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Aquifer flow unit analysis using stratigraphic modified Lorenz plot: a case study of Edem, eastern Nigeria

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Abstract

The present study aimed at evaluating aquifer flow unit of Edem by means of stratigraphic modified Lorenz plot (SMLP) employing vertical electrical sounding. The results from the vertical electrical sounding field data analysis shows that resistivity and thickness of the aquifer layer ranges from 34.8 to 67561.2 Ωm and 29.7 to 147.6 m respectively having an average aquifer thickness value of 70.248 m. Aquifer layer permeability and fractional porosity range from 1.5942 to 1657444 mD and 0.2558 to 0.3265 respectively. Results from stratigraphic modified Lorenz plot delineated a total of eight flow-units, FU1, FU2, FU3, FU4, FU5, FU6, FU7, and FU8 for the aquifer units and three different process speeds. Aquifer flow units FU1, FU3, and FU8 fall within the speed zone, flow units FU5 and FU7 are associated with the baffle zone, while flow units FU2, FU4, and FU6 make up the barrier zone of the process speeds. The aquifer flow unit speed ranges from 265406.4 to 5076424 mD with an average value of 826310.2 mD. The contour maps generated revealed the western part of the study area as characterized with high values of aquifer storage capacity and aquifer flow capacity with the highest storage and flow capacities delineated along the northwestern part of the study area. The Dykstra-Parsons coefficient of 0.99 revealed an extremely heterogeneous aquifer in the study area. This flow unit analysis will serve as a guide in accurate design and management of the aquifers.

Keywords: Aquifer storage capacity, Flow unit, Fractional porosity, Permeability, Heterogeneity

Introduction

Characterization of aquifer flow unit is important in groundwater delineation and exploration. The proper knowledge of the aquifer properties such as porosity, permeability, and hydraulic radius help groundwater explorationists and engineers in improving aquifer characterization [11]. Aquifer characterization involves the incorporation of existing data tools and techniques to identify and classify the flow units according to its capacity. A detailed aquifer characterization enables a precise prediction for the aquifer performance along the aquifer existence. This detailed aquifer characterization is achieved by subdividing the given aquifer sequence into some zones, flow units (FUs), and/or reservoir rock types (RRTs), each with its diagnostic petrophysical behavior [1]. Dividing the aquifer into FUs helps in predicting the petrophysical parameters of the uncored reservoir intervals and in well-to-well correlation. Ebanks et al. [6] stated that flow unit is an identified portion of an aquifer within which the geologic and petrophysical properties that influence aquifer flow is consistent and varies from the properties of other zones. Flow unit is also a pattern of zoning/characterization of the aquifer. It is dependent on the distribution of the aquifer thickness, porosity, and permeability [15, 29]. Aquifer flow unit is influenced by the layer's heterogeneity. Aquifer cycles are not homogeneous, as heterogeneity is a dominant nature with different classification starting from slightly heterogeneous to extremely heterogeneous. Heterogeneity is the complexity of an individual or combination of properties within a known space or time at a specified scale [9]. Heterogeneity can be intrinsic (porosity or mineralogy) or measured as described by the scale, volume, and resolution of the measurement technique [9]. The measured property can be examined employing Dykstra-Parsons coefficient (V_{DP}) to ascertain the degree of aquifer layers complexity. The Dykstra-Parsons coefficient provides an estimate of the true heterogeneity, depending on the location and sampling frequency [18]. Several techniques have been applied by different researchers in recent past to comprehend and delineate aquifer flow units based on its physical structure, process speed, and flow and storage capacities. These techniques include Testerman statistical method, stratigraphic modified Lorenz plot (SMLP) method, cluster analysis method, and flow zone indicator method. These methods have been applied successfully by different researchers in different geologic areas in the delineation of oil and gas reservoir flow units. Their results have been of tremendous advantage in the oil and gas sector as it has been able to assist the industry in identifying reservoirs speed zone, baffle, and seal zones. Groundwater usually located within weathered, fractured, or faulted chambers of rock units has its occurrence, flow, and storability in a rock terrain influenced by the geologic processes. Groundwater which has similar fluid attributes with oil and gas can be identified and explored employing SMLP method. In recent times, greater percentage of the water scheme developed by governmental bodies and non-governmental bodies (NGOs) in Edem are largely non-functional, and with an increasing population of the people in the area, the quantity of water demanded and water supplied vary widely, thus posing a daily threat to water accessibility [29]. With rapid increase in population and agricultural activities in Edem, eastern Nigeria, and failures of boreholes and water scheme development leading to high rate of water scarcity, proper geophysical study is encouraged to be carried out within the study area and its environs. The SML plot, the key method of this study, has been widely applied by many authors to slice the reservoir into some HFUs which are described either as non-conductive (tight, barrier or seal), conductive, or super conductive zones [13]. It has been applied and verified by many authors over the last two decades (e.g., [3, 7, 17, 22, 25, 26, 30]). Subdividing the aquifer or reservoir sequences into some flow units (FUs) is one of the most serious challenges that face reservoir characterization and modeling [1]. It may be a complicated process due to the heterogeneous nature of the hydrocarbons-bearing reservoirs. The stratigraphic modified Lorenz plot (SML) is one of the most important techniques that can be applied to subdivide the reservoir sequence into FUs. It is based on an estimation of the flow and storage capacity of the studied sequence in an accumulative manner.

For accuracy and evaluation of statistical zonation, the stratigraphic modified Lorenz plot (SMLP) was employed. The thrust of this study is to assess the aquifer flow units of Edem and its heterogeneity employing stratigraphic modified Lorenz plot (SMLP) and Dykstra-Parsons coefficient.

Location and geological setting of the study area

The study area is situated in Edem, Nsukka local government area of Enugu state, and lies within the Anambra sedimentary basin, Nigeria (Fig. 1). The study area is characterized with an elevation variation between 300 and 450 m above sea level. The location spreads over an area of about 50.492 km^2 with an estimated total population of 309,633 [27]. The study area is classified into two seasons: the dry season (October–March) and the rainy season (April–October) [16] with temperature varying from 19 °C to 33 °C. The location of the study area lies within the tropical rain forest/Guinea savannah belt of Nigeria. It is located within longitude 7.27° E to 7.38° E and latitude 6.82° N to 6.92° N (Fig. 2). Nsukka Formation and the underlying Ajali Sandstone underlie the study area. There are also the presence of residual hills and dry valleys which are associated with the rock type or geologic formation underlying the area. These two major geomorphic

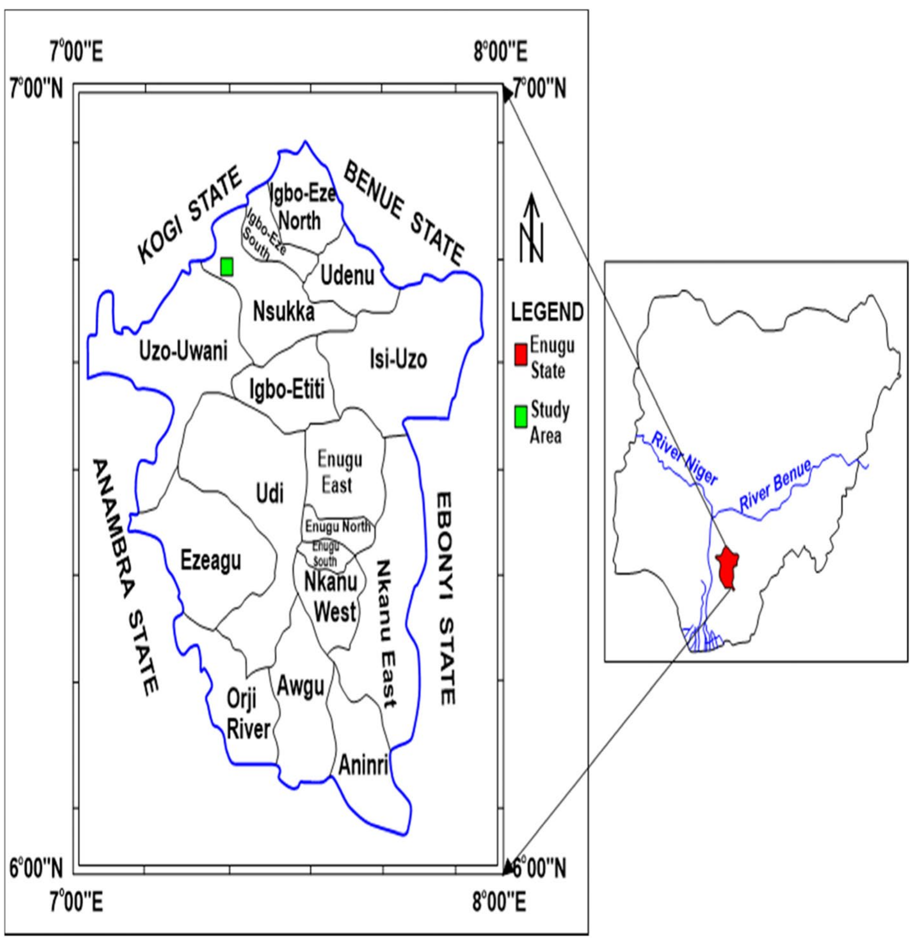

Fig. 1 Map of Enugu state showing the study area

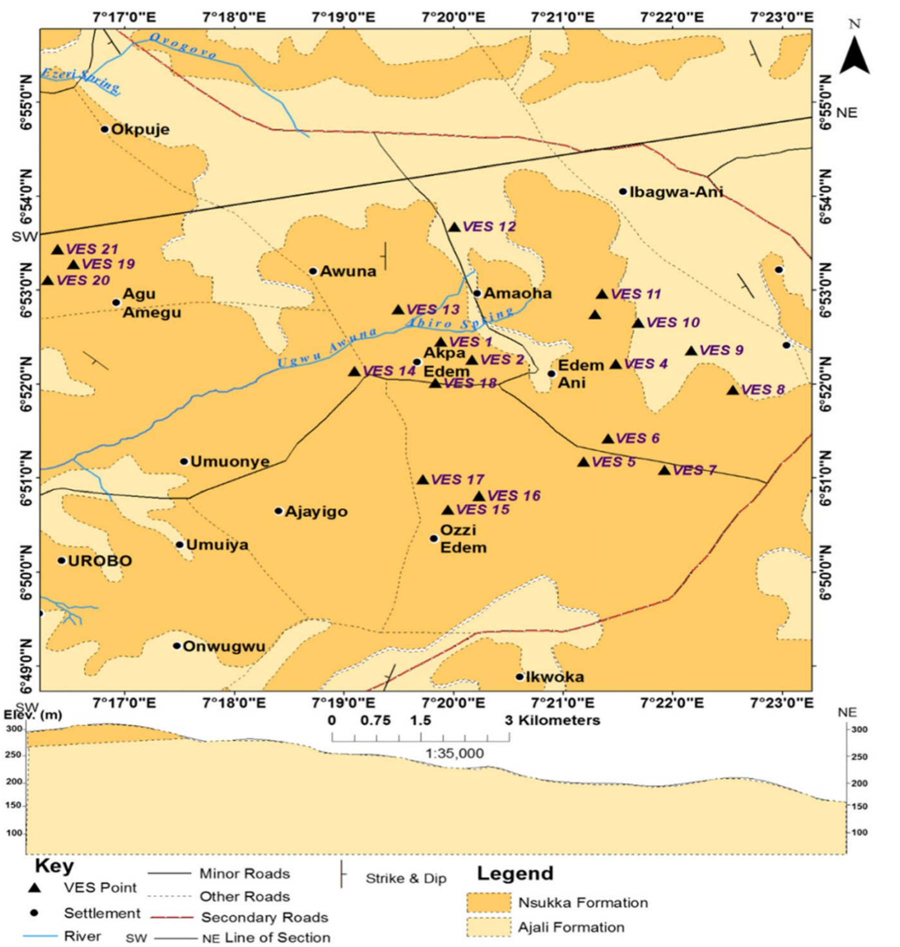

Fig. 2 Geologic map of the study area

structures are the resultant effect of weathering and differential erosion of clastic materials which are remnant of Nsukka Formation [28]. Bounded on the east, west, south, and north of Edem are Nsukka, Nrobo, Obimo, and Ibagwa-ani respectively.

Methods

Vertical electrical sounding was carried out in twenty-one (21) locations of the study area employing Schlumberger electrode configuration to obtain the apparent resistance and other field data. Apparent resistivity (ρ_a) values were calculated from the measured field data. Manual and computer modeling techniques help in reducing the field data to its suitable geological model [32]. WinResist Software was employed to generate the values of the geoelectric layers resistivity, thickness, and depth. The thickness and resistivity values were used to estimate some of the hydraulic properties which were employed in the analysis of aquifer flow units.

Flow unit determination

The field data obtained from the study area was analyzed using the stratigraphic modified Lorenz plot (SMLP) method. This method is a graphical tool which uses various data including the geological framework, storage capacity, and flow capacity. SMLP is a cross-plot of the cumulative flow capacity and cumulative storage capacity of the aquifer, derived from the aquifer geophysical properties. The stratigraphic modified Lorenz (SML) plot is one of the most important techniques that are applied for flow unit (FU) discrimination. It is based on core data, porosity, and permeability which are multiplied by their representative bed thicknesses (h), and the obtained results are called storage capacity (ϕh) and flow capacity ($K_p h$), respectively [13, 23, 25]. The cumulative flow capacity and storage capacity are calculated using the Maglio [23] mathematical models as shown in Equation 1 and 2.

$$\left(K_p h\right)_{cum} = k_{p1}(h_1 - h_0) + k_{p2}(h_2 - h_1) + \cdots + k_{pi}(h_i - h_{i-1}) / \sum k_{pi}(h_1 - h_{i-1}) \tag{1}$$

$$(\varphi h)_{cum} = \varphi_1(h_1 - h_0) + \varphi_2(h_2 - h_1) + \cdots + \varphi_i(h_i - h_{i-1}) / \sum \varphi_i(h_i - h_{i-1}) \tag{2}$$

where k_p is permeability (mD), h is thickness, and $(K_p h)_{\text{cum}}$ is cumulative flow capacity.

ϕ = fractional porosity, $(\phi h)_{\text{cum}}$ = cumulative storage capacity

Some of the hydraulic properties, estimated which enhanced the determination of the flow units, include hydraulic conductivity, porosity, permeability, and tortuosity. Values of hydraulic conductivity were estimated using Equation 3 according Heigold et al. [14].

$$K = \frac{386.40}{{\rho_a}^{0.93283}} \tag{3}$$

Porosity is a property that depends on the grain composition of the soil, and pressure to which it is exposed. Porosity and tortuosity values were determined using Marotz [24] and The Netherland Organisation [31] equations respectively as shown in Equations 4 and 5.

$$\varphi = 25.5 + 4.5 InK \tag{4}$$

where K is hydraulic conductivity

$$\tau = (F\varphi)^{\frac{1}{2}} \tag{5}$$

For an aquifer to be productive, it must be porous and permeable. Permeability of the aquifer layer was estimated following Kozeny [20] and Carman [2] equations shown in Equation 6.

$$K_p = 1014 \frac{\varphi^3}{(1-\varphi)^2} \left(\frac{1}{F_s \tau^2 {S_{gv}}^2} \right) = 1014 \frac{\varphi^3}{(1-\varphi)^2} * \left(\frac{1}{2\tau^2 {S_{gv}}^2} \right) \tag{6}$$

S_{gv} is surface area per unit pore volume ,τ is tortuosity, and F_s is shape factor and it equals 2 for a circular cylinder.

Heterogeneity determination

There are varieties of statistical techniques such as coefficient of variation, Dykstra-Parsons coefficient, and the Lorenz coefficient employed in the quantification of heterogeneity. Dykstra-Parsons coefficient is a permeability model and can be considered as a more statistically robust technique though requiring additional application of statistical methodologies [9]. This study employed Dykstra-Parsons coefficient in quantifying heterogeneity through heterogeneity measures. Heterogeneity measures provide a single value for quantifying samples variability and also provide the ability to compare this variability between different reservoirs. Jensen et al. [19] suggest that heterogeneity measures provide a simple way to assess a reservoir and guide investigations towards more detailed analysis of spatial arrangement and internal structure of a reservoir.

Dykstra-Parsons coefficient (V_{DP}) enables the measurement of water flow performance in layered reservoir by providing the degree of stratification (vertical permeability heterogeneity) and sweep efficiency. V_{DP} values vary from 0 to 1 as classified based on the Dykstra-Parsons coefficient. From the classification, 0 indicates a homogeneous system, between 0 and 0.6 represents small heterogeneity, while values from 0.7 to 1 indicates high to extremely high heterogeneities [21]. The Dykstra-Parsons coefficient was determined using Dykstra and Parsons [5] equation as shown in Equation 7.

$$V_{DP} = 1 - e^{-\sigma} \tag{7}$$

where $\sigma$is the standard deviation.

Figure 3 is a flow chart showing the research methodology.

Results and discussion

The results of this study (Table 1) give values of the geoelectric properties with aquifer layer resistivity ranging from 34.80 to 67561.20 Ωm indicating the presence of low conducting geomaterials; the variations of aquifer resistivity can be attributed to the compact nature of the soil or the geologic composition of the soil. The aquifer thickness ranges from 24.8 to 147.6 m having an average value of 70.248 m. VES 2, 3, 12, 13, 16, 17, and 19, with high values of aquifer thickness compared to other VES points, can be delineated as having substantial quantity of groundwater accumulation. Hydraulic properties were estimated from the values of aquifer resistivity and thickness (Table 1). The hydraulic conductivity (K) range from 0.0121 to 14.0931 ms^{-1}; the values of aquifer fractional porosity range from 0.2558 to 0.3265 with an average value of 0.0290. Permeability is a key parameter that influences the flow in an aquifer varies from 1.57337E−15 to 1.6357−E-09 m^2. Permeability (K_p) in $(\mu\mathrm{m})^2$ were converted to millidarcy (mD) by dividing K_p in $(\mu\mathrm{m})^2$ with a conversion factor of 0.0009869233 $(\mu\mathrm{m})^2$. K_p results in mD as presented in Table 2 varies from 3.7169 to 1657444 mD. The results of these hydraulic properties were employed in the analysis of aquifer flow units.

Aquifer flow units' analysis

The SML plot for the aquifer in Edem is shown in Fig. 4. The structure of the SML plot is a representation of the aquifer flow performance [8]. From the plot, the inflection

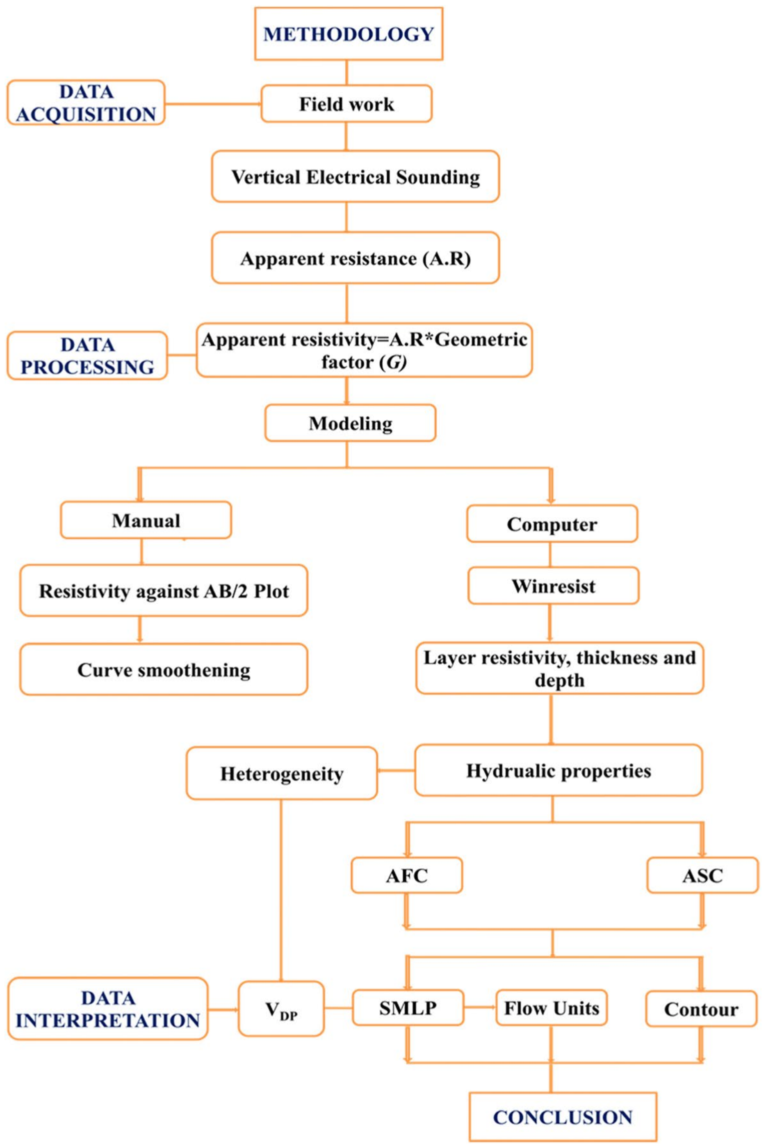

Fig. 3 Flow chart showing research methodology

or break points observed on the crossplot indicate changes in flow or storage capacity and are interpreted to define the number of flow units in the SML plot, allowing for the evaluation of reservoir flow. The results of stratigraphic modified Lorenz plot (SMLP) delineated a total of eight flow units for the aquifer units of the study area (FU1, FU2, FU3, FU4, FU5, FU6, FU7, and FU8) as shown in Fig. 4. These flow units were further classified into three different flow process speeds according to their sloping nature (Table 3).

From SMLP results, areas with abrupt slopes are areas with higher percentage of aquifer flow capacity compared to storage capacity. Steeper slopes indicate faster rates of flow [1]. These areas are delineated as having high reservoir process speed and are known as the speed zones [4]. The speed zones are indicative of permeable

Table 1 Summary of results of geohydraulic properties of aquifer layers in the study area

VES	Location	Long. (°E)	Lat. (°N)	ρ_a (Ωm)	h_a (m)	K_h (m/s)	Fractional Porosity Φ	τ	R_{pi}(m)	S_{gv}(m^{-1})	K_p $(\mu m)^2$	K_p (mD)	AFC (m^2D)	ASC (m)	AFC_{cum} (m^2D)	ASC_{cum} (m)	FUS (mD)
1	Amadimogo	7.3313	6.8737	34.8	29.7	14.0931	0.3265	1.499	4.71E−06	102925.9	1635.77	1657444	49226087	9.697	49226087	9.697	5076424
2	Nwaorie	7.3361	6.8719	114.1	98.4	4.6552	0.3154	1.529	1.643E−06	280406	184.877	187326.3	18432908	31.035	67658995	40.732	1661077
3	Ama-Ahor	7.3305	6.8665	41427.4	81.2	0.0190	0.2604	1.707	9E−09	39120245	3.66829E−03	3.7169	301.8123	21.144	67659297	61.876	1093466
4	Farm School	7.6756	6.7980	114.8	30.0	4.6287	0.3153	1.529	1.634E−06	281819.9	182.175	184589.1	5537673	9.459	73196970	71.335	1026102
5	Ishioyo	7.2716	6.8851	85.6	74.5	6.0865	0.3181	1.521	2.119E−06	220146.6	312.364	316503	23579474	23.698	96776443	95.033	1018346
6	Idina	7.2728	6.9001	794.7	77.2	0.7614	0.2973	1.582	2.95E−07	1434178	5.23919	5308.615	409825.1	22.952	97186268	117.985	823717.2
7	Igoro-Agbor	7.3333	6.8945	57426.6	67.3	0.0140	0.2573	1.719	7E−09	49491239	2.1577E−03	2.186293	147.1375	17.316	97186415	135.301	718297.8
8	Obeke	7.3249	6.8797	7517.2	30.6	0.0936	0.2763	1.65	4.1E−08	9311903	8.65906E−02	87.73796	2684.782	8.455	97189100	143.756	676069.9
9	Owa	7.3232	6.8681	1483.6	24.8	0.4253	0.2915	1.6	1.7E0−7	2420192	1.66491	1686.97	41836.86	7.229	97230937	150.985	643977.5
10	ObinaguOw-erre	7.6774	6.6302	224.1	64.1	2.4801	0.3091	1.547	9.04E−07	494897.6	534.208	54128.68	3469648	19.813	100700585	170.798	589588.8
11	Nkoffi	7.8663	6.8748	241.7	63	2.3112	0.3084	1.549	8.45E−07	527718.9	465.462	47162.92	2971264	19.429	103671849	190.227	544990.2
12	Amenu	7.3533	6.8627	10364.6	83.9	0.0694	0.2733	1.66	3.1E−08	12131731	4.83016E−02	48.94161	4106.201	22.93	103675955	213.157	486383.1
13	Ugwunagbor	7.3566	6.8534	15360.2	83.4	0.0481	0.2696	1.673	2.2E−08	16777855	2.3622E−02	23.93495	1996.175	22.485	103677952	235.642	439980.8
14	Agu-Eke	7.3654	6.8513	67561.2	71.3	0.0121	0.2558	1.724	6E−09	57287468	1.57337E−03	1.59422	113.6679	18.239	103678065	253.881	408372.7
15	Umuchagwu	7.3759	6.8653	29654.3	74	0.0260	0.2635	1.695	1.2E−08	29814438	6.70443E−03	6.793267	502.7018	19.499	103678568	273.38	379247.1
16	Umuchoke	7.3689	6.8717	22569.4	147.6	0.0336	0.2661	1.686	1.5E−08	24172231	1.07033E−02	10.84512	1600.74	39.276	103680169	312.656	331611
17	Ubogidi	7.3613	6.8773	2004.1	82	0.3213	0.2886	1.609	1.3E−07	3120607	9.56679E−01	969.355	79487.11	23.665	103759656	336.321	308513.8
18	Ozalla	7.3363	6.8817	19866.5	51.5	0.0378	0.2672	1.682	1.7E−08	21448754	1.38667E−02	14.05047	723.5992	13.761	103760379	350.082	296388.8
19	Gbugbu	7.3445	6.8000	612.8	120.9	0.9704	0.2997	1.574	3.71E−07	1153530	8.44335	8555.231	1034327	36.234	104794707	386.316	271266.8
20	Amabunagu	7.3386	6.8468	230.9	73.9	2.4119	0.3088	1.548	8.8E−07	507681	50.6497	51320.79	3792606	22.82	108587313	409.136	265406.4
21	Ngbakwu	7.3286	6.8495	82.1	45.9	6.3282	0.3185	1.52	2.199E−06	212529.1	3.37464E−10	341935.3	15694830	14.619	124282144	423.755	293287.7

Table 2 Results of heterogeneity measurement

VES	Location	K_p (mD)	X = Ln (K_p)	(X-X_{av})	$(X-X_{av})^2$
1	Amadimogo	1657444	14.321	7.203	51.883
2	Nwaorie	187326.3	12.141	5.023	25.231
3	Ama-Ahor	3.7169	1.313	−5.805	33.698
4	Farm School	184589.1	12.126	5.008	25.08
5	Ishioyo	316503	12.665	5.547	30.769
6	Idina	5308.615	8.577	1.459	2.129
7	Igoro-Agbor	2.186293	0.782	−6.336	40.145
8	Obeke	87.73796	4.474	−2.644	6.991
9	Owa	1686.97	7.431	0.313	0.098
10	Obinagu-Owerre	54128.68	10.899	3.781	14.296
11	Nkoffi	47162.92	10.761	3.643	13.271
12	Amenu	48.94161	3.891	−3.227	10.414
13	Ugwunagbor	23.93495	3.175	−3.943	15.547
14	Agu-Eke	1.59422	0.466	−6.652	44.249
15	Umuchagwu	6.793267	1.916	−5.202	27.061
16	Umuchoke	10.84512	2.384	−4.734	22.411
17	Ubogidi	969.355	6.877	−0.241	0.058
18	Ozalla	14.05047	2.643	−4.475	20.026
19	Gbugbu	8555.231	9.054	1.936	3.748
20	Amabunagu	51320.79	10.846	3.728	13.898
21	Ngbakwu	341935.3	12.742	5.624	31.629
Summation			149.484		432.632

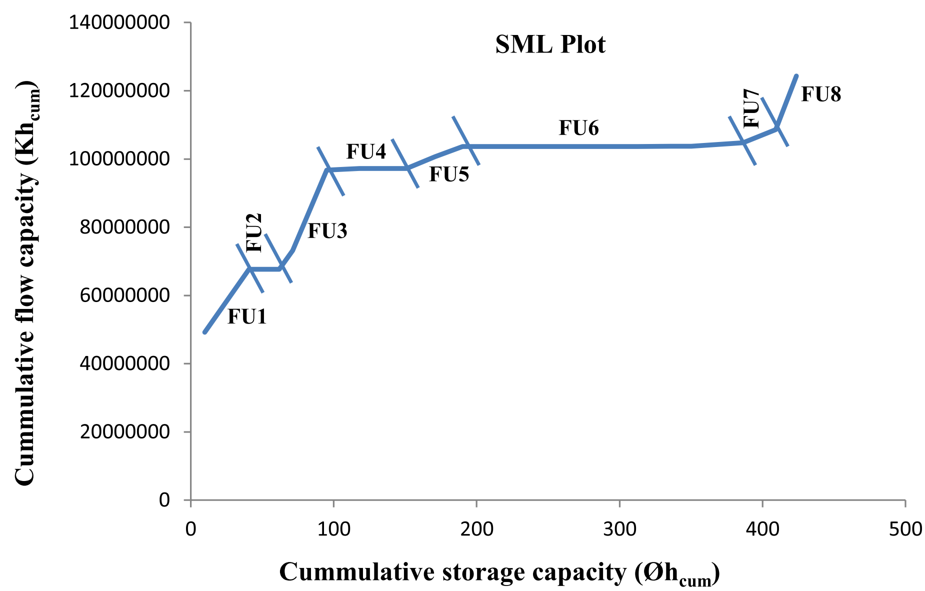

Fig. 4 Graph of SMLP showing the flow units in the study area

high-performance flow units [12]. Aquifer flow units FU1, FU3, and FU8 fall within the speed zone as shown in Table 3 and identified in the SMLP (Fig. 4) with higher degree angle trend of flow capacity. Flow units FU1, FU3, and FU8 have higher

Table 3 Aquifer flow unit characterization

Flow units (FU)	Flow unit characterization		
	Speed zones	Baffle zone	Barrier zone
FU1	✓		
FU2			✓
FU3	✓		
FU4			✓
FU5		✓	
FU6			✓
FU7		✓	
FU8	✓		

porosity and permeability values compared to other flow units of the study area (Table 1). This suggests that sediments deposited in the environments within these flow units have good aquifer qualities [8]. High aquifer storage capacity and small flow capacity are associated with areas along the smooth slopes of the SML plot indicating the ineffectiveness of some pores in contributing to the flow. Such areas are the slightly permeable zones with very low aquifer flow capacity compared to the storage capacity. Areas with these characteristics are the baffle zones of the aquifer. Baffle zone gradient on the SMLP is almost horizontal. Aquifer flow units FU5 and FU7 of the study area are associated with the baffle zone. This may have been caused by the presence of shale that occurred as intercalations in the aquifer and as a result of the aquifer stratigraphically falling within the lower shoreface dominated by silty/mud [8].

Areas on the SMLP with very low or flat slope are regarded as impermeable areas. These areas are the barrier zone of the aquifer. Barrier zone are impermeable zone with very low flow and storage capacities. Flow units FU2, FU4, and FU6 occupy the barrier zone of the study area. This barrier zone indicates area in an aquifer with very low porosity and permeability which may be due to the presence of sealing faults that hinder the flow of fluid. This is justified with the porosity and permeability range of the VES stations 3, 7, 13, 14, 15, and 17 found within the flow units FU2, FU4, and FU6.

The differences in the properties of the various flow units can be attributed to variation in the compaction of the sediments and digenesis with depth. The similarity in petrophysical behavior represented by the storage and flow capacities is the key factor for defining the FU [1]. Samples within the same HFU have a similar porosity contribution to their permeability.

Figure 5 is a contour map showing the variation of aquifer storage capacity (ASC). The variation divides the map into high and low ASC. Zones along the western part of the map are characterized with high values of ASC with low ASC values observed along the eastern part. A fraction along the northwestern part is delineated as having the highest magnitude of ASC compared to other western parts. This variation of ASC could be influenced by the thickness of geological formation and sensitivity of lithofacies [10].

Aquifer flow capacity (AFC) contour map (Fig. 6) shows that greater proportion of the aquifer in the study area is characterized with high percentage values of AFC with the highest percentage observed along the northwestern part of the map. This suggests that

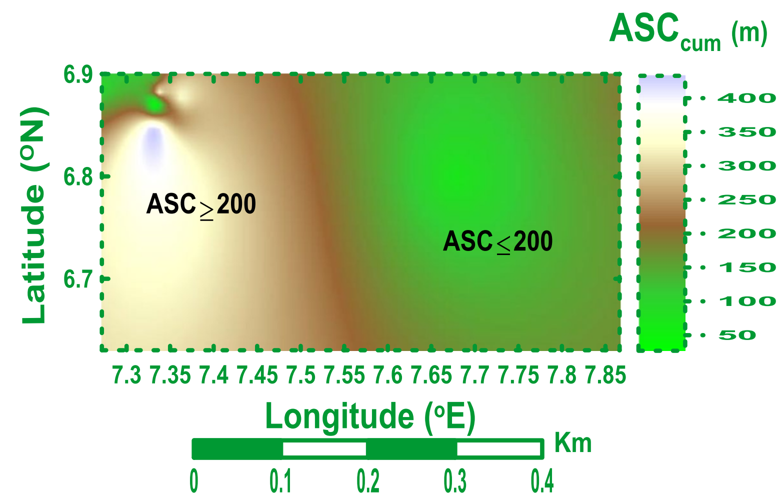

Fig. 5 Contour map showing aquifer storage capacity variation

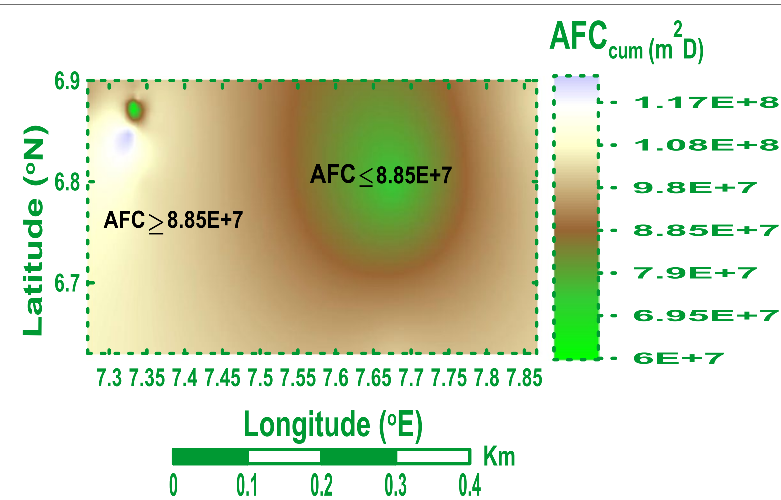

Fig. 6 Contour map showing aquifer flow capacity

the aquifer layers in greater parts of the study area are of good quality, and the pores are all contributing to the flow capacity. Comparing AFC contour map with ASC map, it is observed that the area along the northwestern part having higher ASC compared to other areas corresponds to area with higher AFC. This area can be delineated as having higher aquifer thickness, higher porosity, and higher permeability compared to other areas, thus higher groundwater productivity.

Conclusions

Aquifer characterization in Edem has been carried out by flow unit techniques employing stratigraphic modified Lorenz plot. The results of stratigraphic modified Lorenz plot (SMLP) delineated a total of eight flow-units for the aquifer units of the study area (FU1, FU2, FU3, FU4, FU5, FU6, FU7, and FU8) and three different process speeds. Aquifer flow units FU1, FU3, and FU8 were identified to fall within the speed zone with flow units FU5 and FU7 and flow units FU2, FU4, and FU6 occupying the baffle zone and the barrier zone respectively. The results from field data analysis identified VES 2, 3, 12, 13, 16, 17, and 19, as characterized with higher aquifer thickness magnitude compared to other VES points of the study area. Aquifer storage capacity and aquifer flow capacity were identified from the various contour maps to be high along the western part of the study area with the highest storage and flow capacities delineated along the northwestern part of the area. Contour map of aquifer flow capacity identified the northeastern part and a small proportion along the northwestern part as characterized with low aquifer flow capacity. The aquifer storage capacity as revealed in its map characterizes the eastern part and a slight fraction along the northwestern part with low aquifer storage capacity. Aquifer of the study area was observed to be extremely heterogeneous with a Dykstra-Parsons coefficient of 0.99.

Abbreviations
SMLP: Stratigraphic modified Lorenz plot; FU: Flow unit; V_{DP}: Dykstra-Parsons coefficient; ρ_a: Apparent resistivity; TNO: The Netherlands Organisation; ASC: Aquifer storage capacity; AFC: Aquifer flow capacity; ρ_a: Aquifer resistivity; h_a: Aquifer thickness; τ: Tortuosity.

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Authors' contributions
ETO took part in data acquisition and analysis and interpretation and did much of the writing. DNO contributed in the data interpretation and writing of the manuscript. FNO contributed in the data interpretation and writing of the manuscript. DOU contributed in analyzing and interpreting the data. JCI was involved in the data acquisition, analysis, interpretation, and writing of the manuscript. ASA took part in the acquisition and analysis and interpretation of data. All the authors read and approved the final manuscript.

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Availability of data and materials
All data generated or analyzed during this study are included in this article.

Declarations

Competing interests
The authors declare that they have no competing interests.

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