The Use of Mathematical Models in the Analysis of Flow in a Regional Water Table Aquifer in Nsukka Area, Southeast Nigeria

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Abstract

Groundwater development in Nsukka area is hampered by the incessant failure of boreholes drilled at the eastern boundary of a thick regional sandstone aquifer estimated at over 100km^2 in areal extent.The flow systems were investigated using mathematical models based on the solution of the Laplace equation for steady state flow from flow net and functional analysis. Well data from over forty boreholes were used. The aquifer hydraulic parameters used in the models include hydraulic heads (H),transmissivity (T),hydraulic conductivity (K) and flow gradient(i).Three areas of the flow system have been identified in this work; areas of origin in the groundwater divide in the east associated with high heads that attain a maximum of 328m with gradient values of 1/200 or less ,the through flow or transfer areas of Nsukka plateau with head values generally less than 300m and gradient values of 1/150 or less, and the discharge or termination areas in the west and northwest where heads are 230m or less . The modeled parameters provide baseline data for drilling and design of boreholes and a clear understanding of the flow process.

Keywords: Aquifer,Groundwater, Flow , Model ,Nsukka Nigeria.

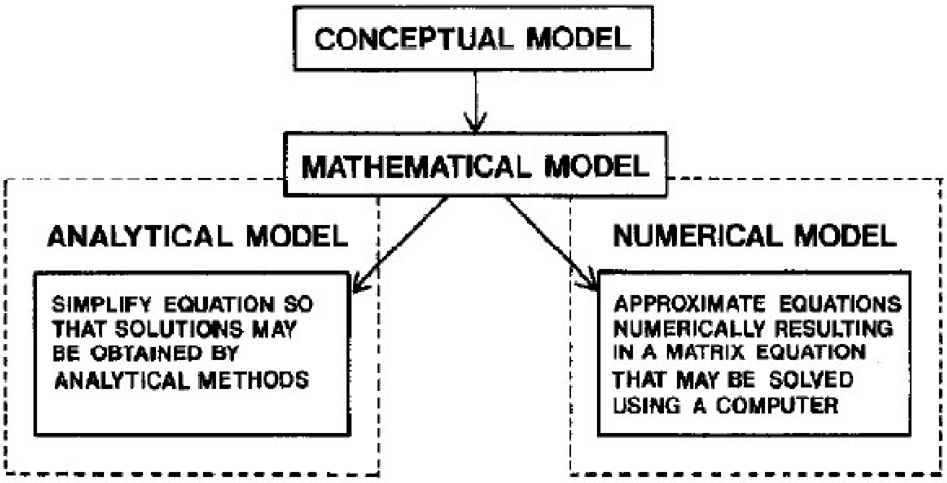
1. Introduction

In Nsukka town, there is virtual absence of surface water bodies, making public and private water supply to depend on ground water resources and seasonal augmentation from rainwater harvesting. To exploit the groundwater reserves, drilling goes down into hundreds of metres in most areas. Routine geophysical works carried out in the area are site specific and do not furnish a spatial guideline for pre-feasibility decisions. For water projects where the budget can be met, drilling success is high but not based on cost-effective planning, leading to spurious inflation of government contracts mis-information of private developers. However towards the eastern part, high failure rates and project abandonments have continued to occur even where drilling contractors claim to have achieved sufficient depths. This scenario persisted till recently after this research work which findings are being utilized in the industry but not disseminated to stakeholders.

A mathematical model is simply a set of equations which, subject to certain assumptions describes the physical processes active in the aquifer(Mercer et al.,1980).Mathematical models may be deterministic, statistical or a combination of the two. The procedure for developing mathematical models have been outlined by various workers including Brachmat et al.(1978),Appel and Bredehoeft(1976),Karplus(1976), and Thomas(1973).These procedures include the conceptualization of the physical system(conceptual model),translation of the physics into mathematical terms(mathematical model),, obtaining a solution using one or more simplifying assumptions to form a subset of the governing equations that is amenable to analytical solution(analytical model).For problems where the simplified analytical models no longer describe the physics of the situation, the partial differential equations can be approximated numerically(numerical model),Analytical methods such as Theis curve analysis are relatively easy to use.

Models are used to make predictions about a ground-water system's response to a stress, to understand the System, design field studies or use as a thinking tool. The rationale for model building was perhaps best expressed by Rosenblueth and Wiener (1945) which submitted that no substantial part of the universe was so simple that it could be grasped and controlled without abstraction. Abstraction consists in replacing the parts of the universe under consideration by a model of similar but simpler structure. Models, formal or intellectual on the one hand, or material on the other, are thus a central necessity of scientific procedure.

Laplace equation is one of the three important partial differential equations usually applicable to groundwater flow problems - Laplace equation for steady state flow problems; Richard's equation for transient flow problems and Poisson's equation which is an extension of Laplace equation to account for the influence of pumping and precipitation. The latter two involve complex mathematics which are solved numerically in part two of this work. Presented here are graphical and analytical solutions to Laplace equation in a flow domain in Nsukka.What follows are the conceptualization and statement of the flow problems of the domain and the application of Hubbert (1940) techniques in the solution of the problem. The implication of this research work is that this Model can be utilized as a guide in the development of groundwater in the area and when the research work is published will provide spatial understanding of the system and provide baseline guide to site-specific pre-drilling data for the area.



2. Methods

2.1 Location Physiography and Geology of Study area.

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. 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(Fig 3.).The vegetation is guinea-savanna type.

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 rain season. Precipitation is high and approximate 1650mm/yr.

The geology and hydrogeology of the area have been extensively studied by various workers. Examples include Simpson (1954), De Swardt and Casey (1963), Nwachukwu (1978), Reyment (1965), Agagu et al. (1985), Egboka and Uma (1986), and 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 2). The Nsukka and Ajalli formations belong to the same hydrostratigraphic unit and give rise to thick water table aquifers. 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.Thicknesses of 336m (Nwachukwu, 1978), and 457m (Reyment, 1965 and Agagu et al, 1985) have been estimated. The Nsukka Formation is the topmost geologic outcrop in Nsukka area. It lacks good exposures and occurs as outliers or residual hills on the Ajali Sandstone (Fig.2). The lithology consists of an alternating succession of sandstone, dark shale and sandy shale.

2.2 Data acquisiton,preparation and presentation.

The following analytical process integrates the effects of basin geometry and geology on unconfined topographic flow in a basin. Earlier statement by king (1899)to the effect that the water table is a subdued replica of the topography provides the preliminary concept. This, in addition to concept of discharge areas (Toth, 1963), the starting point was the modeling of the topography and the delineation of the divides and discharge areas, thus establishing the boundary conditions.

Pumping test records of boreholes drilled under the ADB-assisted Rural Water Supply Project from 1992-1999 from the Enugu State Water Corporation were used. A GPS instrument was used to locate the borehole points' coordinates and their elevations. The data points were captured with the elevations and grid coordinates. Table 1 shows the grid and elevations of borehole points measured with the GPS.The hydraulic heads were calculated from the relation

H (m) = Elevation (m) – Static Water level (m) **(1)**

Where H represents Head in metres, Elevation stands for elevation of the data point referenced to sea level while static water level refers to the level of water in the borehole measured from ground level.

A potentiometric map was prepared using simple triangulation method and thereafter prepared with a contouring software, Surfer 9.3,(Fig 3). The hydraulic gradient is computed from the difference

$$i = \frac{\text{Change in potential}}{\text{change in distance}} = 1/200 \leq I \leq 1/150 \qquad \mathbf{(2)}$$

Pumping test data were analyzed using Cooper-Jacob (1946) method. The layer thicknesses were obtained from the borehole lithologic logs of the various locations. The result is presented in Table 2.

2.3 Mathematical statement of the flow problem and the boundary conditions.

A complete mathematical statement of a groundwater flow problem consists basically of the following parts; specification of the geometry of the flow domain in the aquifer,determination of the independent variables to be used,specifying the initial Conditions(I.C),specifying the conditions which ω or its derivatives have to satisfy on the boundaries specified in the domain and the Continuity equation describing flow in the aquifer.A steady State solution does not require initial conditions.since all the above parts have been specified,the continuity equation of flow is stated as

$$\partial^2H/\partial X^2 + \partial^2H/\partial Y^2 = 0 \qquad (3)$$

Analytical methods involve the use of classical mathematical methods to solve differential equations.One equation of groundwater flow is solved at a time and the result can be applied to one point or line of points in the aquifer (Kresic 1997). In modelling, the first step is to identify the questions to be answered, identify the processes to account for in the model and then formulate appropriate equations for the system

Groundwater flow in the main aquifer is governed by conditions at the boundaries of the regional system.The specification of boundary conditions constrain the problem and make solutions unique.An examination of the Hydraulic Potential Map(Fig 2) clearly shows the elliptical divide at the eastern part. Flows diverge from this topographic high east and west.This serves as a NO FLOW boundary or Dirichlet Boundary (Domenico and Schwartz,1990).The confluence of the flow at the topographic low in the west also makes it a NO FLOW boundary.An equipotential line running NE-SW connecting these two areas is selected as a CONSTANT HEAD boundary with NO FLOW along the line. For the two dimensional Section below(Fig 3), the following conditions apply:

1. Head Change at both eastern and western boundaries is zero
   (for unconfined aquifer)
   $$\partial h/\partial x + \partial h/\partial x = 0 \qquad (4)$$
2. On the water table the pressure is atmospheric so that the head H is a function of the water table equation X.
   $$H = f(x) \qquad (5)$$
   Where H is the hydraulic head
3. The underlying layer is impermeable and as such no vertical leakage or flow from the aquifer to the underlying Mamu Formation.
   As such $\frac{\partial h}{\partial z} = 0$ (6)

The geometry of the model domain is simple and approximate perfect rectangular area and satisfy the simplifying assumptions for analytical solutions.Moreover the Ajalli Formation is homogeneous within the area of study(Amah,J.I,2006).

A further deduction from Toth's work is the representation of the water table configuration by a sinusoidal curve.A graphical solution to the flow problem in a two dimensional flow region was provided (Domenico and Palciaskas, 1973).This study posited that,as long as the water table was not fluctuating too severely in response to recharge and discharge, a steady condition is assumed. The water table graph is therefore a solution to the Laplace equation. This analytical procedure was followed in this study

3.Application

3.1 Equation of the watertable

From the theory of functions involving separation of variables and Fourier analysis (Alan,1979..), the solution of the differential equation is of the form :

$$\phi(x,z) = a_0 + \sum_{n=1}^{\infty} a_n \cosh\frac{n\pi x}{L} \cos\frac{n\pi x}{L} \qquad (7)$$

Where ω = Hydraulic potential, a_0 and a_n are determined from the water table equations for various special cases. The coefficients are determined from:

$$a_0 = \frac{1}{L}\int_0^L \phi(x, z_0)\,dx \qquad (8)$$

$$a_n = \frac{2}{L\cosh(n\pi z_0/L)} \int_0^L \phi(x,z_0)\cos\frac{n\pi x}{L}\,dx \tag{9}$$

(Domenico & Palciauskas, 1973) .

Fig 7 shows the geometrical controls on the spatial distribution of the potential in a two dimensional flow region. Following the analytical method of Domenico and Palciauskas (1973), the water table can be represented by a cosine function of the form:

$$\phi(x,z_0) = A - B\cos\pi x/L \tag{10}$$

The coefficients become ;

$a_0 = A$; $a_1 = \frac{-B}{\cosh(\pi z_0/L)}$ other a's = 0

The solution for Laplace equation then becomes

$$\phi(x,z) = A - \left[\frac{B\cosh(\pi z/L)}{\cosh(\pi z_0/L)}\right]\cos\frac{\pi x}{L} \tag{11}$$

If the boundary values of 234 for Obimo and 323 for Edeoballa are used in Fig 7,

A – B =234

A + B =323, giving A = 278.5 and B = 44.5. The required equation of the water table becomes;

$$\phi(x,z) = 278.5 - \left[\frac{44.5\cosh(\pi z/L)}{\cosh(\pi z_0/L)}\right]\cos\frac{\pi x}{L} \tag{12}$$

Where 278.5 corresponds to midline of flow when the cosine term is zero "i.e"

When x = L/2 implies $\cos\frac{\pi x}{L} = \cos\frac{\pi}{2} = 0$.Also when $Z = Z_0$ implies x = 0 and the cosine term becomes unity ,$\omega(x,z_0) = 234$, the value for the western boundary as required.

3.2 Understanding of the flow system in the area.

Groundwater flow in Nsukka area is topography-driven. The eastern portion of the study area comprising Ohodo, Opi, Edeoballa, Eha-Alumona constitute the groundwater divide (Region **A**) in Fig 4 and Fig 6., where flow goes west and east away from the divide. Here the hydraulic gradient have values of 1/200 and increase downslope to 1/150 at the west and east discharge areas.Macroscopically, the recharge area includes the whole of Nsukka plateau with contributions from localized mounds like Opi/Ohodo mound, Eha-Alumona mound, Obukpa/Ibagwa-Aka mound. Flow from the groundwater divide diverges to the west; southwest and northwest, with the bulk fluid flow westwards. West-bound flow gives rise to subregional discharge areas exist at the Adada River southwest of the area and further northwest from Ibagwa-Ani area while east-bound flow gives rise to a water fall feeding the Uhere river beyond Ogbozalla-opi.

Two flow systems exist within the study area. The upper system results from the overlying Nsukka Formation. This system is a perched system that does not affect the hydraulics of the regional system. The individual flow cells within the upper system are not essentially in hydraulic continuity with the adjacent system cells. Flow is in the main, seasonal but perennial in places. The regional system starts from the groundwater divide in the east at a potential value of about 323m. The divide is an elliptical area with the major axis of about 12km from Opi to Eha-Alumona and the minor axis of about 2.5km across Edeoballa and Ogbozalla(Figs 4 & 6). The divide trends in a NE-SW axis and flow originates from this mound and diverges west, east, southwest, north and northwest, being controlled by slope variation. There is a progressive decrease in potential from East to West and from the recharge mound in the east to the north portion. Here the pattern changes to essentially eastwest flow line.

3.3 Aquifer constants and their effect on well hydraulics

A summary of the aquifer constants from the pumping test data is presented in Table 2 of the appendices.The aquifer constants influence the dynamics of the flow system:

a) The southern part of the recharge mound and the northeast of the area are associated with low hydraulic conductivity and low specific capacity of boreholes. The patterns observed in these areas are associated with the generally smaller thickness of the aquifer proximal to the escarpment and the near vertical flow along the divide. Borehole failures in these areas are caused by insufficient penetration of the saturated aquifer as flow lines are nearly vertical or subvertical resulting in deep water levels.

b) The Northwest (Igboeze) and centre(Nsukka urban) areas are associated with high specific capacity boreholes. The hydraulic conductivity pattern appears to be associated with aquifer thickness which increases westwards .The whole of Igboeze and Nsukka urban constitute the through flow area while further westwards from Obimo Nkpologu,Ibeagwa-Ani,Okpuje areas form the subregional discharge areas that give rise to the Adada River at an elevation of 180m. The base flow goes further west under confinement of the Imo shale to the River Niger.Another surface water body originating from this system occurs north of Ibeagwani(R.Agbeze) within the Igboeze area

(c) Boreholes penetrating the interval of 120m-220m above sea level are the most prolific horizon within the Ajalli Sandstone.This area is associated with high yield wells and low drawdown values.This means that for areas where the topographic elevations attain values of 480m as in the divide,drilling should proceed to at least 260m below ground level. The first successful borehole with the divide was supervised by this researcher and put down to 263m at Umuogbe,Edeoballa in 1993.

Conclusions

This research work has greatly increased the understanding of the dynamics of groundwater flow in Nsukka area.The work provides information on the economy of water supply in the area.Beter cost-effective planning will presently derive from the research findings.Also environmental factors that affect the quality and quantity of the regional aquifer have been clearly determined.Apriori data for planned changes in water and land use in the area can be obtained from this work. Government and private developers of groundwater resources are now better informed about the nature and behavior of the flow systems.This will greatly assist in the curtailment of well failures and better planning and management.The research efforts have been justified by the successes now recorded after this study.

Acknowledgement

The dearth of fund is a major drawback to research work in Nigeria.The materials for this research work came mainly from the authors' field notes as participants in the African Development Bank-assisted Rural Water Supply Projects in Enugu State(1992-2003).Acknowledgement is therefore made to the Management of Enugu State Water Corporation for availing the participants the opportunity to experience this rare field campaign.DHV Consultants BV of the Netherlands for deft Professional work.Acknowledgemnt is also made to Professors K.O Uma and H.I.Ezeigbo who provided the intellectual direction for the modeling efforts.These modest efforts have snowballed into a data repository for research work and appreciation of of modelling as a vital research tool.

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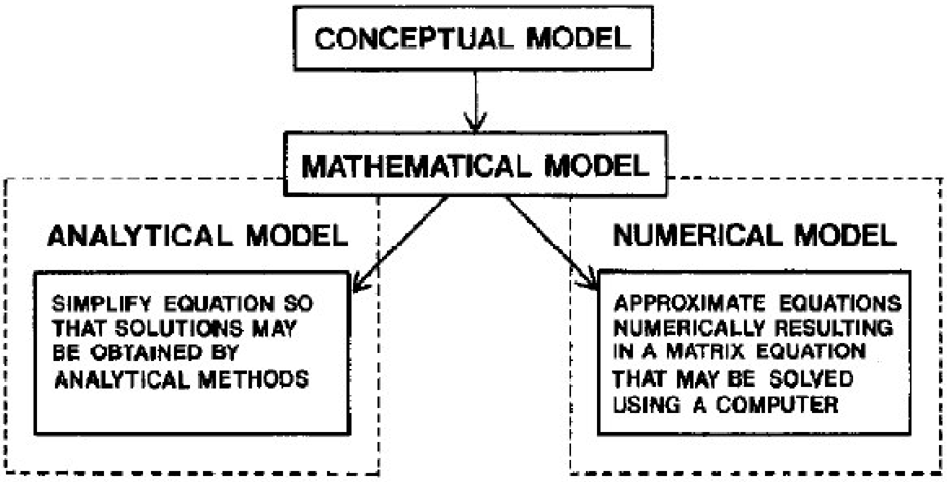


Fig 1 Logic diagram for developing a mathematical model (adapted from Mercer et al.1980)

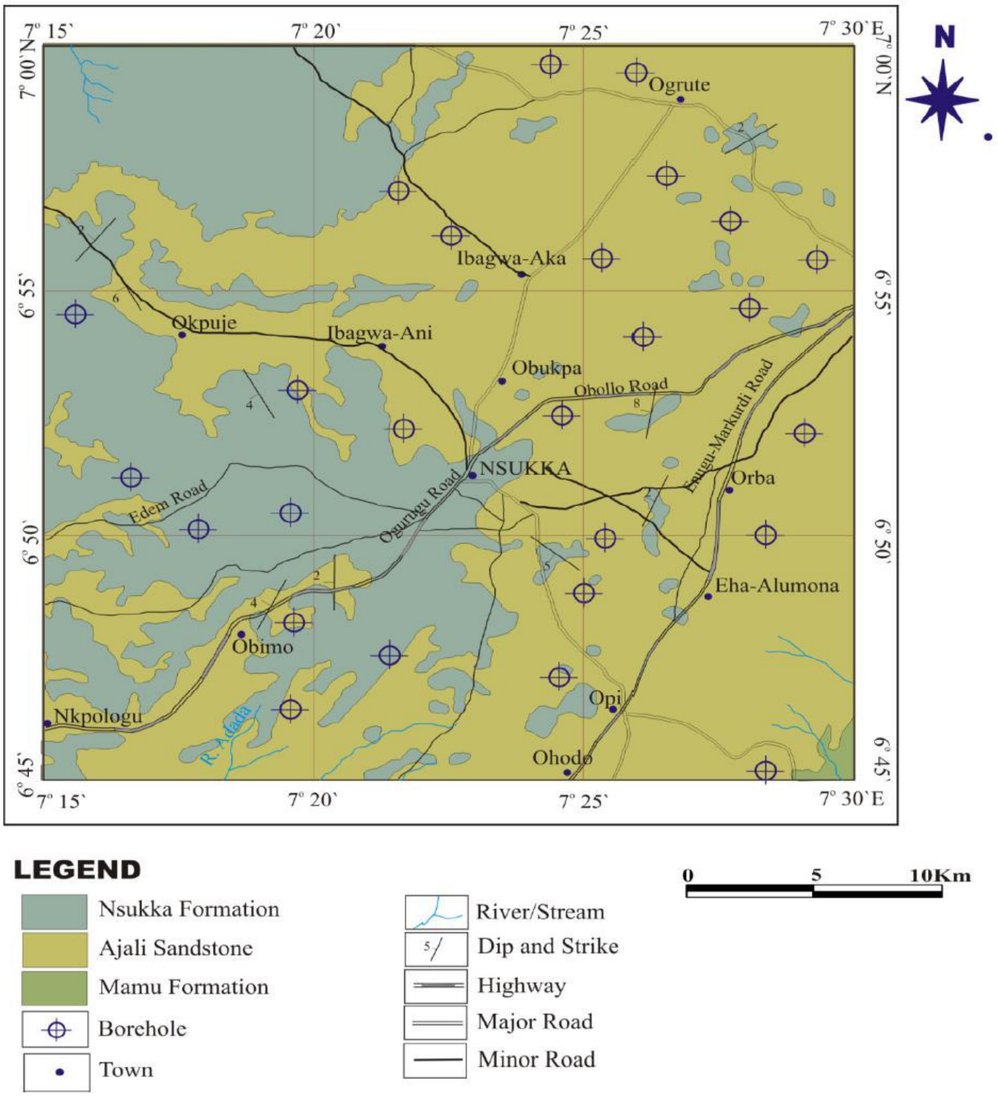
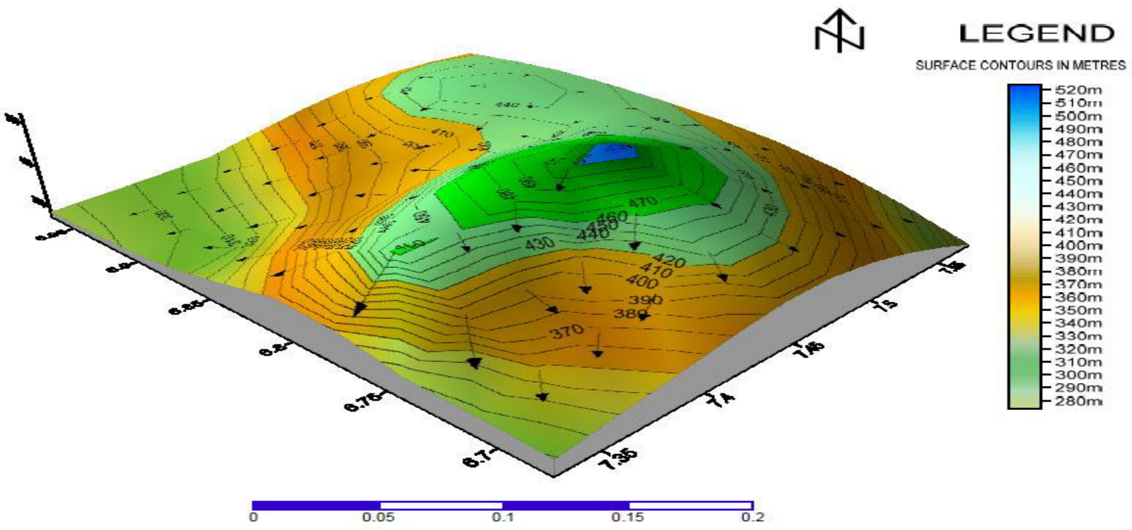


Fig.2 Location map showing geology and borehole points used in the study.



3D SURFACE MODEL OF NSUKKA AREA WITH FLOW VECTORS.

Fig 3. 3D SURFACE MODEL SHOWING THE TOPOGRAPHY AND PHYSIOGRAPHY OF THE

Table 1 Borehole Coordinates and Hydraulic Potential Data

S/N	Borehole Location	Easting(X)	Northing(Y)	Elevation(m)	S.W.L(m)	Hydraulic Potential(m)
1	Akutala-obimo	0538135	0308272	301.5	67.5	234.0
2	Ajuona-obimo	0540418	0308906	477.2	243	234.2
3	Nguru Nsukka	0547346	0310772	497.1	210	287.1
4	Lejja	0546195	0305996	371.0	73	298.0
5	Ohodo	0550013	0304171	462.2	139	323.2
6	Opi	0551533	0306540	467.8	147	320.8
7	Ede-Oballa	0552441	0309130	534.5	221	313.5
8	Eha-Alumona	0555452	0313471	471.0	148	323.0
9	Orba Market	0555362	0316137	424.1	118	306.1
10	Iheaka	0557226	0321348	451.6	165	286.6
11	Ovoko	0555843	0319126	394.5	99	295.5
12	B #9 Nsukka	0548676	0316415	400.5	125	275.5
13	NWR Nsukka	0548610	0316154	415.7	137	278.7
14	Ibagwa-Ani	0542562	0320357	310.7	79	231.7
15	Obukpa	0548244	0320861	387.5	124.2	263.3
16	Ihakpu-Awka	0551150	0322999	387.9	124.45	263.4
17	Ibagwa-Aka	0549687	0322381	381.1	112.3	267.0
18	Umuida	0547480	0331214	316.7	103	213.7
19	Amaebani Nsukka	0549629	0313877	479	173.7	305.3
20	General hospital Nsukka	0550381	0311490	504.6	191	313.6
22	Ogbozalla Opi	554092	308088	511	183	328
23	Ogrute	0555909	0328958	410.3	140	270.3
24	Uhere River	0565394	0298740	274	0	274
25	Amuife	0557706	0326160	445	157.6	287.4
26	Obollo-Afor	0561035	0323163	449.2	150	299.2

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

S/n	Location	W/ level (m)	Elev. (m)	Q(m)	S(m)	Sp.capacity (m^3/hr/m)	T(m^2/d)	b(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	Obimo Ajuona	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	Nkalagu-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

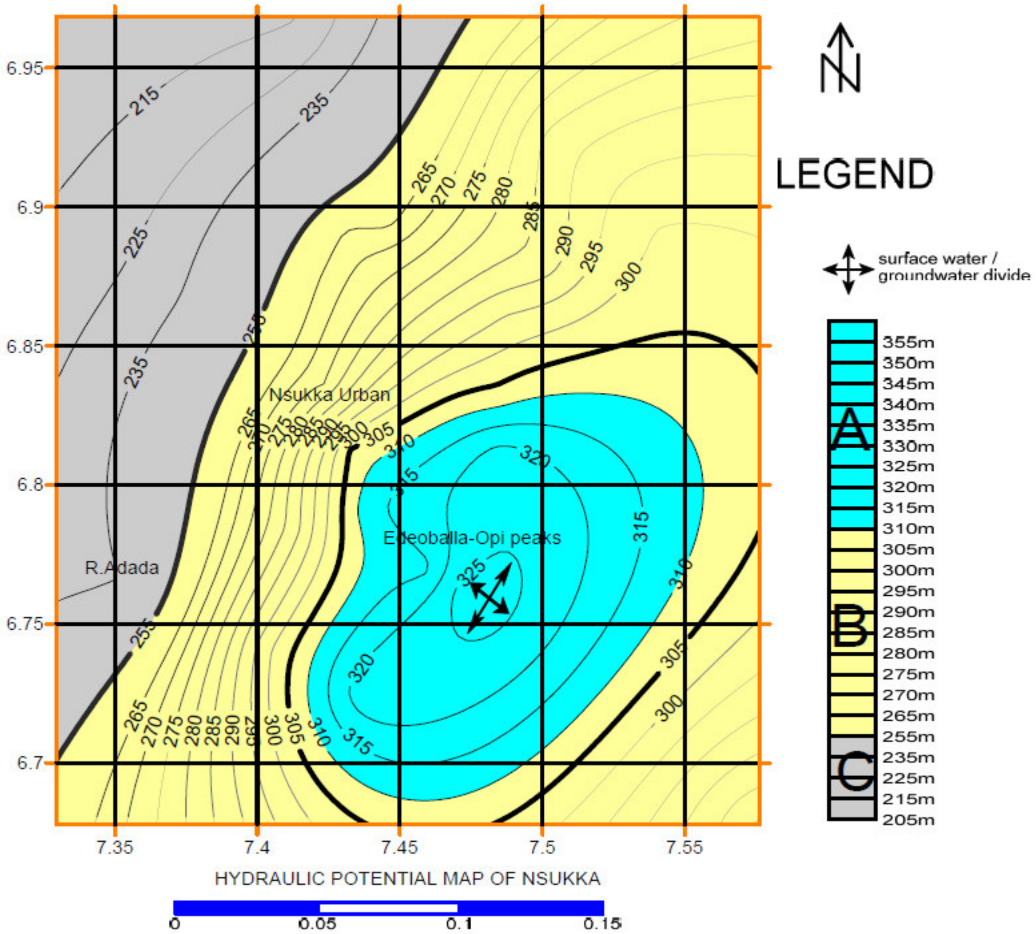


Fig.4 Potentiometric Map showing details of Flow System of Nsukka Area

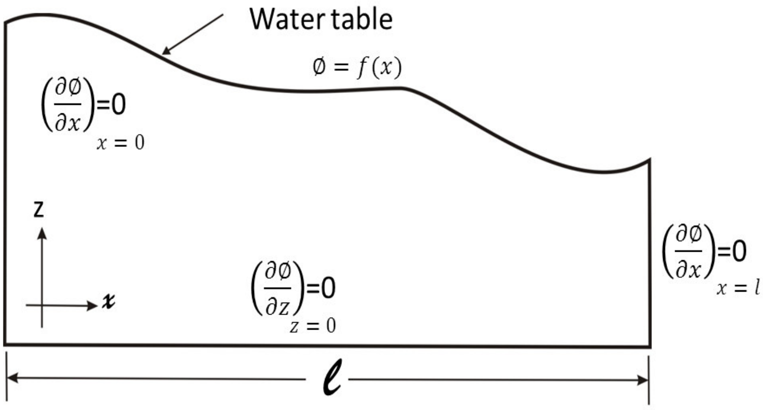


Fig 5 Two-dimensional region demonstrating typical boundary conditions for regional flow (Adapted from Domenico and Schwartz, 1990).

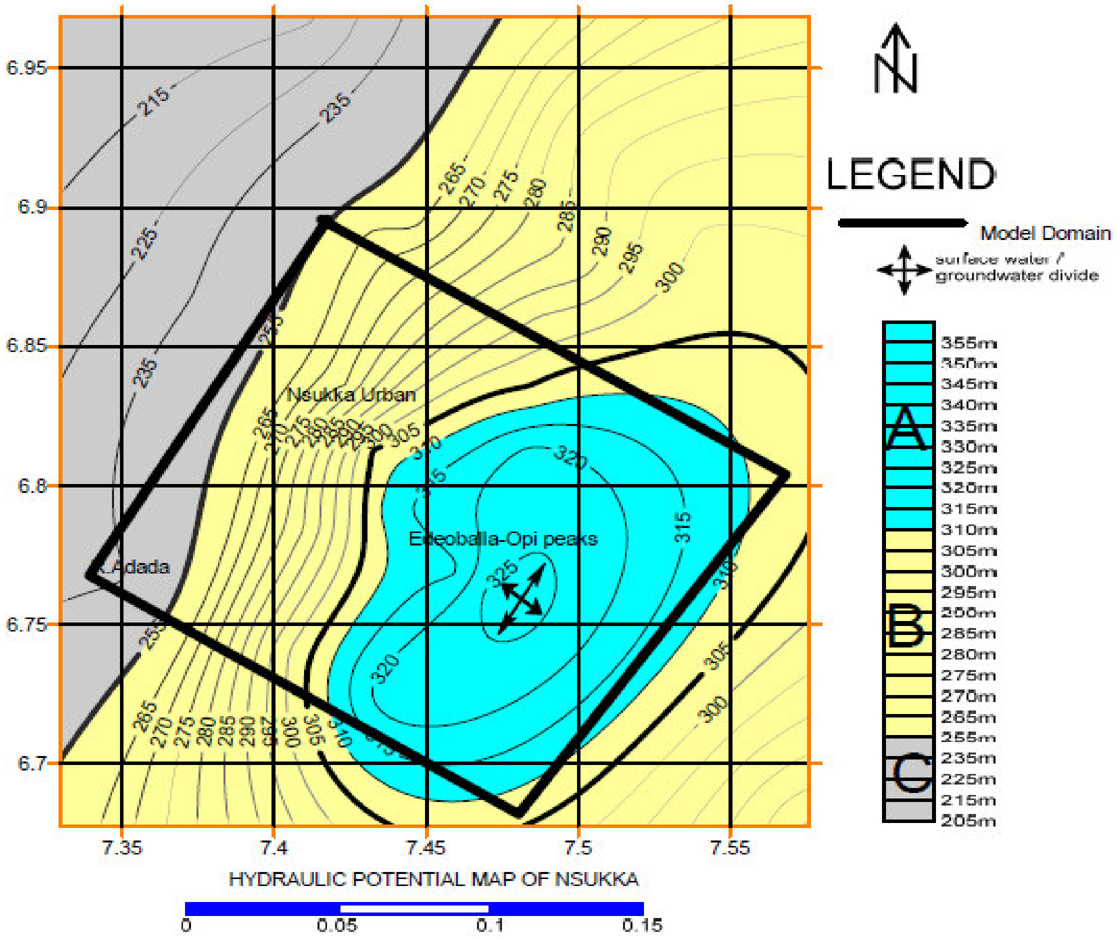


Fig 6 Specification of the Geometry of the Model Boundaries .

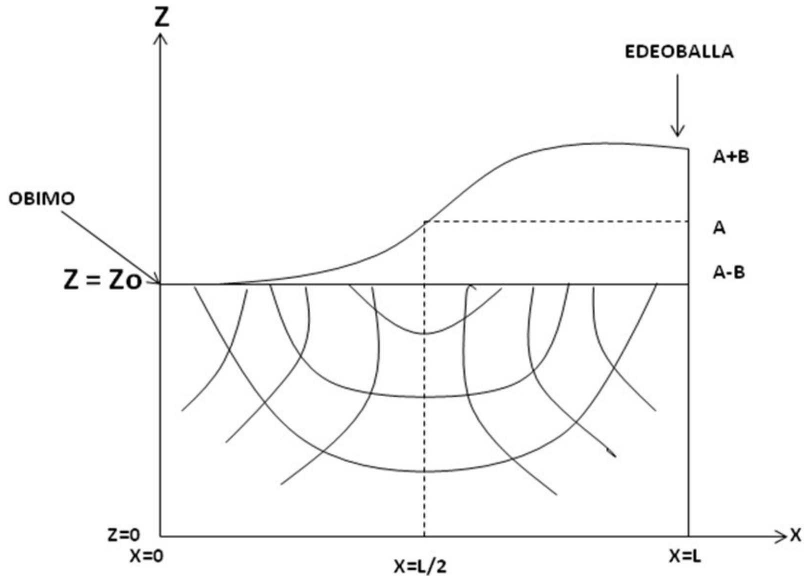


Fig 7. Geometrical Controls on the Spatial Distribution of the potential in a 2D Flow Region (Adapted from Domenico and Schwartz,1990)