



## Groundwater Potential Simulation in a Virtual Geographic Environment (VGE)

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### ABSTRACT

A 3D approach for modelling and simulation of aquifer water yield potential based on AHP, 3D GIS and VES is employed. Fault density, lithology delineated from overburden resistivity survey and surface slope were considered as direct factors that influence the aquifer water yield potential. Using AHP techniques the normalized weight of fault density obtained for fault is 24.31%, 66.87% for lithology and 8.886% for slope. 3D TEN data model was used in 3D modelling of the different subsurface geology according to the assigned weight of the parameter as they influenced aquifer water yield potential. The simulation results show high water contribution when overlay by weathered material follow by sand layer and clay sand layer. The least contributing factor to aquifer water yield potential is clay sand. The used of 3D GIS, VES and AHP techniques in 3D modelling and simulation of aquifer water yield potential will help policy makers and government in groundwater resource planning, management and exploration to meet societal demand while maximising resources.

**Keywords:** GIS, VES, AHP, Aquifer water

### INTRODUCTION

Access to clean and quality water has been a major demand of every society with absolute responsibility resting on the government of such nation. However, increases in population growth in recent years, there have been a corresponding increase in water demand for; human consumption, agriculture and industrial uses. The ability to provide water to meet societal demand is grossly been affected by abnormal weather condition including drought and flooding, pollution among several other factors. Already its projected that by 2025, two-third of the world will be leaving under water stress condition most vulnerable to scarcity are the deserts and some developing countries of the world.

Recent report by United Nations Children's Fund (UNICEF) state that: over seventy millions Nigerians lack access to safe drinking water (Haruna, 2014). This is a source of concerned as the implication to the societal health is catastrophic. To ensure adequate and sustainable exploration and availability of save water, there is a need to develop an effective groundwater exploration model with some level of reliability. Groundwater largely found in pore spaces of rock and soil void offer alternative to surface

water in terms of quality, quantity, reliability and less vulnerable to adverse weather effect. Many researchers have work extensively towards sustainable exploration of groundwater resources to meet societal demand. In light of this dimension, several groundwater exploration models including but not limited to application of VES in groundwater exploration, GIS in groundwater potential mapping, Application of GIS, surface and subsurface parameters integration for groundwater potential mapping, use of remote sensing and GIS in groundwater potential mapping. These researches were able to map and delineate potential groundwater site in a given area but however, suffer a limitation of how much dose each of groundwater parameter contributed to water yield.

Many groundwater exploration models have been developed using Geographical Information System (GIS) multi criteria decision making (MCDM) and Analytical Hierarchy process (AHP) developed by (Saaty, 1980) for decision making when dealing with multiple factors influencing groundwater potential about

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parameter under study. In AHP decision making as applied to groundwater exploration often consider factors such as precipitation, lineament generated from satellite imagery, resistivity data, slope, and proximity to water body's elevation among several others. However, this research has focused on the identification of potential areas without consideration implication of each parameter on the vadose zone which transmit water directly to the aquifer, in addition, the result of these studies are usually in two-dimension, thus, affecting level of reliability and generalization. The ability to visualized the impact of overburden material as well as surface factors which might influence water transmission to the aquifer through recharge process in 3D have received less attention. This has significantly influenced the level of consistency in the application of existing GIS, MCDM and AHP in groundwater exploration.

In addition to inconsistency of application and generalization of the previous studies, stakeholders and policy makers are curious of amount and quality of groundwater yield potential in a given place. As available information regarding aquifer water yield capacity can significantly help in minimising resources while maximising groundwater investment in a given location to meet societal needs. To achieve this objective, there is need to developed a model that do not only consider surface parameter but also study the magnitude of each parameter on aquifer water yield potential as opposed to the previous study. Such model should include the visualization of under study influence of factors under consideration on groundwater yield potential of an aquifer rather than groundwater depth location. To visualized the impact of parameters under study, three-dimensional GIS (3D GIS) is capable of representing and visualizing groundwater in spatial space to near real-world setting.

In light of such limitation, the 3D GIS offered more reliable way of representing abstraction in near-real word to support complex decision making process. (Gong et al., 2004) classify 3D data model into surface based, volume based and hybrid-based model that enable representation of geological phenomenon in 3D. Representation of phenomenon in 3D involves the utilisation of Z value that describes addition

information about width, depth, and height of an X and Y object in a spatial space.

In terms of water volume representation on the subsurface geology as a dynamic field that depends on the particles size, pores spaces and water transitivity ability of the aquifer, 3D volumetric data model has widely been used to represent such dynamic field. The amount, quality and dynamism of groundwater within the different subsurface geology is a function of porosity as defined by void present within geological formation. Thus, the void space largely influenced water transmissivity within the overburden material of the aquifer. Different geological materials have different water transmission ability during recharge and discharge process hence influencing water yield capacity of the surface. Proper knowledge about groundwater potential is considered to be of paramount importance in identify suitable drilling location, management and decision making as well as in protecting groundwater resources against contaminations (Jha et al., 2010). The emerging issues regarding dynamism has encouraged 3D GIS practitioners to represent changes to 3D data models, indexing 3D dynamic spatial layers and analyzing the influence of event based parameters (aquifer yield potential) such as rainfall input, soil infiltration capacity, groundwater flow and increase in urban storm water discharge within stream flow (Izham and Rindam, 2012).

### ***Bida Basin***

Bida basin is between the Cretaceous-to-Upper Maestrichtian Nupe (Bida or Niger) basin and Niger trough/Middle Niger Valley South of the River Niger. The basin lies between longitudes 4°45'E to 6°10'E and latitudes 8°47'N to 9°10'N as depicted in Figure 1. The basin is drained by two major rivers, namely; river Chanchaga and Gbako, and some smaller drainage that empty into Niger River.

### ***Weather and Climate***

Climate describes the average weather condition of a place over a long period of time while weather is the atmospheric condition of a place over a short period of time. The climate and weather condition of the study area is due to the influence of tropical continental (cT) air mass, tropical Maritime (mT) and equatorial easterlies. The tropical continental air mass originate from a high pressure belt of North of tropical of

cancer while the maritime air mass originates from the southern high pressure belt located off coast of Namibia (Odekunle, 2006). The tropical continental air mass and tropical maritime air mass meet to form a zone of inter tropical convergence/divergence zone that brings precipitation and dry season in Bida basin depending on dominant air mass. The inter tropical continental air mass pickup little moisture along its path and thus is dry, bringing dryness condition i.e. dry season while tropical air mass prevalence; brings about wet condition due to its ability to pick large moisture along the coast through which it flow and shading precipitation along the continental part of the country (Odekunle and Adejuwon, 2007, Abaje

et al., 2012). When tropical maritime air mass prevails, it marks the onset of rainy season usually between April to October and dry season between November to March. The length of rainy season has been consistent between 7 to 8 months with three months as most rain and rain peak shifting between August to July. Mean annual rainfall of 1000mm to 1,500mm (Ayoade, 1974, Adefolalu, 1988), while the dry season last between 5 to 6 months (Odekunle, 2006). The mean annual temperature of the study area is between 26.5°C to 27.8°C with maximum temperature between March and June while the minimum is between December and January.

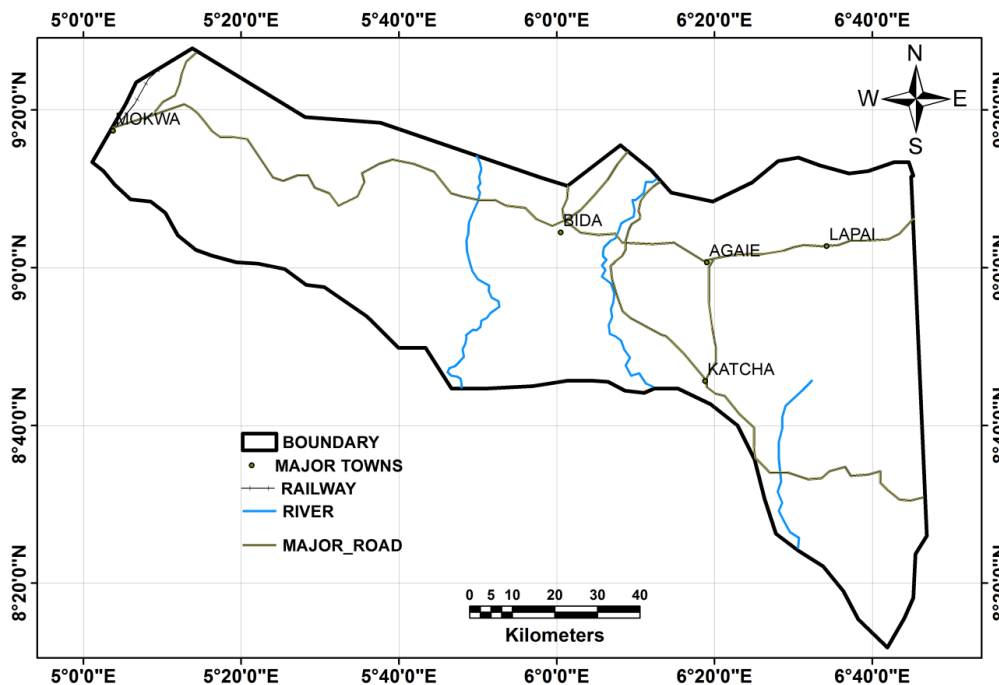


Figure 1. : Map of Bida basin.

**Geology**

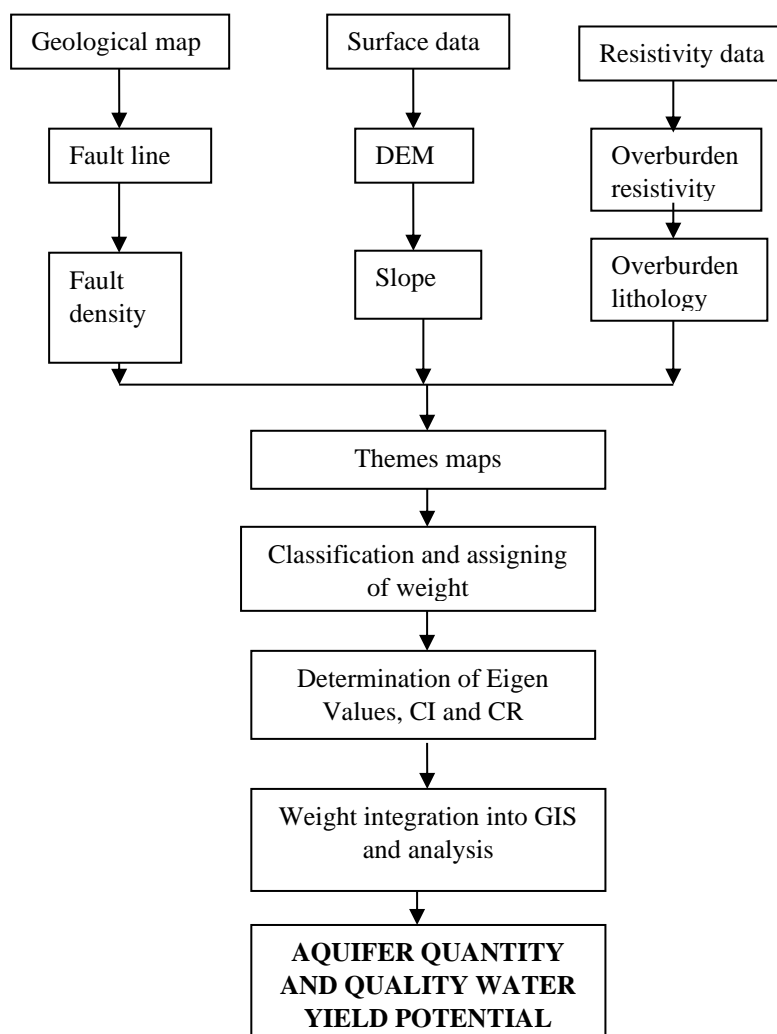
Bida basin is filled with mainly Santonia to Maestrichtian sediments of sandstones, siltstones and superficial alluvial deposits (Obaje, 2009). The lithology of these formations are weathered laterite, sandy clay and clay sand (Bello and Makinde, 2007). The southern part of the study area is characterized by secondary permeability with the following formations; weathered laterite, sandy clay/clayey sand, fractured basement and fresh basement rocks. Generally the rock units in this region are suggested to be highly characterized by

alternating of clay, siltstone, silt, clay and weathered bedrock (Braide, 1990, Akande et al., 2005). These geological materials are liable to form aquifer and permeable zones to the bedrocks in both the sedimentary terrain and the crystalline basement complex existing in the area. In areas underlain by crystalline rocks, presence of structures like fractures, fissures, veins, joints and such other structural deformations of the basement complex control the flow of groundwater and also influence the rate of recharge and discharge of the main aquiferous.

## METHODOLOGY

The methodology employed in this research is summarised in Figure 2. VES was used as a methodology for this research to determine the resistivity of different subsurface formation in the study area. The resistivities of the subsurface

were processed and constrained into available borehole logs in the study area. The factors considered in this model to influence the groundwater potential of an aquifer are: elevation, fault, type of overburden material and land slope..



### Fault

Fault of the study area was extracted from Niger state Geological and is depicted in Figure 1. Fault line is a line features that are relatively straight often of tectonics origin. they serve as important indicator of surface and subsurface information that may influence the movement and storage of groundwater (Adiat et al., 2013). They reflect geological structure such as fault and fracture in a given area.

Fault line have direct influence on the aquifer water yield potential as their depth are not only restricted to the surface but might extend beneath the earth surface. Faults serve as a direct conduit through which water is transmitted to

the aquifer. Fault density (Fd) is the total length of all recorded lineament divided by area under study.

$$\sum_{i=1}^{i=n} \frac{l_1}{A} \text{ (Km}^{-1}\text{)} \quad (1)$$

Where  $\sum l_1$  is the total length of all fault (Km) and A is the area of the grid in Km<sup>2</sup>

Figure 2 is the fault density map of the study area divided into three classes. High fault line density is an indication of high-water storage capacity while low lineament densities indicate low water storage capacity that largely depends on the geology of an area.

### Overburden Resistivity

The overburden resistivity from the resistivity survey was constrained to into the available borehole logs in the study area to determine the corresponding geological formation that over lay the aquifer. The corresponding overburden resistivity values as depicted in Figure 3, conform into sand, clay sand and clay resistivity between 0 to 150Ω correspond to clay between 151-300Ω as clay sand and 301-450Ω as sand and resistivity above 450 was classified as weathered material The overburden geology where then assigned a weight on a Saaty scale (Saaty, 1990) between 1 to 9 according to physical properties of the geological formations. The weight of each geological formation is a function of it porosity and contribution to water yield capacity of the aquifer.

The quantity and quality of groundwater yield potential of an aquifer largely depends on the nature and thickness of the overburden material. Because, overburden material determined to a large extend what quantity of water goes into the aquifer. Different geological formation has different pore spaces hence, leading to varying amount of water that infiltrate into the aquifer.

### Land Slope

Slope described how high or low a place is in relative to sea level. Slop controls the rate of water regime and subsequent infiltration to add to groundwater recharge in a given area. A

relatively low surface slope area, the surface runoff is slow thus allowing more water to infiltrate into the subsurface. However, in a high surface slope area, its opposite of low; often characterized by high surface runoff and low infiltration rate.

The land slope distribution of the Bida basin is shown in figure 4 classified into three classes. The elevation ranges from 51.92 meters to about 268.33 meters as the maximum. The low elevated areas are located to the southern part of the basin while the high elevation is at the northern part of the basin except for few isolated low and moderate elevated areas within the high.

### Weight Assignment and Calculation of Comparison Consistency

The weight of each factor was determine using AHP developed by (Saaty, 1980). The scores were based on the relative weight of pair wise comparison rated between scales of 1-9 in Table 1 in order of relative importance role contributing to aquifer water yield potential. Pair wise comparison matrices of the assigned weights of the map themes along with the individual features were normalized to obtain the Eigen vector as shown in Table 2. The Eigen vector values for each of the map themes were determine using Matlab 2010a. The pair wise comparison represents relative importance of the factors under study.

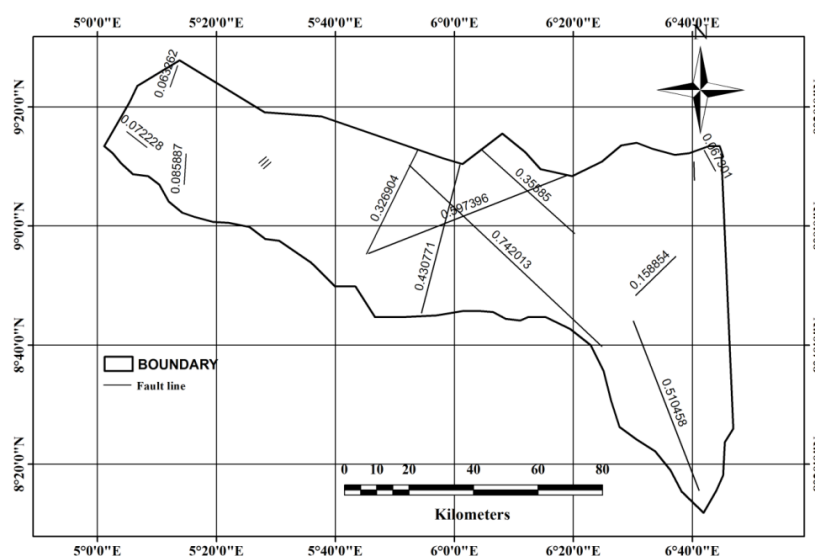


Figure 1: Fault line distribution map

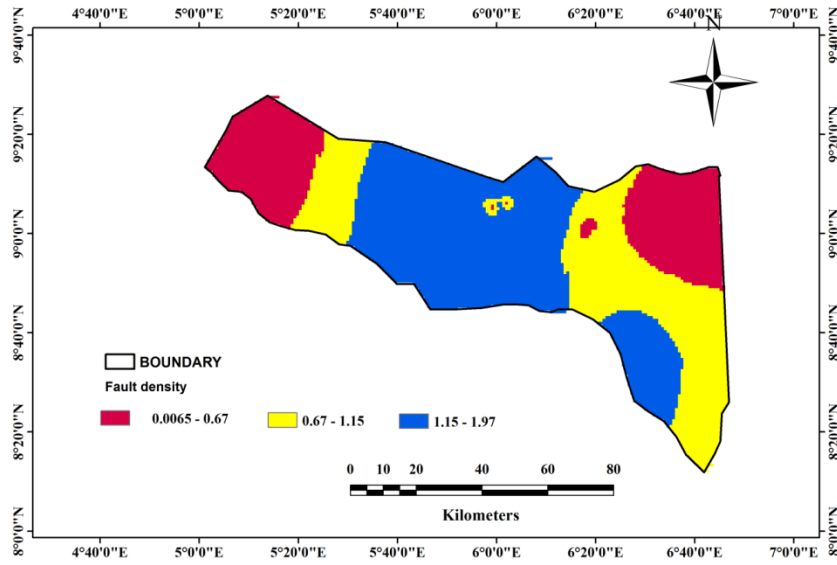


Figure 2: Fault density map

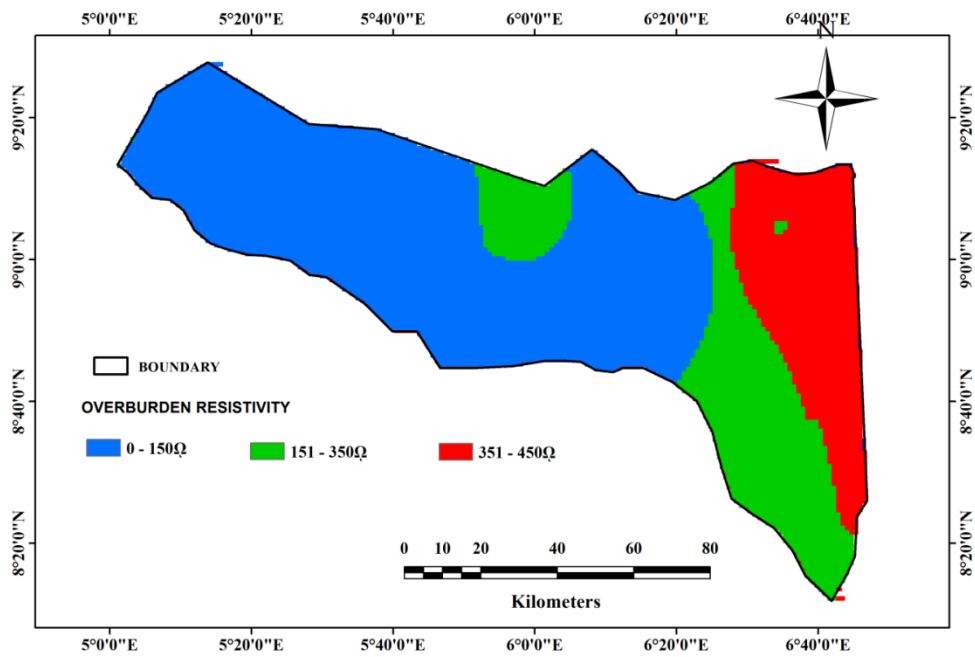


Figure 3: Aquifer overburden resistivity map

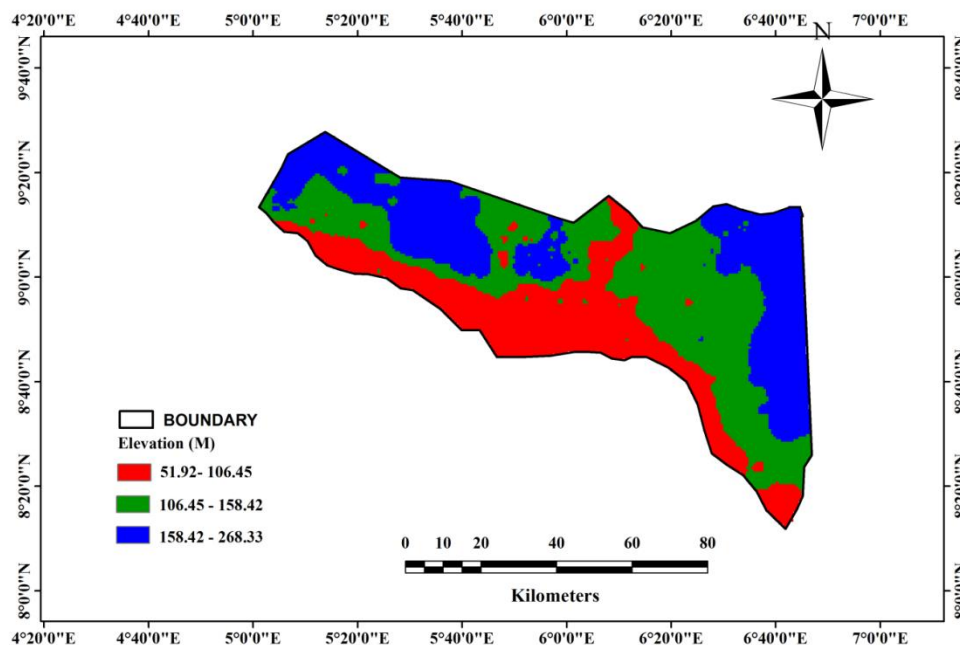


Figure 4: land slope map

Table 1: Saaty scale of weight assignment to parameter under study

less importance		equally important				more important		
Extremely	Very strongly	Strongly	moderately	equal importance	moderate	strongly	very strongly	extremely
1/9	1/7	1/5	1/3	1	3	5	7	9

The consistency index (CI) defined as the measure of consistency was determined using The equation (ii) (Saaty, 1980).

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{ii}$$

Where n=number of factor,  $\lambda_{max}$  = consistency refer to as Eigen value in some literature.

The consistency ratio (CR) was determined using the relation

$$CR = \frac{CI}{RI} \tag{iii}$$

Where CI is the consistency index, RI is the random consistency index defined by a value 0.58 for n=3 (Saaty, 1980)

CR of 1.30% less than 10% was obtained signifying reasonable level of consistency in the pair wise comparison and the weight 66.87%, for fault density, 24.31% for lithology and 8.86% for slope.

Table 2: Pair wise matrix comparison of three factors impact on aquifer yield potential

Parameter	OBL	OBR	Fault	NW (%)
Fault density	1.00	7.00	3.00	66.87
Lithology	0.14	1.00	0.33	24.31
Slope	0.33	3.00	1.00	8.86
Total	1.5	11.00	4.33	100.00

$\lambda_{max}=3.015$   $CI= 0.00755$   $CR= 1.30\%$  OBL=overburden lithology, OBR=Overburden resistivity NW= Normalise weight

Each factor was weighed according to their contribution as indicted in Table 3. Each of the parameter were weight and scored using the rating 1-5 according there water transmission to the aquifer. The rating R was assigned according in order of priority to influenced aquifer water yield.

Table 3: Aquifer parameter water yield potential rating.

P	C	PWCA	R	NW (%)
Fault density	0.0067-0.67	Low	1	24.31
	0.67-1.15	medium	3	
	1.15-1.97	Very high	5	
Lithology	Clay	Very low	1	66.87
	Clay Sand	low	1	
	Sand	High	4	
	Weathered rock	Very high	5	
Slope	51.92-106.45	Relatively flat (Very high)	5	8.86
	106.45-158.42	Gentle slope (low)	1	
	158.42-268.33	High slope (medium)	1	

P=parameter C= classes PWCA= potentiality of water contribution to aquifer R=rating NW=normalized weight

The total weights of the different factors were calculated using weighted linear combination approach in equation (iii). The aquifer groundwater yield potential was delineated and integrated and held in geodata base to allow processing in ArcGIS environment.

$$AYPI = OVBL_{nw}OVBL_i + OVBR_{NW}OVBR_i + FL_{nw}FL_i \quad (iii)$$

Where AYPI= Aquifer Yield Potential index, OVBL is overburden lithology, OVR is overburden resistivity and FL is fault line. nw and i is normalized weight of the factor and i is the weight of individual factor respectively.

### 3D modelling of the delineated geological units

For the purpose of 3D modelling of delineated geological units, VES data was used to build a geodata base held in ArcGIS 10.0 as different shape file. 3D TEN was used to model the overburden material into 3D shape through utilization of solid geometry as a basic primitive 3D data structure. Based on GIS environment analysis, simulation was run on each of the delineated layer to visualize what quantity of water it contributes to the aquifer.

3D TEN is an extension of 2D TIN (Abdul-Rahman and Pilouk, 2007). Figure 5 represents volume-based objects. Objects in 3D TEN are described by connected but non overlapping tetrahedral made up of four vertices, six edges, and four faces (Abdul-Rahman and Pilouk, 2007). They are mostly used in combination with Octree in volume representation. 3D TEN and Octree can be used in 3D dynamic simulations such as fire, mudflow, and water flow, among others. For efficiency, the data may be processed into a primitive form as points, lines or surface. The data model ehenced the expression of complex structure though it create redundancy and its algorithm of tetrahedron creation are not easy to come by (Kolbbelt et al.,

2000). 3D objects are represented with a tightly arrayed but not overlapping tetrahedrons as an extension of TIN with complex spatial topological relations (Tao, 2008). The characteristics attributes of 3D TEN data structure have made it efficient in modelling of an object consisting of volume and rigid properties (Abdul-Rahman and Pilouk, 2007).

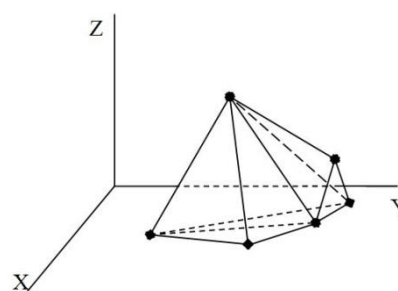


Figure 3.6 :3D TEN model.

3D TEN as internal data structure for this research because of it computational efficiency (Penninga et al., 2006), well defined array of triangle, ease of representation, easy maintenance for visualization using network of non-overlapping tetrahedron (Zlatanova et al., 2002) and flexibility of representing complex



object. 3D TEN advantage in modelling of 3D object according to Abdul-Rahman and Pilouk (2007) is the simplest data structure that can be reduced to point, line, volume representation to enabling the definition and partitioning of real world object. Due to the outlined advantages of 3D TEN, it can be used in manipulating and volume computation of subsurface lithology for this study. The partition ability of 3D TEN enable modelling of non-overlapping volume in a given space (Abdul-Rahman and Pilouk, 2007). 3D TEN is able to represent object accurately with well-defined topological relation while maintaining original attribute.

Water elements and geology formation are two distinct parameters in 3D modelling. Therefore, water elements were considered as volumetric geo-object with distinct shape, size and volume (Izham et al., 2008) which depends on the overburden geology formation void space. I.e. space between aggregates of particles that constitutes the overburden geology.

(Lin et al., 2009) used volumetric soft geo-object to visualized pollution and flooding on a different scale. Therefore, this research, unlike existing work, use volumetric geo object in visualizing aquifer groundwater yield as overlay by different geological formation with the assigned Saaty scale weight. In addition, volumetric rendering of the 3D modelled layer is implemented to enable attribution of dynamic properties to aquifer, overburden geology and water elements. The process of volumetric rendering is based on Darcy's steady state equation of groundwater movement in equation (iv).

$$\frac{\partial(k_x \frac{\partial h}{\partial x})}{\partial x} + \frac{\partial(k_y \frac{\partial h}{\partial y})}{\partial y} + \frac{\partial(k_z \frac{\partial h}{\partial z})}{\partial z} = 0 \quad (iv)$$

Where  $\partial h$ = change in height  $\partial x$ ,  $\partial y$  and  $\partial z$  are the rate of change in groundwater flow over time.

## RESULTS AND DISCUSSION

Faults are linear features that occurred as a result of volcanic or disturbance within the earth surface often associated by earth movement. In groundwater exploration, fault lines allowed the transmission and flow of groundwater within a superficial zones (Roques et al., 2014). Productive aquifer is located near the fault zones

of discontinuity. Therefore, areas of high fault density areas are associated with aquifer close to surface compared to low fault density areas. However, the amount of water delivered to the aquifer is a function of the depth of the fault (Bour, 2013).

In the study area, areas of high groundwater potential and likely high aquifer yield have a fault density 1.15 to 1.19. While areas of moderate aquifer water yield potential have a fault density of 0.67 to 1.15. Low fault density zone is 0.0065 to 0.65. Previous study in Bida basin by (Bashir et al., 2014) has shown that aquifer depth varies proportionally to the fault density distribution.

Lithology has been described by (Edet et al., 1998, Adiat et al., 2013) to be a major factor that controlling quality and quantity of groundwater in a given area. Different geological formation offered different influence on groundwater availability, movement and distribution in a given area of study. The important factor influencing groundwater potential is mostly the prevalent geology formation in a given place. Therefore, the 3D modelling of geology influence on aquifer water yield potential consider in this study is clay, clay sand, sand and weathered material as mapped from the overburden resistivity of the aquifer. Based on the field knowledge of the study area and available borehole logs, the corresponding formations to the resistivity were delineated.

Clay soil control the degree of infiltration rate and responsible for the formation of aquitard such that the higher the clay content the lower the permeability of the subsurface. Very small clay overburdens the aquifer exist in the south western part of the basin. In this area, as shown in Figure 5a, the aquifer is expected to have a low water yield capacity due to poor network of void between clay particles that is opaque to free flow of water (Adelana et al., 2008). Although, much water is retained on the surface of the overburden clay, only little is transmitted to the aquifer. For groundwater exploration, promising well on this kind of overburden material offered low water potential. (Hugman et al., 2012).

Clay sand or silt overlaying an aquifer has relative more network of void compare to clay due to trace of sand within it (Jarvis and Knight, 2002, Coquet et al., 2004). Figure 5(b) is simulation results overlaying an aquifer. A water

element within the overburden layer is relatively low compare to Figure 5(a) due to the physical characteristics of the clay sand particles. An aquifer overlay by sand clay is likely to yield slightly more water compared to clay. Though, promising well cannot be guaranty in this kind of geology due amount of water transmitted from other layers to the vadose zone but a relatively moderate potential and reliability of aquifer can be assesses within this formation (Christiansen et al., 2010).

Sand layer has a well establish network of interconnected network of void spaces through which water is transmitted to the aquifer. Figure 5(c) shows simulation results run on sand overlaying an aquifer. The large void spaces allow easy percolation of groundwater to the aquifer. In this kind of condition, the aquifer overlay by sand has high water yield potential since all water transmitted from the vadose or aquitard is delivered directly into the aquifer. However, quality of water offered by such aquifer will largely depend on the thickness and type of geology formation that overlay the sand layer (Edet and Okereke, 1997).

Weathered material consist of bulder pables such as silt, fine grains of soil and other porous particles that might be formed from weakning of undergroug rocks. These materials have a larger and well interconnected pore spaces that allow infiltration of water to the aquifer layer compare to the sand layer. Groundwater exploration in a rocky terrain or sedimentary formation regions this layer may be delineated as the aquifer that is capable of yielding water to some certain degree of reliablity. However, in this study, since the overburden geological formation was delineated from resistivity survey, hig resistivity of grater than  $400\Omega$  were delineated as weathered material (Loke, 1999). The effective porosity of weathered material is usually greater than 0.5 percent (Schwatz and Zhang, 2003).

Therefore in the 3D simulation of this layer, more water is transmitted to the aquifer leading to high water yield potential from an aquifer overlay by weathered material. The simulation time of this layer is usally shorter compare to other large due to large particles size of this layer.

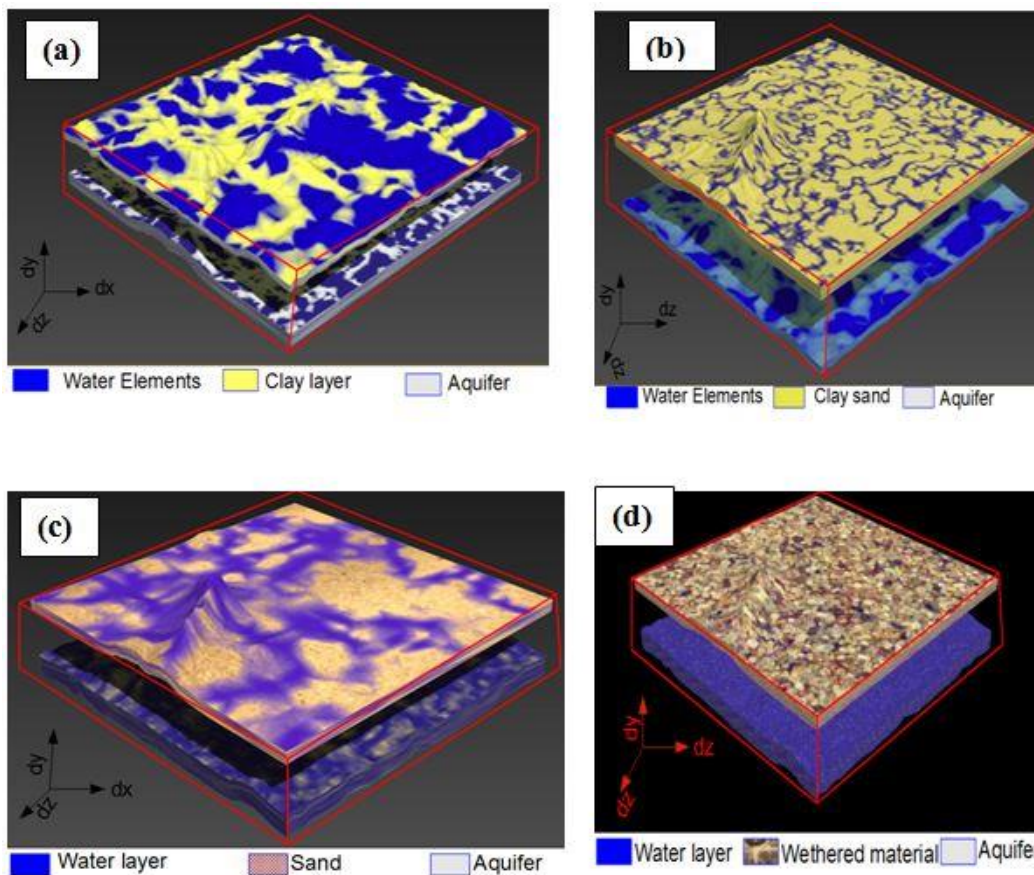


Figure 5: 3D simulation of aquifer overlay by (a) Clay, (b) clay sand, (c) sand and (d) weathered rock.

## Conclusion

In this study, the effectiveness of 3D GIS, AHP and 3D TEN data model have been employed in modelling and analysis of aquifer groundwater yield potential in Bida basin. In other to determine the potential of an aquifer and its reality, slope, fault and lithology were weighed appropriately on saaty's scale of 1-9. The weight of every individual factor was determined by their degree of potential to influence aquifer water yield potential. The normalized weight, eigen vector and consistency index were calculated to avoid bias in weight. 3D TEN data model was used to model the aquifer and overburden formations into 3D and potential of the overburden weight to aquifer water yield was used to simulate aquifer water yield. The water layer was modelled by employing volumetric soft geo-objects while the 3D simulation of flow part and rate was run according to Darcy's law of steady groundwater flow. The study has established that 3D GIS, AHP and 3D TEN data model techniques can be employed in visualization of aquifer yield potential based on nature of geology formation, fault density and slope of an area. Feature research in this dimension while requires the development of real time simulation model compared to pumping test at different locations with different geological formations.

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