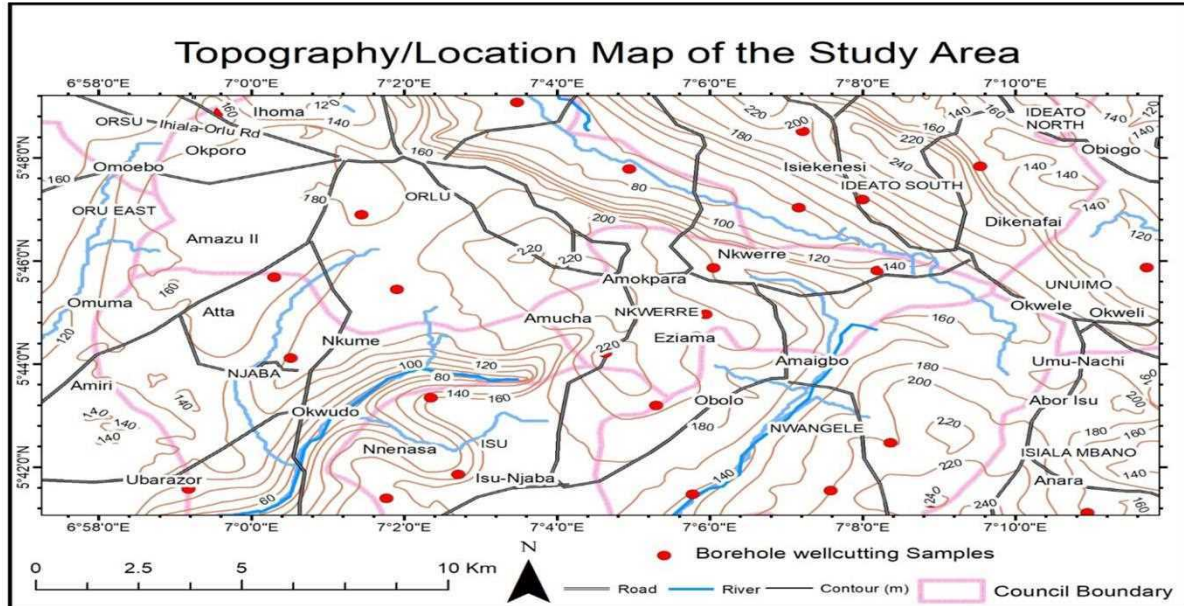


Figure 1: Map showing location of study area and features of interest

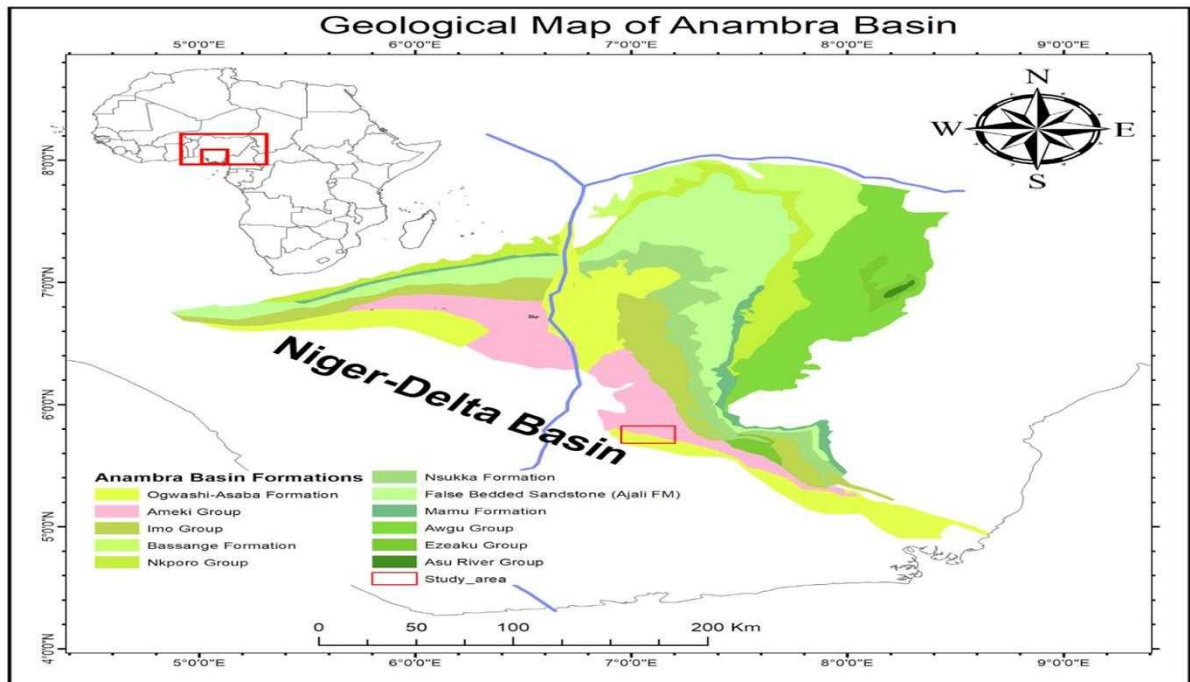


Figure 2: Geological map of Anambra Basin showing the study area (red line) (source: Nigerian Geological Survey Agency)

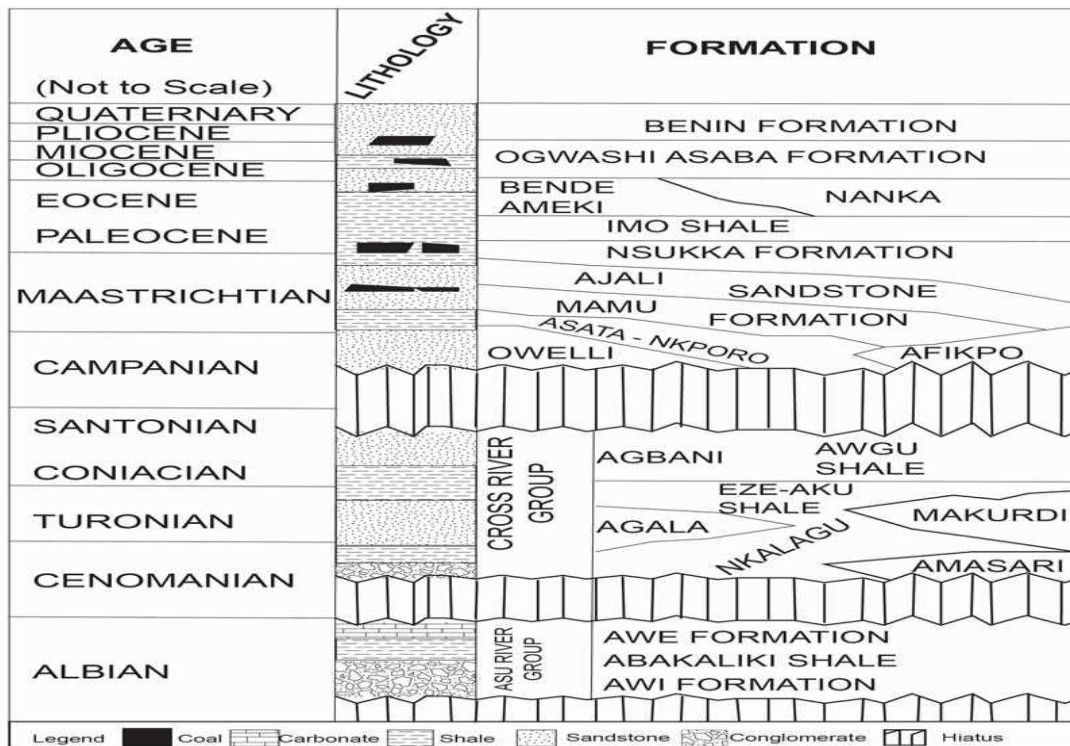


Figure 3: Stratigraphic and lithologic section of Lower Benue Trough and Anambra Basin (after Akaegbobi et al., 2000)



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Sample collection

In this study, a total of 25 sand samples were collected. from local borehole drillers who often collect well cuttings at 10ft intervals of drilling using the percussion method. The samples were collected from 25 boreholes (25 samples were collected from how many boreholes?) aquifer sections. The sand samples are well cuttings which are chipped away by the drill bit during the drilling process and are transported to the surface by the mud stream. They are then caught at the desander/desilter outlets as composite samples where a portion of the samples is washed. A guideline by American Association of Petroleum Geologist (AAPG, 2022) describes the process.

Laboratory procedures and data analysis

A portion of the washed sample was used for particle size determination by sieve analysis as described by Sampaio *et al.* (2007). Folk and Ward (1957) graphic measures were used to compute the statistical properties of the grain size including mean, standard deviation (Sorting), skewness and kurtosis. The percentage of the mass of sand retained on each sieve is used to generate a granulometric curve. Ten (10) empirical relationships, including Hazen, Hazen Simplified, Slichter, Terzaghi, Bayer, Sauerbrei, USBR, Barr, Alyamani and Sen, Chapius, were used to estimate hydraulic conductivities from grain size data (Table 1). These methods have been applied by various researchers to study the aquifer properties of sedimentary rocks within Nigeria's sedimentary basins (Egboka and Uma, 1986; Uma *et al.*, 1989; Ishaku *et al.*, 2011; Abdullahi, 2013; Ozoko and Ezeugwu, 2022). Porosity, specific yield, and retention were calculated using empirical relationships proposed by Vukovic and Soro (1992) and Robson(1993) (Table 2).

Well pumping data were available for 10 locations. The pumping test data is for a single-well aquifer test which consists of monitoring water-level decline in a well before, during, and after a known volume of water is removed by pumping at a constant rate from a formation open to the well (Frus and Halford, 2018). The Jacob-Cooper method, which has also been used by Pongmanda and Suprapti (2020) to estimate aquifer properties of single-well pumping tests, was used to estimate the aquifer transmissivity and hydraulic conductivities.



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In places where pumping test data were not available, a portion of the washed well cuttings (fifteen in number) were subjected to a permeameter test (Constant Head) for hydraulic conductivity determination (K). This method is commonly used to test soils with high permeability such as sands (Olson and Daniel, 2014). The assembly includes a soil sample holder, a water reservoir, a constant head tank, a drain valve, a graduated cylinder, and tubing to connect these components (Das, 2014). The test was performed following ASTM standard D2434-68 and is based on Darcy's experiment that relates hydraulic conductivity to discharge (American Standard for Material and Test [ASTM], 2006; Tijani and Nton, 2009).

Table 1: Empirical relationship between hydraulic conductivity and grain size parameters

Source	Equation	Applicability
Hazen Simplified (Freeze and Cherry, 1979)	$K = 10(\mu/\rho g)d_{10}^2$	Uniformly graded sand, $n=0.375$, $T = 10^\circ\text{C}$
Slichter (Youngs, 2000)	$K = 1 \times 10^{-2} n^{3.287} d_{10}^2$	$0.01\text{cm} < d_{10} < 0.06\text{cm}$
Terzaghi (1925)	$K = 6.1 \times 10^{-3} ((n - 0.133)/(1 - n)^{1/3})^2 d_{10}^2$	Sandy soil, coarse sand
Beyer (1964)	$K = 5.2 \times 10^{-4} \log(500/U) d_{10}^2$	$0.006\text{cm} < d_{10} < 0.06\text{cm}$ $1 < U < 20$
Sauerbrei (Vuković and Soro, 1992)	$K = 3.75 \times 10^{-3} \tau ((n^3/(1 - n^2)) d_{10}^2$	Sand and sandy clay $d_{17} < 0.05\text{cm}$
USBR (United States Bureau of Reclamation) (Bialas, 1966)	$K = 4.8 \times 10^{-4} (10^{0.3}) d_{20}^{1.15}$	Medium grained sands with $U < 5$; derived for $T = 15^\circ\text{C}$
Barr (2001)	$K = 1/(36(5 \times 1.35^2)) x ((n^3/(1 - n^2)) d_{10}^2$	Unspecified
Alyamani and Sen (1993)	$K = 1300 [I_o + 0.025(d_{50} - d_{10})$	Unspecified
Chapius (2004)	$K = \frac{\mu}{\rho g} 10^{1.291 \frac{n}{1-n} - 0.645} d_{10}^{\left(\frac{10^{0.5504 - 0.3937 \frac{n}{1-n}}}{2} \right)}$	$0.3 < n < 0.7$; $10 < d_{10} < 2.0\text{mm}$; $2 < U < 12$; $d_{10}/d_5 < 1.4$
Uma et al. (1989)	$K = 3.8 d_{10}^2$	Moderately consolidated

Where T = water temp. ($^\circ\text{C}$), $\rho = 3.1 \times 10^{-8}T^3 - 7.0 \times 10^{-6}T^2 + 4.19 \times 10^{-5}T + 0.99985$, $g = 980\text{cms}^{-2}$,
 $\tau = 1.093 \times 10^{-4}T^2 + 2.102 \times 10^{-2}T + 0.5889$, $\mu = -7.0 \times 10^{-8}T^3 + 1.002 \times 10^{-5}T^2 - 5.7 \times 10^{-4}T + 0.0178$,
 d_i^g = the maximum grain diameter in fraction I , d_i^g = the minimum grain diameter in fraction I ,
 d_{10} = grain size (cm) corresponding to 10% by weight passing through the sieves,
 d_{20} = grain size (cm) corresponding to 20% by weight passing through the sieves,



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d_{50} = grain size (cm) corresponding to 50% by weight passing through the sieves,
 d_{60} = grain size (cm) corresponding to 60% by weight passing through the sieves; $U = d_{60}/d_{10}$
 l_0 = x-intercept (grain size) of a percent grain retention curve plotted on arithmetic axes and focussing on data below 50% retained

Table 2: Empirical relationship between specific yield, specific retention, porosity & grain size parameters

Parameter	Equation	Author
Specific Retention (SR)	$SR = 0.0550 - 0.1335 \log d_{50}$ Where d_{50} is the size of which 50% of the grains are finer	Robson (1993)
Porosity (n)	$n = 0.255 \times (1 + 0.83^U)$ Where U is coefficient of uniformity (d_{60}/d_{10})	Vuković and Soro (1992)
Specific Yield (SY)	$SY = n - SR$	Robson (1993)

RESULTS

The cumulative frequency curves of grain size distribution for 25 aquifer sand samples are displayed in figure 4. Interestingly, the steepest area of these curves is between 0.1-1 phi, while the other ends remain relatively flat. This observation implies that medium-grained sand is the dominant texture. Furthermore, the graphic statistics presented in Table 3, reveal that the majority of the samples are composed of medium-sized sand, with a range of 0.071 to 1.533phi. Additionally, the standard deviation (SD), skewness, and kurtosis, which range from 0.193 to 1.935phi, 0.262 to 0.880, and 0.385 to 9.976 respectively, imply that the particle size fraction varies widely and is mostly symmetrical with a peak. In terms of sorting, the samples are mostly poorly sorted.

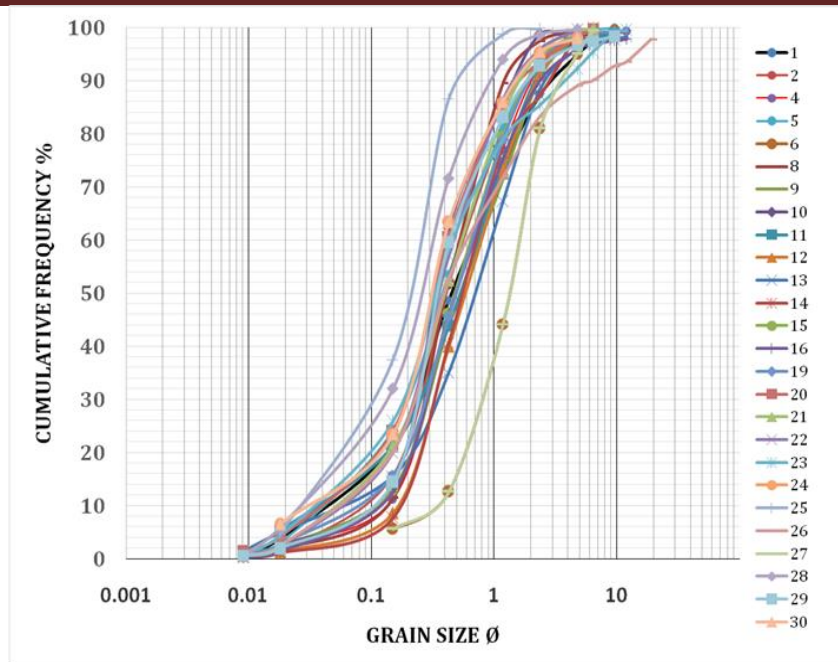


Figure 4: Grain size distribution curve for all the aquifer samples



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Table 3: Calculated values of graphic parameters for sediments from the Southern Anambra Basin after Folk and Ward (1957)

ID	Mean (Mz)	SD (δi)	Skewness (Ski)	Kurtosis (K_G)	Texture	Sorting
1	0.848	1.23	0.743	4.991	Medium Sand	Very Poor
2	0.657	0.73	0.69	2.785	Medium Sand	Poor
4	0.767	0.797	0.663	2.978	Medium Sand	Poor
5	0.618	0.722	0.652	2.587	Medium Sand	Poor
6	0.071	0.105	0.88	0.385	Coarse Sand	Very Poor
7	0.527	0.453	0.563	1.651	Medium Sand	Poor
8	0.84	0.853	0.634	2.986	Medium Sand	Poor
9	0.573	0.522	0.708	1.766	Fine Sand	Poor
10	0.775	0.856	0.564	2.994	Medium Sand	Poor
11	0.129	0.231	0.839	0.989	Medium Sand	Poor
12	0.953	1.063	0.558	3.994	Medium Sand	Poor
13	0.863	0.902	0.694	3.446	Medium Sand	Poor
14	0.723	0.704	0.61	2.484	Medium Sand	Poor
15	0.827	1.003	0.709	3.98	Medium Sand	Poor
16	1.027	1.935	0.638	9.976	Medium Sand	Poor
19	0.717	0.757	0.6	2.786	Medium Sand	Poor
21	0.6	0.63	0.603	2.185	Medium Sand	Very Poor
22	0.52	0.547	0.624	1.982	Fine Sand	Poor
23	0.793	1.391	0.826	5.99	Fine Sand	Moderate
24	0.46	0.591	0.67	2.388	Medium Sand	Very Poor
25	0.187	0.193	0.663	0.67	Very Coarse Sand	Poor
26	0.997	0.778	0.599	1.192	Fine Sand	Poor
28	0.343	0.372	0.476	1.382	Fine Sand	Poor
29	0.407	0.322	0.461	1.265	Medium Sand	Very Poor
30	0.463	0.561	0.643	2.188	Medium Sand	Poor

The fractional porosity values in Table 4 range from 0.260 to 0.392, indicating the volume of void space in the sediment. This void space, or porosity, is crucial as it determines how much water the sediment can hold. Specific yield (SY) and specific retention (SR) range from 0.039 to 0.274 and 0.125 to 0.322, respectively, as shown in Table 4. These values indicate the water-holding capacity of the sediments, with SY indicating the amount of water that is released from the sediment under gravity drainage, and SR indicating the amount of water that is retained in the sediment under tension. Figures 5a, 5b, and 5c present the spatial distribution of porosity, specific yield (SY), and specific retention (SR) across the study area. The northeastern portion of the study area has higher values of porosity; the mid-northwestern areas have the lowest porosity, while other areas have porosity values that vary



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between these two regions. SY has higher values within the mid-Southwestern regions and northeastern region, while northwestern areas have lower porosity

Table 4: Estimated Porosity, Specific yield and Specific retention of the aquifer sand samples from the Southern Anambra Basin

ID	LONGITUDE	LATITUDE	Porosity, (n)	Specific Retention. (SR)	Specific Yield. (SY)
1	7.119	5.784	0.27	0.107	0.163
2	7.005	5.761	0.332	0.107	0.225
4	7.008	5.735	0.362	0.106	0.256
5	6.986	5.693	0.275	0.15	0.125
6	7.126	5.692	0.355	0.103	0.253
7	7.039	5.723	0.288	0.039	0.322
8	7.133	5.787	0.384	0.149	0.235
9	7.101	5.764	0.335	0.105	0.23
10	7.182	5.685	0.392	0.153	0.239
11	7.024	5.782	0.26	0.105	0.154
12	6.993	5.815	0.286	0.104	0.182
13	7.045	5.698	0.268	0.102	0.166
14	7.159	5.797	0.379	0.104	0.274
15	7.088	5.720	0.348	0.107	0.241
16	7.029	5.690	0.348	0.106	0.242
19	7.096	5.691	0.311	0.106	0.205
21	7.058	5.818	0.275	0.149	0.139
22	7.137	5.764	0.288	0.151	0.19
23	7.032	5.757	0.341	0.151	0.127
24	7.139	5.708	0.278	0.151	0.125
25	7.099	5.749	0.276	0.158	0.134
26	7.082	5.796	0.292	0.149	0.139
28	7.148	5.688	0.361	0.155	0.13
29	7.120	5.809	0.285	0.151	0.223
30	7.195	5.765	0.374	0.152	0.126

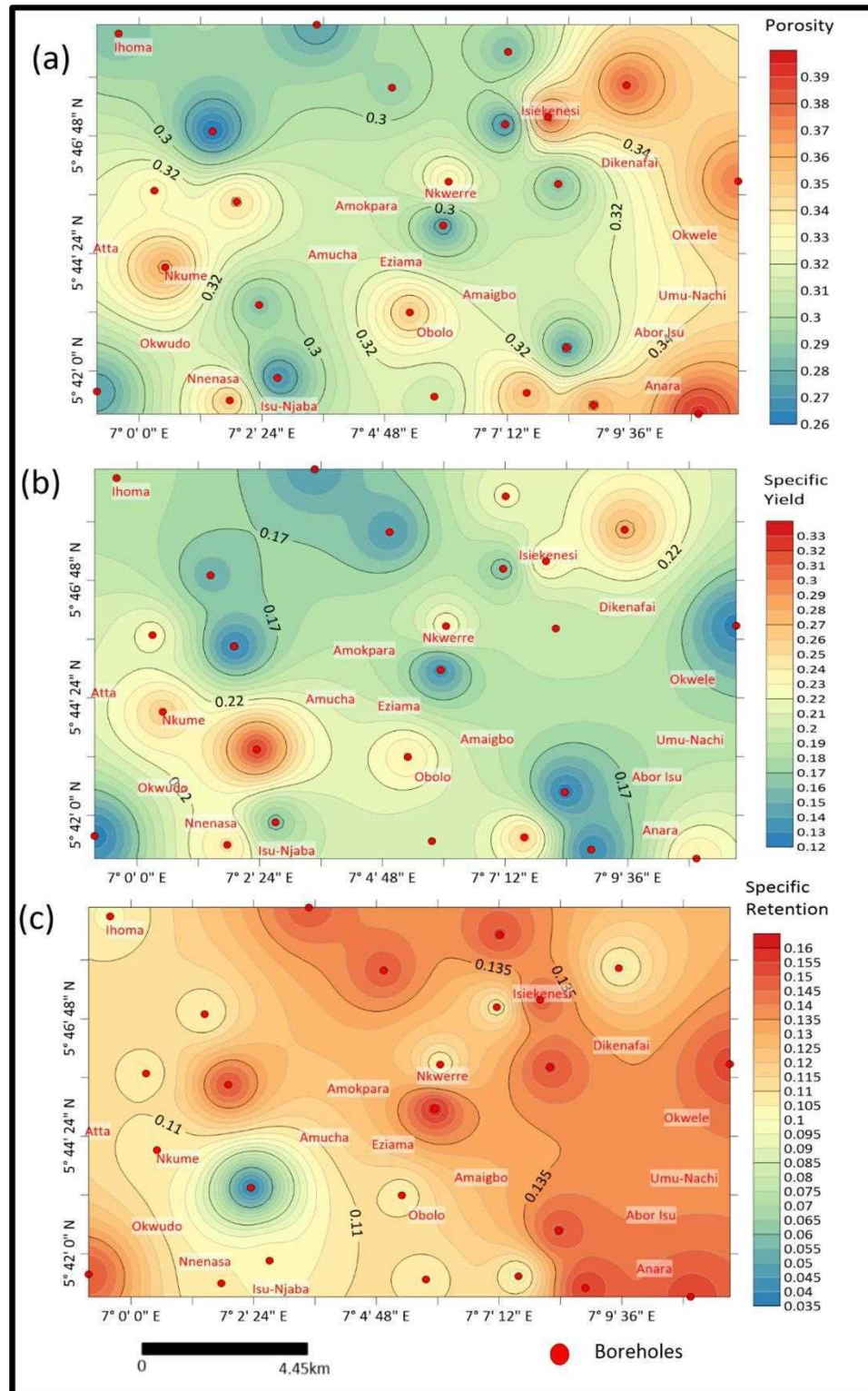


Figure 5: Porosity (a), Specific yield (b) and Specific retention (c.) estimates of the aquifer sand samples from the Southern Anambra Basin



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Table 5 presents the estimated hydraulic conductivities for various models, namely Hazen Simplified, Slichter, Terzaghi, Beyer, Sauerbrei, USBR, Barr, Alyamani and Sen, Chapuis, and Uma. The respective ranges of these models are as follows: 1.31-22.37m/day, 0.31-6.85m/day, 0.5-12m/day, 1.4-19m/day, 1.22-16.71m/day, 1.42-13.37m/day, 0.36-9.3m/day, 0.01-8.72m/day, 0.17-11.3m/day, and 0.02-10.64m/day. The overall range of the empirical relationship is wide, spanning from 0.01 to 22.37m/day. The average hydraulic conductivity for each of the above-listed models is respectively: 8.1484m/day, 2.0484m/day, 3.5576m/day, 7.0908m/day, 5.8484m/day, 6.4932m/day, 2.5848m/day, 1.4636m/day, 2.712m/day and 2.39m/day. The overall average hydraulic conductivity value is calculated to be 4.03m/day. Table 6 presents the results of permeameter and pumping test hydraulic conductivities. The hydraulic conductivity from the pumping test ranges from 0.89 to 7.06m/day with an average value of 3.099m/day. On the other hand, the hydraulic conductivity from permeameter tests ranges from 0.0864 to 25.488m/day with an average value of 10.76m/day which is higher than that from pumping tests because the aquifer sands used in permeameter testing were in a disturbed state. Figure 6 presents the average hydraulic conductivity from the empirical relationships with horizontal lines representing values of pumping and permeameter averages for comparison. Figure 7 shows the correlation matrix of Pumping and Permeameter hydraulic conductivity with those from the empirical relationship of grain size K. There is a fairly strong (>0.5) relationship of Pumping test K with Uma, while the correlations with Hazen simplified, Beyer, and USBR are weak. The Permeameter hydraulic conductivity correlation is strong (>0.6) with those from Beyer and Sauerbei

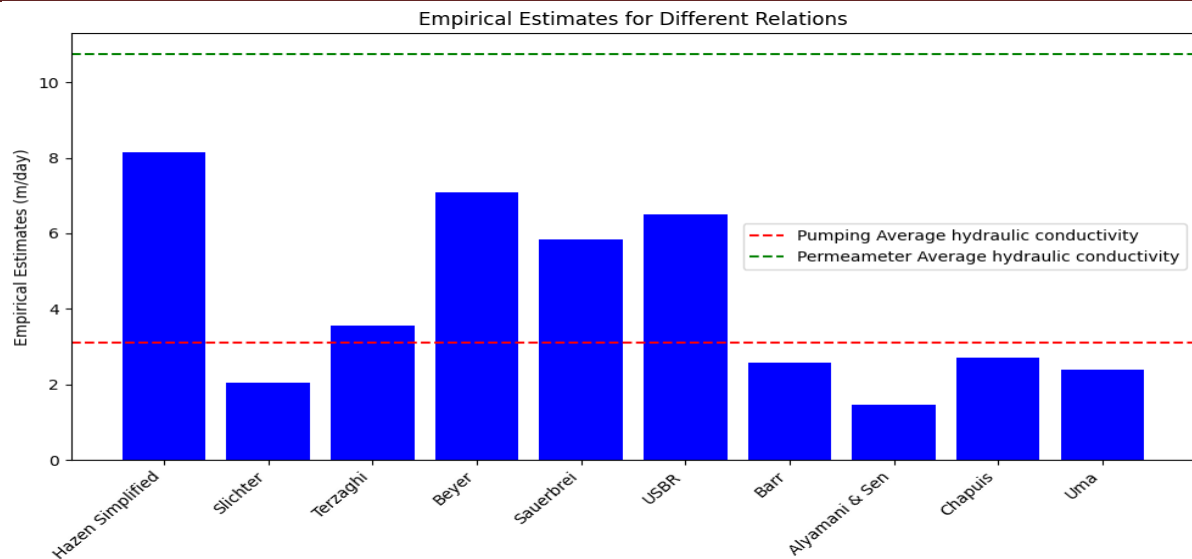


Figure 6: Average hydraulic conductivities estimated from empirical relationships, with lines of average pumping test, and average constant head permeameter result

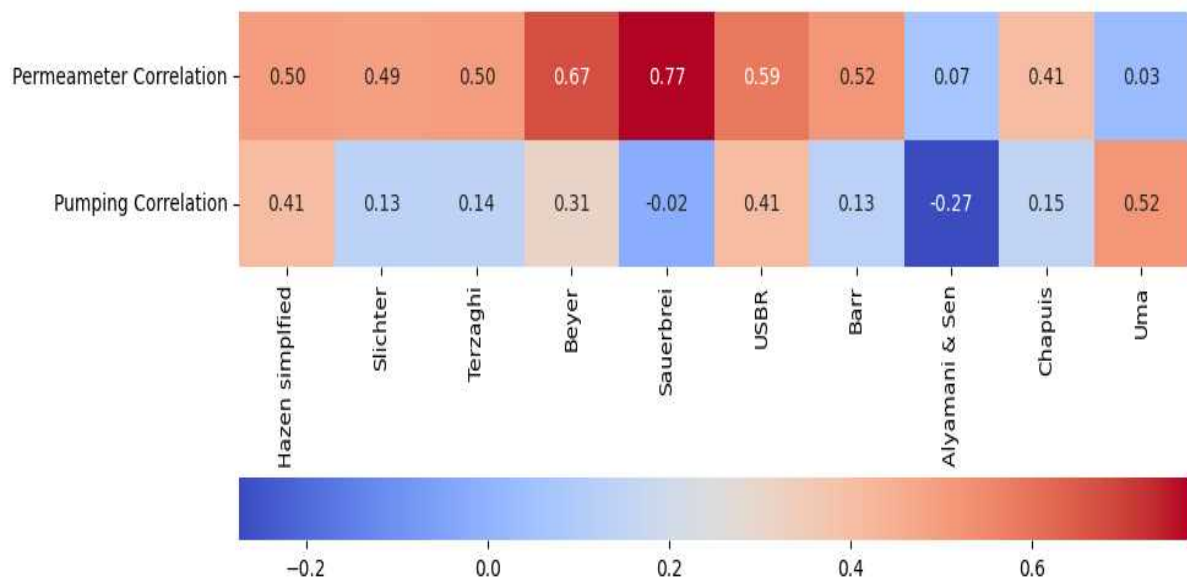


Figure 7: Spearman Correlation matrix of pumping and permeameter test with empirical methods of estimating hydraulic conductivity



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Table 5: Computed values of hydraulic conductivities (m/day) of the aquifer sands from Southern Anambra Basin using empirical relations

ID	A	C	D	E	F	K	L	M	N	P
1	2.74	0.59	0.9	3.1	2.12	4.55	0.66	0.76	0.39	0.66
2	10.08	2.5	4.16	9.94	7.59	10.24	3.02	0.52	2.73	2.66
4	20.99	5.86	10	18.9	14.17	13.37	7.55	4.8	8.56	6.44
5	3.2	0.73	1.18	3.41	2.28	3.66	0.85	0.07	0.53	0.53
6	10.19	1.5	4.46	4.4	2.91	3.59	1.81	2.32	4.84	0.02
7	3.73	0.96	1.6	3.6	3.36	3.8	1.18	0.01	0.82	6.44
8	22.37	6.85	12	19	16.71	11.77	9.3	8.72	11.3	4.73
9	13.92	3.51	5.86	13.6	9.84	12.91	4.28	0.47	4.24	4.73
10	4.96	1.37	2.3	4.5	4.52	4.12	1.75	0.28	1.4	0.40
11	2.63	0.55	0.9	3.1	2.15	5.08	0.62	3.58	0.36	0.02
12	9.26	1.58	2.95	3.57	1.87	4.68	1.75	2.05	1.73	1.18
13	6.19	1.36	2.2	6.9	5.72	3.74	1.55	2.67	1.2	10.64
14	8.99	1.15	2	3.9	1.62	4.67	1.54	1.27	2.91	4.73
15	12.75	3.34	5.6	12	9.94	11.42	4.15	1.2	4.05	5.55
16	13.45	3.48	5.9	13	9.96	11.82	4.31	1.24	4.25	2.10
19	7.49	1.81	3	7.6	6.2	9.42	2.15	0.01	1.77	0.82
21	4.53	1.08	1.8	4.6	3.36	4.88	1.28	0.01	0.9	1.18
22	5.34	1.38	2.3	5.1	4.64	5.42	1.7	0.16	1.3	0.40
23	2.33	0.54	0.9	2.5	1.92	2.97	0.63	0.18	0.35	0.30
24	8.81	2.55	4.4	7.7	8.03	6.57	3.34	1.31	3.2	0.21
25	1.88	0.49	0.8	1.8	1.56	1.42	0.62	0.03	0.37	0.99
26	4.59	1.05	1.7	4.9	3.27	5.51	1.22	0.05	0.86	0.43
28	1.31	0.31	0.5	1.4	1.22	1.69	0.36	0.18	0.17	0.26
29	13.29	4.12	7.14	11.2	13.17	8.7	5.63	3.42	6.3	3.97
30	8.69	2.55	4.39	7.55	8.08	6.33	3.37	1.28	3.27	0.30

A = Hazen simplified C = Slichter, D = Terzaghi, E = Beyer, F = Sauerbrei, K = USBR, L = Barr, M = Alyamani & Sen, N = Chapuis, P= Uma



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Table 6: Hydraulic conductivity measurements of pumping and permeameter tests across the study area

ID	Longitude	Latitude	method	Hydraulic Conductivity (m/day)
1	7.119296	5.783919	pumping	2.64
2	7.004979	5.761419	pumping	4.07
4	7.008483	5.735331	constant head	25.488
5	6.986187	5.692982	pumping	2.13
6	7.126288	5.692452	constant head	0.0864
7	7.039074	5.722509	constant head	29.1168
8	7.133282	5.786578	constant head	26.0928
9	7.100778	5.764411	constant head	18.7488
10	7.182351	5.685302	constant head	19.5264
11	7.023943	5.781637	constant head	1.5552
12	6.993285	5.814891	constant head	0.0864
13	7.045081	5.697668	constant head	4.6656
14	7.158942	5.797278	pumping	4.59
15	7.088224	5.719967	constant head	18.576
16	7.029427	5.689971	constant head	21.9456
19	7.096176	5.69128	pumping	7.06
21	7.057948	5.817927	pumping	3.2
22	7.136532	5.763553	pumping	4.17
23	7.031686	5.757492	constant head	1.5552
24	7.139386	5.707864	pumping	1.3
25	7.099019	5.74946	pumping	0.89
26	7.082402	5.796418	constant head	3.888
28	7.148066	5.688397	constant head	1.0368
29	7.120217	5.808583	constant head	15.6384
30	7.195295	5.764587	pumping	0.94

DISCUSSION

The aquifer of the Anambra Basin have been described as mostly medium-grained sand by several authors (Tijani and Nton, 2009; Chukwura *et al.*, 2015). Oluyemi *et al.* (2022) reported average graphic mean ranges of 1.15-2.17 ϕ for sandstones within the Ogwashi-



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Asaba Formation, which are slightly coarser than the particle range reported in this study. The poorly sorted nature of the sediments in this study aligns with the findings of Akpofure and Oborie (2019) for the sediments of the Benin Formation.

The porosity values reported in this study are consistent with those of aquifer materials within the Southern Anambra Basin (0.2-0.26) as reported by Obasi *et al.* (2013), and can be considered to have moderate porosity. Higher porosity often corresponds to a lower degree of diagenesis (Scherer, 1987). Several other factors contribute to the porosity of a sediment including the degree of sorting and roundness of particles, where well-sorted and rounded particles typically lead to higher porosity. The presence of sedimentary structures like bedding planes or fissility, and the degree of fracturing or jointing can create additional spaces within the material. The specific yield (SY) and specific retention (SR) values reported in this study (0.039-0.274 and 0.125-0.322, respectively) align with the findings of Ekanem *et al.* (2022) for the Benin Formation (specific yield and specific retention ranges of 0.040–0.107 and 0.242–0.623). SR and SY are important parameters in groundwater hydrology that describe the ability of a porous medium to store and release water under different conditions. Higher values of SY indicate that the sediments are more permeable and have a greater capacity to release water.

In terms of the empirical estimates of average hydraulic conductivity for the research area, the order from highest to lowest is Hazen Simplified > Bayer > USBR > Sauerbrei > Terzaghi > Chapuis > Barr > Uma > Slichter > Alyamani & Sen. Pumping tests are generally believed to provide the best measurement of aquifer materials as they capture complexities present in a given aquifer (Wrzesiński and Markiewicz, 2022). Both pumping and permeameter hydraulic conductivities fall within the range of medium to high groundwater potentials. These potentials are defined as 10^{-1} to 10m/day (medium), and 10 to 10^3 m/day (high) according to Vrbka *et al.* (1999). Pumping test analysis of hydraulic conductivities of the Benin Form of the nearby Niger-Delta Basin, which is also present within the Anambra Basin, reported ranges of 0.655m/day-31.3m/day (Nwankwor *et al.*, 2016). This is consistent with the findings in this study. Dikeogu *et al.* (2021) reported a range of 3.55m/day to 206.5m/day for the Benin Formation at Ohaji/Egbema. The hydraulic conductivities estimates provided by



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Terzaghi, Barr, Chapuis and Uma are similar to those from pumping tests while those given by Hazen Simplified, Beyer, Sauerbrei, and USBR overestimate the average pumping test hydraulic conductivity by a wide margin. In terms of the correlation of the pumping test results with those from empirical relationships, the findings from this study contrast with those of Pucko and Verbovšek (2015), in their study, most of the empirical K, including USBR, Hazen, Kozeny-Carmen, Bayer, and Slichter, all showed strong correlations (>0.93) with pumping test hydraulic conductivities. This is because K values from empirical relationships are known to vary widely and do not yield consistent results in all areas.

CONCLUSION

This study investigated the groundwater potential of the Anambra Basin using the hydrosedimentological approach; empirical relationships from grain size data as cost-effective alternatives to the geophysical electric resistivity method of groundwater investigation. The results showed that the aquifer materials are mainly medium-sized and poorly sorted sands. The hydraulic conductivity values obtained from both pumping tests and permeameter measurements indicated that the area is of moderate to high groundwater potentials. Four empirical models (Terzaghi, Barr, Chapuis, and Uma) were found on average to be consistent with the pumping test, the most reliable method of hydraulic conductivity measurement.

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