A STATUS REVIEW OF THE HYDROLOGICAL CHARACTERIZATION OF THE BASEMENT COMPLEX AQUIFERS IN TARABA STATE, N. E. NIGERIA

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ABSTRACT

The availability and access to fresh water is an important issue all over the world. Groundwater constitutes the only reliable water supply for drinking and irrigation purposes. Recently there has been increased interest in ground water resources resulting from a combination of an increase in its development for public and domestic use; an increase in mining, agricultural, and industrial activities which might impact ground water quality; and an increase in studies of already contaminated aquifers. Decision-making agencies involved in these groundwater activities require studies of the aquifers to develop reliable information on the hydrologic properties and behaviour of aquifers and aquitards. Aquifer testing is a common tool used by hydrogeologists to characterize aquifers flow system boundaries. The most reliable type of aquifer test usually conducted is a pumping test. Pumping tests are a practical and reliable means of estimating aquifer hydraulic properties, well performance, yield, zone of influence of the well and boundary conditions. Proper pumping test practices greatly assist in the interpretation and the value of the pumping test data. This paper is a review of methods of pumping test analysis and use of hydraulic parameters obtained in characterization of aquifer. A case history of the use of pumping test analysis in aquifer characterization in some parts of Nigeria is also highlighted.

Keywords: Groundwater, Aquifer, Pumping testing, Estimation, Storativity, Transmissivity.

INTRODUCTION

A very important aspect of groundwater remediation is the capability to once determine accurate estimates of aquifer hydraulic characteristics. This is largely dependent on the availability of reliable data from a pumping test. Pumping test is a controlled field experiment in which a well is pumped at a controlled rate and water-level response (drawdown) is measured in one or more surrounding observation wells and optionally in the pumped well (control well) itself**(Figs 1a** and **1b).** An aquifer is an underground layer of water-bearing permeable rock or unconsolidated materials (gravel, sand, or silt) from which groundwater can be extracted using a water well **(Fig 2a).** The study of water flow in aquifers and the characterization of aquifers is called hydrogeology. Related terms include aquitard, which is a bed of low permeability along an aquifer,and aquiclude (or aquifuge), which is a solid, impermeable area underlying or overlying an aquifer. When water is pumped from the pumping well the pressure in the aquifer that feeds that well declines. This decline in pressure will show up as change in hydraulic head known as drawdown in an observation well. Response data from pumping tests are used by groundwater hydrologists to estimate the hydraulic properties of aquifers, evaluate well performance and identify aquifer boundaries. Hydraulic characteristics which can be estimated, if the test is designed and implemented properly, include the hydraulic conductivity (vertical and horizontal permeability), coefficient of storage (storativity) and transmissivity.Additional aquifer characteristics which are sometimes evaluated, depending on the type of aquifer, include: specific yield, and confining layer leakage. The hydraulic characteristics of aquifers are also important properties for both groundwater and contaminated land assessments and also for safe construction of engineering structures (Singh, 2005). Depending on the location of observation wells, it may be possible to determine the presence and location of aquifer boundaries (recharge or no-flow) and their distance from the pumped well and piezometers. If measurements are made on nearby springs, it may also be possible to determine the impact of pumping on surface-water features.The pumping test usually has duration of 2 to 12 hours with periodic water level and discharge measurements. The pump is generally allowed to run at maximum capacity with little or no attempt to maintain constant discharge. Discharge variations are often as high as 50 percent. Short-term pump tests with poor control of discharge are not suitable for estimating parameters needed for adequate aquifer characterization. If the pump test is, however, run in such a way that the discharge rate varies less than 5 percent and water levels are measured frequently, the test data can also be used to obtain some reliable estimates of aquifer performance. It should be emphasized that an estimate of aquifer transmissivity obtained in this manner will not be as accurate as that obtained using an aquifer test including observation wells. By controlling the discharge variation and pumping for a sufficient duration, it is possible to obtain reliable estimates of transmissivity using water level data obtained during the pump test. However, this method does not provide information on boundaries, storativity, leaky aquifers, and other information needed to adequately characterize the hydrology of an aquifer.Application of field hydrogeological method in aquifer parameter estimation is time consuming and capital intensive. In the alternative, surface geophysical method may provide rapid and effective techniques for groundwater exploration and aquifer evaluation.

General Importance of Pumping Test

Pumping tests are conducted for a number of possible reasons (B.C. Ministry of Environment, Lands and Parks (MELP), 1999; Driscoll, 1986):

a) To evaluate the well and aquifer response to pumping at different rates; for example, a step test in which the well is pumped at incrementally increasing rates and corresponding changes in water level are measured. Such a test is also useful for determining the optimum rate of pumping;

b) To evaluate hydraulic properties, such as transmissivity, storativity and hydraulic conductivity, of an aquifer supplying water to the well. The resulting values can then be used quantitative analyses such as modelling well

head protection areas, or modelling well or aquifer behaviour under different conditions;
c)To evaluate the potential for interference between a pumping well and nearby wells or water courses.
d) To use the information about the pumping rate and resulting pumping water levels as a critical guide to order a properly sized pump.
e)In order to evaluate the long-term capacity of a well, and confirm its ability to supply a desired quantity of water over time.

Pumping tests are considered the most reliable method for determining well capacity or yield, in comparison to estimates made by a driller at the time of well construction, or empirical pumping 'runs' in which water is pumped from the well at a desired rate without measuring the change in water level (BCMELP, 1999). Water quality parameters such as turbidity, total dissolved solids, or chloride may be monitored at the same time as a well is pumped to determine whether there is any noticeable change; for example, if there is an increase in pumping of sand or fine sediments into the well at higher rates of discharge, or if there is measurable sea water intrusion occurring in coastal area wells. Water samples for analysis of chemical parameters are typically also taken during pumping to assess water quality**.** Pumping test is also important because the information gathered during the test assists the driller in determining the;

- Rate at which to pump the well

- Depth at which to place the pump.

In layered systems, pumping tests are also useful in estimating properties of aquitards (vertical hydraulic conductivityand specific storage). They can identify and locate recharge and no-flow boundaries that may limit the lateral extent of aquifers as well.

Principles of Pumping Test

The principles of a pumping test involves applying a stress to an aquifer by extracting groundwater from a pumping well& measuring the aquifer response to that stress by monitoring drawdown as a function of time. These measurements are then incorporated into an appropriate well flow equation to calculate the hydraulic parameters of the aquifer. It can be applied for single and multi wells (observations). It is important to note that;

- **Static water level:** Is the level of water in the well when no water is being pumped or taken out.
- **Dynamic Water level**: Is the level of water in the well when water is being drawn from the well. The cone of depression occurs during pumping when water flows from all directions towards the pump.

Fig 1a: Pumping test in the field

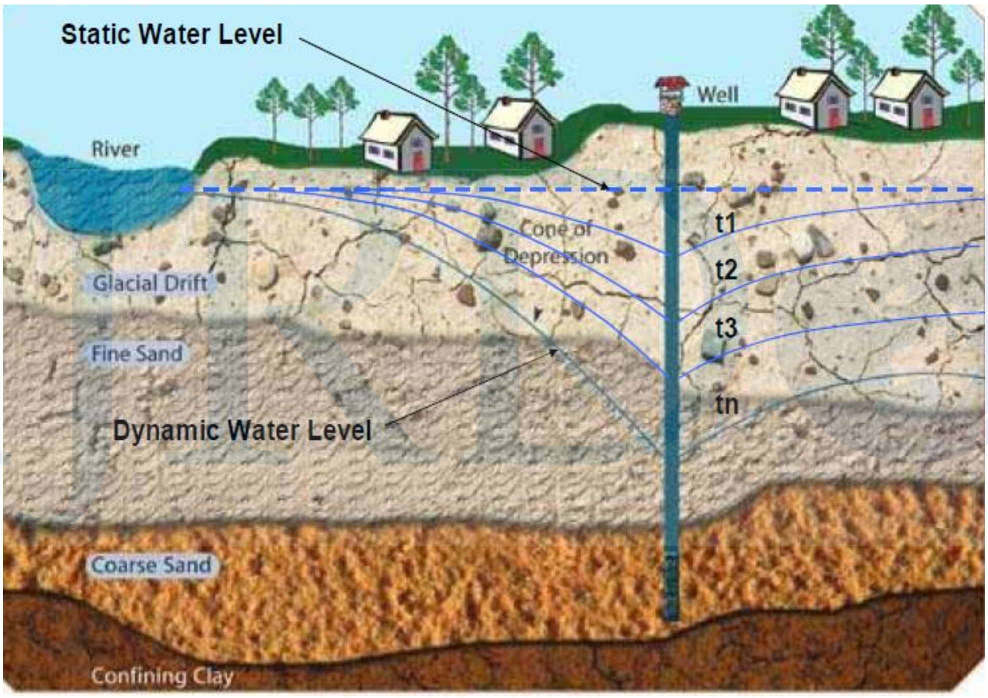

Fig 1b: Representation of a well being pumped as decline in water level shows up as drawdown.

AQUIFER

The word, literally means 'water bearer' and refers to a layer of rock or sediment that contains enough accessible water to be of interest to humans. It is a geologic unit that can store and transmit water at rates fast enough to supply reasonable amounts to wells. Water in an aquifer is stored between the grains of rock. Aquifers can be either consolidated rock (such as sandstone) or unconsolidated (e.g. sands and gravels). The intrinsic permeability of aquifers would range from 10^{-2} Darcy upward. Aquifers must be both permeable and porous and include such rock types or units as unconsolidated sands and gravels, sandstone, conglomerate, fractured limestone and dolomites, basalt flows, fractured plutonic and metamorphic rocks. Fractured volcanic rocks such as columnar basalts also make good aquifers. The rubble zones between volcanic flows are generally both porous and permeable and make excellent aquifers. An aquifer is filled with moving water and the amount of water in storage in the aquifer can vary from season to season and year to year. Ground water flow through an aquifer is dependent on the permeability. But no matter how fast or slow, water will eventually discharge or leave an aquifer and must be replaced by new water to recharge it; every aquifer has a recharge and discharge zone(s). For a well to be productive, it must be drilled into an aquifer. Rocks such as granite and schist are generally poor aquifers due to very low porosity. However, if these rocks are highly fractured, they make good aquifers. The boundaries of an aquifer are usually gradational into other aquifers, so that an aquifer can be part of an aquifer system. There are two types of aquifers.

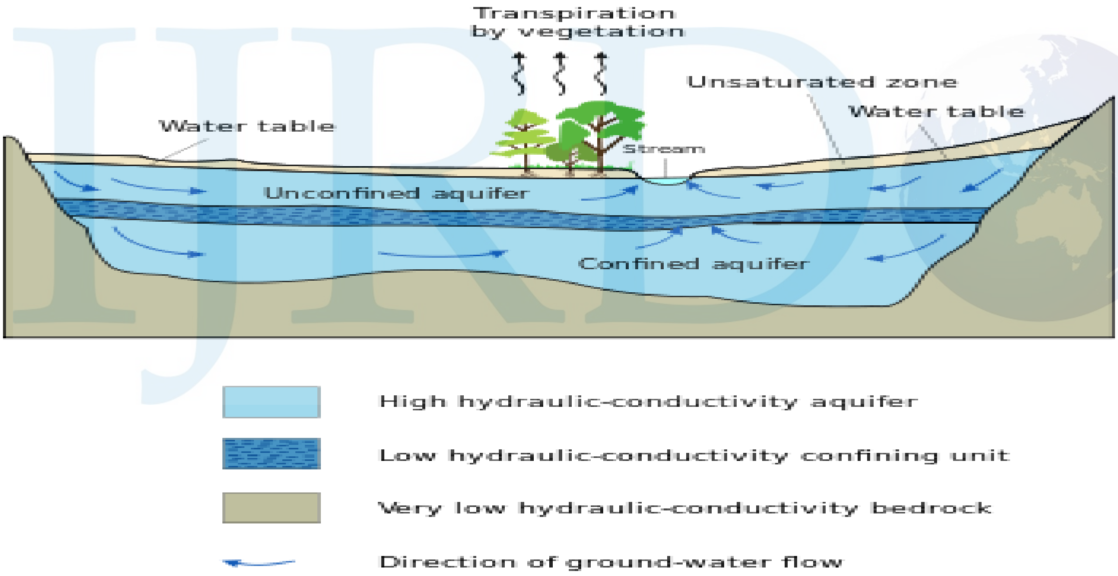

Fig. 2a: Typical aquifer cross section

TYPES OFAQUIFER

Confined Aquifer

This is an aquifer whose upper and lower boundaries are defined by aquicludes. I.e. confined aquifer lies between two layers of less permeable rocks (Confining layers) and is filled with water. Water trickles down through cracks in the upper layer of less permeable rock, a nearby water source, such as an underground river or lake, or a nearby unconfined aquifer.

A confining layer is a geologic unit having little or no intrinsic permeability-less than 10^{-2} darcy. This is a somewhat arbitrary limit and depends upon local conditions. In areas of clay, with intrinsic permeabilities of 10^{-4} darcy, a silt of 10^{-2} darcy might be used to supply water to a small well. On the other hand, the same silt may be considered a confining layer if it were found in an area of coarse gravel with intrinsic permeability of 10^{2} darcys. Groundwater moves through most confining layers, although the rate of movement is very slow. Confining layers are sometimes subdivided into aquitards, aquicludes, and aquifuges. An aquifuge is an absolutely impermeable unit that will not transmit any water. A confined aquifer has at least one aquitard at its top and, if it is stacked with others, an aquitard at its base**.**

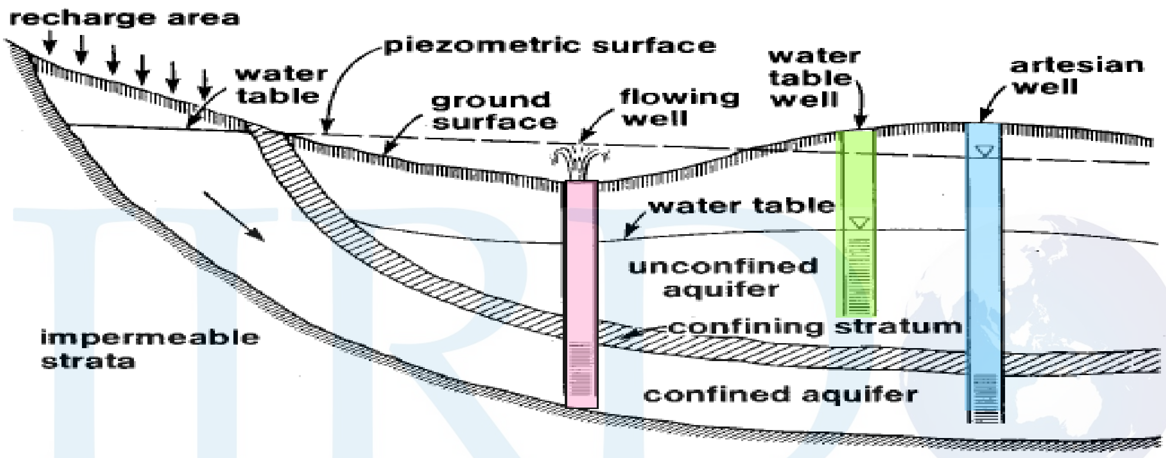

Figure 2b: Schematic diagram combination of confirmed and unconfined Aquifers (Todd, 1980)

An aquitard is a layer of low permeability that can store groundwater and transmit it slowly from one aquifer to another. The term leaky confining layer is also applied to such a unit. An aquiclude is also a unit of low permeability, but is located such that it forms an upper or lower boundary to a ground water flow system. Confining layers can be important elements of regional flow systems, and leaky confining layers can transmit significant amounts of water if the cross sectional area is large.

A portion of a confined aquifer in which the piezometric surface is not only above the ceiling of the aquifer, but also above ground surface, is referred to as an **artesian aquifer**. Artesian aquifers are overlain by a confining layer, and their recharge can occur either in a recharge area, where the aquifer crops out, or by slow downward leakage through the leaky confining layer **(Fig 5).** If tightly cased well is placed through the confining layer, water from the aquifer may rise considerable distances above the aquifer, indicating that the water in the aquifer is under pressure **(Fig 2b)**. If the potentiometric or piezometric surface of an aquifer is above the land surface, a flowing artesian well may occur. Water will flow from the well casing without need for a pump and if a pump were installed, the amount of water obtained from the well could be increased.

Semi-Confined Aquifer

An aquifer is called a semi-confined aquifer when a saturated layer with relatively small horizontal hydraulic conductivity (the semi-confining layer or aquitards) overlies a layer with a relatively high horizontal hydraulic conductivity so that the flow of groundwater in the first layer is mainly vertical and second layer mainly horizontal.

Unconfined Aquifer

Aquifers can be close to the land surface, with continuous layers of materials of high intrinsic permeability extending from land surface to the base of the aquifer. Such an aquifer is termed a water-table aquifer or unconfined aquifer. An unconfined aquifer is covered by permeable rock and can receive water from the surface. Recharge to the aquifer can be from downward seepage through the unsaturated zone **(Fig 2c)**.

Recharge can also occur through lateral groundwater flow or upward seepage from underlying strata. The water table of an unconfined aquifer rises or falls depending on the amount of water entering and leaving the aquifer. It is only partly filled with water. The top of an unconfined aquifer is the water table. **Unconfined** aquifers are sometimes also called water table or phreatic aquifers, because their upper boundary is the water table or phreatic surface. Typically (but not always) the shallowest aquifer at a given location is unconfined, meaning it does not have a confining layer (an aquitard or aquiclude) between it and the surface. The term "perched" refers to ground water accumulating above a low-permeability unit or strata, such as a clay layer. Generally it is used to refer to a small local area of ground water that occurs at an elevation higher than a regionally extensive aquifer.The difference between perched and unconfined aquifers is their size (perched is smaller).

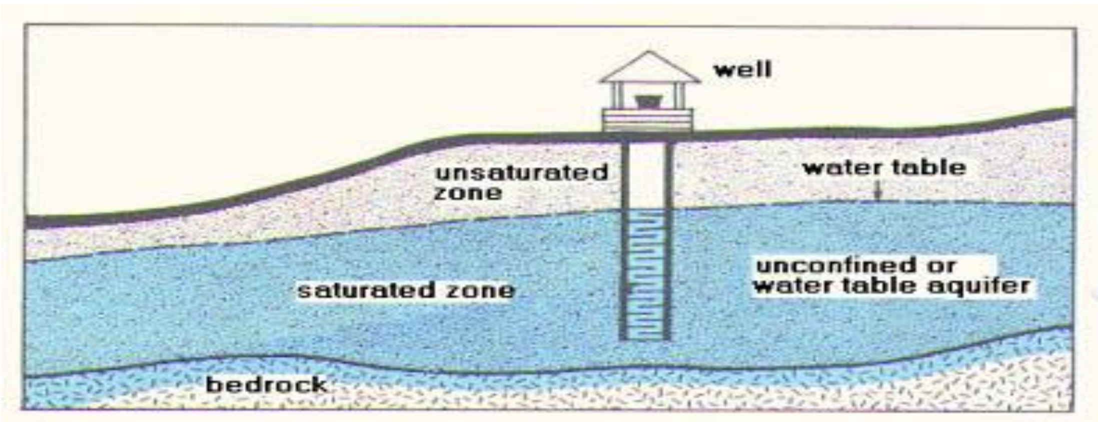

Fig 2c: Unconfined aquifer system

Perched Aquifer

A special case of a phreatic aquifer is the perched aquifer. It is **(fig 3)** a phreatic aquifer of limited areal extent, formed on a semipervious, or impervious, layer that is present between a persistent water table of a phreatic aquifer and ground surface. A perched aquifer may exist only for a limited period of time, as its water is drained into the underlying phreatic aquifer. It may also be seasonal or ephemeral, existing during, periods of high precipitation, disappearing at other times.

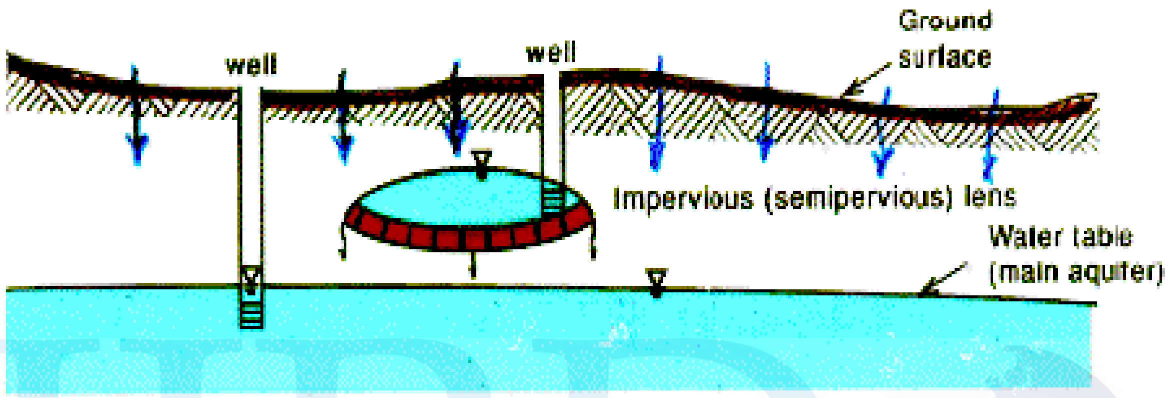

Fig. 3: Perched Aquifer

AQUIFER HYDRAULIC CHARACTERISTICS

Many investigation techniques are commonly employed with the aim of estimation of spatial distribution of hydraulic parameters. Field estimations of these parameters are not always available and usually appear to be problematic (Mendosa et al., 2003, and Zecharia et al., 1988).

Specific Storage or Storativity (S)

Storativity reflects the ability of an aquifer to release water. It is the volume of water released from a saturated confined aquifer per unit cross-sectional area of the aquifer column, per unit decrease in hydraulic head. It is a measure of the amount of water a confined aquifer will give up for a certain change in head. It has no dimension. If the distinction between confined and unconfined is not clear geologically (i.e., if it is not known if a clear confining layer exists, or if the geology is more complex, e.g., a fractured bedrock aquifer), the value of storativity returned from an aquifer test can be used to determine it (although aquifer tests in unconfined aquifers should be interpreted differently than confined ones). Confined aquifers have very low storativity values (much less than 0.01, and as little as 10^{-5}), which means that the aquifer is storing water using the mechanisms of aquifer matrix expansion and the compressibility of water, which typically are both quite small quantities. Unconfined aquifers have storativities greater than 0.01 (1% of bulk volume); they release water from storage by the mechanism of actually draining the pores of the aquifer, releasing relatively large amounts of water.

Hydraulic Conductivity (K)

Hydraulic Conductivity (K) [m/min]**:** Also known as constant of permeability is the rate of flow of water through a unit cross sectional area of an aquifer, at a unit hydraulic gradient. It is also understood as the rate at which a fluid will flow through an aquifer medium, considering the properties of both the aquifer medium (i.e. permeability) and the fluid (i.e. viscosity). In English units the rate of flow is in gallons per day per square foot of cross sectional area. Hydraulic conductivity is one of the most complex and important of the properties of aquifers in hydrology as the values found in nature:

- Range over many orders of magnitude
- Vary a large amount through space
- Are directional
- Are scale dependent
- Must be determined indirectly through field pumping tests, laboratory column flow tests or inverse computer simulation (sometimes also from grain size analyses), and
- Are very non-linearly dependent on the water content, which makes solving the unsaturated K for a single material varies over a wide range than saturated K values for all types of materials.

Table 1: Saturated Hydraulic Conductivities (K) Values found in nature. (Bear, 1972)

K (cm/s)	**10^2**	**10^1**	**10^0=1**	**10^{-1}**	**10^{-2}**	**10^{-3}**	**10^{-4}**	**10^{-5}**	**10^{-6}**	**10^{-7}**	**10^{-8}**	**10^{-9}**	**10^{-10}**
K (ft/day)	**10^5**	**10^4**	**10^3**	**10^2**	**10**	**1**	**0.1**	**0.01**	**0.001**	**0.0001**	**10^{-5}**	**10^{-5}**	**10^{-5}**
Relative Permeability	Pervious				Semi-pervious				Impervious				
Aquifer	Good					Poor				None			
Unconsolidated Sand &Gravel	Well Sorted Gravel		Well Sorted Sand or Sand & Gravel			Very Fine Sand, Silt, Loess, Loam							
Unconsolidated Clay &Organic					Peat		Layered Clay			Fat/ Unweathered clay			
Consolidated Rocks	Highly Fractures Rocks				Oil Reservoir Rocks			Fresh Sandstone		Fresh Limestone, Dolomite		Fresh Granite	

Table 2. Hydraulic Conductivity for various unconsolidated sedimentary materials and sedimentary rocks

Material	Hydraulic conductivity (m/sec)
Gravel	$3x\ 10^{-4}$ to $3x10^{-2}$
Coarse sand	$9x\ 10^{-7}$ to $6x10^{-3}$
Medium sand	$9x\ 10^{-7}$ to $5x10^{-4}$
Fine Sand	$2x\ 10^{-7}$ to $2x10^{-4}$
Clay	$1x10^{-11}$ to $4.7x10^{-9}$

Table 3: Hydraulic Conductivity of Sedimentary rocks

Rock Type	Hydraulic conductivity (m/sec)
Karst and Limestone	$1x\ 10^{-6}$ to $2x10^{-2}$
Limestone, dolomite	$1x\ 10^{-9}$ to $6x10^{-6}$
Sandstone	$3x\ 10^{-10}$ to $6x10^{-6}$
Shale	$1x\ 10^{-13}$ to $2x10^{-9}$

Transmissivity(T)

Transmissivity (m^2/min) is the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It is equal to the hydraulic conductivity times the thickness of an aquifer. It is a measure of how much water can be transmitted horizontally, such as to a pumping well. Transmissivity can be determined from pumping test. An aquifer may consist of a number of soil layers e.g. ***n.*** The transmissivity for horizontal flow (**Ti**) of the **i**- th layer with a saturated thickness **d_i** and horizontal conductivity **Kh_i** is:**$Ti = Kh_i\ d_i$**. Transmissivity is directly proportional to horizontal permeability **(Kh_i) and thickness (d_i).** Expressing **Kh_i in m/day** and **d_i** in m, the transmissivity (**Ti**) is found in units **m^2/day.** The total transmissivity (Tt) of an aquifer is **$Tt = \sum Ti = \sum Kh_i\ d_i$ where** $\sum$ signifies the summation over all layers. When a soil layer is above the water table, it is not saturated and therefore does not contribute to transmissivity. When the soil layer is entirely below the water table, its saturated thickness corresponds to the thickness of the soil layer itself. When the water table is inside the soil layer, the saturated thickness corresponds to the distance of the water table to the bottom of the layer. As the water table may behave dynamically, this thickness may change from place to place or from time to time, so that the transmissivity may vary accordingly. **In a semi-confined aquifer,** the water table is found within a soil layer with negligibly small transmissivity, so that changes of total transmissivity **(Dt)** resulting from changes in the level of water table are negligibly small. When pumping water from an unconfined aquifer, where the water table is inside a soil layer with a significant transmissivity, the water table may be drawn down whereby the transmissivity reduces and flow of water to the well diminishes.

As defined above, transmissivity is the rate of flow of water transmitted horizontally through a unit thickness of an aquifer under a unit hydraulic gradient **(Fetter, 2001).** The hydraulic conductivity for both unconsolidated and bedrock aquifers is calculated by dividing transmissivity by the estimated aquifer thickness. The calculated conductivity is therefore sensitive to the value of aquifer thickness used, which is defined according to site-specific conditions. There is no consistent standard method for determining aquifer thickness for wells completed into either bedrock or unconsolidated materials for the purposes of generating a hydraulic conductivity value from transmissivity estimates

Specific yield or Drainable porosity(S_y)
The volume of water released from storage in an unconfined aquifer, per unit aquifer thickness, per unit decrease in groundwater level. It is a measure of the amount of water an unconfined aquifer will give up when completely drained under the forces of gravity;$S_y$is dimensionless and typically ranges from **0.01 to 0.03**.

Drawdown
This is the difference in elevation of the water level before the well was pumped and the level at a given time after pumping commenced in either the pumping well or the observation well. It is indicated by the expression $\mathbf{h_0}$**-h** (Change in hydraulic head); where **h** is the hydraulic head at a time **t** since pumping began, and $\mathbf{h_o}$is the hydraulic head before pumping started. This amount of water level decline in a well due to pumping is usually measured relative to static(non pumping) conditions Drawdown decreases with radial distance from the pumping well and increases with the length of time that the pumping continues. During the initial stages of a pumping test, drawdown in the pumping well may be influenced by the removal of water that is stored within the well casing, referred to as borehole storage, casing storage, or wellbore storage (Driscoll, 1986). As a well is pumped, water is initially drawn from within the well column; as this storage is utilized, water then begins to be drawn from the aquifer formation surrounding the well (Driscoll, 1986).

Boundary Conditions
In some cases, flow of water toward a well within an aquifer may be affected by the presence of a hydraulic boundary. In this case, as the area of influence around the pumping well expands over the test duration, the rate of drawdown during later test stages may change, reflecting a change in the properties of the aquifer materials at distance from the well (Driscoll, 1986). For **unconsolidated aquifers,** a negative boundary or a low impermeable boundary may be encountered where there is a decrease in permeability of the aquifer materials, the thickness of the aquifer diminishes, or the edge of the aquifer is reached. Conversely, a positive boundary in an unconsolidated aquifer may represent an increase in permeability of aquifer materials or recharge from an adjacent surface water body such as a river. In the case of a **bedrock aquifer** a negative boundary can indicate dewatering of a fracture, while a positive boundary may indicate interception of the zone of influence around the pumping well

with a saturated fracture, a major fault or fracture zone, or the influence of a surface water body (Driscoll, 1986). For both unconsolidated and bedrock aquifers a positive boundary, during which there is no further drawdown observed in the well or perhaps recovery of the water level, indicates that aquifer recharge is occurring at the same or greater rate than the well is being pumped **(Driscoll, 1986).** This type of boundary often yields a zero value of the derivative.

PRINCIPLE OF PUMPING TEST AND EQUIPMENT REQUIREMENT

Planning Stage

Prior to performing a pumping test in the field, one should spend time in the office developing a thorough plan for the test. With careful planning, the pumping-well test can yield data to compute the aquifer transmissivity and also indicate the general type of aquifer. Proper planning includes; test design, acquisition and preparation of field equipment, measurement and control of flow rates, measurement locations and schedules (with pre- and post-test collection periods) for water levels,disposal of pumped water and test duration.

Equipment Test

The equipment test ensures that the pumping equipment, discharge measuring devices, flow meters, V-notch and water level, monitoring equipment are functioning correctly. It will also allow for the gathering of data to allow planning of subsequent pumping tests.

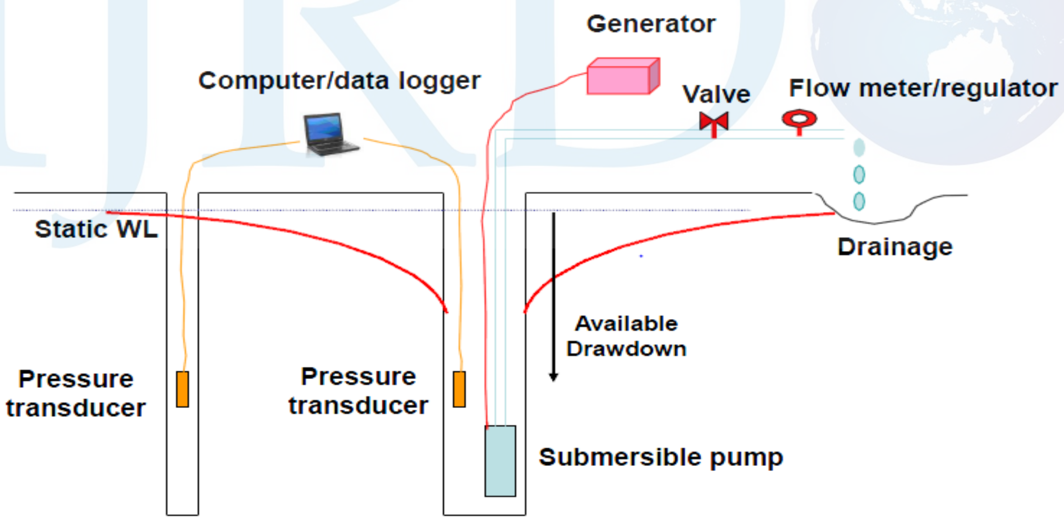

Fig 4: pumping test equipment field setup

PUMPING TEST METHODS

Two basic types of pumping tests carried out are;

1. Step-drawdown tests

a) Determines well efficiency

b) Determine the well specific capacity at various discharge rates.

c) Determines effective pumping rate for constant-rate pump test

2. Constant-rate tests

a) Single well – Transmissivity and hydraulic conductivity

b) Multi-well – Transmissivity, hydraulic conductivity, storage coefficient, verify yield of a production well

Additional Important tests include;

3. Yield Test

4. Recovery Tests

Step-Drawdown Test

This is to establish short term yield versus draw-down data. The test comprises pumping the well in a series of steps, each at a different discharge rate. A minimum of four steps is advisable, with the maximum yield. The test proceeds through a sequence of constant-rate steps at the control well to determine well performance characteristics such as well loss & well efficiency. A well is pumped at a constant rate for a given period of time. The pumping rate is successively increased or stepped for each of several time intervals (typically 1 hour per step & four steps). Each step of the test should be equalled in duration and for operational and data analysis reasons it is common for steps to be 100minutes in duration.The water level is measured during each step (interval), & drawdown is calculated for each pumping rate. Monitoring well data are analyzed to develop models. Test usually lasts a few hours.

Constant-Rate Test

This is the most commonly used pumping test method for obtaining estimates of aquifer hydrologic properties & to verify yield of a production well as well as long-term sustainability of an aquifer. The pumping well is pumped at a constant rate, & water level data are collected in the pumping well and in monitoring wells to determine transmissivity (T), hydraulic conductivity (K), the storage coefficient (S), and other hydrologic parameters. Test usually lasts at least one day.

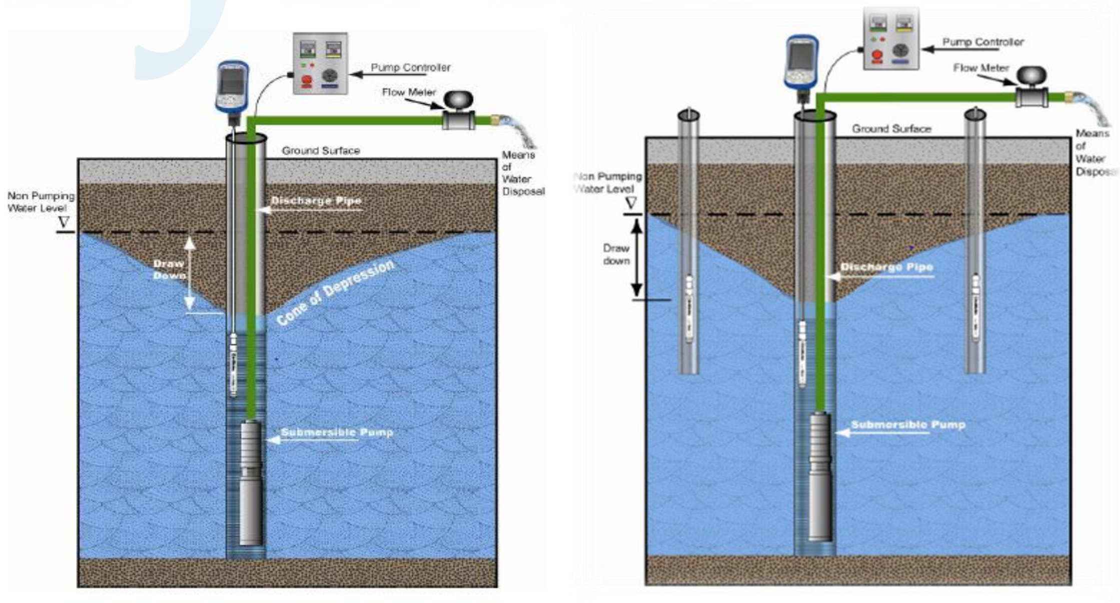

Fig 5: Setup for Pumping test; a) Step-drawdown Test ; b) Constant-Rate Test.

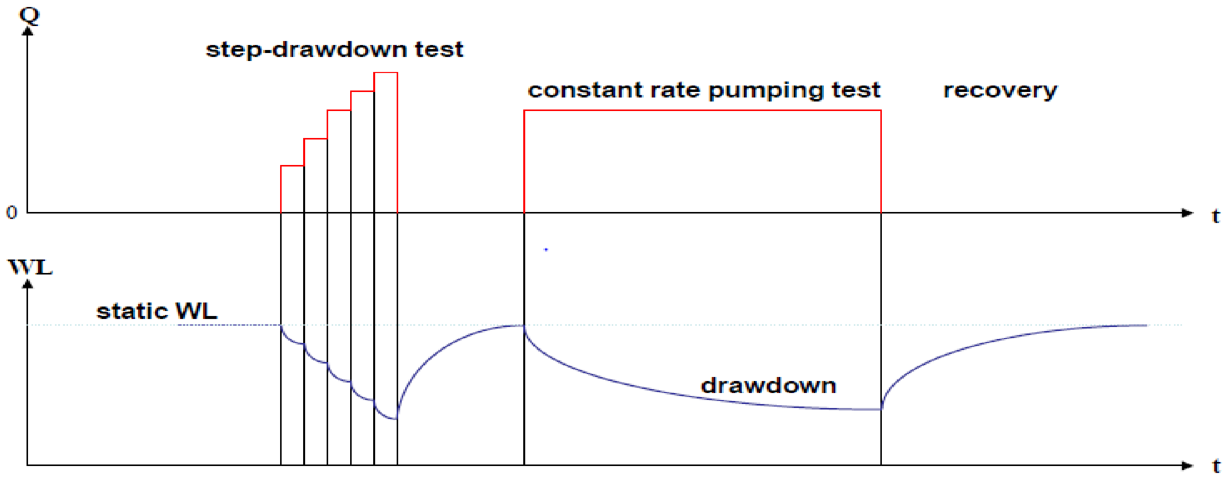

Fig 5C: Summary plot of well test Stages as function of Water level/drawdown against time

Pumping Tests with Observation Wells

If it is feasible, drawdown should be measured in one or more observation wells situated close to the pumping well. These observation wells are often constructed especially for the pumping tests. However, domestic supply wells, abandoned wells, other wells in the well field, or those under construction are sometimes used. The use of one or more observation wells can enable the hydrogeologists compute the storativity or specific yield of the aquifer. In most cases, the hydrogeologists will be able to employ only one observation well especially if the aquifer is deep and the area is undeveloped, with no existing wells available. The selection of the location of the single observation well is critical. It should be located at a radial distance such that the time-drawdown data collected during the planned pumping period will fall on a type curve of unique curvature. If a test bore is made, the geologist should know the type of aquifer system to be confronted. The formation characteristics are then estimated, and using the correct formula with the planned pumping rate, time draw-down curves for several hypothetical observation wells at different distances are plotted. On the basis of these curves, the location of the single observation well is selected. As a general rule, it will be closer for a water-table well than for a confined well. If there are two observatory wells, the second should be in a radial line with the first, but at ten times the distance. If there are more than two wells, they should form two or more radial lines from the pumping well. This will indicate any radial anisotropy in the aquifer. Ideally, Observation wells should fully penetrate the aquifer, so that they measure the average head in the formation at the location. Also the distance from the pumping well to each observation well should not be too close (say $\geq$ 5m or more); this should be measured with a steel tape.

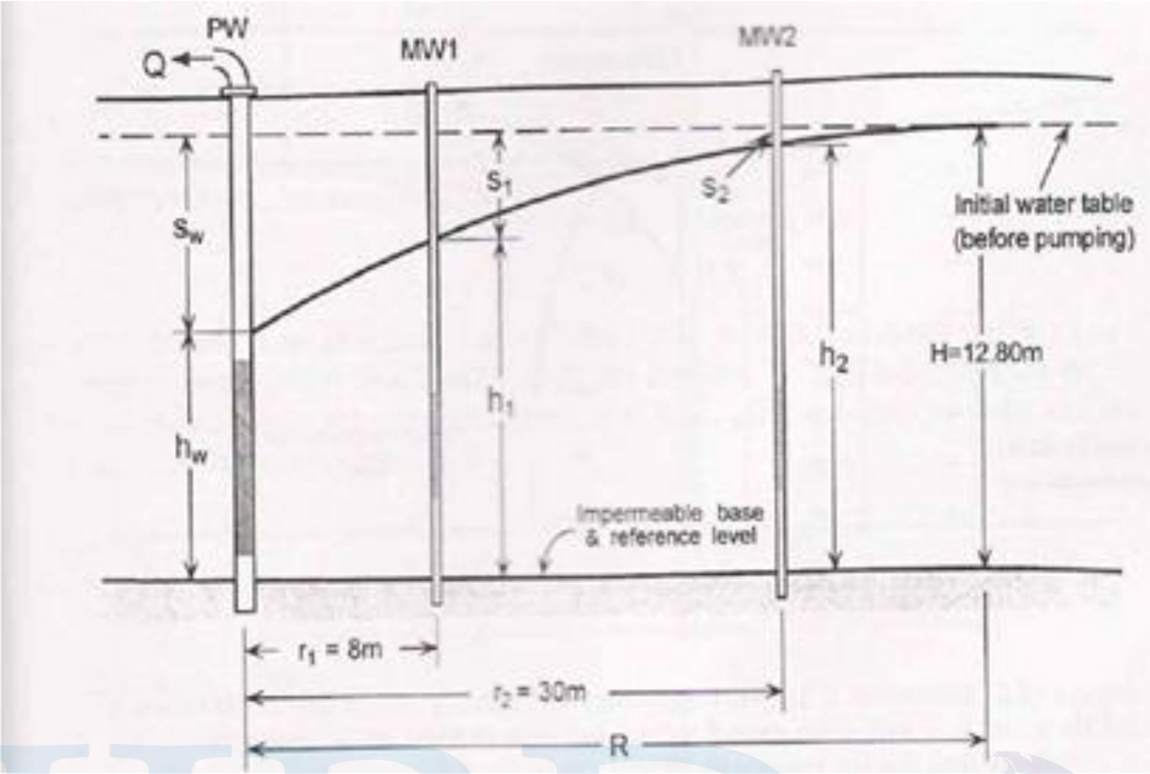

Fig 8: Pumping Well With Observation wells in Unconfined Aquifer

4.7 Pumping Test Measurements

1. Recovery Test Measurements: Upon completion of pumping, the water level recovery is measured for a period of time not less than 1/3 the length of the pumping test. During recovery, the water level measurements should be made in accordance with the previous baseline data collection schedule.

2. Well Discharge Rate: Among the arrangements to be made for pumping tests is a discharge rate control. This must be kept constant throughout t test and measured at least every hour, and any necessary adjustments shall be made to keep it constant.

3. Drawdown Measurements:

During the pumping test, drawdown measurements in the pumping well and observation wells are recorded to an accuracy of 1 inch (or 1/10th of a foot). Drawdown is measured, at a minimum, in accordance with the schedule below:

Table4: Drawdown Measurement schedule

Elapsed Time	Measurement Frequency
0-10 minutes	1 per minute
10-20 minutes	Every 2 minutes
20-60 minutes	Every 5 minutes
60- 180 minutes	Every 15 minutes
180-360 minutes	Every 30 minutes
360 to completion	Every 60 minutes

4. Water level measurementfor pumping and observation wells may be taken as follows:

Table 5: Water level measurement Scheme for Pumping well

Time since start of pumping(minutes)	Time intervals(Minutes)
0-5	0.5
5-60	5
60-120	20
120-shutdown of pump	60

Table 6: Water level measurement Scheme for Observation wells

Time since start of pumping(minutes)	Time intervals(Minutes)
0-5	30secs
5-15	1
15-50	5
50-100	10
100-300	30
5-48hr	60
48hr-Shutdown of pump	480 (8hr)

CASE STUDIES OF CHARACTERIZED AQUIFERS

Hydrogeological Characterization of Basement Aquifers in Taraba State, N.E. Nigeria

The area of study covers the basement complex area of Taraba State. It lies between latitude $9^{0}00^{I}$ N and $12^{0}00^{I}$N and longitude $6^{o}30^{I}$E to $9^{o}30^{I}$E and has an aerial extent of about 41,200 km^2. The study area is underlain by undifferentiated Basement Complex rocks particularly the migmatites, generally vary from coarsely mixed gneisses to diffused textured rocks of variable grain size and are frequently porphyroblastic **(Macleod, et al 1971).**Tertiary to Recent basalts also occur in the area **(Fig. 7).** This rock unit constitutes principally the undifferentiated igneous and metamorphic rocks of Precambrain age **(Grant, 1971).** Recent surveys carried out in 1997 and 1998 by the Petroleum (Special) Trust Fund (PTF) under the National Rural Water Supply Programme revealed that more than 90% of the people in Taraba State lack adequate and potable water supply.

Description of Aquifers

In basement terrain, groundwater development is met with difficulties due to lack of primary porosity in the bedrock. The secondary porosities such as joints, fault and weathered zones are the sources of groundwater occurrence and movement **(Wright and Burgess, 1992, Chiton and Foster, 1995, Foster et al 2008, Srinivasa, 2000).** Hence, the secondary porosity and weathered zones constitute the different aquifer systems. Borehole lithologic logs revealed two water bearing zones in the area; namely the **weathered zone** and **the fractured-rock zone (Fig. 8).** The basement complex rocks of the study area were subjected to different degrees of weathering which led to the formation of thick weathered materials in some places. The weathered materials range in thickness from 3m to 37.73m with an average of 17.8m, and consist of sandstone, clays and silts. The fractured-rock zone is overlain by the weathered zone and acts as conduit for groundwater movement. The zone is recharged by infiltration through the upper weathered zone.

Evaluation of Aquifer Properties

Available data on thirty-nine (39) hand pump boreholes were analysed for the determination of Transmissivity (T) and hydraulic conductivity (K). Attempts were not made to isolate the aquifer properties of **the weathered overburden aquifers** and that of the **fractured-rock aquifers**. This is because in the course of drilling these boreholes, both aquifers were merged and screened. The basement aquifer properties evaluated reveal that the transmissivity values (MacDonald et al, 2005 b) range from $0.3m^2$/day to $19.7m^2$/day with an average of $2.90m^2$/day **(Table 2)**. Most values are below $5.0m^2$/day; and according to Offodile (2002), a transmissivity range of 5 to $50m^2$/day could be regarded as high potential in crystalline rock situations. By the above standard, the aquifers in the area are classified as aquifers of negligible to high potentials. The hydraulic conductivity is simply computed from the relationship **$T = Kb$** where **b** represents the aquifer thickness. This was obtained by subtracting static water level from overburden and fractured-rock zone. Results from **Table 7**also reveal hydraulic conductivity values ranging from 3.0×10^{-2}m/day to 7.0×10^{-1}m/day with an average of 1.90×10^{-1}m/day; which according to Todd, 1980 reveals

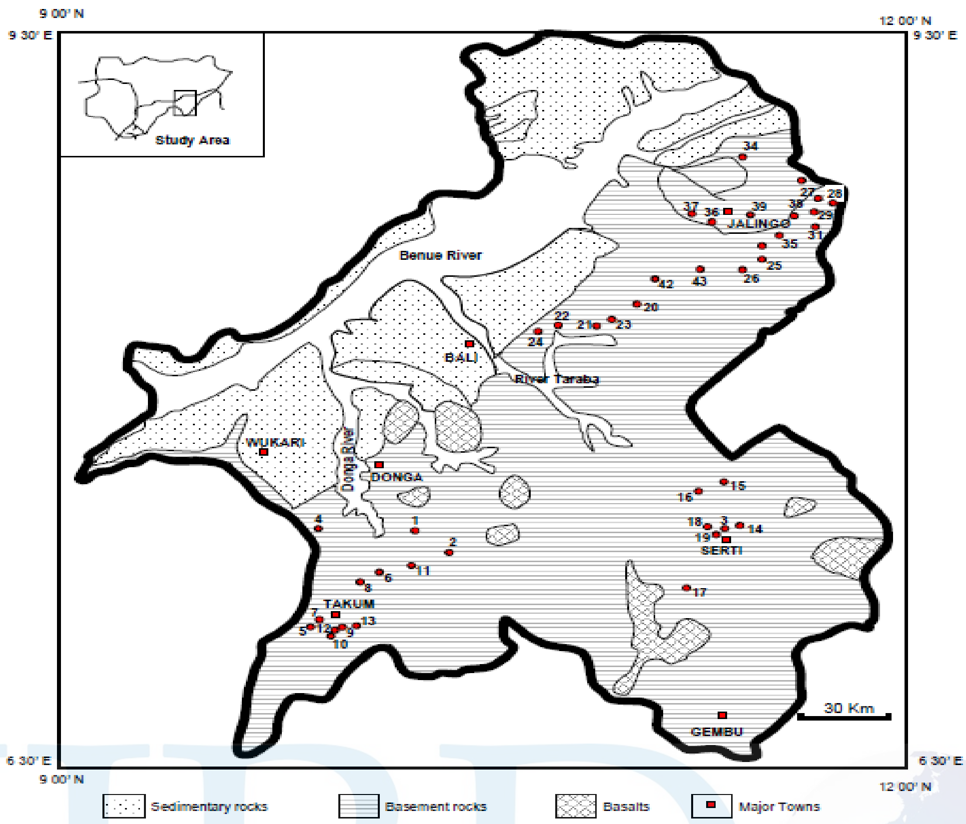

Fig. 7: Borehole location map and drainages of the study area. Modified from Badafash consulting engineeers

moderate hydraulic conductivity. Specific capacity values computed for the boreholes vary from 0.60m^3/day/m to31.30m^3/day/m . Higher values occur in BH7, BH8, BH9, BH24, BH37 and BH43 with low drawndown values **(Table 8).** The specific capacity can be related directly to aquifer properties K and T **(Dike, 1994).** Though, specific capacity data do not show correspondence with transmissivity, hydraulic conductivity and borehole yield, but here two boreholes (BH6 and BH19) exhibit such a relationship **(Table 2).** The uncorresponding relationship between specific capacity values T, K and borehole yields could be attributed to differences in degree of weathering, presence or absence of fractures in some places and method of construction of the wells .The performances of the boreholes have been classified into 4 groups based on the range of specific capacity values **(Table 8).** Based on specific capacity values, most of the boreholes (79%) have moderate performance which corresponds to moderate hydraulic conductivity values (3.3. x 10^{-2}m/day to 7.0 x 10^{-1}m/day) and negligible to high transmissivity values (0.3m^3/day to 19.7m^2/day). Borehole yields range from 6.77m^3/day to 21.6m^3/day with an average of 14.41m^3/day. According to **Babatola, 1997**, total yield of the boreholes is about 620.04m^3/day which can sustain a population of 24, 802 based on water supply standard of 25 litres per day for rural communities. The basement aquifers, therefore, when fully developed can sustain domestic, agricultural and industrial activities. On the basis of the aquifer types and characteristics identified.

Table 7: Hydraulic characteristics of some handpump boreholes in the study area

BH Na	LOCATION	DEPTH (m)	YIELD (m^3/day	SWL (m)	DRAWDON (m)	SC (m^3/day/m)	AQUIFER THICKNESS (m)	TRANSMISSITY (m^3/day)	HYDRAULIC CONDUCTIVITY (M/day
1.	Mararaba Baissa	19.00	6.77	6.97	11.25	0.60	ND	0.39	ND
2.	Nasarawa	12.90	14.40	5.90	2.00	7.20	ND	ND	ND
3.	Bunduwa	48.18	12.96	5.86	7.21	1.80	ND	0.51	ND
4.	Chanchanji	96.10	17.28	6.80	4.60	3.76	ND	2.57	ND
5.	Kwambai 2	24.80	11.52	8.51	3.30	3.49	ND	1.75	ND
6.	Muji 2	4.00	12.10	7.00	4.51	2.68	8.00	1.29	1.60×10^{-1}
7.	Jenuwarikya	50.76	12.67	6.71	0.63	20.11	22.29	5.80	2.6×10^{-1}
8.	Basang	48.00	17.28	4.50	0.91	18.99	19.50	5.00	2.6×10^{-1}
9.	Kpakye	45.00	17.28	3.20	1.71	10.11	14.80	18.10	1.22×10^{-1}
10.	Kpambo Yirom	54.20	12.67	5.00	7.26	1.75	14.00	0.61	4.4×10^{-2}
11.	Sabongida	59.00	11.23	6.30	11.30	0.99	12.40	0.43	3.4×10^{-2}
12.	Nzurkwem	80.00	12.96	13.55	ND	ND	34.50	0.97	2.8 x $\times 10^{-2}$
13.	Lissam	51.60	11.23	5.20	13.40	0.91	8.50	0.38	4.5 4.4×10^{-2}
14.	Yelwa	49.18	12.96	4.36	9.50	1.36	19.64	0.64	3.3 4.4×10^{-2}

15.	Kwaitab	50.67	15.84	8.46	3.70	4.28	14.54	0.88	6.1 4.4 x 10^{-2}
16.	Karamti	41.97	14.40	4.37	3.75	3.84	30.63	1.46	4.8 4.4 x 10^{-2}
17.	Mayoselbe	44.90	14.40	8.42	3.34	4.31	10.58	1.01	9.5 4.4 x 10^{-2}
18.	Saukakahuta	48.00	ND	5.90	ND	ND	9.10	ND	ND
19.	Tudunwada	26.70	17.28	8.80	3.30	5.24	6.20	2.10	3.4 4.4 x 10^{-1}
20.	Gangpenton	55.20	17.28	7.33	9.16	1.89	10.67	0.57	5.3 4.4 x 10^{-2}
21.	Hamdallahi	51.46	17.28	6.63	3.96	4.36	6.37	1.44	2.3 x 4.4 x 10^{-2}
22.	Garbachede	91.30	13.25	2.55	1.04	12.74	ND	4.50	ND
23.	Garin Yusufu	55.80	14.40	7.80	3.40	4.24	22.20	1.91	8.6 4.4 x 10^{-2}
24.	Sansani	46.40	18.70	4.32	6.22	3.01	10.68	1.87	1.8 4.4 x 10^{-1}
25.	Gangdole	42.54	17.28	7.68	2.02	8.55	28.32	19.7	7.0 4.4 x 10^{-1}
26.	Dakka	103.20	14.40	5.85	4.77	3.02	ND	2.53	ND
27.	Tudunwada	59.20	10.51	6.20	6.88	1.53	ND	0.54	ND
28.	Bitako	55.70	14.40	2.97	2.59	5.56	32.10	2.93	9.1 x 10^{-2}
29.	Lakwati	61.67	11.23	2.60	4.81	2.33	ND	0.87	ND
30.	Monkin	37.36	11.23	9.50	9.66	1.16	ND	0.76	ND
31.	Yakoko	34.35	14.40	9.44	4.79	3.01	ND	0.59	ND
32.	Gov. Lodg. Zing	16.90	14.40	8.00	1.53	9.41	ND	3.20	ND
33.	Yonko	27.96	15.84	4.21	9.37	1.67	ND	0.56	ND
34.	Mararaba Kunini	54.00	14.40	5.28	ND	Nd	3.00	1.51	5.0 x 10^{-1}
35.	Tsoro Dangung	45.83	17.57	8.60	1.47	11.95	13.40	2.98	2.2 x 10^{-1}
36.	Jekadafari	42.00	14.40	3.00	6.80	2.12	ND	0.57	ND
37.	NTA Vill. Jalingo	42.00	20.16	6.56	7.93	2.54	28.44	1.23	4.3 x 10^{-2}
38.	Wuro Sambe	37.00	11.52	26.00	ND	ND	ND	ND	ND
39.	Sabongari Jalingo	49.00	14.40	5.27	4.67	3.08	37.73	1.14	3.0 x 10^{-2}
40.	Kantiyel	31.00	21.6	10.05	ND	ND	ND	ND	ND
41.	Tutare	30.00	21.6	4.92	0.69	31.30	26.58	15.7	5.9 x 10^{-1}
42.	Jauro Manu	45.87	10.08	6.87	1.33	7.58	26.13	3.6	1.4 x 10^{-1}
43.	Garin Shuaibu	23.86	11.52	8.26	2.04	5.65	ND	1.92	ND

BH: Borehole; ND: No data

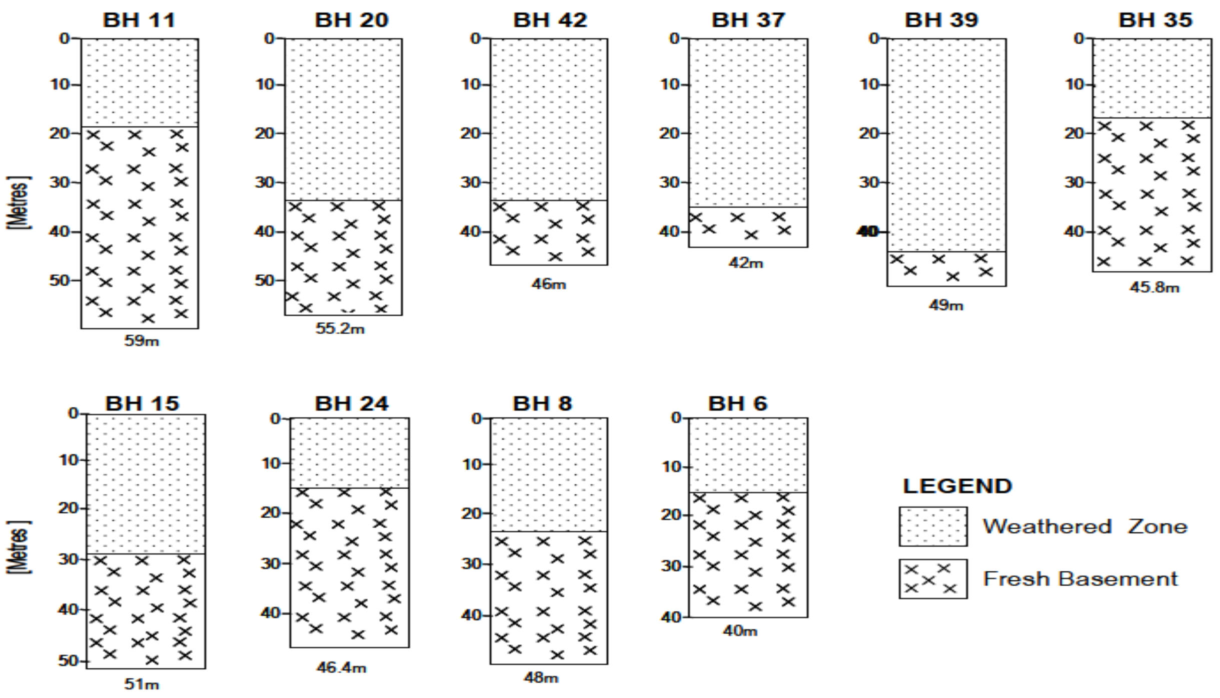

Fig10: Lithologic Section of Some Hand Pump Boreholes in the Basement areas

Table 8: Classification of specific capacities in the study area

Group	Specific Capacities Range (m^3/day/m)	Borehole performance
1	<31.30	Excellent performance BH 41
2	11.95-31.30	Good performance BH7, BH8, BH22, BH35
3	1.16-11.95	Moderate performance BH2, BH3, BH4, BH5, BH6, BH9, BH10, BH14, BH15, BH16, BH17, BH19, BH20, BH21, BH23, BH24, BH25, BH26, BH27, BH28, BH29, BH30, BH31, BH32, BH33, BH36, BH37, BH39, BH42, BH43,
4	0.60-1.16	Poor performance BH1, BH11, BH13

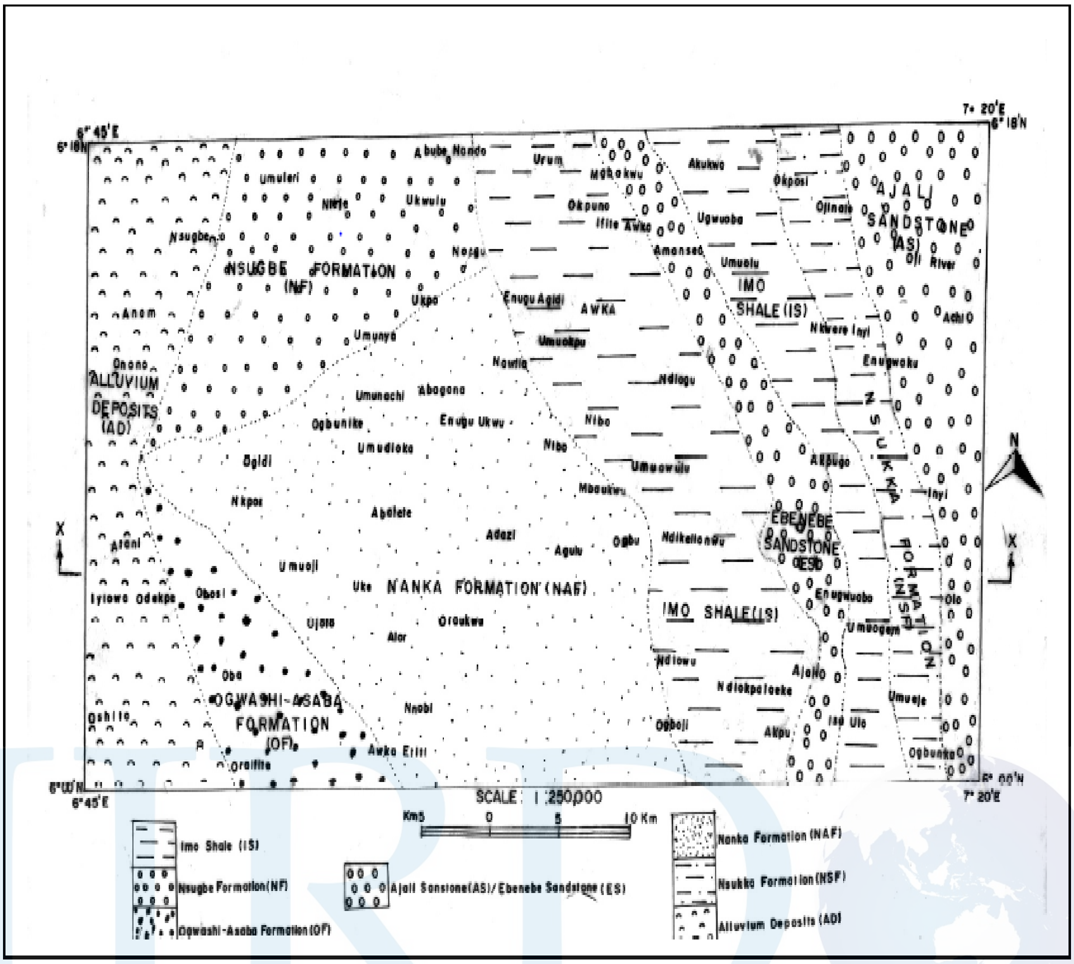

Fig 11: Geologic map showing Nanka formation and other units within the Anambra Basin South-Eastern Nigeria.

Evaluation of the Aquifer Characteristic of Nanka Sands

The area lies within latitudes 6°00N and 6°18’N and longitudes of 6°45’E and 7° 20’E covering area of about 1706km^2 within the Anambra Basin. The main geologic units of the study area are the Nanka Sands (Eocene), which is overlain by Ogwashi-Asaba Formation (Oligocene) and underlain by highly fractured and fissile Imo Shale (Paleocene**)** **(Fig.9).** Occurrence of groundwater in the area is mainly in the friable Nanka Sands. Subsurface information inferred from geophysical survey gives more realistic picture of groundwater potential of an area (Amaresh et al., 2006).

Lithologically, the Nanka Sands consist of distinct units of sands, shale-siltstone and finely laminated shale. Sand subunits comprise uncemented, medium to coarse grained and pebbly quartz sand, with thickness varying from 50 to 90m (Nwajide and Hoque, 1979). The sandy units of the Formation form thick viable aquifer (Egboka et al., 1985). Hydrogeological method was applied in combination with Vertical Electrical Sounding (VES) to attempt an evaluation of aquifer characteristics of

Nanka sands. **In a porous media such as the study area,** hydrogeological properties of the aquifers do not generally vary rapidly as a result, direct linear relations between resistivity and hydraulic parameters (K and T) are expected to exist. Hydraulic conductivity and aquifer depth are fundamental properties describing subsurface hydrology. Available information from pumping test analysis was combined with the VES results to calculate aquifer parameters (T_c and K_c). The application of surface geophysical methods in combination with pumping tests at a few locations provides a cost effective and efficient alternative to aquifer parameter estimation (Soupios et al., 2005).The transmissivity (T) of aquifer is related to the field hydraulic conductivity (K) by the equation.

$T = K\,b$ **....................................(1)**

Hence, $K = Tb^{-1}$

According to Niwas and Singhal (1981) in a porous medium

$T_c = K\,R\boldsymbol{\rho}^{-1}$

$T_c = K\,S\boldsymbol{\rho}$**………………………(2)**

Where T_c = calculated transmissivity (m^2 day) from VES

R = Total transverse resistance (ohm-m^2)

S = Total longitudinal conductance (ohm^{-1})

ρ = Resistivity of the saturated layers (ohm-m)$K_c = T_{cb}^{-1}$**……………………..….(3)**Where K_c = calculated hydraulic conductivity $mday^{-1}$ from VES result

b = thickness of the saturated layer (m).

Results

Jvalues estimated from the VES results range from 0.06 to 3.75m/day. These values compared favourably well with those obtained from pumping test analysis. The Tc and Kc values also compared well with the value obtained by Ezeigbo et al., 1995 from pumping test in **Table 10** for the lower confirmed aquifer systems of Nanka sands.

Table 9: Aquifer parameters estimated from geophysical data

VES No	B	P (Ohm-m)	Longitudinal Conductance	Transverse Resistance	(K) m/day	(T) m^2/day	Kc m/day	Tc (m^2/day)
2	34.6	295	0.1173	10207	0.17	9.51	0.17	5.88
5	5.2	659	0.0079	3426.8	3.73	33.74	3.73	19.50
6	1.9	407	0.0047	773.3	0.25	1.50	0.25	0.48
12	34.3	606	0.0566	29785.8	0.29	1.07	0.29	9.95
15	15.2	1130	0.0135	17176	0.29	2.34	0.29	4.41
22	53.8	1205	0.0446	64829	0.12	3.58	0.12	6.46

The result of the hydrogeophysical investigation in the Nanka Formation reveal 3 to 5 geoelectric units indicating confined aquifer system in the formation. The sandstone units at a depth of 7 to 108m constitute the aquifer unit in the study area. The saturated layers are confined in places by shale layer. Based on the obtained result, the integration of hydrogeophysical data and available pumping test data have proved to be rather significant in the quantitative estimation of aquifer parameters. The interpreted resistivity data were transformed into aquifer parameters (T) and (K) for VES locations with valuable pumping test data. The calculated aquifer parameters were consistent and well defined within the range of observed aquifer parameters obtained from pumping test. The calculated transmissivity (Tc) values vary between 0.48 to 19.50m^3/h while the calculated hydraulic conductivity (Kc) values vary from 0.06 to 3.75m^2/h.

Table 10: K and T values for the lower confined aquifer system of Nanka Sands from Pumping test Analysis (Ezeigbo and Obiefuna 1995)

Location	B (m)	Mean K (m/h)	Mean T (m^2/h)
Ogbunike	**15.81**	**0.20**	**3.25**
Ukpo	**15.0**	**0.03**	**0.45**
Otuocha	**16.3**	**0.62**	**10.11**
Abatete	**15.0**	**0.16**	**2.40**

Electrical resistivity method is one of the most useful techniques in groundwater geophysical exploration, because the resistivity of rocks is sensitive to its ionic content (Alile, et al., 2011). Also Vertical Electrical Sounding (VES) method has been successfully employed in sedimentary environment in water-table and hydraulic gradients estimation (Emenike, 2001 and Onwuemesi et al, 2006).

Summary.

Pumping test is an aquifer test conducted by pumping water from one well at a steady rate and for at least one day, while carefully measuring the water levels in the monitoring wells. This test is conducted to evaluate an aquifer by "stimulating" the aquifer through constant pumping, and observing the its "response" (drawdown) in observation wells. For the pumped aquifer, one seeks to determine hydraulic characteristics such as transmissivity, hydraulic conductivity and storativity. These hydraulic properties can be used to characterize an aquifer as confined or unconfined, prolific or not prolific, borehole performance etc**.**Water levels may also be measured simultaneously within nearby wells or surface water bodies to evaluate the response of the aquifer at a distance from the discharging point or pumping well.Aquifer pumping tests are typically interpreted by using an analytical model of aquifer flow such as the Theim and Theis solution to match the data observed in the real world, then assuming that the parameters from the idealized model apply to the real-world aquifer. Major tests carried out include; step-drawdown tests, constant-rate tests, recovery and yield tests.Groundwater aquifers may be characterized basically as either confined or unconfined. Others may include; semi-confined, artesian, perched aquifer, phreatic and leaky aquifers etc. In the hydrogeological characterization of basement aquifers in Taraba State, N.E. Nigeria, borehole lithologic logs revealed two water bearing zones in the area; namely the weathered zone and the fractured-rock zone. The aquifers were weathered overburden aquifers and fractured-rock aquifers .Result obtained from hydrogeophysical investigation in Nanka Formation reveal 3 to 5 geo-electric units indicating confined aquifer system in the formation. The sandstone units at a depth of 7 to 108m constitute the aquifer unit in the study area. The saturated layers are confined in places by shale layer.

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