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Discovery of Perched Aquifer When Assessing Aquifer Potential along the floodplain of the Upper Benue River, NE Nigeria

B.A. Ankidawa
Department of Agric. & Environmental Engineering, SEET, PMB 2076, Modibbo Adama University of Technology, Yola, Nigeria

ABSTRACT
Groundwater is an important resource for irrigation water and its use for irrigation depends on environmental factors affecting long-term sustainability. The stratigraphy and groundwater distribution of the unconfined alluvial aquifer of the Upper Benue River, northeast Nigeria, were assessed using boreholes exposures and geo-electric resistivity. The aim was to assess the area's groundwater potential and to contribute to improved management of the water resources for irrigation activities in the context of aridification of the Sahel and of the existence of an upstream dam in a neighbouring country. The research provides an update of the groundwater data bank of the area. Twenty four vertical electrical soundings, using the Schlumberger electrode array, were conducted with maximum current electrode spacing of 100 m. Twelve boreholes were drilled in order to comparethe geoelectrical soundings with subsurface stratigraphy. The data obtained were interpreted using the partial curve matching technique and software for resistivity data interpretation. The depth and resistivity of the subsurface layers were determined. The possible perched aquifer formations were observed in three differentlocations, which reflect a low-permeability stratigraphic unit such as lens of clayey silt within alluvial sands. These small aquifers may mislead farmers as to the productivity of their wells.

KEY WORDS: *Vertical electrical sounding, Upper Benue River, Alluvial floodplain, possible perched aquifer, Yola region.*

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I. INTRODUCTION

Groundwater is the main source for domestic, industrial and agricultural uses in semi-arid environments with strongly developed dry seasons, such as north eastern Nigeria. Groundwater management faces similar sustainability issues to surface water resources. The quantity and location of groundwater depends on the geological characteristics of the rock formation. Over-extraction of groundwater can lower water tables which impacts upon the dependent users, such as irrigation activities. Added difficulties of groundwater are that they are hidden below the surface and moving slowly, so that the full impact of over-use may take many years to detect (Burazer et al. 2010). Globally groundwater exploitation for irrigation is rapidly increasing due to agricultural production and population increase (Jamala et al. 2011; Shamsudduha et al. 2011; Sikandar and Christen 2012; Costabel and Yaramanci2013).

Study of groundwater geology is necessary for all the activities of human life, because groundwater is more advantageous than surface water, it is more stable than surface water and it is reliable in times of drought due to large storage under the surface (IAH 2012). Groundwater tends to be of good quality, as it protected from surface contamination (MacDonald et al. 2005; Wada et al. 2012).

The impact of climate change on groundwater through changes in recharge is an important aspect for future water resource management (Holman et al. 2011; Sivandran and Bras2012). The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) identified a range of impacts associated with climate change and variability, including decrease in yields in runoff and water availability in Africa (IPCC, 2007). The impacts of climate change as described in the Fourth Assessment Report (Boko et al., 2007) of the IPCC relate to agriculture. The projection for developing countries and Africa in particular, that between 75 – 250 million and 350 – 600 million people, in Africa will be exposed to increased water stress by the 2020s and 2050s respectively, and that rain-fed cereal yields will be reduced in some areas by up to 50% within the same time frame. This projection will likely affect the northern parts of Nigeria, which consists of arid and semi-arid regions.

The impacts of climate change on groundwater resources have been addressed in many studies around the globe. Different modelling approaches have been used for the assessment of impact of climate change on groundwater resources. For example, Neukum and Azzam (2012) and Dobler et al.(2012) quantified the impact of climate change on groundwater recharge on alluvial floodplain in Germany. Jyrkama and Sykes (2007) investigated the future spatial variation of the groundwater recharge in the Grand River watershed, Ontario, Canada, by using the hydrologic model HELP3. Their result show increasing groundwater recharge in the future. Hsu et al. (2007) investigated the impact on groundwater quality and quantity of the Pingtung Plain in Taiwan using numerical modelling (MODFLOW SURFACT).The results showed an alarming decrease of groundwater levels in parts of the Plain. Herrera-Pantoja and Hiscock (2008) used a daily soil moisture balance approach to analyse the impact of climate change on potential groundwater recharge and showed a decrease of groundwater recharge for areas in Great Britain by up to 40%.Irrigation in Nigeria has become an issue of vital importance considering the present population growth rate. Recent reports show that the population is increasing by 3.5% annually, while food production is increasing by only 2.5% (Jamala et al., 2011).

For effective water supply for irrigation activities along the floodplain of River Benue valley of Yola region, Nigeria, it is important to understand the groundwater conditions. The Lake Geriyo irrigation project near Yola (Figure 1) was established in 1976 by the Federal Government of Nigeria in order to promote irrigation activities in the State, which is still under expansion. The project started with only 24 ha and 52 farmers, and presently, the project have expanded to over 400 ha under cultivation and more than 1,500 farmers (Personal communication with Mr D.D. Mamatso, project manager Geriyo irrigation project, UBRBDA, Yola, 20th April 2012). The Lake Geriyo irrigation project has a great impact on its immediate community and environs because it creates employment opportunities, economic empowerment and reduces youth's restiveness at a time when other areas of labour employment are less active. Understanding the condition of the groundwater will help in managing and planning for the future irrigation activities in the area.

The aquifer systems in the semi-arid Sahelian northern Nigeria are subjected to tremendous stress. This is compounded by inadequate information on the recharge of the aquifers, groundwater flow patterns and contaminant transport mechanism. The operation of the Lagdo Dam constructed upstream in neighbouring Cameroon where Nigeria have no control, is another factor that could have an adverse effect on the shallow aquifers of the floodplain. For now the dam has a positive effect downstream by maintaining a high level of water in the River Benue during the dry season. Any change in the operation of the dam could have an effect on its downstream users, as already seen when water is suddenly released without adequate warning.

Perched aquifers are expected in shallow formations in floodplain along rivers in arid and semi-arid regions: Robinson et al.(2005) identified 33 perched aquifers along the semi-arid region of Pajarito Plateau, America; perched aquifer in shallow dolomite underlain by sandstone (Carter et al. 2011); perched aquifers in the Judea aquifer semi-arid region Israel (Peleg and Gvirtzman, 2010); perched aquifers in alluvial formations associated with rivers and lakes (Rosenberry 2000; Niswonger and Fogg 2008); thick unsaturated zones in arid climates (Robinson et al. 2005). However for River Benue, which is the second most important river in the Niger drainage basin, it is the first time that perched aquifer, have been identified, because they have never been studied.

Two studies in the valley of River Benue by Arabi et al.(2010) and Nur and Kujir (2006) using Schlumberger vertical electrical sounding to determine weathered and fracture zone on sandstone obtained a range of resistivity values between 600 and 896 Ωm. Their results are within the range to what was obtained in this investigation of the average resistivity range of 49 – 1,460 Ωm. Also in the southern part of Nigeria, Eke and Igboekwe (2011) applied resistivity soundings to explore groundwater in some villages in Ohafia in the Abia province, and their studies identified some viable locations for the development of a water borehole for groundwater resource. Similarly, a study by Arshad et al.(2007) in Pakistan used electrical resistivity survey to determine the lithology and groundwater on an agricultural land, resistivity values ranges between 19 to 205 Ωm. The values were correlated to lithology and groundwater potential. A study by Ndlovu et al.(2010) to map groundwater aquifer on rural area in Zimbabwe using vertical electrical sounding, the resistivity values range between 50 to 1,032 Ωm, the average resistivity values obtained in this study ranged from 49 – 1,460 Ωm.

The area is drained by the River Benue, which is the largest and only perennial river in the area. The Nigerian part of River Benue is fed by two major streams, River Benue and River Faro in Cameroon (Figure 1). The Lagdo Dam keeps the groundwater of alluvial aquifers at high level downstream, during the dry seasons especially for the Yola region, where 80% of the population practices irrigation farming along the River Benue valley. Records show that the depth of the aquifer differs from place to place because of variational geo-thermal and geo-structural occurrence (Okwueze 1996; Perez-Bielsa et al. 2012). A unique relationship between the geoelectric layers and the lithologic layers can be delineated from the interpretation of resistivity sounding data. One of the aims of electric resistivity prospecting is the prediction of lithologic layering and depth to fresh bedrock. It is necessary to investigate how effectively this is done by comparing geoelectrically delineated layers with the actual lithologic layers from drilling logs. Groundwater investigation is faced with many uncertainties; it is pertinent that the right exploration techniques are utilized in the delineation of subsurface water-bearing formations (Sikandar and Christen 2012). A study by Majumdar and Das (2011), which carried out VES investigation in the Sagar Island region in India to assess lithology and groundwater condition, showed that resistivity relationship was established.

The objective of this research was to assess the sustainability of groundwater along the floodplain of Yola region. This will contribute to improved management of the water resources of the area by informing the farmers of the limited productivity of perched aquifers and the need to drill deeper. It will also help to mitigate the impact of climate change and changes in the management plan of the Lagdo Dam. Accurate acquisition of geoelectrical data, subsequent analysis and interpretation of the data are valuable contributions in locating aquifer potentials in alluvial floodplains, and the investigation will also serve as an avenue to update the groundwater data bank of the area.

Geology and topography of the study area

Following a recent survey to update the topographic map details, it has been established that the elevation of the Yola region varies from 149 to 228 m above mean sea level and falls within the upper Benue Basin with a catchment area of about 750 km2 (Figure 1). The region has a tropical climate with dry and rainy seasons. The dry season extends from late November to May, and is characterized by the Harmattan wind blowing from the Sahara Desert. The prominent landforms are the Adamawa highlands, which are characterized by high relief surrounded by irregular slopes and plains (Ankidawa et al. 2010). The information was computed from 52 year precipitation data obtained from UBRBDA, Yola hydrological unit. The lowest temperature in the area is 15°C and the highest is 45°C with a mean temperature of 30°C. The mean annual precipitation of the area is about 914mm; the region is characterized by arid to semi-arid climates. Eighty five percent of the precipitation falls between July to September, but the months of July and August receive the largest amounts of the total precipitation. Year to year precipitation variability is high with a coefficient of variability of 25%. As a result, the region could be subjected to drought (Figure2) characterized by sporadic water shortages with severe adverse implications for agricultural activities, especially irrigation during the dry season period. Potential evapotranspiration considerably exceeds precipitation with total annual values between 1,676 to 2,788 mm. These phenomena explain the dependence on groundwater for water supply and irrigation in the region.

The area is underlain by sedimentary deposits, which consist of two stratigraphic units: a coarse Quaternary river alluvium and the Bima sandstone, which is a Cretaceous sedimentary unit (Figure 1). The alluvial deposits of the River Benue and its tributaries consist of sands, silts, clays, silty-clays and pebbly-sands (Ezeigbo et al. 1996 cited in Obiefuna et al. 1999). Outcrops of the Bima sandstone are massive in places and in other places they exhibit cross-stratification (Carter et al. 1963; Onugba and Aboh 2009; Obiefuna and Orazulike 2011).

In 2012 substantial flooding inundated the area, causing loss of life, widespread destruction, and the displacement of >3000 families.

II. METHODOLOGY

Field work was carried out in April and May 2011, 2012 and 2013.Resistivity soundings and borehole drilling were used to assess the groundwater condition at the peak period of the dry season. The drilling logs at each borehole locations were compared with geoelectric soundings and the resistivity value at each depth as determined. The drilling logs were made on five transects at twelve different points along the floodplain of River Benue.VES was used to determine the electrical resistivities and depths of the subsurface layers with the aid of a sensitive ABEM Self Averaging System (SAS) 1000 Terrameter. The four electrodes are positioned symmetrically along a straight line, the current electrodes on the outside part and the potential electrodes on the inside part according to the recommendation of the manufacturer. To change the depth range of the measurements, the current electrodes are displaced outwards while the potential electrodes are left on fixed position(Arshad et al. 2007; Tizro et al. 2010; Tessema et al. 2012; Vuilleumier et al. 2013; Orlando 2013; De Carlo et al. 2013). The potential electrodes are moved only when the signal becomes too weak to be measured. Study by Khalil and Santos (2013) used VES to explore groundwater on the alluvial floodplain of Wadi El Natrun, Egypt, and they found promising groundwater potential from the resistivity soundings.

Twenty four Schlumberger VES measurements were conducted with maximum spacing (AB/2) of 100 m and twelve different boreholes were drilled. The VES points were separated by 1000 m intervals (see Figure 1).The geoelectric stations VES (1 to 12) were located near the drilled boreholes; so that sedimentological information obtained from logs could be used to calibrate the VES field curves. The interpretation of a resistivity sounding survey is by classifying the observed apparent resistivity curves into types(Orlando 2013). This classification is primary made on the basis of the shape of the curves, but also its relation to the geological situation in the subsurface of the area. The apparent resistivities from the field were plotted against half current electrode spacing (AB/2) in the log-log graph. The curves obtained from the resistivity data were studied qualitatively in terms of their forms and character in the pattern of resistivity variation with depth and attributed of conducting bodies below the surface at the points of the observation of the anomalies. The model parameters estimated from the data were used for computer iterative operations to interpret the data. In the iterative interpretation method, the field data were compared with the data derived from a layer model obtained by curve matching. This procedure was repeated for all the VES points until a sufficient agreement between the model data and the field data was obtained. Therefore the model parameters, observed data and computed data as well as theoretical curves for the area covered in this study are used in delineating the geoelectric sections and geological sections respectively.

The particle size distribution for the sediment samples were analyzed using a Cilas 1180 instrument. Before starting the measurement, each sample was weighed to 0.05g and soaked in 10 ml of 10% tetra sodium pyrophosphate and left over night to deflocculate. The samples were then introduced into the Cilas; care was taken in introducing the amount of sample into the Cilas mixing chamber to avoid high obscuration. Background measurements and rinsing were performed in between each sample measurement in order to keep the result consistent and reliable. Twenty seconds for ultrasound, pumping and fast pumping were used respectively for each sample before taking readings. Each sample was run three times for the data consistent and reliability. The data obtained were then analyzed using Gradistat software developed by Blott (2011). The statistical analysis was carried out on the data obtained including mean, median, skewness, kurtosis and standard deviation.

Twelve boreholes of a diameter of 80 mm were drilled using locally made augering equipment at different locations in the floodplain. The drilling logs show variations in the groundwater levels for the area at different points, which ranges from 6 to 18 m deep. The drilling were made in five different transects which shows the variation for the groundwater level as moving away from River Benue valley as shown in Figure 9 below.The twelve boreholes drilled were compared with the geoelectric sounding results obtained in the area in order to determine the aquifer potentials of the floodplain.

A Promark3 dual frequency GPS instrument was used to determine the height elevation for constructing contour map of the area. The ProMark3 GPS instrument was set at 10 seconds as logging time.

The water levels in the wells were determined by using the automatic MAlog itmsoil piezometer instrument (Itmsoil 2012) and converted to absolute water levels and displayed using the ArcGIS software.

III. RESULTS

The resistivity results reveal five different types of curves, for the twenty four resistivity sounding points in the floodplain. See results in Table 1.Three groups of electro-stratigraphic earth models were obtained from the analysis of the resistivity data (Table 2): these are five electro-stratigraphic model groups, four electro-stratigraphic model groups and three electro-stratigraphic model groups. The fifth group of the electro-stratigraphic model shows a decrease in resistivity values with an increase in the layer thickness. Generally the layer shows a low resistivity values, indicating better groundwater saturation condition. The high value of resistivity at the top layer may correspond to the unsaturated zone, as observed by Van Overmeeren (1989). The resistivity values for the fourth electro-stratigraphic model decreases as the layer thickness increases, indicating better groundwater saturation condition. Similarly the third group of the electro stratigraphic model shows increase in resistivity value with an increase in layer thickness, it exhibit low resistivity value at the bottom of the layer, providing an indication of the aquifer potential at that point. The comparisons of drilling logs with geo-electric resistivity soundings are presented in Figures 3 to 8. The depth of the boreholes varies from 6 to 18 m depth. From the transects 2, 3, 5, 6, 7, 8, and 9 it was observed that in general the groundwater level of the floodplain decreases as it moves away from the River Benue valley. However transects 1, 4, and 10 show an increase in groundwater level away from River Benue valley (see Figure 3). The latter suggests perched aquifer formations in those locations (see Figures 3 and 4). This could be as a result of sediment type such as lens of clay. Water in perched aquifers does not have contact with the groundwater flows. Once the available water is extracted for use, the aquifer will go dry. Therefore water in the perched aquifers are limited and should be avoided by the farmers.

The occurrence of clayey silt beds intermixed with sandy silt sediments may serve as aquitards which probably form perched aquifers in some locations in the floodplains. Perched aquifers are found in the unsaturated zone, where groundwater accumulates over relatively impermeable layers. Usually drilling is stopped where water reached. The aquifer in the alluvial floodplain is made up of fine to medium grained sand with occasional sandy silt. As the aquifer formation approaches sandy silt, it tends to be coarser and serves as water-bearing formations at the drilling points. The clayey silt lens tends to be coarser as moving away from the River Benue valley and thicker at the top of the formation. The sand formations are more dominant closer to the river Benue valley, while away from River Benue sandy silt and clayey silt formations are more dominant.

The results obtained from the computer modelling are presented in Table 3, from the resulting curve and their final model parameters after iterations. The results are quantitative interpretations of observed curves in the field with the computed curves. The VES fitting errors range between 0.9 to 3.99 %, with an average of 2.73% (Table 3), which fall within the acceptable error limits of 0 to 15%.

IV. DISCUSSION

The integration of the VES with the cored sediment and the local geology of the area have been successfully used for the detection of the groundwater levels of the floodplain. From the VES data, the thickness, resistivity values of the layers and the exact water level at each of the borehole location were determined. The apparent resistivity curve indicates three types of subsurface layers in the floodplain. These layers consist of surface layer (top sediment), middle layer and saturated (bottom sediment) layer. The average resistivity of the surface, middle and saturated layers ranged from 160 to 328, 702 to 1,460 and 49 to 185 Ωm respectively. Similar resistivity values in the range of 20 to 2862 Ωm by Okiongbo and Odubo (2012) in southern part of Nigeria along alluvial floodplain indicate good groundwater potential. The higher resistivity values at the top are compared with the unsaturated zone layer while the lower resistivity value at the bottom is compared with the groundwater saturation condition. The low values showed the potential water bearing zone and the aquifer potentials of the floodplain. It was also observed that no exact clear mark in the resistivity ranges correspond to different layer formations; but if a layer exhibits high resistivity, then the layer could be a dry or soft formation. If in the medium range, it could be suggested a layer composed of porous formation or water bearing-layer (aquifers), while low values of resistivities suggest the presence of water-bearing layers (aquifers).The perched aquifer formations were identified in the field from both the drilling logs and resistivity soundings. The depth of the main groundwater table in an alluvial aquifer becomes slightly deeper away from the river (hence shallower closer to the river). From the drilling logs and resistivity results some locations away from the river shows low resistivity at a depth of 6.5 m at the borehole location 2, at a depth of 6.15 m at the borehole location 8 and at a depth of 7 m at the resistivity sounding location 22 (see Figures 3 and 4). These low resistivity values at the near surface depth may reflect the presence of perched aquifers while those at deeper depths are interpreted to indicate the main aquifer. Similar observation was reported by Park et al.(2007) who identified perched aquifer from electrical resistivity soundings along the alluvial floodplain of Geum River in semi-arid environments of Korea.

The perched aquifer formations observed in the floodplain could be as a result of sedimentary formations in the area. The existence of a low-permeability clayey silt layer in a high-permeability sand formation can lead to the formation of discontinuous saturated lenses, with unsaturated conditions existing both above and below aquifer formation (Freeze and Cherry 1979). Mbiimbe et al.(2008) carried a study on the groundwater potentials in an Upper Benue River Basin, but on deep borehole logs. Their results show three groundwater systems. The upper was unconfined and corresponded to the Quaternary river coarse alluvium, the middle was semi confined and corresponded to the Yolde Formation and the lower was confined and corresponded to the Bima Formation. Similarly, a study by Nur et al.(2001) explored groundwater in the Yola region mostly in towns; they compared VES results with boreholes logs and water table found to lie between 48 to 51 m. Hence much deeper than in the floodplain, but no mention of perched aquifer was made in these two studies. Perched groundwater may exist in a particular place or location depending on the availability of information or investigation, such as geology of the area, sedimentology, groundwater levels, hydraulic heads, etc. Perched aquifers identified in this study include information obtained from resistivity surveys, augering drilling up to the water levels and beyond, interpretation of the field sedimentological logs, and hydraulic heads along the floodplain. Perched aquifers have been predicted and observed to form above low-permeability barriers such as lenses of clays in an arid region (Carter et al. 2011).A study by Robinson et al.(2005) identified 33 perched aquifers along the semi-arid region of the Pajarito Plateau, USA, by using electrical geophysics and direct water-level measurements. However, in the present study combinations of resistivity sounding, drilling log and groundwater measurement were used for the identification of the perched aquifer formation across the floodplain .

V. CONCLUSIONS

Based on the results it can be concluded as follows:

The resistivity soundings have revealed information on the groundwater levels of the area. The result has also helped in the identification of the aquifer potentials of the area. Three layer formations in the floodplain were delineated; these are from top to bottom unsaturated, middle and saturated layer formations. Vertical electrical soundings finding show promising groundwater bearing formations with a resistivity value of 49 and 1,460 Ωm. The low values showed the potential water bearing zone and the aquifer potentials of the floodplain.

The integration of sedimentological log data with surface geoelectric studies in the delineation of the aquifer systems in the area enhances the accuracy of the results. However this study is trying to understanding the subsurface location of the shallow aquifer systems.

Therefore this study has also revealed a new unexpected result:

Perched aquifers were identified in three different locations along the floodplain. The farmers should be advised on the difficulty of extracting the groundwater in those locations, if they continue using the perched aquifer points observed in the area. Therefore the farmers using wells in those locations should be advised to drill their tube wells beyond the perched aquifer depth in order to get to actual groundwater level which will be lasting longer.

In conclusion,

The information obtained is going to be relevant to the development of an effective water scheme for irrigation activities along the floodplain and possibly beyond nearby areas underlain by the same formation, and will constitute a background information or useful guide for more elaborate groundwater development programme in the area. Any shift such as climate change and any possible changes in the management of Lagdo Dam upstream which is out of the control of Nigeria, will have to take in account unconfined and confined aquifers.

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REFERENCES

[1] Ankidawa, B.A., Balla,S.K., Tanko,J.A.(2010). Assessment of water quality of metropolis, Adamawa State – Nigeria.J Eng Sci Tech 5(3): 79 – 82.
[2] Arabi, S.A., Dewu,B.B.M., Muhammad,A.M., Ibrahim,M.B., Abafoni,J.D.(2010).Determination of weathered and fractured zones in part of the basement complex of north-eastern Nigeria.J Eng Tech Res 2(11): 213 – 218.
[3] Arshad, M., Cheema,J.M., Ahmed,S.(2007). Determination of lithology and groundwater quality using electrical resistivity survey.Int J Agric Biol 9: 143 – 146.
[4] Blott, S.(2011). Gradistat version 8.0: A Grain Size Distribution and statistic Package for the Analysis of Unconsolidated Sediments by Sieving or Laser Granulometer. Kenneth Pye Associated Limited, UK.
[5] Boko, M.,Niang,I., Nyong,A., Vogel,C., Githeko,A., Medany,M., Osman-Elasha,B., Tabo,R., Yanda,P,(2007). Africa In: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P Palutikof, P.J. Van der Linden and C.E. Hanson, Eds. Cambridge University Press, UK 433 – 467.
[6] Burazer, M., Zitko,V., Radakovic,D., Parezanovic,M.(2010).Using geophysical methods to define the attitude and elevation of water-bearing strata in the Miocene sediments of the Pannonian Basin.J Appl Geophys 72: 242 – 253.
[7] Carter, J.D., Barber,W.,Tait,E.A.(1963).The Geology of parts of Adamawa, Bauchi and Bornu Provinces in North-Eastern Nigeria.Geol Surv Nigeria Bull 30: 1 – 109.
[8] Carter, J.T.V., Gotkowitz,M.E., Anderson,M.P.(2011). Field verification of stable perched groundwater in layered bedrock uplands. Ground Water 49(3): 383 – 392.
[9] Costabel, S.,Yaramanci,U.(2013).Estimation of water retention parameters from nuclear magnetic resonance relaxation time distributions.Water Resour Res49(4):2068–2079, doi:10.1002/wrcr.20207.
[10] De Carlo, L., Perri,M.T., Caputo,M.C., Deiana,R., Vurro,M., Cassiani,G.(2013). Characterization of a dismissed landfill via electrical resistivity tomography and mise-à-la-masse method.J Appl Geophys 98: 1 – 10.
[11] Dobler, C., Burger,G., Stotter,J.(2012). Assessment of climate change impacts on flood hazard potential in the Alpine Lech Watershed.J Hydrol 461: 29 – 39.
[12] Eke, K.T., Igboekwe,M.U.(2011).Geoelectric investigation of groundwater in some villages in Ohafia Locality, Abia State, Nigeria.British J ApplSci Tech 1(4):190 – 203.
[13] Ezeigbo, H.I., Iliya,A.G., Zira,D.K.(1996).Water resources of Jimeta-Yola Metropolis, Adamawa State, Nigeria. Jour. of Min. and Geosci. In Obiefuna, G.I., Nur, A., Baba, A.U., Bassey, N.E., 1999. Geological and geotechnical assessment of selected gully sites, Yola area, northeast Nigeria.J Env Hydrol7:1 – 13.
[14] Food and Agricultural Organization (1997) Irrigation Potential in Africa. FAO Land and Water Bulletin 4. Food and agriculture Organization of the United Nations,1 – 191.
[15] Freeze, R.A., Cherry,J.A.(1979).Groundwater.Prentice Hall, Englwood cliffs, NJ,1 – 604.
[16] Herrera-Pantoja, M.,Hiscock,K.M. (2008).The effect of climate change on potential groundwater recharge in Great Britain. HydrolProces 22: 73 – 86.
[17] Holman, I.P., Allen, D.M., Cuthbert, M.O., Goderniaux, P. (2011).Towards best practice for assessing the impacts of climate change on groundwater. Hydrogeol J 20: 1 – 4.
[18] Hsu, K.C., Wang,C.K., Chen,K.C., Chen,C.T., Ma,K.W.(2007). Climate-induced hydrological impacts on the groundwater system of the Pingtung Plain, Taiwan. Hydrogeol J 15(5): 903 – 913.
[19] International Association of Hydrogeologists(2012). IAH Groundwater eNews. Available online at www.iah.org. Last accessed on 21st July 2012.
[20] Itmsoil(2012). Instrumentation and Monitoring MAlog User Manual.Itmsoil holding Ltd 1 – 60.
[21] Jamala, G.Y., Shehu,H.Z., Garba,A.T.(2011). Evaluation of factors influencing farmers' adoption of irrigated rice production in Fadama soil of North Eastern Nigeria.JDevelopAgricEcon3(2): 75 – 79.

[22] Jyrkama, M.I., Sykes,J.F.(2007). The impact of climate change on spatially varying groundwater recharge in the Grand River Watershed, Ontario,J Hydrol 338(3-4):237 – 250.
[23] Khalil, M.A., Santos,F.A.M.(2013). 2D and 3D resistivity inversion of Schlumberger vertical electrical soundings in Wadi El Natrun, Egypt: A case study.J Appl Geophys 89: 116 – 124.
[24] MacDonald, A.M., Davies,J., Calow,R.C.,Chilton,J.(2005). Developing groundwater: a guide for rural water supply.ITDG Publishing, Rugby, UK,1 – 400.
[25] Majumdar, R.K., Das,D.(2011). Hydrological Characterization and Estimation of Aquifer Properties from Electrical Sounding Data in Sagar Island Region South 24 Parganas, West Bengal, India.Asian J Earth Sci 4(2): 60 – 74.
[26] Mbiimbe, E.Y., Ezeigbo,H.I., Dike,E.F.C.(2008).Groundwater Potentials of Numan and Environs, Adamawa State, North-Eastern, Nigeria.Conti J Earth Sci 3: 59 – 70.
[27] Neukum, C.,Azzam,R.(2012). Impact of climate change on groundwater recharge in a small catchment in the Black Forest, Germany.Hydrogeol. J 20: 547 – 560.
[28] Ndlovu, S., Mpofu,V., Manatsa,D., Muchuweni,E.(2010). Mapping Groundwater Aquifers using Dowsing Slimgram Electromagnetic Survey Method and Vertical Electrical Sounding Jointly in the Granite Rock Formation: A Case of Matshetshe Rural Area in Zimbabwe.J Sust DevelopAfrica 12(5): 199 – 208.
[29] Nigerian Geological Society (2006). Geological Map of the Study Area,Published by Geological Survey Department, Ministry of Petroleum and Mineral Resources, Nigeria. Revised Edition.
[30] Niswonger, R.G.,Fogg,G.E.(2008).Influence of perched groundwater on base flow.Water Resour Res44(3): 1 – 5,W03405, doi:10.1029/2007WR006160.
[31] Nur, A., Obiefuna,G.I., Bassey,N.E.(2001).Interpretation of Geological data of the Federal University of Technology, Yola, Nigeria.J Env Hydrol 9(3):1 – 10.
[32] Nur, A., Kujir,A.S.(2006).Hydro-geoelectric study in the northeastern part of Adamawa State.J Env Hydrol 14: 1 – 7.
[33] Obiefuna, G.I., Nur,A., Baba,A.U., Bassey,N.E.(1999). Geological and geotechnical assessment of selected gully sites, Yola area, Northeast, Nigeria.J Env Hydrol 7: 1 – 13.
[34] Obiefuna, G.I., Orazulike,D.M.(2011).Geochemical and Mineralogical Composition of Bima Sandstone Deposit, Yola Area, NE Nigeria.Res J Env Earth Sci 3(2): 95 – 102.
[35] Okiongo, K.S.,Odubo,E.(2012). Geoelectric sounding for the determination of aquifer transmissivity in parts of Bayelsa State, South-South Nigeria.J Water ResourProtect4: 346 – 353.
[36] Okwueze, E.E.(1996).Preliminary findings of the groundwater resource potentials from a regional geo-electric survey of the Obudu basement area. NigeriaGlobal J Pure Appl Sci 2(2): 201 – 211.
[37] Onugba, A.,Aboh,H.O.(2009).The Tritium Content of Precipitation and Groundwater at Yola, Nigeria.Sci. world J 4(2): 23 – 28.
[38] Orlando, L.(2013). Some considerations on electrical resistivity imaging for characterization of waterbed sediments.J Appl Geophys 95: 77 – 89.
[39] Park, Y.H., Doh,S.J., Yun,S.T.(2007). Geoelectric resistivity sounding of riverside alluvial aquifer in an agricultural area at Buyeo, Geum River watershed, Korea: An application to groundwater contamination study. Env Geol 53: 849 – 859.
[40] Peleg, N., Gvirtzman, H. (2010). Groundwater flow modelling of two-levels perched karstic leaking aquifers as a tool for estimating recharge and hydraulic parameters. J Hydrol 388: 13 – 27.
[41] Perez-Bielsa, C., Lambán, L.J., Plata, J.L., Rubio, F.M., Soto, R. (2012). Characterization of a karstin aquifer using magnetic resonance sounding and electrical resitivity tomography: a case-study of Estaña Lakes (northern Spain). Hydrogeol J 20(6): 1045 – 1059.
[42] Robinson, B.A., Broxton,D.E.,Vaniman,D.T.(2005).Observations and modelling of deep perched water beneath the Pajarito Plateau.Vadose Zone J 4: 637 – 652.
[43] Rosenberry, D.O.(2000).Unsaturated-zone wedge beneath a large, natural lake.Water Resour Res36(12):3401–3409, doi:10.1029/2000WR900213.
[44] Shamsudduha, M., Taylor, R.G., Ahmed, K.M.,Zahid, A. (2011).The impact of intensive groundwater abstraction on recharge to a shallow regional aquifer system: evidence from Bangladesh. Hydrogeol J 19: 901 – 916.
[45] Sikandar, P., Christen,E.W. (2012).Geoelectrical sounding for the estimation of hydraulic conductivity of Alluvial Aquifers.Water Resour Manage 26: 1201 – 1215.
[46] Sivandran, G., Bras,R.L.(2012).Identifying the optimal spatially and temporally invariant root distribution for a semiarid environment.Water Resour Res48(12):W12525, doi:10.1029/2012WR012055.
[47] Tessema, A., Mengistu, H., Chirenji, E., Abiye, T.A., Demlie, M.B. (2012). The relationship betweenlineaments and borehole yield in North West Province, South Africa: results from geophysical studies. Hydrogeol J 20(2): 351 – 368.
[48] Tizro, A.T., Voudouris,K.S., Salehzade,M., Mashayekhi,H.(2010) Hydrogeological framework and estimation of aquifer hydraulic parameters using geoelectrical data: a case study from West Iran.Hydrogeol J 18:917 – 929.
[49] Van Overmeeren, R.A.(1989). Aquifer boundaries explored by geoelectrical measurements in the coastal plain of Yemen: A case equivalent,Geophys., 54(1), 38 – 48.
[50] Vuilleumier, C., Borghi, A., Renard, P., Ottowitz, D., Schiller, A., Supper, R., Cornaton, F. (2013). A method for the stochastic modelling of karstin systems accounting for geophysical data: an example of application in the region of Tulum, Yucatan Peninsula (Mexico). Hydrogeol J 21(3): 529 544.
[51] Wada, Y., L. P. H. van Beek, and M. F. P. Bierkens (2012). Nonsustainable groundwater sustaining irrigation: A globalassessment. Water Resour. Res., 48, W00L06, doi:10.1029/2011WR010562.

Table 1: Resistivity curve types and their description. VES – vertical electrical soundings; ρ - resistivity

Location	Curve type	Description
VES 2, 13 and 23	A	ρ1<ρ2<ρ3
VES 1, 4, 5, 7, 11, 12, 16, 22 and 24	H	ρ1>ρ2<ρ3
VES 3, 9, 14, 18 and 21	HK	ρ1>ρ2<ρ3>ρ4
VES 6 , 8, 15, 17, 19 and 21	K	ρ1<ρ2>ρ3
VES 10	Q	ρ1>ρ2>ρ3

Table 2: Average resistivity and thickness values for the three groups of electro-stratigraphic earth model

Model type		FirstLayer	Secondlayer	Thirdlayer	Fourthlayer	Fifth layer	Location
Five	Resistivity(Ωm)	159.46	1,460	49.21	174.47	184.50	VES 5, VES 12 and VES 15
	Thickness(m)	0.74	5.44	5.45	16.12	-	
Four	Resistivity(Ωm)	246.19	1,402.42	470.07	154.55	-	VES 1, VES 3, VES 4, VES 9, VES 11, VES 13, VES 14, VES 18, VES 19, VES 21, VES 22 and VES 24
	Thickness(m)	1.90	4.84	22.36	-	-	
Three	Resistivity(Ωm)	327.69	702.03	545.13	-	-	VES 2, VES 6, VES 7, VES 8, VES 10, VES 16, VES 17, VES 20 and VES 23
	Thickness(m)	3.29	11.62	-	-	-	

Table 3: Results obtained from the computer output of the twenty four vertical electrical sounding point stations

----	Thickness of Layer (m)				Resistivity (Ωm)					Resistance (Ωm)				Conductivity (Sm-1)				Elevation (depth) (m)				Fitting Error (%)
	H1	H2	H3	H4	ρ1	ρ2	ρ3	ρ4	ρ5	R1	R2	R3	R4	δ1	δ2	δ3	δ4	E1	E2	E3	E4	
VES 1	0.66	5.98	13.8	-	156.8	68.65	21.38	135.4	-	103.5	410.6	295.9	-	0.042	0.0871	0.646	-	0.66	6.64	20.47	-	1.85
VES 2	1.65	26.16	-	-	10.72	16.02	279.2	-	-	17.77	419.3	-	-	0.154	1.63	-	-	1.65	27.8	-	-	2.49
VES 3	1.64	2.14	48.1	-	735.5	3600.4	128.2	186.1	-	1206.6	7735.5	6167.9	-	0.0022	5.967	0.375	-	1.64	3.78	51.89	-	1.72
VES 4	2.41	11.59	3.44	-	27.48	18.9	4001.6	1.47	-	66.32	219.2	13773.3	-	0.087	0.613	8.601	-	2.41	14	17.45	-	3.73
VES 5	1.52	13.65	6.01	16.28	17.26	20.13	49.39	112	283.1	56.72	274.8	297.2	4.3	0.0408	0.678	0.121	0.145	1.52	15.2	21.19	37.5	3.72
VES 6	3.25	2.77	-	-	116.5	3252.7	105.8	-	-	378.8	9016.7	-	-	0.0278	8.522	-	-	3.25	6.02	-	-	2.6
VES 7	4.21	3.10	-	-	36.58	3.95	318.8	-	-	15.4	12.31	-	-	0.115	0.785	-	-	4.21	7.32	-	-	1.35
VES 8	1.59	11.61	-	-	508.8	937.3	108.7	-	-	812.2	10887	-	-	0.0031	0.0123	-	-	1.59	13.2	-	-	2.41
VES 9	0.259	6.14	85.2	-	193.7	492.1	144.1	391.1	-	50.27	3024.4	12278.7	-	0.0013	0.0124	0.591	-	0.25	6.4	91.6	-	3.81
VES 10	3.06	10.23	-	-	1800.1	179.4	102	-	-	5512.6	1836.8	-	-	0.0017	0.057	-	-	3.06	13.3	-	-	0.9
VES 11	0.49	6.17	3.45	-	260.7	60.08	8.34	119	-	128.1	420	28.77	-	0.0018	0.0906	0.413	-	0.49	6.66	10.11	-	1.66
VES 12	0.2	1.98	7.27	5.55	432.2	36.42	22.52	14.02	152	86.44	72.12	163.7	77.81	0.0046	0.0543	0.322	0.395	0.2	2.18	9.45	15	1.1
VES 13	1.5	1.58	33.2	-	23.89	90.76	59.09	128.5	-	36.04	143.4	196.9	-	0.6631	0.0174	0.562	-	1.5	3.08	36.33	-	2.03
VES 14	10.13	5.13	13.1	-	27.12	2.16	99.01	0.146	-	274.8	11.14	1301.5	-	0.373	2.36	0.132	-	10.13	15.27	28.41	-	3.05
VES 15	0.506	0.675	3.08	26.5	28.93	4324	75.71	397.4	118.4	14.56	2920.6	233.5	10548.3	0.0175	0.00156	0.0407	0.0667	0.506	1.18	4.26	30.8	3.76
VES 16	7.5	5.29	-	-	50.86	8.01	456	-	-	381.6	42.44	-	-	0.147	0.661	-	-	7.5	12.8	-	-	2.92
VES 17	1.36	2.71	-	-	43.17	1003.7	133	-	-	59.1	2722.9	-	-	0.0317	0.0027	-	-	1.36	4.08	-	-	2.98

VES18	1.32	1.72	4.6	-	61.65	255	6.14	400.8	-	81.86	440.8	28.26	-	0.0215	0.00678	0.749	-	1.32	3.05	7.65	-	3.34
VES19	1.28	6.71	20.1	-	869.5	1664.4	372.9	73.77	-	1121.1	11174.7	7480.3	-	0.00148	0.00403	0.0537	-	1.28	8	28.06	-	4.2
VES20	1.45	5.89	-	-	373.6	888.2	132.2	-	-	542.2	5232.7	-	-	0.00388	0.00663	-	-	1.45	7.34	-	-	2.94
VES21	0.577	1.18	5.14	-	100.5	9873.6	26.37	216.3	-	58.04	11717.5	135.6	-	0.00574	0.0012	0.195	-	0.577	1.76	6.9	-	3.92
VES22	1.38	5.78	4.89	-	491.2	701.6	24.28	187.4	-	678	4062.1	118.3	-	0.00281	0.00825	0.201	-	1.38	7.17	12.06	-	2.98
VES23	5.54	36.80	-	-	8.91	29.02	3270.5	-	-	49.42	1053.5	-	-	0.521	1.25	-	-	5.54	41.84	-	-	2.06
VES24	1.12	3.91	33.3	-	6.23	1.43	749.4	14.56	-	7.04	5.62	24924.3	-	0.18	2.72	0.0443	-	1.12	5.04	38.3	-	3.99
Mean Value	2.275	7.45	18.98	16.12	265.91	1147.00	445.61	158.53	184.5	489.10	3077.34	4494.94	3543.47	0.102	1.06	0.87	0.20223	2.275	9.71	25.61	27.77	2.730

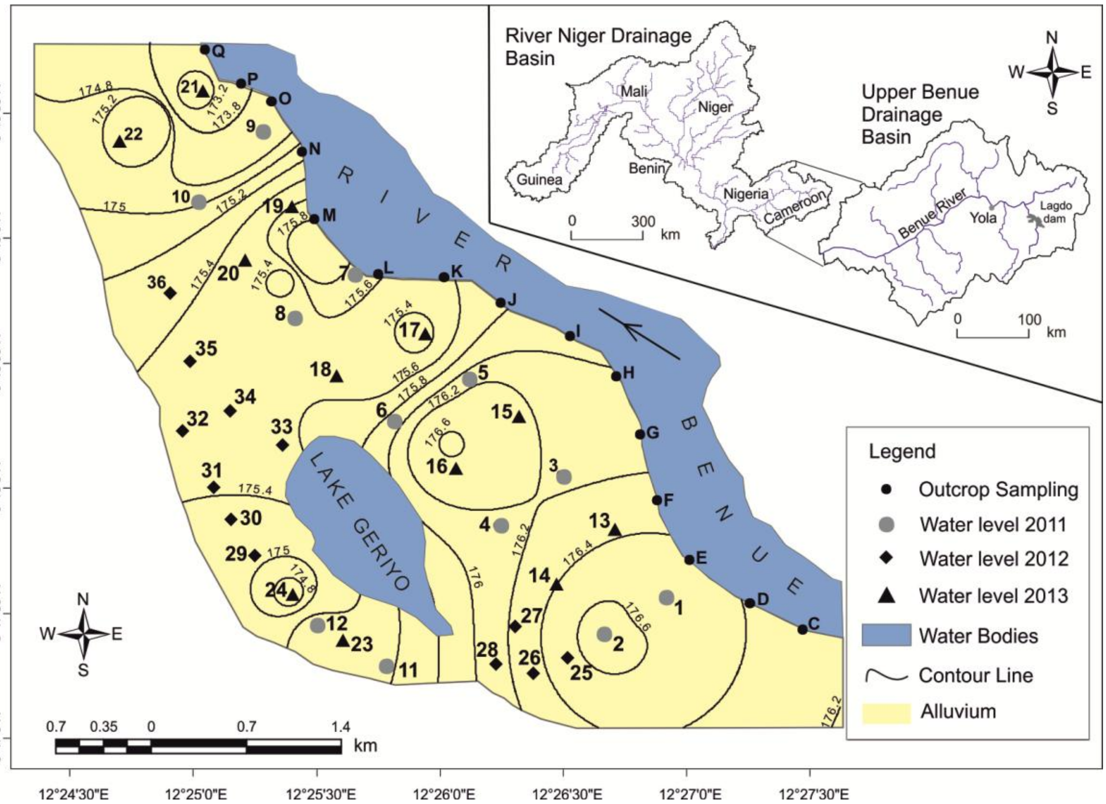


Figure 1: A. Topographic map of the study area showing sampling location along outcrop and on the floodplain of River Benue Yola region. (Modified after Nigeria Geological Survey, 2006

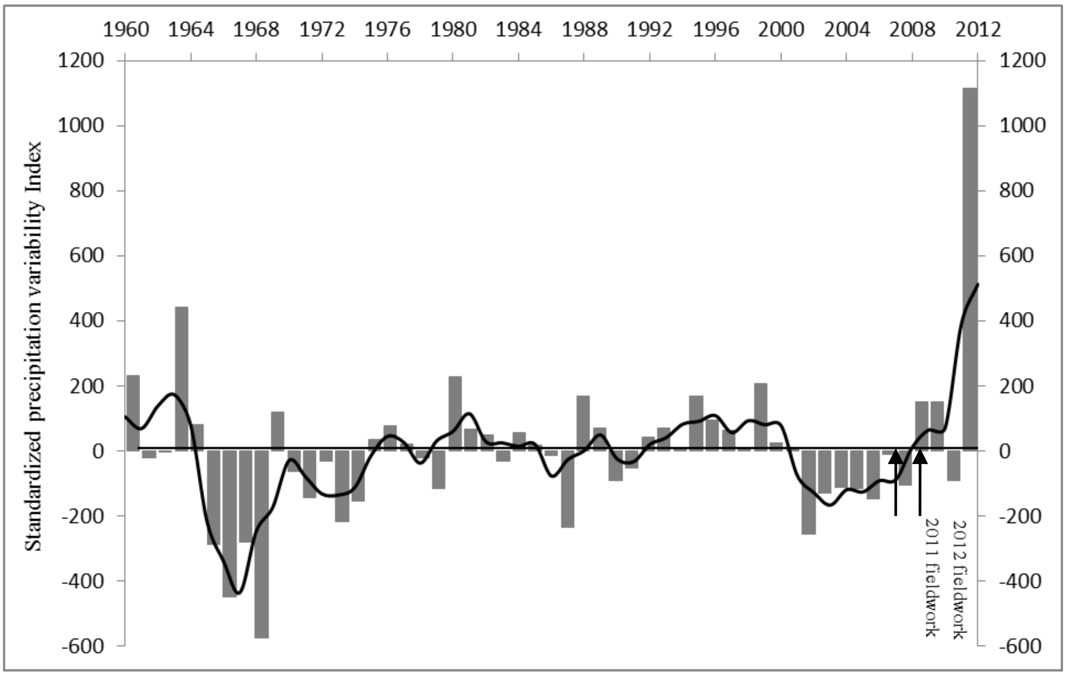


Figure 2: Standardized precipitation index (anomaly) plot (1960 – 2012). Thick line is the 3-year running mean. The arrows show the period for the fieldwork in 2011, 2012 and 2013 before starting of the rainy season.

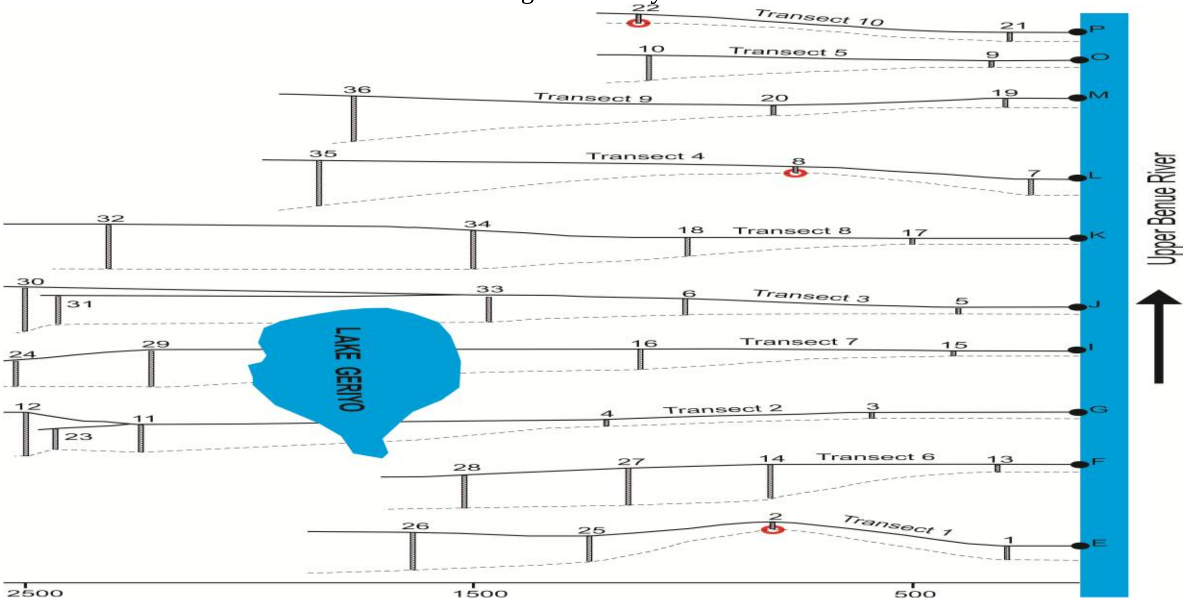
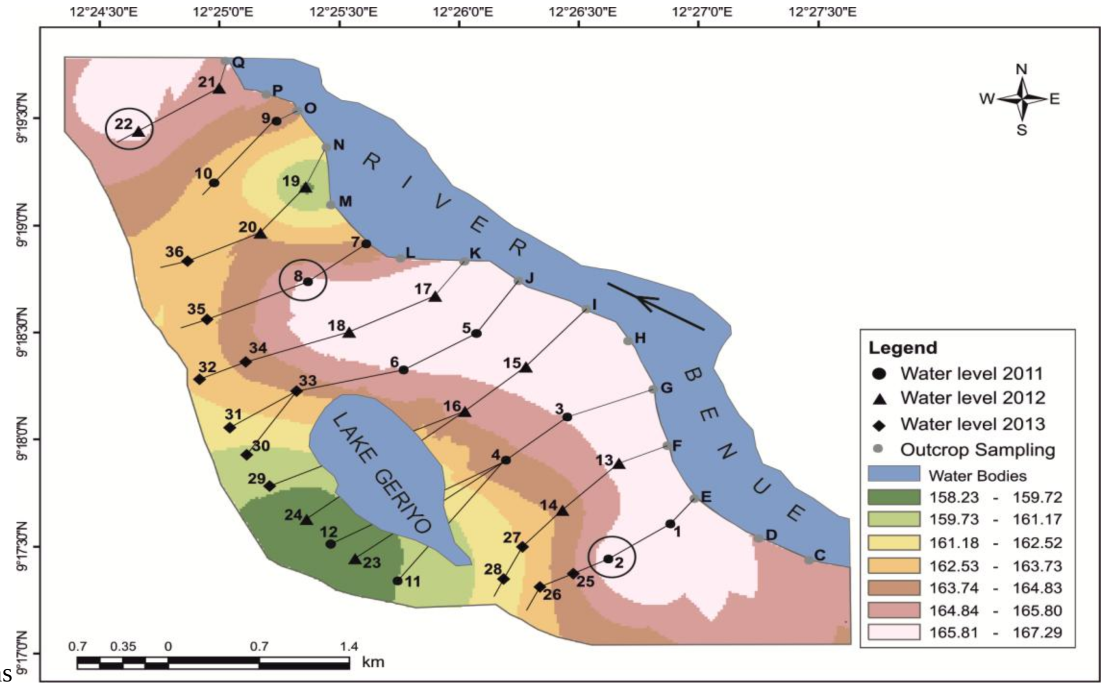


Figure3: Graph showing the groundwater levels in the location of the ten vertical electrical sounding transects and proposed position of perched aquifers (grey circles) as moving away from River Benue Valley, Yola region.



Locations

Figure 4: Spatial distribution of thefloodplain groundwater levels showing the proposed perched aquifer formations (black circles). The white and pink locations shows high water levels in wells, it identified perched aquifer formations along floodplain of Benue River. The values 158.23 – 167.29 are elevations in metres of groundwater levels on the floodplain.