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Evaluation of aquifer hydraulic conductivity and transmissivity of Ezza/Ikwo area, Southeastern Nigeria, using pumping test and surficial resistivity techniques

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Abstract Aquifer hydraulic parameters including hydraulic conductivity and transmissivity play a very important role in the assessment and management of groundwater. Conventionally, these parameters are best estimated employing pump test, which is usually expensive and time-consuming. The use of surficial electrical resistivity data integrated with few available pumping test data provides a cost-effective and efficient alternative. A total of thirty-five (35) vertical electrical soundings with a maximum half-current electrode spacing of 150 m using the Schlumberger array were used in this study. Five (5) of these soundings were parametric soundings carried out in the vicinity of monitoring wells for correlation and comparative purposes. The empirical relationships between the hydraulic parameters derived from the pump test data and the aquifer resistivity data were established for the Ebonyi and Abakaliki Formations, respectively, and, in turn, used to estimate aquifer hydraulic parameters in areas away from wells. Aquifer hydraulic conductivity estimated across the study area varies from 0.49 to 1.5735 m/day with a mean value of 0.9205 m/day for the Ebonyi Formation, while the Abakaliki Formation has hydraulic conductivity values that vary from 0.0775 to 1.3023 m/day, with a mean value of 0.2883 m/day. The transmissivity values estimated across the study area range between 0.29 and 57.27 m^2/day with a mean value of 6.59 m^2/day. Transmissivity values obtained were interpreted with Krásný's transmissivity classification, and this delineated the study area into three groundwater potential zones: very low, low, and intermediate zones. The study shows that the areas underlain by the Ebonyi Formation have a higher groundwater potential than those underlain by the Abakaliki Formation. These findings are supported by the geology of the area, which revealed that the Abakaliki Formation is dominated by shales with very low permeability, while the Ebonyi Formation consists of shales with alternations of sand/sandstones, which statistical analysis of the different model equations used in estimating the hydraulic parameters of the study area revealed that the new model empirical equations proposed and used in the present study proved to be the best alternatives to pumping test data.

Keywords Aquifer potential · Hydraulic conductivity · Pump test · Transmissivity · Vertical electrical sounding

Introduction

In the study area, surface water is a major source of water for domestic purposes, but due to challenges of

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population growth, climate change, and contamination from anthropogenic sources, its potentials have been pushed to its very limit (Opara et al., 2020; Urom et al., 2021). Groundwater is the second largest freshwater reservoir in the world, accounting for 12% of the world's freshwater reserve, the largest resource being ice-locked water (87%), while surface water accounts for just around 1% of the world's freshwater reserves (Gleick, 2011). Groundwater presents itself as a viable and safe source of potable water and a widely accepted and better alternative to surface water resources (McDonald et al., 2002; Singh, 2007). The search for groundwater in the study area was intensified because of the dearth of clean and potable surface water as most surface water across the study area are either saline, contaminated by mining activities, or infested with coliform and other pathogens (Obarezi & Nwosu, 2013; Obiora et al., 2015). Most surface water within the study area over the years have been plagued by Guinea worm which has further compounded the status of the surface water (Aghamelu et al., 2013; Okoronkwo, 2003). Also, the availability and productivity of groundwater in boreholes within the study area are usually problematic because most of the boreholes drilled are either abortive, unproductive, or have extremely low yields.

Successful exploration, exploitation, and effective management of groundwater resources therefore require an adept knowledge of the aquifer conditions including their geometrical and hydraulic parameters (Amos-Uhegbu, 2013; Ezeh, 2012; Hasan et al., 2020; Ogbuagu et al., 2018). These aquifer hydraulic parameters include transmissivity and hydraulic conductivity values. The conventional means of determining these parameters are usually through pumping test (Butler et al., 1999), but this approach is usually expensive and may be challenging in places where wells are widely spaced; thus, the interpolation of aquifer properties between the wells is usually difficult and often incorrect, since geological conditions vary relatively over very small distances (Bogoslovsky & Ogilvy, 1977; Muldoon & Bradbury, 2005). Vertical electrical sounding (VES) is an alternative means of estimating hydraulic properties of the groundwater system before drilling (Ekwe & Opara, 2012; Mbonu et al., 1991; Opara et al., 2020; Ugada et al., 2013). The integration of hydraulic parameters evaluated via pump testing in nearby monitoring wells and aquifer resistivity parameters estimated through geo-electrical techniques has been fully achieved by several authors (Chenet al., 2001; Dasargues, 1997; Ejiogu et al., 2019; Ekwe et al., 2020; Frohlichet al., 1996; Harry et al., 2018; Hasan et al., 2020; Heigold et al., 1979;Kalinski et al., 1993; Kelly & Frohlich, 1985; Mbonu et al., 1991; Nwosu etal., 2013; Ponzini et al., 1984; Purvance & Andricevic, 2000; Sinha et al.,2009; Ugada et al., 2013). Ugada et al. (2013) made use of the Dar Zarrouk parameters to estimate the aquifer properties of Umuahia. Ngwoke (2013) determined aquifer parameters in Ishiagu, Ebonyi State, using geo-electric methods. Also, Ekwe et al. (2020) determined aquifer parameters from geo-sounding data in parts of the Afikpo sub-basin, southeastern Nigeria. However, Sinha et al. (2009) proposed a hydrogeological model of the relationship between geo-electric and hydraulic parameters of an anisotropic aquifer.

Also, analytical equations generated by the integration of surface resistivity techniques and pumping test data had been used to estimate aquifer hydraulic parameters in different parts of Nigeria by some authors (Ejiogu et al., 2019; Emberga et al., 2021; Opara et al., 2020; Urom et al., 2021). These studies suggested that the estimation of hydraulic parameters from geologically constrained geo-electrical equations is feasible. However, such a relationship depends on specific areas and may have limited application in other areas except in areas of similar geology (Hasan et al., 2019; Purvance & Andricevic, 2000; Rehfeldt et al., 1992; Salem, 1999; Urom et al., 2021). An empirical equation that is formation-specific and constrained by the geology of the study area was proposed and used in the present study. The predictive accuracy of the model derived from the present study was increased by carrying out parametric soundings at locations with existing monitoring wells from which pumping test data were acquired. This was done to avoid overestimating or underestimating the predicted aquifer hydraulic parameter values (Opara et al., 2020).

Conventionally, the only direct method of estimating aquifer parameters is the pumping test technique. However, in most developing countries of the world, there is a serious dearth of pumping test data due to the huge cost of this very important analysis. To solve this problem, some classical publications have been made on how to estimate aquifer parameters from geophysical methods (e.g., Heigold et al., 1979; Niwas & Singhal, 1981, etc.). However, both the Heigold et al. (1979) and Niwas and Singhal (1981) equations generally used in the area to estimate hydraulic parameters from resistivity data were generated using data from overseas in areas with little or no relationship with the geology of the study area. The present study which is centered on alternative means of estimating aquifer hydraulic characteristics in areas with limited pumping test data using surficial resistivity methods therefore proposed and used a set of new empirical models together with the Heigold et al. (1979) and Niwas and Singhal (1981) equations. These new sets of models were generated with empirical data from the study area and are therefore constrained by the local geology of the area. The various model equations were therefore comparatively used and ranked to know the best alternative model equations that can be used to estimative aquifer hydraulic parameters from resistivity data on a regional scale when pumping test data are scarce or not readily available.

The idea behind this therefore is to improve the predictive capacities of the empirical equations used to estimate aquifer hydraulic characteristics from resistivity data. The objective is to provide an empirical relationship that is formation-specific, i.e., based on the local geology of the area because it is believed that incorporating the effect of local geology will improve the quality of the predictions using resistivity data. This study therefore aims to establish a relationship between aquifer parameters (hydraulic conductivity and transmissivity) and electrical resistivity-related parameters (aquifer resistivity, transverse resistance, etc.) and to make use of this relationship to estimate aquifer hydraulic parameters in areas with a paucity of pumping test data.

Location and geology of the study area

The study area which is in southeastern Nigeria lies between latitude 6° 4′ 76″ N and 6° 11′ 94″ N and longitude 7° 58′ 32″ E and 8° 9′ 99″ E (Fig. 1) and occupies an area of 442.57 km^2. The fieldwork which involved field surficial electrical resistivity data acquisition took place between the 20th and 24th September 2019.

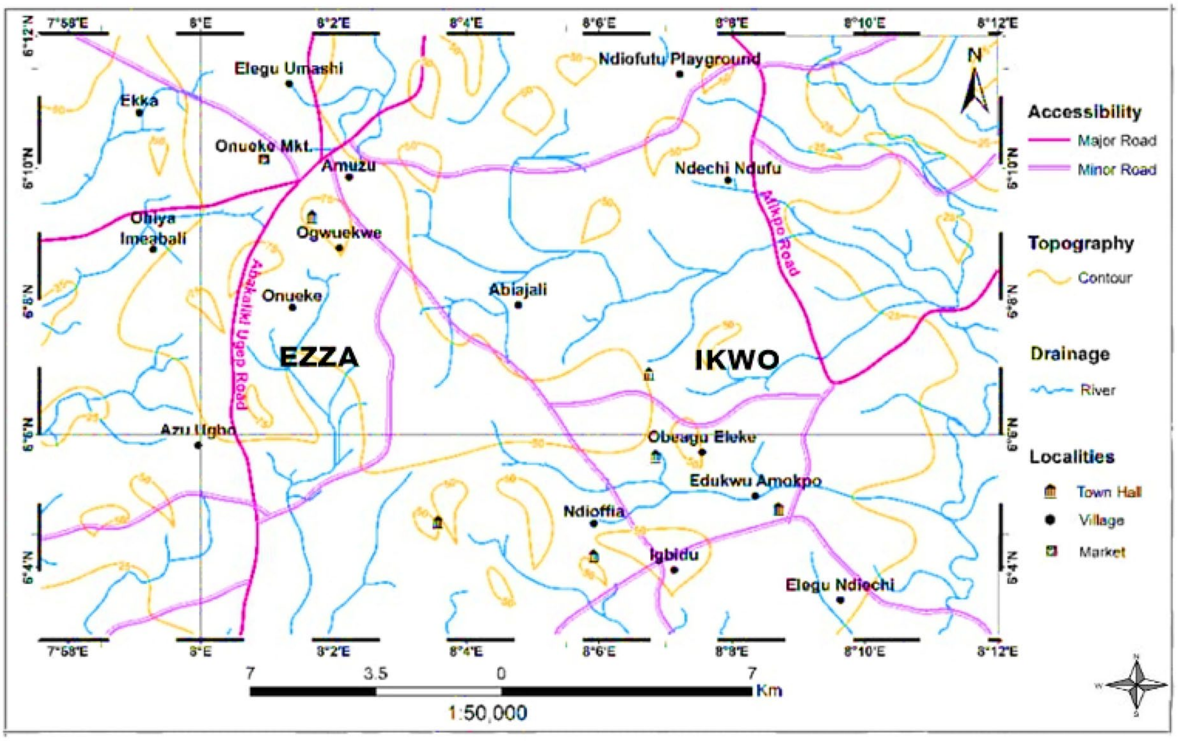


Fig. 1 Accessibility and drainage map of the study area

Based on the works of Reyment (1965), the study area falls within the Asu River Group formed during the Albian age and was folded into a northeast trend known as the Abakaliki Anticlinorium. Agumanu (1989) subdivided the Asu River Group based on stratigraphy into the Ebonyi Formation and Abakaliki Formation. The Ebonyi Formation (Mid-Albian) is underlain by the Abakaliki Formation (Late Albian–Cenomanian). The Ebonyi Formation dominates the eastern axis of the study area, which is made up of shales, rapid alternations of sandstones, siltstones, wacke stones, oolithic and serpulid stones, and mudstones (Fig. 2) (Oli et al., 2020).

The eastern axis of the study area on the other hand falls within the Abakaliki Formation, which is mostly dark-gray to black shales, and mudstones interspersed with siltstones, small feldspathic sandstones, and black micritic limestones. The stratigraphy of this formation indicates a reducing depository condition and anoxic environment, which aligns with Agumanu's (1989) concept of formation. The sandstones occur as minimal litho-facies or lenses.

Methodology

Pump testing was carried out in a total of five (5) wells in the study area to determine the aquifer hydraulic parameters. The constant rate pumping method with a single well was adopted, with drawdown observations on the same well. The static water level was measured before the start of the pumping test using the electrical water level probe (dipper). A 1.5 Hp submersible pump was installed into the well, and pumping was done for 180 min. Dynamic water levels in the boreholes were measured at stopwatch intervals. After pumping was stopped, residual drawdowns were also measured at different time intervals.

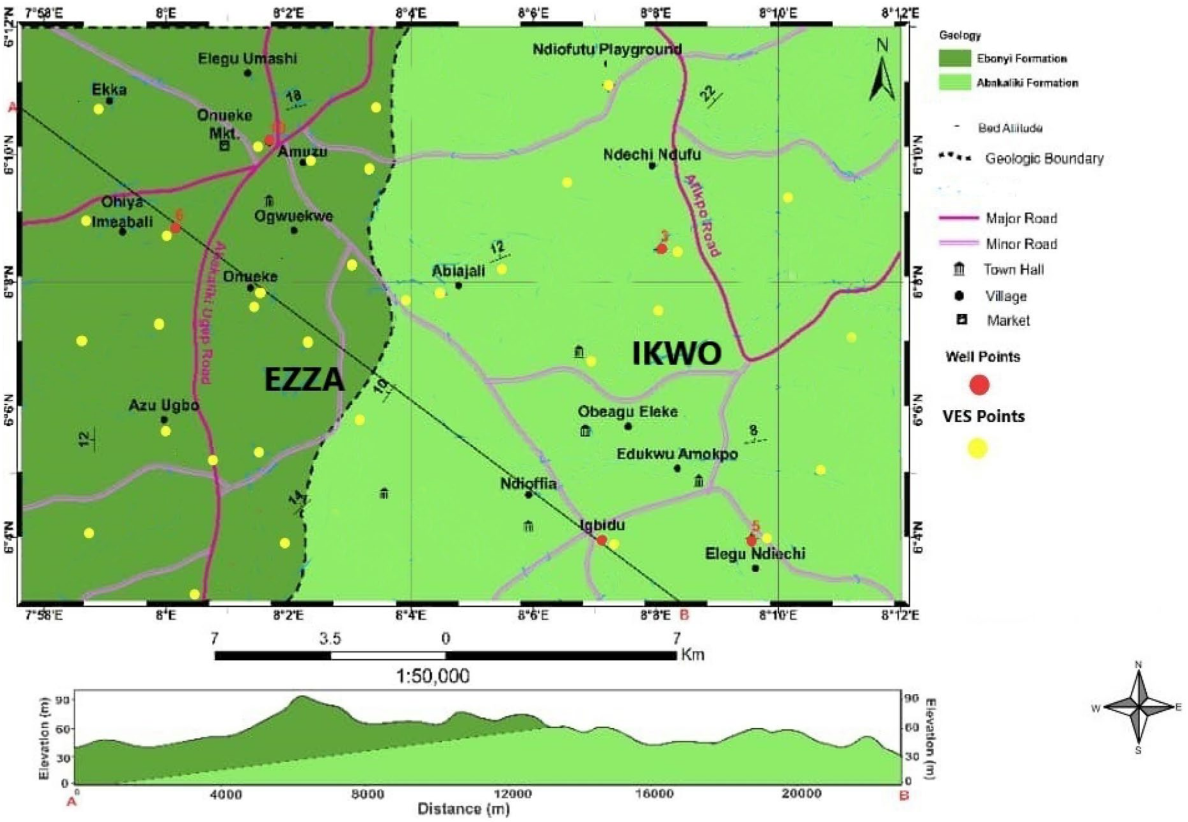


Fig. 2 Geologic map of the study area showing the VES and well locations

Also, thirty-five (35) sounding points were selected in the study area with a parametric sounding performed at each of the wells where the pumping test was conducted, with the aid of an ABEM Terrameter (SAS 4000). The sounding points were geo-referenced using a handheld Global Positioning System (GPS). The VES data acquisition was executed using the Schlumberger array, with a maximum half-current (AB/2) electrode separation of 150 m and half-potential (MN/2) electrode separation of 15 m. Apparent resistivity (ρa) values were deduced from the observed field data using Eq. (1):

$$\rho_a = \pi\left(\frac{a^2}{b} - \frac{b}{4}\right)\frac{\Delta V}{I} \tag{1}$$

Estimation of geo-hydraulic parameters

Estimates of geo-hydraulic parameters from pumping test

The Cooper and Jacob solution method was used to determine the aquifer-derived parameters (transmissivity and hydraulic conductivity) from the pumping test. This was achieved using a computer software (Aquifer Win32) by plotting drawdown against their respective time data acquired in the semi-log format during the pumping test. The transmissivity values were calculated using the formula by Freeze and Cherry (1979) as shown in Eq. (2):

$$T = \frac{2.3Q}{4\pi\Delta S} \tag{2}$$

where T = transmissivity in m^2/day, Q = discharge rate in m^3/day, and ΔS = change in drawdown over one logarithmic cycle.

The hydraulic conductivity was calculated from the transmissivity and aquifer depth values, which is, in this case, assumed to be the length of the screen, using the equation by Freeze and Cherry (1979) as shown in Eq. (3):

$$K = \frac{T}{B} \tag{3}$$

where K = hydraulic conductivity in m/day, b = aquifer thickness in m, and T = transmissivity in m^2/day.

Estimates from surficial resistivity data

Several electrical resistivity-based empirical equations have been previously used to estimate aquifer hydraulic and transmissivity values across the study area. These empirical equations include the equations of Niwas and Singhal (1981) and Heigold et al. (1979) and the proposed new model.

The determination of aquifer hydraulic characteristics can be accomplished by using parameters of transverse resistance and longitudinal conductance from Dar-Zarrock parameters. Niwas and Singhal (1981) developed, on one hand, an empirical relation between transmissivity and transverse resistance and, on the other, longitudinal conductance and transmissivity. Based on Darcy's law, the fluid discharge Q is given by Eqs. (4) and (5):

$$Q = KIA \tag{4}$$

And from Ohm's law

$$J = \delta E \tag{5}$$

where K = hydraulic conductivity, I = hydraulic gradient, A = cross-sectional area perpendicular to the direction of flow, J = current density, E = electric field intensity, and δ = electrical conductivity (inverse of resistivity).

Considering a prism of an aquifer material having a unit cross-sectional area and thickness h, Niwas and Singhal (1981) combined Eqs. (4) and (5) to get the equation given in Eq. (6):

$$T = k\delta R = KL/\delta \tag{6}$$

where T = aquifer transmissivity, R = transverse resistance, δ = aquifer conductivity, and L = longitudinal conductance.

It is well documented that quantitative representations of vertical electrical sounding data contribute to the creation of geo-electric layers in resistivity measurements. Layer parameters like aquifer depth and thickness therefore can be better identified with information from geo-electric layers. The resulting layer parameters are usually used to determine the Dar-Zarrock parameters. Therefore, the product of the aquifer's apparent resistivity (ρ) and the aquifer's thickness (h) results in transverse resistance (R) as shown in Eqs. (7) and (8):

$$R = hp \tag{7}$$

$$K_{NS} = k\delta\rho \tag{8}$$

Niwas and Singhal (1981) maintained that areas with similar geologic settings and water quality usually have fairly constant diagnostic constants (diagnostic constants is the product of the hydraulic conductivity (k) from pumping test and the electrical conductivity (δ). Based on this, therefore, the aquifer hydraulic parameters which vary spatially across an area both for the areas with pumping test values and areas without wells can be estimated from resistivity data measured at the surface of the earth.

Also, the Heigold et al. (1979) equation was used in this study to estimate hydraulic parameters across the study area. The Heigold et al. (1979) empirical equation is based on the relationship between hydraulic conductivity (K) obtained from pumping test from monitoring wells and water resistivity estimated from resistivity data carried out close to the wells as shown in Eq. (9):

$$K_{HG} = 386.40Rw^{-0.93283} \tag{9}$$

where Rw is aquifer resistivity. Then, the transmissivity of the aquifer (T) can now be estimated using the relationship given by Niwas and Singhal (1981) in Eq. (10):

$$T = k\delta T = ks/\delta = kh \tag{10}$$

where δ is the electrical conductivity (inverse of resistivity) and S is the longitudinal conductance.

Finally, a new set of formation-specific empirical equations that has a relationship with the intrinsic rock properties in the study area were proposed and used in the present study. Using the empirical relationship established between hydraulic conductivity derived from the pumping test in the study area and aquifer resistivity on one hand and that between transmissivity and transverse resistance, a set of two formation-specific model equations that are geologically constrained and sensitive were generated. Hydraulic conductivity and transmissivity acquired from the wells where pumping tests were conducted were plotted against aquifer resistivity and transverse resistance values, respectively, obtained from parametric soundings at the well locations in the different formations (Fig. 3a, b, c, and d), which thereafter were used to estimate transmissivity and hydraulic conductivity at locations where pumping test was not conducted.

These cross-plots yielded two sets of novel empirical equations of hydraulic conductivities (K) and transmissivities for Ebonyi and Abakaliki Formations, respectively, as given in Eqs. (11)–(14):

$$K^{ebfm} = 4.1559Rw^{-0.319} \tag{11}$$

$$K^{afm} = 0.0114Rw^{0.7792} \tag{12}$$

$$T^{ebfm} = 5330.4R^{-0.928} \tag{13}$$

$$T^{afm} = 0.0092R^{0.8117} \tag{14}$$

where K^{ebfm} = hydraulic conductivity for the Ebonyi Formation, K^{afm} = hydraulic conductivity for the Abakaliki Formation, T^{ebfm} = transmissivity for the Ebonyi Formation, T^{afm} = transmissivity for the Ebonyi Formation, Rw = aquifer resistivity, and R = transverse resistance. The coefficient of determination (R^2) for K^{ebfm}, K^{afm}, T^{ebfm}, and $\mathrm{T}^{\mathrm{afm}}$ was found to be 1.0, 0.997, 1.0, and 1.0, respectively, exhibiting a very strong positive relationship between the parameters.

Results and discussion

Interpretation of layer parameters

VES data were used to extract interpreted curves (Fig. 4). Interpretation of the geo-electric curves across the study area revealed four to seven (4–7) geo-electric layers with different intra-facies and inter-facies changes (Table 1). The curve types were observed to be mainly of the QH, QHK, QHKH, QQH, KHK, QHAK, and QQHK types. Ngwoke (2013) stated that the existence of several curve types shows a non-uniformity of resistivity patterns across the study area. The non-uniformity of layering and modification of layer properties is due to differential weathering, fracture anisotropy, and other geological factors, which generally result in differences in resistivity trends across the area of study. The dominant curve type is the QH curve with approximately 37%, QHK with 23%, and HK type with 9%, with the QQH, KHK, and QHAK

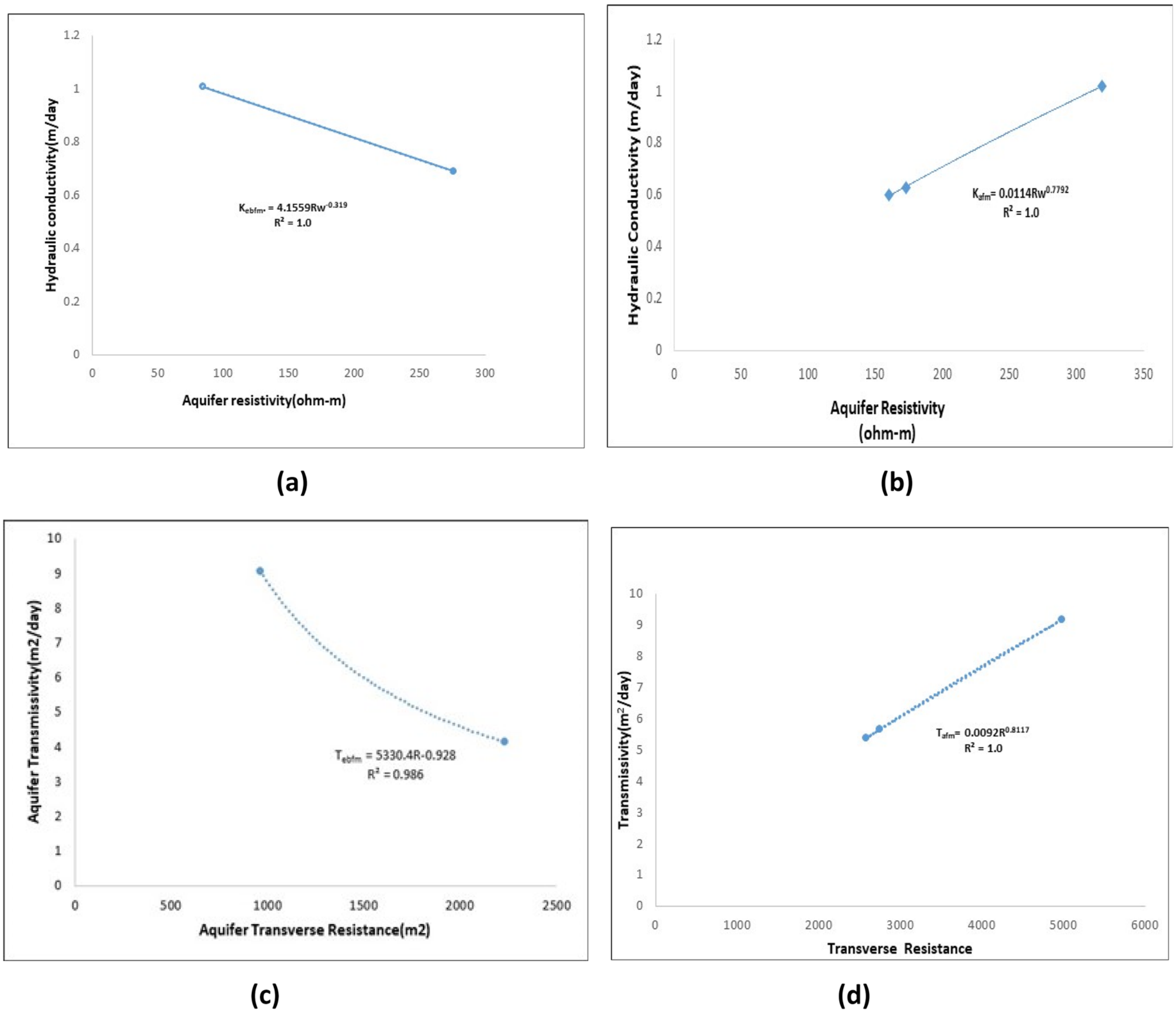


Fig. 3 Cross-plots showing relationships between aquifer hydraulic parameters and VES estimated parameters: **a** K^{ebfm}, **b** K^{afm}, **c** T^{ebfm}, **d** T^{afm}

accounting for 6%, respectively, while QQHK, KH, HA, and QHK each account for 5%.

Aquifer hydraulic parameters

The results of aquifer hydraulic parameters acquired using the pump testing techniques in the five wells are presented in Table 2. The pumping test data were analyzed and plotted using Copper–Jacob straight line curve with the aid of Aquiwin-32 software. Sample plots of the processed pumping test data acquired from the study area are presented in Fig. 5.

Aquifer hydraulic conductivity (K) estimates of the study area

Hydraulic conductivity (*K*), which is a measure of the ease with which a fluid will pass through a medium, and transmissivity (*T*), which is the rate of flow of fluid under a unit hydraulic gradient through a unit width of the aquifer of thickness, were estimated using the Niwas and Singhal (1981) (K_{NS}) equation, Heigold et al. (1979) (K_{HG}) equation, and the new empirical equations as shown in Table 3.

Hydraulic conductivity values estimated from the Heigold model using (Eq. (11)) for the Ebonyi Formation vary from 0.75 to 22.6 m/day, with a mean

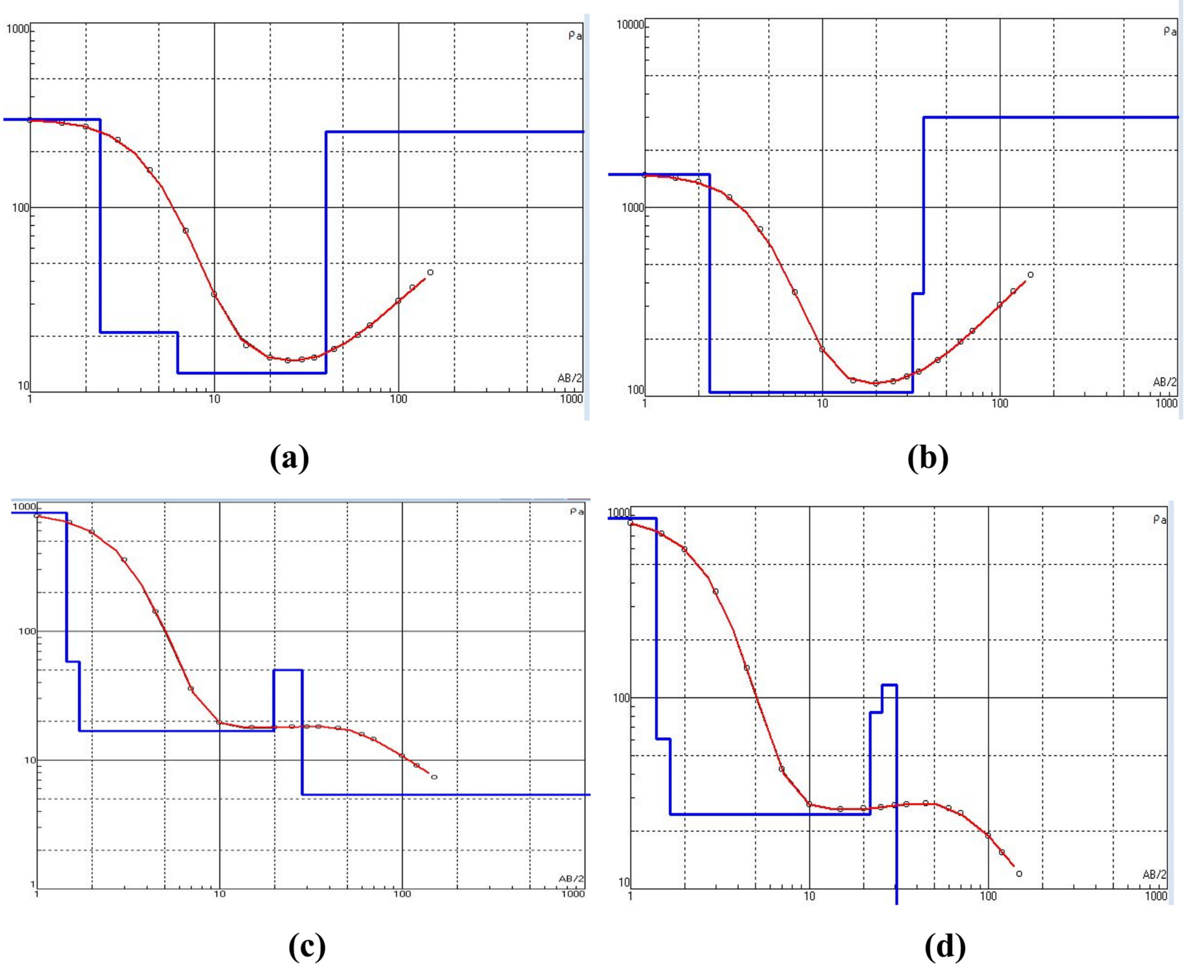


Fig. 4 Sounding curves from **a** VES 4, **b** VES 7, **c** VES 18, **d** VES 20

value of 5.84 m/day, while that of the Abakaliki Formation varies from 1.78 to 39 m/day and has a mean value of 17.8 m/day. From the hydraulic conductivity map (Fig. 6a), the areas underlain by the Abakaliki Formation (Eastern axis) have a higher value compared to those areas underlain by the Ebonyi Formation (western axis). This is in agreement with the geology of the study area as previously explained by Agumanu (1989). Generally, across the study area, shales dominate the Abakaliki Formation and usually have a lower hydraulic conductivity when compared with the Ebonyi Formation, which has an alternating sequence of sandstones, siltstones, and shales. Using the Niwas and Singhal (1981) empirical equations, aquifer hydraulic conductivity was estimated by taking the product of the diagnostic constant (kδ) and aquifer resistivity (ρ) at VES locations as shown in Eq. (8). The average diagnostic constant of 0.00721 was used for areas underlain by the Ebonyi Formation, while areas underlain by the Abakaliki Formation have a mean diagnostic parameter of 0.00352. The estimated hydraulic conductivity of the study area for the Ebonyi Formation ranges from 0.15 to 5.87 m/day, with a mean value of 1.32 m/day. For the Abakaliki Formation, which is overlain by the Ebonyi Formation, the estimated hydraulic conductivity ranges from 0.04 to 0.61 m/day, with an average of 0.25 m/day. Areas with higher aquifer hydraulic conductivity usually have higher hydraulic connectivity and permeability and are generally

Table 1 Summary of interpreted layer parameters from the study area

VES	Location	Longitude	Latitude	Resistivity values of the layers(ohm-m)							Layer depth (m)						Curve type	No of layers	Geologic formation
				p1	**p2**	**p3**	**p4**	**p5**	**p6**	**p7**	**d1**	**d2**	**d3**	**d4**	**d5**	**d6**			
1	Ekka	7°58′32.21″ E	6°10′58.67″ N	662.2	196.9	102.3	84.6	744			0.69	11.99	22.92	34.28			QQH	5	Ebonyi Fm
2	Onueke Market	8°01′45.10″ E	6°10′ 13.13″ N	915.2	825.5	275.6	850.4				2.9	12.5	20.6				QH	4	Ebonyi Fm
3	Abiaji Village Square, Nganbo-Ogele	8°4′31.07″ E	6°7′31.36″ N	780.4	428.8	219.6	944.5				11.4	33.1	42.3				QH	4	Ebonyi Fm
4	Amuzu Primary School	8°4′19.59″ E	6°12′20.64″ N	830	58.1	16.75	50	5.4			1.45	1.7	19.7	28.2			QHK	5	Ebonyi Fm
5	Ndiuhu Amana	8°5′44.10″ E	6°8′19.93″ N	300	60	22.5	130	11.4	20.8		1.8	4.14	22.99	31.39	48.99		QHKH	6	Ebonyi Fm
6	Nganbo Ndiagu Amagu	8°2′27.72″ E	6°5′51.29″ N	440	286	36.5	12	45.5			2.55	3.7	13.7	220.7			QQH	5	Ebonyi Fm
7	Nganbo Agu	8°1′11.86″ E	6°7′58.73″ N	870	60.9	24.5	84	116	6.6		1.4	1.67	21.83	25.5	30.57		QHAK	6	Ebonyi Fm
8	Sacred Heart Catholic Church Onueke	8°1′18.34″ E	6°7′54.51″ N	720	360	57	107.5	65			2	13.6	44.85	53.75			QHK	5	Ebonyi Fm
9	Ndufu Idembia Community Hall	7°58′11.20″ E	6°7′42.75″ N	825	330	68	106	65			1.9	13.3	56.5	12.3			QHK	5	Ebonyi Fm
10	Nganbo Ohainya Ezzama	7°58′37.08″ E	6°9′2.18″ N	320	48	3.85	58	24			1.9	10.64	11.54	35.77			QHK	5	Ebonyi Fm
11	Nganbo Amaeze-kwe	8°4′24.74″ E	6°7′34.57″ N	280	560	40	273	210			1.75	3.76	22.76	35.26			KHK	5	Ebonyi Fm
12	Ezeugwu Okofia	8°0′37.27″ E	6°5′40.06″ N	2151.7	814	14.1	35.8				8.25	12.3	31				QH	4	Ebonyi Fm
13	Oriegu-Market Square 1	7°58′6.48″ E	6°7′1.63″ N	345	205	103	36	198	3125		0.5	1.2	4	12	18		QQHK	6	Ebonyi Fm

Table 1 (continued)

VES	Location	Longitude	Latitude	Resistivity values of the layers(ohm-m)							Layer depth (m)						Curve type	No of layers	Geologic formation
				p1	**p2**	**p3**	**p4**	**p5**	**p6**	**p7**	**d1**	**d2**	**d3**	**d4**	**d5**	**d6**			
14	Oriegu-Market Square 11	7°58′11.45″ E	6°6′59.67″ N	45	26	25	98	458	4578		0.8	1.5	3	8	18		QHAK	6	Ebonyi Fm
15	Azu Ugbo Village Square	8°0′14.57″ E	6°5′20.43″ N	939.1	443.3	174.8	789.5				9.6	21.3	38.4				QH	4	Ebonyi Fm
16	Ohiya Imeabali	8°00′06.85″ E	6°08′54.33″ N	461.8	365.5	701.5	383.6				2.2	5.6	14.4				HK	4	Ebonyi Fm
17	Ishieke Ndufu Igbudu	8°1′17.84″ E	6°2′54.55″ N	910	974.5	160	603.1				3.4	18	34				QH	4	Ebonyi Fm
18	Oguwekwe Village Hall	8°1′43.34″ E	6°9′16.93″ N	299.5	21	12.6	256				2.4	8.7	48.9				QH	4	Ebonyi Fm
19	Our Lady Fatima Catholic Church	7°58′55.33″ E	6°9′19.40″ N	1232.6	1199	173	765.3				2.4	6.6	105.8				QH	4	Ebonyi Fm
20	Ochufuagba Community Primary School	7°59′13.05″ E	6°7′23.66″ N	1300	195	38	240				1.8	5	77				QH	4	Ebonyi Fm
21	Community Primary School Ugwuogo	7°57′48.36″ E	6°7′0.94″ N	2100	630	95	150				2.5	9.8	52				QH	4	Ebonyi Fm
22	Amuzu Townhall	8°1′19.89″ E	6°10′5.03″ N	1500	105	230	3000				2.3	32	37				HA	4	Ebonyi Fm
23	Ndechi Ndufu achara	8°8′4.84″ E	6°8′31.50″ N	983.1	928.8	172.9	1329				8.3	17.3	33.2				QH	5	Abakaliki Fm
24	Ishieke, Ndufu Igbudu	8°1′17.84″ E	6°2′54.55″ N	910	974.5	160	603.1				3.4	18	34				QH	4	Abakaliki Fm

Table 1 (continued)

VES	Location	Longitude	Latitude	Resistivity values of the layers(ohm-m)							Layer depth (m)						Curve type	No of layers	Geologic formation
				p1	**p2**	**p3**	**p4**	**p5**	**p6**	**p7**	**d1**	**d2**	**d3**	**d4**	**d5**	**d6**			
25	Elegu Ndiechi Ekpomaka	8°9′34.99″ E	6°4′0.76″ N	921.1	835	319	839.1				2.9	15.5	31.1				QH	4	Abakaliki Fm
26	Elegu Ettem	8°10′51.80″ E	6°5′50.93″ N	2205	150	29.1	200	14.3			0.76	6.6	23	82.8			QH	5	Abakaliki Fm
27	Ekpelu	6°2′52.88″ N	8°8′11.30″ E	733	340	32.1	46.9	458			1.8	5.03	22.1	46			QHK	5	Abakaliki Fm
28	Ndiofeke	6°9′12.20″ N	8°10′7.62″ E	84.1	459	17.4	24.5	12.8			0.75	2.15	6.18	17.7			KHK	5	Abakaliki Fm
29	Enyacha-rigne (Ndiagu Amagu)	6°7′11.88″ N	8°7′59.73″ E	293	105	330	26.6	279			0.924	2.81	15.8	59.4			HK	5	Abakaliki Fm
30	Ndiagu Amagu Primary School Enyibivhiri 1	6°4′30.02″ N	8°5′19.26″ E	11.5	72.9	51.6	11.7	44.7			1.13	2.76	5.43	40.1			QHK	5	Abakaliki Fm
31	Eke Ettam Market Square	6°8′51.77″ N	8°7′19.04″ E	158.1	12.9	4.36	25.2	14.8	127	604	2.18	2.21	6.02	17.67	50	115.4	QHK	7	Abakaliki Fm
32	Amainyima	6°10′14.64″ N	8°8′39.24″ E	190	184	312	17.7	112	348		1.58	3.16	7.47	25.5	68.5		HKA	6	Abakaliki Fm
33	Ndiagu Amagu Primary School Enyibivhiri 11	6°4′30.02″ N	8°5′19.26″ E	129	57.1	831	23.2	141	17.9		1.58	1.83	5.64	51.6	98.4		HK	6	Abakaliki Fm
34	Ndufu Inyiamagu Obeagu playground (1)	6°4′36.96″ N	8°3′15.95″ E	749.9	2533	86.24	330	94.1	1448	2617	0.75	2.15	6.055	17.78	50.98	167.1	QHK	7	Abakaliki Fm

Table 1 (continued)

VES	Location	Longitude	Latitude	Resistivity values of the layers(ohm-m)							Layer depth (m)						Curve type	No of layers	Geologic formation
				p1	**p2**	**p3**	**p4**	**p5**	**p6**	**p7**	**d1**	**d2**	**d3**	**d4**	**d5**	**d6**			
35	Ndufu Inyiamagu Obeagu playground (11)	6°4′39.96″ N	8°3′30.85″ E	23.1	270	13.9	20.7	15.4	50		0.75	2.58	14.6	59.4	113		KH	6	Abakaliki Fm

associated with higher groundwater potential (Opara et al., 2020). The hydraulic conductivity map generated from the estimates predicted using the Niwas and Singhal model is shown in Fig. 6b.

Also, Eqs. (11)–(12) which represent the new model equations proposed and used in this work were used to estimate the hydraulic conductivity values of the Ebonyi and Abakaliki Formations within the study area. Hydraulic conductivity values estimated using the new model for areas underlain by the Ebonyi Formation range from 0.49 to 1.5735 m/day with a mean value of 0.9205 m/day, while those underlain by the Abakaliki Formation have hydraulic conductivity values that vary from 0.0775 to 1.3023 m/day, with a mean value of 0.2883 m/day. There is a high level of agreement between the hydraulic conductivity estimated from the pumping test and that from the new model derived from the present study when compared with Niwas and Singhal and Heigold model as shown in Table 2. This shows that the model equation proposed and used in the present study which is geologically constrained is more effective in estimating aquifer hydraulic parameters across the study area. From the hydraulic conductivity contour map of the study area generated from values estimated using the new model (Fig. 6c), there exists a hydrogeological divide with the Ebonyi Formation in the western axis of the study area having higher hydraulic conductivity values and therefore a more prolific aquifer system than the Abakaliki Formation which is in the eastern axis of the study area with lower hydraulic conductivity values. These findings are in agreement with previous works done in the study area (Agumanu, 1989; Ekwe et al., 2015; Oli et al., 2020). Within the Abakaliki Formation, areas with hydraulic conductivity greater than the surrounding formation are believed to be associated with highly fractured shale zones which improved the porosity and permeability of the formation.

Estimation of aquifer transmissivity (T) of the study area

Aquifer transmissivity estimated across the study area using the new model ranges between 0.29 and 57.27 m^2/day with a mean value of 6.59 m^2/day. The transmissivity values within the area underlain by the Ebonyi Formation vary from 0.63 to 57.27 m^2/day with a mean value of 8.23m^2/day, while

Table 2 Computed hydraulic conductivity and transmissivity values derived from different models

VES point	Location	K from pumping test m/day	K from new model m/day	K from Niwas and Singhal m/day	K″ from Heigold m/day	Transmissivity (T) from pumping test m^2/day	Transmissivity (T) from Heigold (m^2/day)	Transmissivity (T) from new model (m^2/day)	Transmissivity from Niwas Singhal (T) (m^2/day)	Geologic formation
VES 1 *	Ekka	1.01	1.01	0.61	6.15	9.0662	69.9	9.09	6.93	Ebonyi Fm
VES 2 *	Onueke Market	0.69	0.69	1.99	2.04	4.1457	16.6	4.16	16.09	Ebonyi Fm
VES 3	Abiaji Village Square, Nganbo-Ogele		0.74	1.58	2.53		23.3	4.56	14.56	Ebonyi Fm
VES 4	Amuzu Primary School		1.19	0.36	10.05		85.4	19.39	3.06	Ebonyi Fm
VES 5	Ndiuhu Amana		0.88	0.94	4.12		34.6	8.08	7.87	Ebonyi Fm
VES 6	Nganbo Ndiagu Amagu		1.32	0.26	13.48		134.8	22.33	2.63	Ebonyi Fm
VES 7	Nganbo Agu		0.91	0.84	4.58		23.2	14.34	4.24	Ebonyi Fm
VES 8	Sacred Heart Catholic Church Onueke		0.93	0.77	4.92		272.8	1.67	42.95	Ebonyi Fm
VES 9	Ndufu Idembia Community Hall		1.08	0.49	7.54		325.9	3.22	21.17	Ebonyi Fm
VES 10	Nganbo Ohainya Ezzama		1.14	0.42	8.75		212.0	6.39	10.13	Ebonyi Fm
VES 11	Nganbo Amaezekwe		0.69	1.97	2.06		25.8	2.81	24.60	Ebonyi Fm
VES 12	Ezeugwu Okofia		0.49	5.87	0.74		3.0	2.90	23.76	Ebonyi Fm
VES 13	Oriegu-Market Square 1		0.77	1.43	2.78		16.7	7.47	8.56	Ebonyi Fm
VES 14	Oriegu-Market Square 11		0.59	3.30	1.27		12.7	2.14	33.01	Ebonyi Fm
VES 15	Azu Ugbo Village Square		0.80	1.26	3.13		53.5	3.17	21.54	Ebonyi Fm
VES 16	Ohiya Imeabali		0.63	2.63	1.57		5.3	7.16	8.96	Ebonyi Fm
VES 17	Ishieke Ndufu Igbudu		0.82	1.15	3.40		54.7	3.64	18.57	Ebonyi Fm

Table 2 (continued)

VES point	Location	K from pumping test m/day	K from new model m/day	K from Niwas and Singhal m/day	K″ from Heigold m/day	Transmissivity (T) from pumping test m^2/day	Transmissivity (T) from Heigold (m^2/day)	Transmissivity (T) from new model (m^2/day)	Transmissivity from Niwas Singhal (T) (m^2/day)	Geologic formation
VES 18	Oguwekwe Village Hall		1.57	0.15	22.58		142.2	57.27	0.95	Ebonyi Fm
VES 19	Uur Lady Fatima Catholic Church		0.80	1.25	3.16		313.2	0.63	123.69	Ebonyi Fm
VES 20	Ochufuagba community primary school		1.30	0.27	12.98		934.8	3.44	19.72	Ebonyi Fm
VES 21	Community Primary School Ugwuogo		0.93	0.68	5.52		233.1	2.42	28.89	Ebonyi Fm
VES 22	Amuzu Town hall		0.94	0.76	5.03		149.4	3.05	22.48	Ebonyi Fm
VES 23*	Ndechi Ndufu achara	0.63	0.63	0.61	3.16	5.6585	50.2	5.69	9.68	Abakaliki Fm
VES 24*	Ishieke, Ndufu Igbudu	0.60	0.59	0.56	3.40	5.3789	54.7	5.40	9.07	Abakaliki Fm
VES 25*	Elegu Ndiechi Ekpomaka	1.02	1.02	1.12	1.78	9.1713	27.8	9.22	17.52	Abakaliki Fm
VES 26	Elegu Ettem		0.16	0.10	16.65		273.1	1.37	1.68	Abakaliki Fm
VES 27	Ekpelu		0.17	0.11	15.20		259.8	1.54	1.93	Abakaliki Fm
VES 28	Ndiofeke		0.11	0.06	26.90		108.4	0.29	0.25	Abakaliki Fm
VES 29	Enyacharigne (Ndiagu Amagu)		0.15	0.09	18.11		791.3	2.83	4.09	Abakaliki Fm

Table 2 (continued)

VES point	Location	K from pumping test m/day	K from new model m/day	K from Niwas and Singhal m/day	K″ from Heigold m/day	Transmissivity (T) from pumping test m^2/day	Transmissivity (T) from Heigold (m^2/day)	Transmissivity (T) from new model (m^2/day)	Transmissivity from Niwas Singhal (T) (m^2/day)	Geologic formation
VES 30	Ndiagu Amagu Primary School Enyibivhiri 1		0.08	0.04	38.96		1348.0	1.20	1.42	Abakaliki Fm
VES 31	Eke Ettam Market Square		0.09	0.05	32.29		1043.0	1.38	1.68	Abakaliki Fm
VES 32	Amainyima		0.11	0.06	26.48		477.4	0.99	1.12	Abakaliki Fm
VES 34	Ndiagu Amagu Primary School Enyibivhiri 11		0.13	0.08	20.57		945.5	2.64	3.75	Abakaliki Fm
VES 34	Ndufu Inyiamagu Obeagu playground (1)		0.39	0.33	5.57		185.0	6.32	11.00	Abakaliki Fm
VES 35	Ndufu Inyiamagu Obeagu playground (11)		0.12	0.07	22.88		1025.0	2.36	3.26	Abakaliki Fm

* Pumping test and Vertical Electrical Sounding conducted

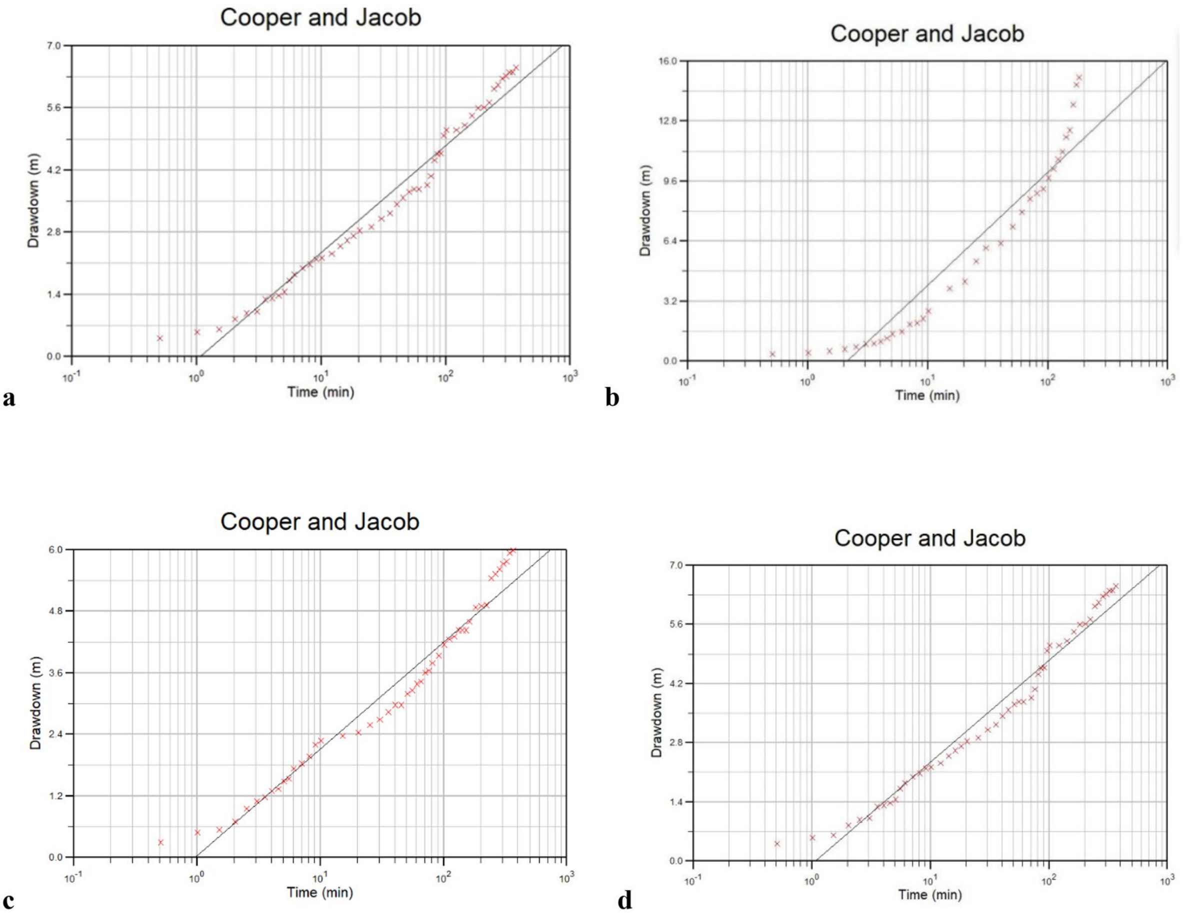


Fig. 5 Pumping test curves analyzed using Cooper and Jacob method for **a** Ekka Ezza, **b** Onueke market, **c** Ndiechi Ndufu Achara, **d** Ishieke Ndufu Igbudu

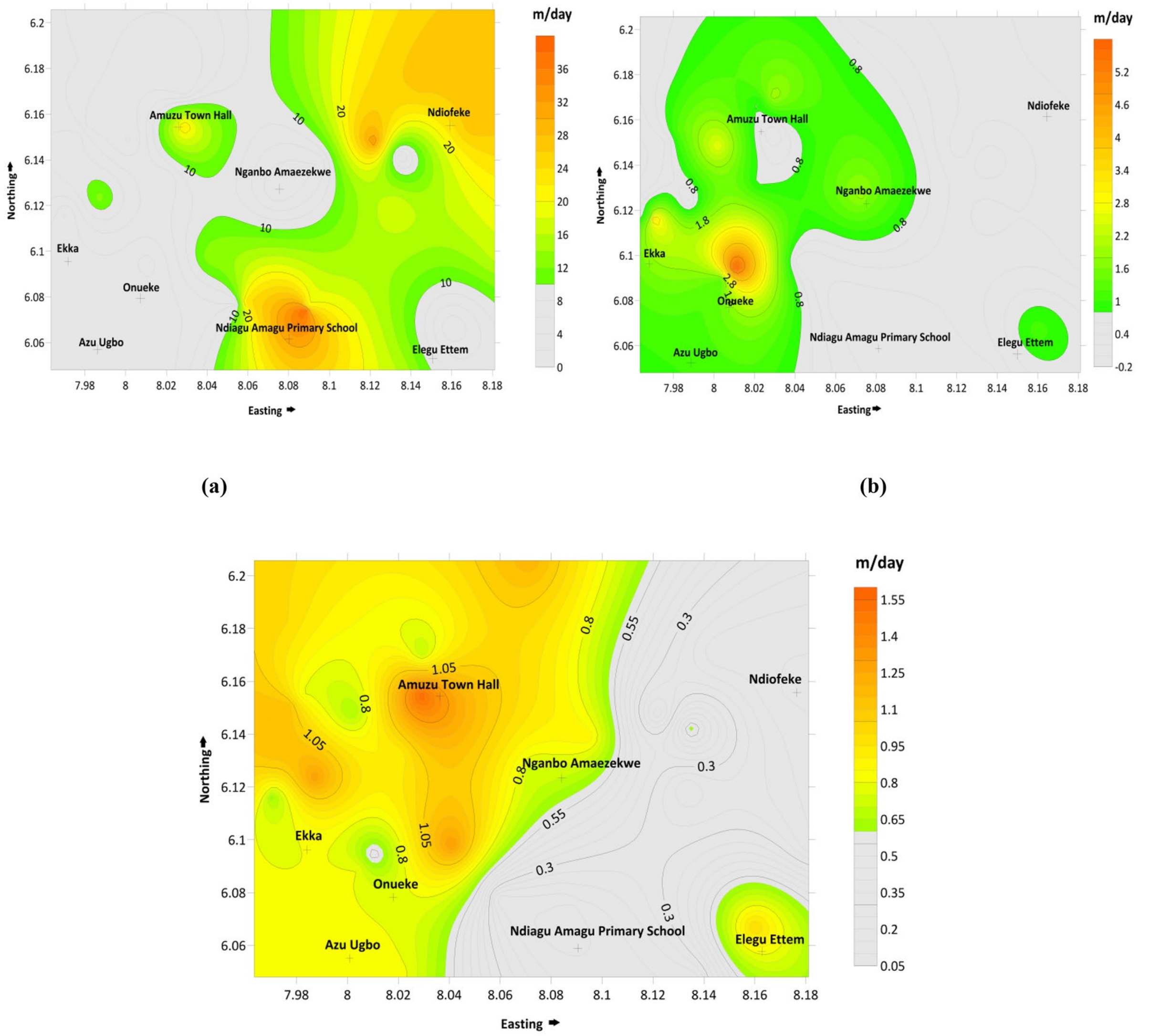
that of the Abakaliki Formation ranges from 0.29 to 9.22 m^2/day with a mean value of 3.44 m^2/day. The contour map of the transmissivity values estimated using the new model is shown in Fig. 7a. Also, Niwas and Singhal's model was also used to estimate transmissivity across the study area as shown in Eq. (10) by using the product of the aquifer hydraulic conductivity estimates made from the Niwas and Singhal (1981) equation and the aquifer thickness. The estimated values for the Ebonyi Formation therefore ranges between 0.95 and 124 m^2/day with a mean value of 20.19 m^2/day, while that of the Abakaliki Formation ranges from 0.25 to 17.5 m^2/day with an average of 5.54 m^2/day. Based on these predictions, therefore, the Ebonyi Formation has higher transmissivity values than the Abakaliki Formation as shown in Fig. 7b. Finally, the aquifer transmissivity values estimated by multiplying the hydraulic conductivity values estimated using the Heigold model by the thicknesses of the aquifer for the Ebonyi Formation range from 3.01 to 934 m^2/day with a mean value of 142 m^2/day, while that of the Abakaliki Formation range from 50.2 to 1347 m^2/day with a mean value of 507 m^2/day, with the map shown in Fig. 7c. Analysis of the transmissivity contour map of the study area, estimated by using the Heigold model (Fig. 7c), suggests that areas underlain by the Ebonyi Formation have a lower transmissivity than areas underlain by the Abakaliki Formation. This in particular is not in agreement

Table 3 A paired *t* test for the different models

Statistics	K (m/day) from pumping tests	K (m/day) from new model
Mean	0.7880	0.7860
Variance	0.0421	0.0431
St. deviation	0.2052	0.2076
Observations	5	5
Pearson correlation	0.9998	
T value	0.698	
Observed mean difference	0.002	
Standard deviation difference	0.001	
Statistics	**K (m/day) from pumping tests**	**K m/day) from Niwas and Singhal**
Mean	0.7880	0.9780
Variance	0.0421	0.3725
St. deviation	0.2052	0.6103
Observations	5	5
Pearson correlation	−0.0252	
T value	0.548	
Observed mean difference	0.190	
Standard deviation Difference	0.405	
Statistics	**K (m/day) from pumping tests**	**K(m/day) from Heigold model**
Mean	0.7880	3.3060
Variance	0.0421	3.0125
St. deviation	0.2052	1.7356
Observations	5	5
Pearson correlation	0.2962	
T value	0.029	
Observed mean difference	2.518	
Standard deviation difference	1.530	

with the geology of the area, thereby showing that the Heigold model is defective for the study area. Heigold et al. (1979) equation therefore typically under-predicts areas which are not similar geologically to the study area from where the empirical equation was generated.

Statistical analysis was carried out to ascertain the reliability of the different empirical equations/models in estimating hydraulic conductivity by comparing them with the values from the widely accepted pumping test technique. A paired *t* test was used to compare the values of the standard deviation, mean, variance, and Pearson correlation of the various hydraulic conductivities estimated from other models with those from the pumping test as shown in Table 3. From Table 3, it was observed that *K* values estimated from the new model equations when compared with K values from the pumping test revealed a Pearson correlation of 99%. This represents a strong positive correlation. The other models (K_{NS} and K_{HG}) presented a strong negative correlation with that from the pumping test. The observed mean difference of hydraulic conductivity estimated from Niwas and Singhal (1981) equation, Heigold et al. (1979) equation, and the new model equation when compared with the values of the pumping test showed that the new model values have a lower observed mean difference than the others (Table 3). This validates the efficiency of the model derived from the present study in estimating hydraulic conductivity when there is dearth of pumping test data.



(a)

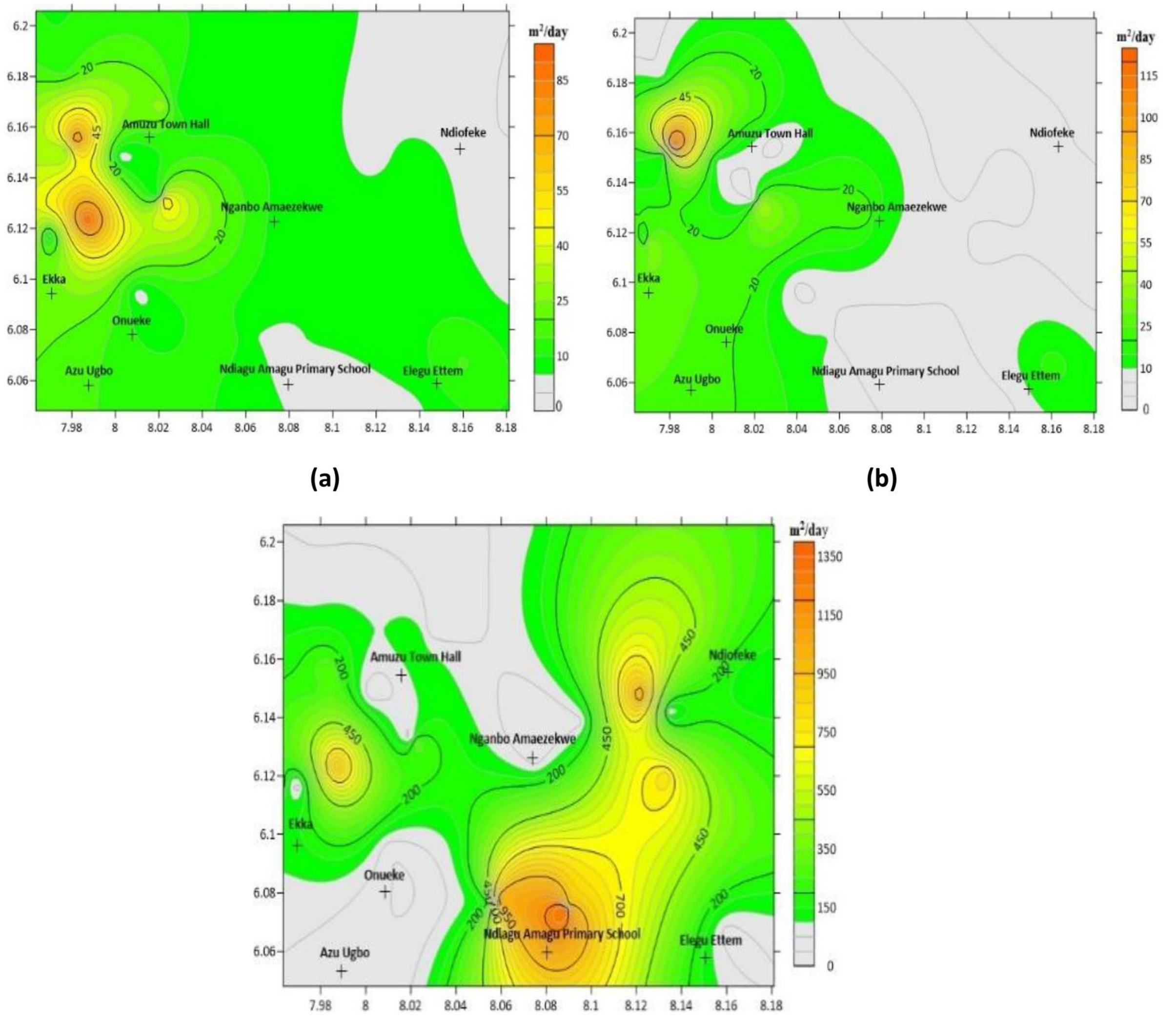
(b)

(c)

Fig. 6 Contour map of the study area showing hydraulic conductivity, m/day: **a** Heigold model, **b** Niwas and Singhal model, **c** model derived from the present study

Groundwater potential

The groundwater potential of the study area was assessed based on the transmissivity of the aquifer at each sounding point estimated using the new model. Krasny's (1993) classification of transmissivity magnitude as shown in Table 4 was used to assign groundwater supply potentials of the various locations in the study area. Based on Table 5, it was observed that the aquifer potentials of the study area range from low to intermediate. The groundwater potentials at two (2) of the locations representing 6% of the study area have groundwater potential which can only sustain limited consumption, with twenty-nine (29) of the locations which represent 83% of the study area capable of providing groundwater potentials that can serve for private consumption, while the remaining four (4) locations which represent 11% of the study area hold



(a)

(b)

(c)

Fig. 7 Contour map of the study area showing transmissivity in m^2/day: **a** model derived from the present study, **b** Niwas and Singhal model, **c** Heigold model

Table 4 Classification of transmissivity magnitude (After Krasny, 1993)

Magnitude of transmissivity (m^2/day)	Designation	Groundwater supply potential
> 1000	Very high	Regional importance
100–1000	High	Lesser regional importance
10–100	Intermediate	Local water supply
1–10	Low	Private consumption
0.1–1	Very low	Limited consumption
< 0.1	Imperceptible	Very difficult to utilize for local water supply

Table 5 Transmissivity classification based on data collected in the study area

Location	Transmissivity (m^2/day)	Designation of transmissivity magnitude	Groundwater supply potential
Ekka	9.09	Low	Private consumption
Onueke Market	4.16	Low	Private consumption
Abiaji Village Square, Nganbo-Ogele	4.56	Low	Private consumption
Amuzu Primary School	19.39	Intermediate	Local water supply
Ndiuhu Amana	8.08	Low	Private consumption
Nganbo Ndiagu Amagu	22.33	Intermediate	Local water supply
Nganbo Agu	14.34	Intermediate	Local water supply
Sacred Heart Catholic Church Onueke	1.67	Low	Private consumption
Ndufu Idembia Community Hall	3.22	Low	Private consumption
Nganbo Ohainya Ezzama	6.39	Low	Private consumption
Nganbo Amaezekwe	2.81	Low	Private consumption
Ezeugwu Okofia	2.90	Low	Private consumption
Oriegu-Market Square 1	7.47	Low	Private consumption
Oriegu-Market Square 11	2.14	Low	Private consumption
Azu Ugbo Village Square	3.17	Low	Private consumption
Ohiya Imeabali	7.16	Low	Private consumption
Ishieke Ndufu Igbudu	3.64	Low	Private consumption
Oguwekwe Village Hall	57.27	Intermediate	Local water supply
Uur Lady Fatima Catholic Church	0.63	Low	Private consumption
Ochufuagba community primary school	3.44	Low	Private consumption
Community Primary School Ugwuogo	2.42	Low	Private consumption
Amuzu Town hall	3.05	Low	Private consumption
Ndechi Ndufu achara	5.69	Low	Private consumption
Ishieke, Ndufu Igbudu	5.40	Low	Private consumption
Elegu Ndiechi Ekpomaka	9.22	Low	Private consumption
Elegu Ettem	1.37	Low	Private consumption
Ekpelu	1.54	Low	Private consumption
Ndiofeke	0.29	Very low	limited consumption
Enyacharigne (Ndiagu Amagu)	2.83	Low	Private consumption
Ndiagu Amagu Primary School Enyibivhiri 1	1.20	Low	Private consumption
Eke Ettam Market Square	1.38	Low	Private consumption
Amainyima	0.99	Very low	Limited consumption
Ndiagu Amagu Primary School Enyibivhiri 11	2.64	Low	Private consumption
Ndufu Inyiamagu Obeagu playground (1)	6.32	Low	Private consumption
Ndufu Inyiamagu Obeagu playground (11)	2.36	Low	Private consumption

a groundwater potential that can serve as a local water supply. These areas that can sustain local water supply are dominated by areas underlain by the Ebonyi Formation. The aquifer potential map of the study area is shown in Fig. 8.

The results of this study have helped to delineate the groundwater potential zones within the study area. Evidently, the findings of the present study thus revealed a groundwater divide in line with the geology of the study area with the Ebonyi Formation having a higher groundwater potential than the Abakaliki Formation. The findings of the present study are in agreement with the results of previous studies within the study area (Ekwe et al., 2020; Obiora et al., 2015; Oli et al., 2020).

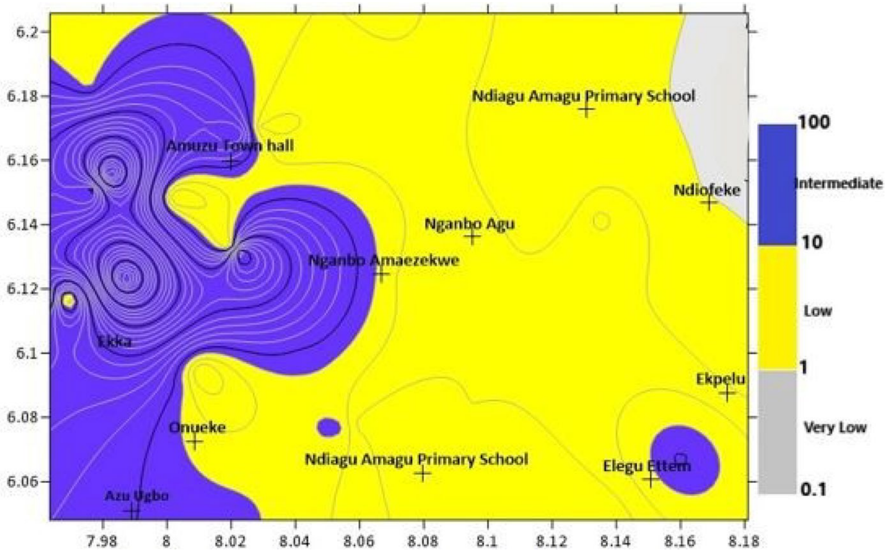


Fig. 8 Groundwater potential map of the study area

Conclusion

The present study has clearly demonstrated the effectiveness of the application of surficial resistivity data in aquifer hydraulic estimation. Aquifer hydraulic parameters including aquifer hydraulic conductivity and transmissivity were estimated using multiple resistivity-based empirical equations even in areas with a paucity of pumping test data. These analytical and empirical equations which have been used with fairly high level of success were improved by adopting formation-specific equations which were constrained geologically. Statistical analysis of aquifer hydraulic parameters estimated from the different models revealed that the new model proposed and used in the present study clearly showed values that have the closest relationship with values obtained from the pumping test. Transmissivity estimated from the new model suggested that areas underlain by the Ebonyi Formation have a greater aquifer potential when compared with those areas underlain by the Abakaliki Formation. This can be explained by the geology, as areas within the Abakaliki Formation with higher aquifer potential are suspected to be highly fractured shales. This is also validated by Krasny's groundwater potential classification of the study area, with areas underlain by the Ebonyi Formation having greater groundwater prospects than those underlain by the Abakaliki Formation. Therefore, exploitation should be focused more on areas underlain by the Ebonyi Formation for a greater yield. The study therefore clearly revealed a pronounced groundwater divide between the Ebonyi and Abakaliki Formations of the study area.

The closeness of the estimated results obtained from the interpretation of the vertical electrical sounding results with those obtained from pumping tests from available borehole locations has further shown the validity of the present study. Electrical resistivity method is therefore a useful tool for understanding the aquifer systems in the study area. The study has shown that direct current electrical resistivity methods are not only useful in groundwater exploration or delineation of aquifer geometry but can also be effective in the estimation of aquifer hydraulic parameters.

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Data availability Data available on request.

Declarations

Conflict of interest The authors declare no competing interests.

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