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Statistical modeling of the hydrostratigraphy and hydraulics of the Cretaceous aquifers in Nsukka, North of the Anambra basin, Southeast Nigeria

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ABSTRACT

The hydraulic parameters and hydrostratigraphy of the thick Cretaceous aquifers namely; the Upper Maestritchtian Nsukka Formation, and the Middle Maastritchian Ajalli Sandstone Formation were computed and geostatistically analysed in this paper.The two aquifers belong to the same hydrostratigraphic units in that they exhibit similar hydraulic characteristics with similar lithologies at depths where regional saturation occurs The hydraulic conductivity (K), Transmissivity (T) and specific capacity of the boreholes when correlated from layer to layer showed high spatial variability. Transmissivity (T) is highly variable from 35m^2/day around the southeastern boundary at Diogbe to 2219.17m^2/day at Ibagwa-aka. The hydraulic conductivity varies from 0.56m/day to 30.52m/day following the same trend. The hydraulic conductivity field shows a highly heterogeneous layering pattern when referenced to a vertical stratigraphic column with an equivalent horizontal conductivity K_x 0f 9.28m/day and vertical hydraulic conductivity K_y of 5.86m/day, giving an anisotropy factor of 1.58. The Nsukka and Ajalli Formations are considered by this research report to be homogeneous but anisotropic consisting of at least five hydrostratigaphic units of about 50m layer thickness laid in succession .The asymptotic longitudinal dispersivity (A_L) of the sequence is estimated at 30.5m.The layer within 120m-220m above sea level is the most prolific layer. The utility of this research lies in the understanding of the producing zones of the sequence, parameter estimates for aquifer management ,hydrodynamic dispersion studies and contaminant modelling in the area.

Keywords: statistical modeling, Hydraulic properties, Hydrostratigraphy, Solute transport, Heterogeneity.

INTRODUCTION

1.1 Research Purpose and Objectives

Analysis of the groundwater resources of Nsukka area has been studied at various scales by previous researchers (Egboka 1983,Egboka and Uma 1986,and Ofoma and Ezeigbo 1997).These studies document some basic aquifer properties that serve many useful purposes. Not much has been done in the area of flow and solute transport as these studies were constrained by limited data ,scope and research methodology. In spite of these previous studies, there are still large gaps in the understanding of the aquifer behaviour especially with respect to flow dynamics and solute transport mechanism. Specific capacities of boreholes vary spatially in the area while large hydraulic conductivity contrast exist between layers within the thick sandstone sequence(Amah,J.I,2006).

The flow velocity is basically governed by Darcy's law, where the determination and variation in hydraulic conductivity are a challenge as it can vary several orders of magnitude within short distances. Large hydraulic conductivity contrasts cause groundwater to follow complex preferential paths in heterogeneous porous media. The effects of longitudinal dispersivity is crucial in order to describe first arrival or breakthrough of contaminants to a point of compliance or a drinking water supply well.(Gelhar et al.,1992).A number of large –scale field tracer experiments were conducted in North America, the most famous being experiments in the sandy aquifers of Borden and Cape Cod(Freyberg et al.,1986,Garabedian et al.,1991)These experiments show that longitudinal dispersivity reflects spatial variation in hydraulic conductivity which can be described by use of geostatistical tools. A critical review of data on field-scale dispersivities in aquifer was done by Gelhar et al,1992.They noted that the longitudinal dispersivities ranged from 10^{-2} to 10^{8}m for scales ranging from 10^{-1} to 10^{5}m from 59 different field sites,but the largest scale for high reliability data was only 250m.

This report is a first step towards the development of a realistic flow and transport models for the Nsukka and Ajalli Sandstone aquifers. Regardless of the type of model that one may utilize, account must be taken of the dispersion processes, the primary mechanism of spreading of contaminants in groundwater. The objectives of this research are: (1) To determine the various hydrostratigraphic boundaries within the thick Formation. (2) Determine the hydraulic parameters necessary for the modelling of transport and flow of contaminants.(3) Determine which horizons within the Ajalli-Nsukka sequence that is most suitable for borehole development. (4)Establish the spatial and temporal variability of the various aquifer parameters within the sequence.(5).Estimate the maximum thickness of the sequence from borehole logs.

1.2 Location and Physiography .

Nsukka town is the centre of the study and covers the area within latitudes 6°45'N-7°00'N and longitudes 7°15'E-73°0'E(See Fig 1,Fig 2).. The area is part of the Anambra sedimentary basin .The main geomorphic features comprise high peaked hills and undulating slopes criss-crossed with dry valleys. The vegetation is guinea-savanna type. The topography is highly undulating and peak at the Edeoballa-Opi area at 533m.From here there is a gentle downward slope both east and west. Because of the fragile nature of the sandstone, there are numerous gully sites and valleys west of the study area while the eastern portion is dominated by the cuesta topography.

There are two seasons-the dry season and the rain season. The dry season is completely devoid of moisture and starts from November to April. Temperatures attain maxima of 34 degrees in the dry season and can attain minima of 22 degrees during the rainy season. Precipitation is high and approximate 1650mm/yr.

1.3 Geologic and Hydrogeologic setting.

The geology and hydrogeology of the area have been extensively studied by various workers. Previous works on the stratigraphy , petrography and hydrogeology of the formations were carried out by Simpson (1954);De Swardt and Casey (1963), Nwachukwu (1978),Reyment (1965),Agagu et al (1985) Egboka and Uma (1986),Ozoko (1988).

Three main Formations outcrop in the area. The Nsukka Formation(Upper Maastritchian) that presents essentially as outliers and laterite crusts in the hilly areas; the Ajalli Sandstone(Middle Maastritchian) made up of friable cross-bedded sandstone that is the main aquifer; the underlying Mamu Formation(Lower Maastritchian) comprises sandstone, shales, sandy-shales and coal outcrops towards the eastern extremity of the Nsukka area(Fig 1). Eroded remnants of the Nsukka Formation constitute outliers and numerous springs issue out from the flanks of the outliers. The perched systems produced by the Nsukka Formation are localised within topographically controlled flow cells that are not in hydraulic continuity with adjacent cells (Amah, J.I, 2006).

The sandstone is generally white in colour but is sometimes iron-stained. Intercalations of mudstone and shale occur at various horizons, creating semi-confining conditions in places. Thicknesses of 336m (Nwachukwu, 1978), and 457m (Reyment, 1965 and Agagu et al, 1985) have been estimated. The Nsukka Formation is the topmost geological outcrop in Nsukka area. It lacks good exposures and occurs as outliers or residual hills on the Ajalli Sandstone. The lithology consists of an alternating succession of sandstone, dark shale and sandy shale.These two formations belong to the same hydrostratigraphic unit(Egboka and Uma,1986), and give rise to thick water table aquifers. Where the hydraulic arrangement does not permit spring formation, flow goes vertically downward to contribute to the regional system furnished mainly by the Ajalli Sandstone. Regional flow is essentially from east to west. Ozioko(1988) reported a dp range of 3°-6° in the West-North-West directions and a lithology dominated by medium grained population in the Ajalli Sandstone while Amah(2006) reported the dominance of the fine-medium grains within the population from over 40 deep wells in the area. Amah reported the saturated thickness range of 80m in the east at Edeoballa to more than 150m in the west at Obimo.

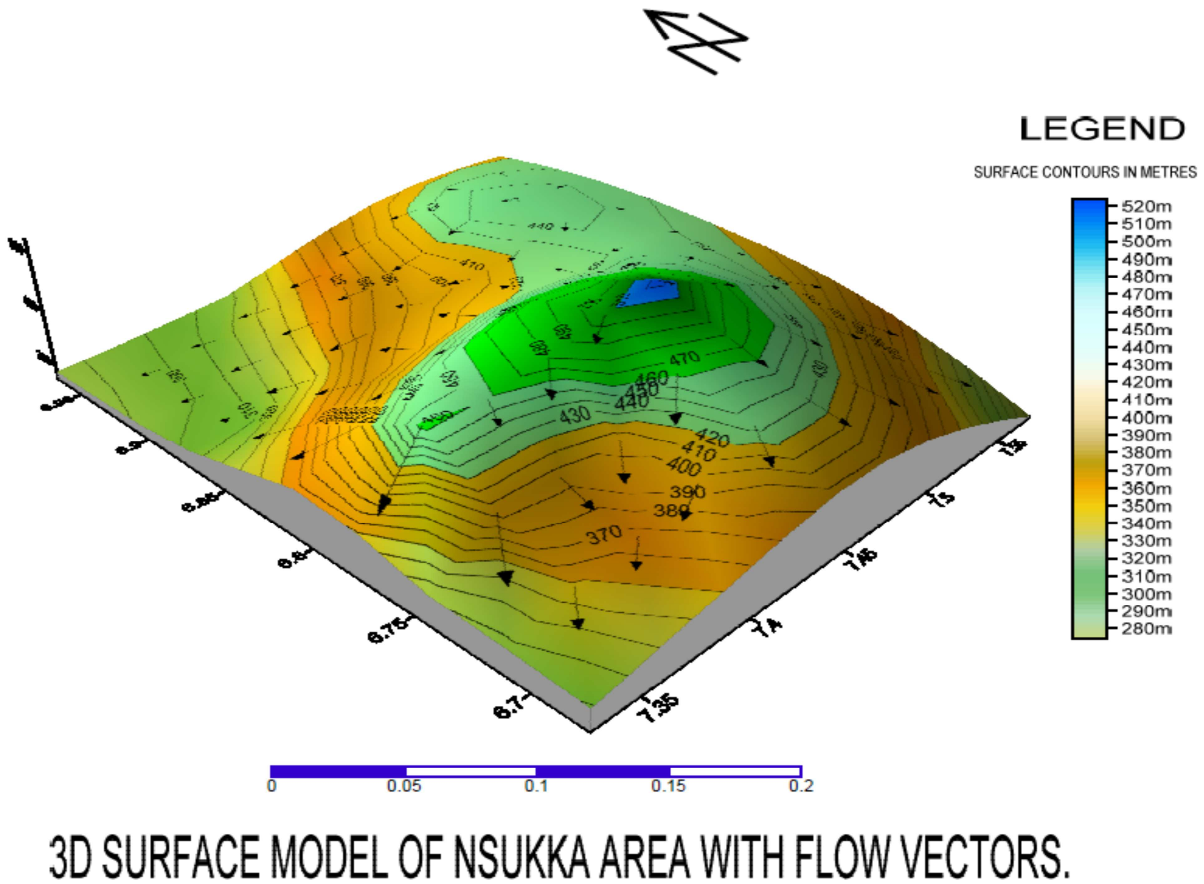

Fig 2 Topographic Model of Nsukka area

Table 1.Stratigraphic Sequence in Nsukka Area

Age/Period	Epoch	Formation	Dorminant Lithology
Cretaceous	Upper Maestrichtian Middle Maestrichtian Lower Maestrichtian	Nsukka Formation Ajalli Sandstone Mamu Formation	Sandstone,clay,lignite Sandstone Clay and Shale

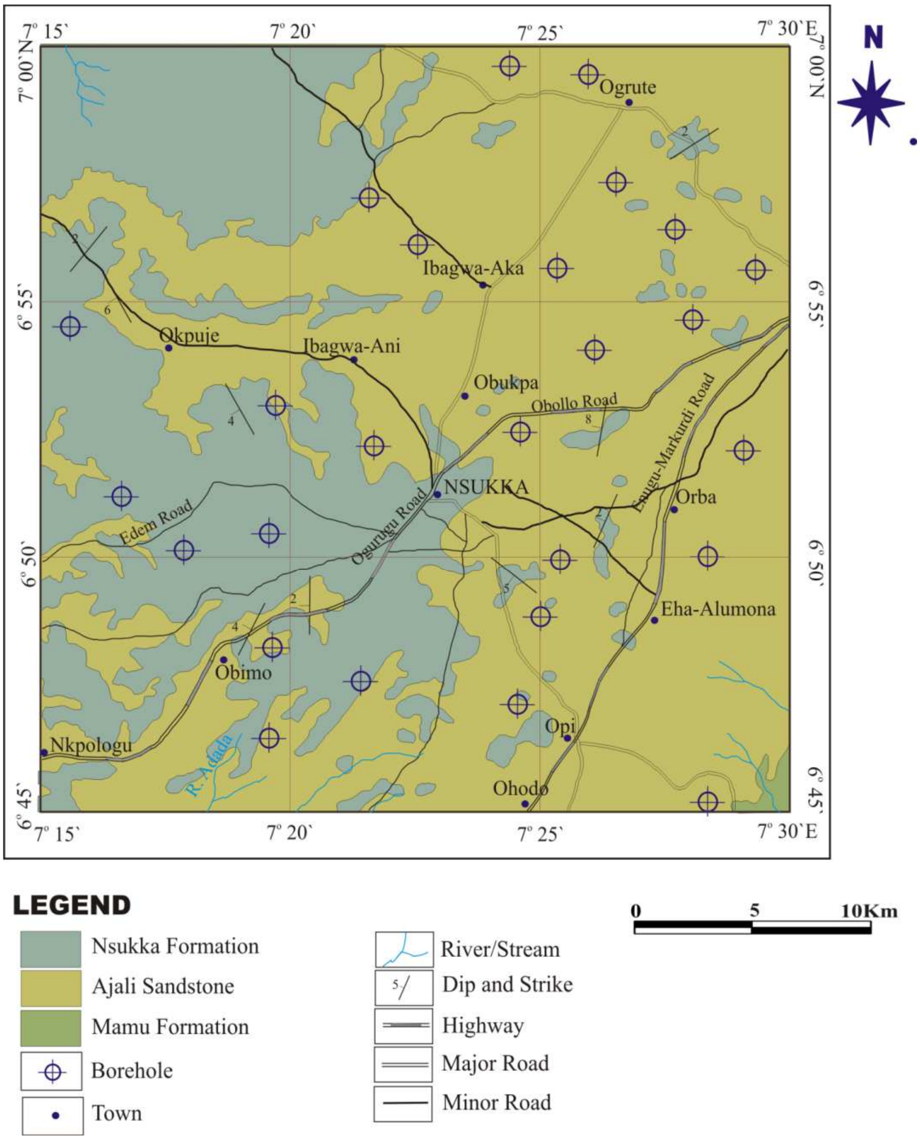

Fig 1 Geologic Map of the study Location with Borehole Points

MATERIALS AND METHODS

2.1 Data Acquisition and processing

The data source was from the ADB-assisted Rural Water Spply Project carried out by the Enugu State Water Corporation from 1992-1999. Pumping test data from over 40 boreholes were analyzed and the formation constants omputed using the Cooper-Jacob (1946) solution to the Theis equation.The storage coefficient was estimated using grainsize technique (Nwankwor 1995). The summary of the aquifer constants are presented in Table 2. Grainsize analysis of the lithologic samples obtained from various wells were carried out.From the examination of the result of the analyses,layers having similar lithologies and aquifer properties were noted.Layers with similar characteristics were correlated from one borehole to another and a composite section was made(Fig 4). The cyclicity of the sequence was noted as similar layers occurred at various horizons.

2.2 Determination of Aquifer Parameters

2.1.1 Hydraulic Conductivity and Transmissivity of the aquifer

The hydraulic conductivity is represented by K and has the unit of velocity. It is related to the Transmissivity T by the formula:

$$T = Kb \quad (1)$$

Where b is the aquifer thickness as determined from the well-site data. The transmissivity T was calculated from the Cooper-Jacob (1946) method according to the formula:

$$\Delta s = \frac{2.3Q}{4\pi T} \quad (2)$$

WhereΔs is the drawdown per log cycle. The values of K were computed for various layers at various locations(see Table 2)

An equivalent horizontal conductivity was computed for the sequence using Leonards(1962) method:

$$K_x = \frac{\sum(MiKi)}{\sum Mi} \quad (3)$$

Similarly, $$K_z = \frac{\sum M}{\sum(Mi/Ki)} \quad (4)$$

Where K_x is the equivalent horizontal conductivity and K_z the equivalent vertical conductivity, K_i is the homogenous hydraulic conductivity of an individual layer and M is the layer thickness.

2.1.2 Darcy Velocity:

The Darcy velocity was determined from the equation

$$V = Ki \quad (5)$$

Where K = hydraulic conductivity,

i = hydraulic gradient computed from the map of the hydraulic heads

The linear or pore velocity was determined from:

$$V = Ki/n_e \quad (6)$$

where ne is the effective porosity.The results of the above computations are presented in Table 1

TABLE 1 Summary of aquifer parameters in nsukka

S/N	AQUIFER PARAMETER	UNIT	VALUE
1	Hydraulic Gradient(i)	dimensionless	1/150 -1/200
2	Darcy velocity(V)	m/day	0.02m/d-0.06m/d
3	Linear or pore velocity(V_{avg})	m/day	0.05/d -0.16m/d
4	Horizontal hydraulic conductivity(K_x)	m/day	9.28/d
5	Vertical hydraulic conductivity(K_z)	m/day	5.86m/d
6	Effective Porosity(ne) *	%	37
7	Asymptotic longitudinal dispersivity(A_L)	m	30.5m
8	Anisotropy factor($K_{x/}$ K_z)	dimensionless	1.58

** value determined by Morris and Johnson 1967*

2.1.3 Computation of Linear Dispersivity

The aquifer parameters were further subjected to geostatistical analysis due to their spatial variability. When data vary over several orders of magnitude, they are often best described by a lognormal distribution (Freeze and Cherry,1989).For the hydraulic conductivity, the following equations describe the distribution:

$$Yi = LnKi \quad (7)$$

$$Y = \frac{1}{n}\Sigma Yi, I = 1..............., n \quad (8)$$

$$S_y^2 = \frac{1}{n}\Sigma(Yi-Y)^2, I = 1...., n \quad (9)$$

Where Yi is the log hydraulic conductivity, Y the mean hydraulic conductivity and S_y^2 the variance in hydraulic conductivity. The log transformed hydraulic conductivity values from 20 boreholes are presented in Table 3.

The specific capacities, hydraulic conductivities and transmissivities of the boreholes were correlated based on the composite stratigraphic section in Fig 3. The result is presented in Table 2

Table 2 Summary of Aquifer Constants from Pumping Test Analysis of Borehole Data

S/n	Location	W/level (m)	Elevation (m)	Q(m)	S(m)	Sp.capacity (m^3/hr/m)	Transmissivity (m^2/d)	Thickness (m)	K (m/d)
1	Nsukka urban	136	400.5	101	9.96	10.14	1386.26	84	16.50
2	Nguru-Nsukka	210	497.1	60	13.51	4.41	146.4	56	2.61
3	Ede-oballa	221	534.5	51.6	4.05	12.74	906.5	74	12.25
4	Obimo-Akutara	67	301.5	100	18.0	5.55	351.36	56	6.27
5	ObimoAjuona	243	477.2	71.2	12.85	5.52	183.95	45	4.09
6	Ihakpu-Awka	130	387.9	67.5	6.85	9.85	741.16	79	9.38
7	Imufu	114	335	79.1	6.97	11.34	1240.77	102	12.16
8	Unadu	118	320	70.1	4.75	14.75	1539.43	62	24.83
9	Umuida	103	316.7	72	5.48	13.14	1317.63	77	17.11
10	Ibagwa-Aka	112.3	381.1	96	7.02	13.67	2219.17	72.7	30.52
11	Amufie	157	445	63.3	4.75	13.33	842.49	83	10.15
12	Olido	135	396	66	8.49	7.77	222.98	45	4.95
13	Ogrute	140	410.3	62	4.47	13.87	1008.55	94	10.73
14	Itchi	118	310.9	108.2	6.83	15.84	1218.52	72	16.92
15	Iheaka	165	451.6	66	6.3	10.47	345.09	44	7.84
16	Ozalla	197.86	457	66	9.02	7.32	131.76	52.14	2.53
17	Nkal-Obukpa	138.55	366	37.5	10.09	3.75	457.51	31.45	14.54
18	Umunko	183.65	457	55.4	18.1	3.04	35.78	63.35	0.56
19	Ohebe-dim	169.12	366	60	7.43	8.07	1464.03	68.88	21.25
20	Umuna	176.15	457	46.4	5.84	7.945	582.26	83.85	6.94

Table 3 Log-transformed Hydraulic Conductivity Data

S/N	Location	K(m/d)	LnK	Elevation of screened layer (m.a.s.l).
1	Akutala-obimo	6.27	1.8358	109
2	Imufu	12.16	2.4982	140
3	Ohebe-dim	21.25	3.0564	151
4	Itchi	16.92	2.8285	150.9
5	Unadu	24.83	3.2121	160
6	Umuida	17.11	2.8397	140
7	Ogrute	10.73	2.3730	170
8	Ibagwa-aka	30.52	3.4184	190
9	Amufie	10.15	2.3175	201
10	Nkalagu-obukpa	14.54	2.6769	216
11	Nsukka-Urban	16.50	2.8034	217
12	Umuna	6.94	1.9373	217
13	Iheakpu-awka	9.38	2.2386	220
14	Ajuona-Obimo	4.09	1.4085	222
15	Ozalla	2.53	0.9282	227
16	Olido	4.95	1.5994	236
17	Umunko	0.56	0.5798	236
18	Nguru-Nsukka	2.61	0.9594	250
19	Iheaka	7.84	2.0592	270
20	Edeoballa	12.25	2.5055	303

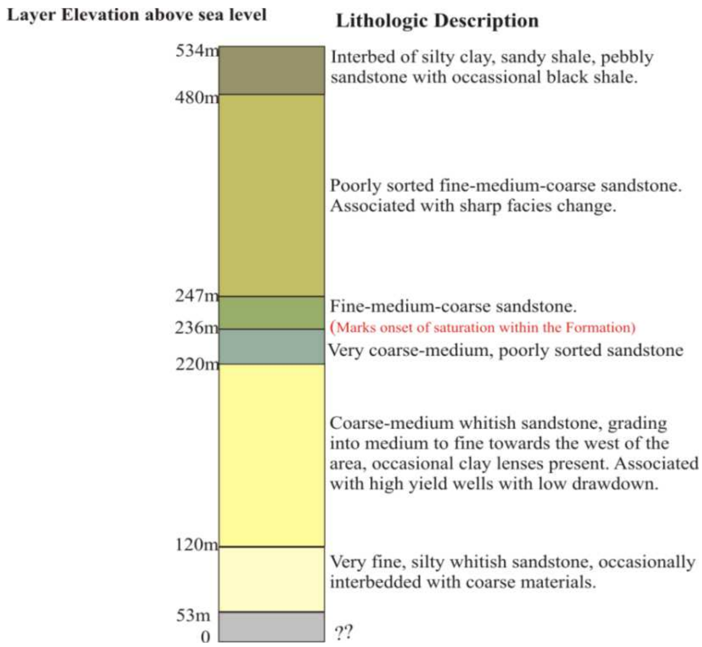

Fig 3. Composite Stratigraphic Section in Nsukka area

Table 4 Summary of Correlation of K,T, Lithology and Elevation of layer

Layer	Lithology	Specific Capacity (m^3/h/s)	K (m/d)	T (m^2/d)	Depth of layer (m.a.sl)
1	Very fine Sandstone	3.04-5.5	0.55-	35-351	109-120
2	Medium-coarse sandstone	10-16	10-21	1000-1500	120-220
3	Verycoarse-medium poorly sorted Sandstone	5-10	5-9	200-750	220-236
4	Veryfine Sandstone	3-5	1-3	35-150	236-247
5	Fine-medium – coarse sandstone	4-11	2-12	150-900	247-303

The above correlation was further checked using the autocovariance(τ) and autocorrelation function(ρ) to determine how the correlation between any two hydraulic conductivity values decays with the separation or lag.A lag is simply some constant separation interval.The values were grouped into 10 class intervals at a spacing of 20m,starting from 100m above sea level. An autocorrelation function is given as (Freeze and Cheery,1989):

$$\rho(h) = exp\frac{(-h)}{\lambda} \quad (10)$$

Where (ρ) is the autocorrelation of the population at a separation h.The correlation length scale (λ) is the separation in the given direction at which ρ takes a value of e^{-1} or 0.37 or τ declines to 0.37 of the covariance at lag zero Fig 4.The correlation length is important because it measures the spatial persistence of zones with similar prperties(Domenico and Schwartz,1990).In equation (4),only the modulus of h is used.For a finite number of vertical values of log hydraulic conductivity,sample covariance(c_y) and autocorrelation function(τ_y) can be calculated from pairs of equally spaced data.The autocovariance function at a separation(h) is :

$$C_y(h) = \frac{1}{m}\Sigma[Y(y)-Y][Y(y+h)-Y],i........,n \quad (11)$$

Where **m** is the number of pairs of sample points at a given separation.The autocovariance coefficient divided by the variance gives the correlation length(Table 5).The longitudinal dispersivity is estimated from:

$$A_L = \frac{\sigma_y^2\lambda}{\gamma 2} \quad (12)$$

Where σ_y^2 is the variance of the log-transformed hydraulic conductivity and λ is the correlation length and γ is a factor considered to be unity(Dagan,1982).

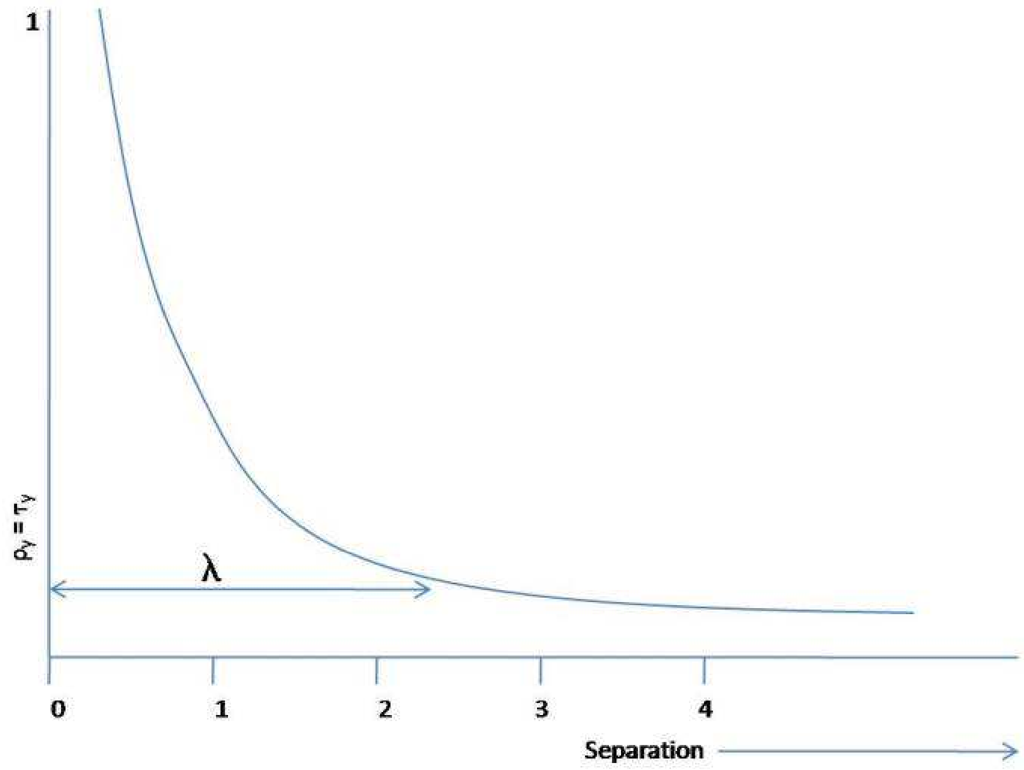

Fig 4 Example of an autocorrelation function with correlation length defined as separation at which ρ=0.37(Modified from Freeze and Cheery,1989)

Fig 4.Example of an autocorrelation function

Table 5 Worksheet for the determination of Correlation length and Variance for Nsukka Hydraulic Conductivity Field

i	Yi	Yi-Y	$(Yi-Y)^2$	(Yi+1-Y)	(Yi+2-Y)	(Yi+3-Y)	(Yi+4-Y)	(Yi-Y)(Yi+1-Y)	(Yi-Y)(Yi+2-Y)	(Yi-Y)(Yi+3-Y)	(Yi-Y)(Yi+4-Y)
100-120	1.8358	-0.3742	0.14	0.4589	0.8223	0.163	1.2084	-0.1717	-0.3077	-0.061	-0.4521
121-140	2.6689	0.4589	0.21	0.8223	0.163	1.2084	0.1847	0.3774	0.0748	0.5545	0.0847
141-160	3.0323	0.8223	0.68	0.163	0.1847	0.1847	-1.3709	0.134	0.9937	0.1519	-1.1273
161-180	2.373	0.163	0.03	1.2084	-1.3709	-1.3709	-1.2506	0.1969	0.0301	-0.2235	-0.2038
181-200	3.4184	1.2084	1.46	0.1847	-1.2506	-1.2506	-0.1508	0.2232	-1.6566	-1.5112	-0.1822
201-220	2.3947	0.1847	0.03	-1.3709	-0.1508	-0.1508	0.2955	-0.2532	-0.231	-0.0279	0.0546
221-240	0.8391	-1.3709	1.88	-1.2566	0.2955	0.2955		1.7144	0.02067	-0.4051	
241-260	0.9594	-1.2506	1.56	-0.1508				0.1886	-0.3696		
261-280	2.0592	-0.1508	0.02	0.2955				-0.0446			
281-300	2.5055	0.2955	0.09								
Σ	22.086		6.1					2.365	-1.2596	-1.5223	-1.8261
1/nΣ	2.21		0.61					0.263	-0.157	-0.22	-0.3

From the above Table,

σ_y^2 = 0.61 , λ = 50m since ?-0.22/0.61? ≈0.37 .

Therefore the asymptotic longitudinal dispersivity(A_L) is:
.$\frac{0.61\times50}{1\times1}$ = 30.5m for the Ajalli Sandstone aquifer

RESULTS AND DISCUSSION

3.1 Stratigraphy

A composite picture of the aquifer system is made up of seven layers.The upper two layers belong to the Nsukka Formation .These layers outcrop at the highland areas and occur only as isolated outliers on the underlying Ajalli Formation.Where they occur,the topmost layer of about 50m in thickness comprises silt interbedded with clay,sandy shale and pebbly sanstone with occassional black shale.The hydraulic arrangement whereby the sandy unit lies on a shale/clay unit gives rise to a perched aquifer system giving rise to springs and availablility of hand-dug wells in few isolated areas..This generally occurs at about 480m above sea level.Underlying this layer is about 230m of poorly sorted fine-medium-coarse sandstone.This layer is associated with sharp faecies change and is transformational in that it cuts across the Nsukka and Ajalli Formations which all belong to the same hydrostratigraphic unit.

Within the broad valleys where the Ajalli outcrops,the saturation usually starts at about 247m to 236m above sealevel.This layer is about 11m of fine-medium-coarse sandstone.Underlying this layer is another thin layer of about 16m of very coarse-medium poorly sorted sandstone which terminates at about 220m.The prolific layer within the Ajalli Sandstone starts from 220m-120m above sea level.This layer has considerable thickness of up to 100m.It is associated with high yield boreholes with low drawdown.The lithology comprises medium –coarse well sorted whitish sandstone with occasional clay lenses which act as semi-confining beds.Below this is a fine –silty sandstone layer which is associated with low yields and low specific capacity(Fig 3).

3.2 Hydaulic Properties

Groundwater flow in the area is driven by the topography which furnishes a gradient of 1/200 from the eastern divide.From here flow west and east of this divide gains momentum,increasing to 1/150 in most of the through flow areas and decreases in gradient at the termination areas . The Darcy velocity varies from 0.02m/d to 0.06m/d while linear velocity varies from 0.05m/day to 0.016m/day. The sequence has an equivalent horizontal hydraulic conductivity of 9.28m/d while an equivalent vertical hydraulic conductivity is 5.86m/d,giving rise to anisotropy of 1.58.The physical meaning of this difference in the horizontal and vertical conductivities is that the sequence is homogeneous but anisotropic referring to the above differences. The correlation length scale of the sequence λ is 50m,implying that every 50m of the vertical squence is a stratigraphic boundary characterizd by distinct stratigraphic and hydraulic properties. The asymptotic longitudinal dispersivity AL is 30.5m giving an idea of linear dispersion or breakthrough from a point contaminant source.

CONCLUSION

The modelling of contaminant plume migration is essential in solute transport migration.The baseline parameters for this kind of study is a first step in model building.The study has clearly determined the aquifer properties and hydraulics for better management of the groundwater system.The relatively high value of the dispersivity highlights the heterogeneity and potential of contaminant spreading,underscoring the need for proactive preventive measures against contamination.Environmental authorities can be guided in the choice of refuse disposal sites based on this study. The sandstone sequence is homogeneous laterally but vertically hetreogeneous making the stratigraphic unit to be homogeneous but anisotropic.This kind of arrangement enhances linear and longitudinal dispersion in porous media.

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