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A SIMULATION OF GROUNDWATER FLOW AND POSSIBLE IMPACTS OF CLIMATE CHANGE, EKU, SOUTHERN NIGERIA

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Climate change has significant impact on groundwater resource management. The impact can partially be understood by using scenarios modeling to analyze how climate change affects groundwater quantity. Different recharge scenarios corresponding to varying amounts of rainfall were defined to represent changes in climate. The scenarios were used to analyze the availability and sustainability of groundwater resources in the town of Eku and its environs in Delta State, Nigeria. The groundwater modeling was done using the MODFLOW code as embedded in the Groundwater Modeling System. Results showed that under conditions of decreased recharge, indicating dryer climate, groundwater levels declined significantly. This decline was even more significant with increase in projected pumping rates. These scenarios of increased abstraction under average recharge have little effect on the availability and sustainability of groundwater in the area. However, considerable increases in abstraction beyond permissible pumping rates may result in large drawdowns and decline in heads that do not necessarily cause groundwater mining. This study demonstrates the efficacy of using the MODFLOW code and Groundwater Modeling System in understanding aquifer management.

INTRODUCTION

Groundwater is arguably one of man's most important resources. Groundwater is of great significance due to its usefulness. Its availability at sustainable quantity and quality is essential for household drinking, industry and agricultural purposes. Climate change is one of the major factors that affect groundwater availability. Climate change has significant effect on precipitation which in turn affects groundwater. Groundwater is constantly recharged by precipitation both directly and indirectly. Seasonal fluctuations in rainfall affects the availability of groundwater in aquifers in terms of quantity as well as quality (Kumar and Singh, 2015). The Intergovernmental Panel on Climate Change (IPCC, 2007), defined climate as "the average weather in terms of the mean and its variability over a certain time-span and a certain area". A statistically significant variation of the mean state of the climate or of its variability lasting for decades or longer is known as climate change.

Aquifers generally are replenished by effective rainfall, rivers, and lakes. This water may reach the aquifer rapidly, through macro-pores or fissures, or more slowly by infiltrating through soils and permeable rocks overlying the aquifer. A change in the amount of effective rainfall will alter recharge, but so will a change in the duration of the recharge season. Increased rainfall generally is likely to result in increased groundwater recharge. However, higher evaporation may mean that soil deficits persist for longer and commence earlier, offsetting an increase in total effective rainfall. The response of aquifers to recharge by precipitation and withdrawal of groundwater can be understood by the use of groundwater flow models. A groundwater model is a computer-based representation of the essential features of a natural hydrogeological system that uses the laws of science and mathematics (Kumar, 2013). These models attempt to represent reality through a set of mathematical equations helping us to understand the inter-relationship between the physical, chemical and biological processes that affect the movement of groundwater. In order to solve the equations that constitute the flow model, it is necessary to make specific assumptions and simplifications of the aquifer and the physical processes governing groundwater flow (Kumar, 2013). The most important of these assumptions are embodied in the conceptual model of the aquifer.

The Modular Finite Difference Groundwater Flow Model (MODFLOW) code is one example of the most widely used groundwater modeling packages. The aim of this study is to use the MODFLOW code to investigate the impact of climate change on groundwater resources of the town of Eku and its environs in Delta State, Nigeria. The specific objectives are: to develop a conceptual model of the hydrogeology of the area, and use the conceptual model to develop a three-dimensional groundwater flow model. The model is then used to predict the impact of increases in groundwater demand on the groundwater resource in the area, and to analyze the impact of recharge, representing climate change, on groundwater availability and sustainability in the area.

THE STUDY AREA

General

Eku is one of the major towns in Ethiope East Local Government Area of Delta State, Nigeria (Figure 1). It is located between latitudes 5° 39' 16" N and 6° 14' 22" N of the equator, and longitudes 5° 33' E and 6° 30' E of the Greenwich Meridian. The area is of sub-urban to rural setting accessible by good road networks with its major road being the Eku-Agbor road. The land in Eku is fertile with the major occupation of the people associated generally with agriculture most especially production of cassava, palm oil and vegetables. The demand for water for these uses is high, including groundwater.

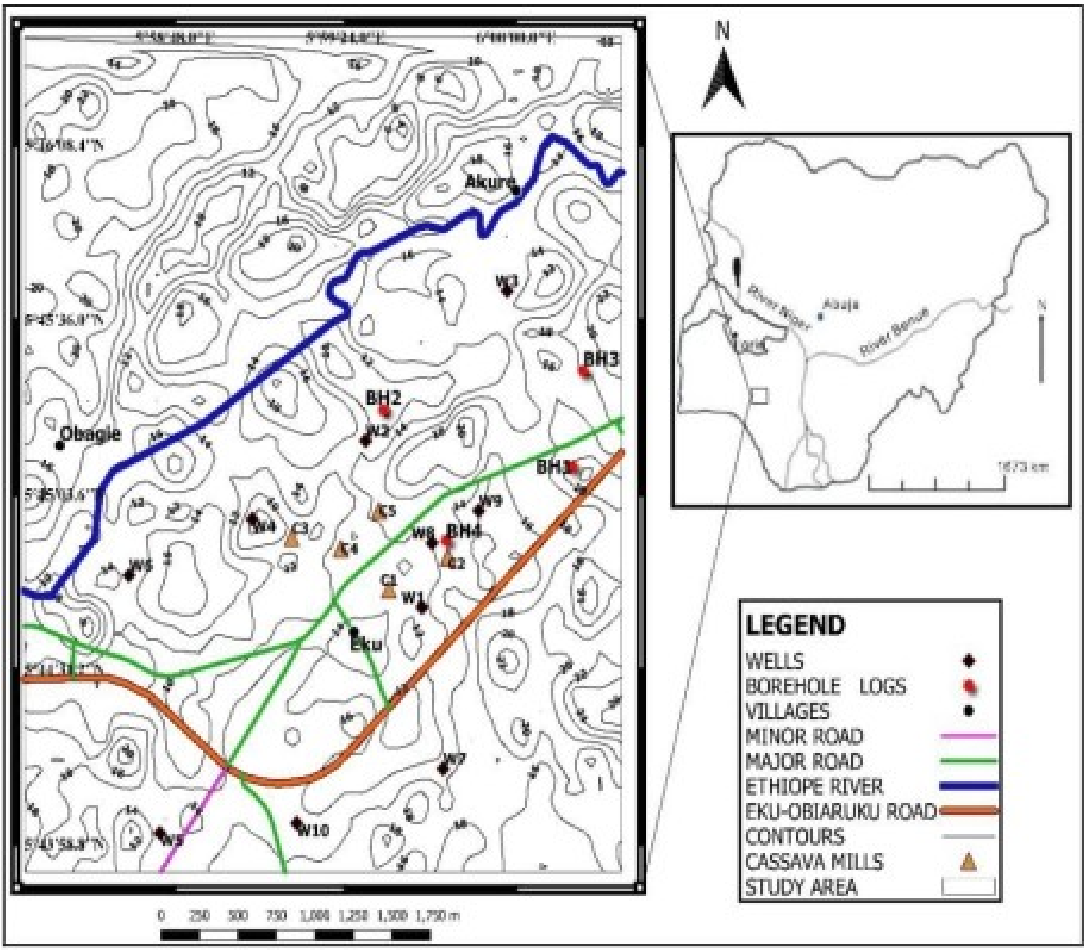

Figure 1. Location of the study area

The surface area of Eku is relatively flat with elevations of less than 15 m above msl with no major hills.Flooding and erosion are major problems especially during the annual rainy seasons. The most significant drainage landmark in the area is the Ethiope River which drains the entire watershed of Eku. The town of Eku has been observed to generally experience a warm humid climate with high relative humidity, high rainfall and marked wet (April – October) and dry (November – March) seasons. The mean maximum temperatures for the wet season and dry season are 29.3 °C and 33.6 °C respectively, while the mean minimums are 22.6 °C and 24.6 °C, with the hottest months being February and March. The vegetation of the area is characterized by fresh water swamp forest, herbaceous plant rainforest and open herbaceous regrowth plants. Eku lies within the Quaternary Sombreiro – Warri deltaic plain with prominent seasonal freshwater swamps, which overlie the Benin Formation of the Niger Delta Sedimentary Basin, comprising variable deltaic sediments of sands, clays and silts. Its geology arises from a succession of transgressions and regressions of the three main Tertiary subsurface lithographic units of Akata, Agbada and Benin Formations (Short and Stauble, 1967, Nwajide 2013, Oyebanjo et al., 2018).

Literature review pertinent to the study area

Groundwater modeling has received extensive usage in recent times to better understand aquifer response to abstraction and recharge. There are different kinds of models used in groundwater flow modeling which can be broadly classified into analytical and numerical models. Tóth (1963) used, for the first time, analytical solutions to investigate groundwater flow. From his study he classified groundwater flow systems as local, intermediate and regional. He attributed the geology, general topography as well as climate to be major factors for the formation of these three sub-flow systems in a homogeneous and isotropic aquifer. Freeze and Witherspoon (1966) were the first to use numerical models to simulate steady state regional flow patterns. The advantage of these numerical models lie in their ability to simulate three-dimensional groundwater flow in heterogeneous and anisotropic groundwater basins, although they can also solve problems under isotropic and homogeneous conditions. Their models were used to analyze the effects of water table configuration and hydraulic conductivity on regional flow patterns and to quantify basin yields (Freeze and Witherspoon, 1968).

Modeling studies of regional groundwater flow in the Niger Delta, Nigeria are limited. Ophori (2006, 2007) simulated large-scale groundwater flow in the Niger Delta with the MODFLOW code and Groundwater Modeling System (GMS). His results showed local and intermediate flow systems of significance in the area. Atakpo (2009) used numerical packages, MODFLOW and MODPATH, to simulate the conceptual understanding of the geology and hydrogeology of the Olomoro area attained from electrical resistivity survey and discovered that the average groundwater flow velocity of the area was about 388 m/year. Okocha and Atakpo (2013) used the finite difference block centered technique via groundwater vistas software to carry out a steady state groundwater flow simulation in the Ethiope River. Rainfall and recharge data were essential to their study. They found that there was possibility for additional groundwater exploitation in the watershed through drilling of boreholes. Sule and Ayenigba (2017) utilized the MODFLOW-GMS package to develop a conceptual model for River Meme, Kogi State. Their calibrated steady- and transient-state models were followed by a predictive run for ten years. They found that if the rate of abstraction was increased by up to 60%, the groundwater system would still be sustainable as a main source of supply for domestic consumption. This current study is another contribution to these earlier modeling studies in the Niger Delta and Nigeria.

Geology and hydrogeology of the Niger Delta

The Cenozoic Niger Delta, which hosts the town of Eku, is situated at the intersection of the Benue Trough and the South Atlantic Ocean where a triple junction developed during the separation of the South American and African plates in the late Jurassic period (Whiteman, 1982). During the Cenozoic, until the Middle Miocene, the Niger Delta grew through pulses of sedimentation over an oceanward-dipping continental basement into the Gulf of Guinea, thereafter progradation took place over a landward-dipping oceanic basement. A 12,000 m thick succession of overall regressive, offlapping sediments resulted that is composed of three diachronous siliciclastic units: the deep-marine pro-delta Akata Group, the shallow-marine delta-front Agbada Group and the continental, delta-top Benin Group (Obaje, 2009). The boundaries of the Niger Delta are defined by the Anambra Basin and Abakaliki High to the north, the Cameroun Volcanic Line to the east, the Dahomey Embayment to the west and the Gulf of Guinea to the south (Tuttle et al., 1999). The Niger Delta has an aerial extent of 75,000 km² and is located between latitude 4°30’ and 5°20’ N and longitude 3° and 9° E. It is the second largest delta in the world with a coastline spanning about 450 km terminating at the Imo River entrance (Awosika, 1995). The Niger Delta constitutes three broad lithostratigraphic units namely: (1) The Akata Formation which is a basal marine shale unit, (2) the Agbada Formation which is a coastal marine sequence of alternating sands and shales, and (3) the Benin Formation which consists of a sequence of continental massive sands. These three formations (Figure 2), reflect a gross coarsening-upward progradational clastic wedge (Short and Stauble, 1967), deposited in marine, deltaic, and fluvial environments (Weber and Daukoru, 1975, Weber, 1986). The Akata Formation is the oldest among the three lithostratigraphic units of the Niger Delta Basin. The formation is estimated to be

7000 m thick (Doust and Omatsola, 1989). The lithologies consist mainly dark gray shales and silts, with rare streaks of sand of probable turbidite flow origin. Sand percentage is less than 30%. Akata shales were interpreted to be deepwater lowstand deposits by Stacher (1995). The formation grades vertically into the Agbada Formation. The Agbada Formation is the major petroleum-bearing unit of the Niger Delta Basin (Tuttle et al., 1999). It overlies the Akata Formation and underlies the Benin Formation. Lithologies present include alternation of sand and shale layers with percentage of sand ranging from 30% to 70%, and is characterized by paralic to marine-coastal and fluvial-marine deposits (Pochat et al., 2004). The Benin Formation is the uppermost unit of the Niger Delta Basin. The age of the formation is estimated to range from Oligocene to Recent (Short and Stauble, 1967). It is estimated to be 2000 m thick and consists of continental flood plain sands and alluvial deposits. Sand percentage in this formation is the highest ranging from 70% to 100%.

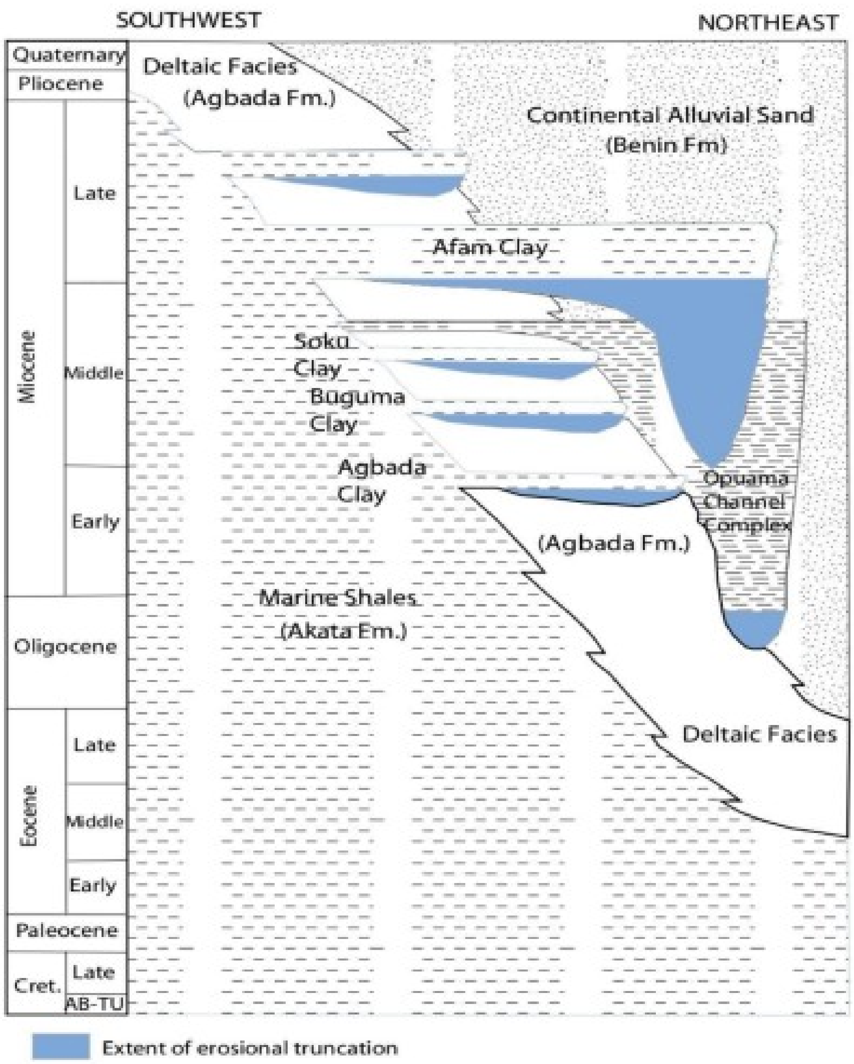

Figure 2. Stratigraphic Succession of the Niger Delta Basin showing the three major lithostratigraphic units (Tuttle et al., 1999).

Although the hydrogeology of the Niger Delta is very complex, it has been found that the most important aquifers in the Niger Delta are the Deltaic and Benin Formations (Adelana et al., 2008). Most of the boreholes in the northern parts of the Niger Delta tap unconfined aquifers. In most of these boreholes the geological sequence consists of continuous sandy formations from top to the bottom with clay intercalations. However, some aquifers occur under confined conditions resulting in artesian flows. The unconfined water-table in the Niger Delta area is very close to the ground surface, ranging from 0 to 9 m below ground level in the Deltaic Formation and 3 to 15 m below ground level in the Benin Formation (Adelana et al., 2008). The aquifers are steadily recharged by precipitation and major rivers as the area is renowned for having heavy rainfall estimated to be over 2400 mm per year in major regions. Confined aquifers also occur in both the Deltaic and Benin Formations with confining beds of clay about 36 m thick and total depth of the aquifer below the bed being approximately 100 m. The confined aquifers consist mainly of very coarse to medium-grained sands. The specific capacity for this formation varies between 140 and 180 $m^3/d/m$ (Adelana et al., 2008).

MATERIALS AND METHODS

Topographic map

The required topographic map for this study was generated using Google Earth Pro and QGIS software as well as the GPS Visualizer website. Google Earth Pro is a free software that allows visualization, assessment, overlay, and creation of geospatial data. Although not a true GIS, Google Earth Pro is a user-friendly software that can be used to view its extremely high-resolution satellite imagery, upload or download geospatial data in its native interoperable file format (KML), and also find locations. Path trace, which is one of the tools present in the software, was utilized for the purpose of this research. The search space in the software was used to zoom in the location of the study area and the path of interest traced and then saved in a *'kmz'* file type before being imported to the GPS Visualizer using the "look up elevation" feature. GPS Visualizer is a powerful but user-friendly online platform used in creating maps and profiles from geographical data. The website generates coordinates and elevations within the traced path from the Google Earth Pro which is then saved as delineated text. The saved delineated text is then imported as a layer into the Quantum Geographic Information System (QGIS) version 3.14.0 *"pi"* which is a software used to compose maps and interactively explore geospatial data. For the purpose of this study, the QGIS software was used to create the final contour map of the study area as well as grid the map for use in the GMS software which is the principal software for the MODFLOW package.

Hydraulic data

Hydraulic data such as water levels were used for the modeling. Elevation and water levels were attained from ten wells within the study area (Table 1). The hydraulic head in each well was obtained by subtracting the depth to the water from the surface elevation of the area. Borehole logs were used to delineate and simplify the aquifer that was modeled.

Code selection

The GMS software version 10.5 uses the MODFLOW package. MODFLOW was developed by the United States Geological Survey (USGS). It uses the groundwater flow equation, which is a combination of the continuity equation and Darcy's law, to describe and predict aquifer system behaviour and to simulate groundwater dynamics in both steady state and transient state (McDonald and Harbaugh, 1988). MODFLOW was run to generate steady-state flow, which assumes that groundwater level remain constant with time in homogeneous and isotropic geologic conditions. In

Table 1. Elevation, Water Level and Hydraulic Heads of ten wells.

Longitude	Latitude	Location	Elevation (m)	Depth to Water (m)	Hydraulic Heads (m)
5° 59’ 41”	5° 44’ 42”	W1	12	6.25	5.75
5° 59’ 28”	5° 45’ 13”	W2	13	6.00	7.00
5° 59’ 59”	5° 45’ 41”	W3	14	6.10	7.90
5° 59’ 05”	5° 44’ 58”	W4	10	4.28	5.72
5° 58’ 44”	5° 44’ 00”	W5	15	7.00	8.00
5° 58’ 38”	5° 44’ 48”	W6	13	7.40	5.60
5° 59’ 45”	5° 44’ 12”	W7	15	5.33	9.67
5° 59’ 42”	5° 44’ 54”	W8	12	5.38	6.62
5° 59’ 53”	5° 44’ 59”	W9	14	6.43	7.57
5° 59’ 14”	5° 44’ 01”	W10	16	6.70	9.30

MODFLOW, the three-dimensional movement of groundwater with constant density through porous media is described by the partial-differential equation (Bear, 1979):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-Q=S_s\frac{\partial h}{\partial t}$$

where,

Kxx, Kyy and Kzz = values of hydraulic conductivity along the x, y and z coordinate axes,

h = the potentiometric head,

Q = volumetric flux per unit volume and represents source and/or sink of water,

S_s = the specific storage of the porous media, and

t = time.

Creating the grid

The MODFLOW Grid approach was used for this modeling work. The domain was gridded into cells in the x, y, z axes which represent the width, length and depth respectively. The grid had 20 cells in the x-axis, 25 cells in the y-axis and 5 cells in the z-axis based on the number of rock layers inferred and simplified from the borehole logs. The scale of the map was used to determine the length of the x and y-axes while the length of the z-axis corresponds with the depth of the aquifer being modeled.

Boundary conditions

Boundary conditions specify how water in an aquifer interacts with the environment outside the model domain. Selection of boundary conditions is a key step in model design because they significantly control the flow pattern. The River Ethiope, which bounds the model domain to the north, is treated as a boundary condition. The vertical boundary below the river was treated as no flow because of flow symmetry into the river. All other vertical boundaries were assumed to be no-flow because they were located far enough from the town of Eku in the center of the area of interest in the study. The bottom of the model was 60 m deep. This bottom boundary was assumed to be impermeable because available field data indicated that the sediment permeability at this depth was considerably low. The top boundary had variable boundary conditions. The River Ethiope was simulated with the river package which needed the conductance and elevation of the river. Conductance is a factor that relates the difference in head to the rate of flow. River Ethiope has an elevation of 7 m. The conductance was estimated using the relationship:

$$C = K/t * w$$

where,

C = conductance per unit length of the river bottom [L/T]

t = thickness of the river-bottom material [L]

w = width of the river-bottom material [L]

K = hydraulic conductivity of river-bottom material [L/T]

The value of K that was used for the river-bottom material was 0.001 m/s as reported by Irabor and Olobaniyi (2007). The thickness was 3.7 m as measured along the course of the river in Eku (N5°45'19.1", E5°58'58.1"). The width as measured by Google Earth Pro was 30 m. The conductance was therefore equal to 0.00811 m/s. First-type boundary conditions were specified at the surface where hydraulic heads (Table 1) were known. Groundwater recharge was specified at all other locations at the surface. Recharge rate is a very important parameter in groundwater flow modeling and is the major aspect of the scope of this study. Recharge occurs when water seeps into the ground to replenish underground aquifers. Rainfall, which is an index of climate change, is a major factor affecting recharge as the amount of rainfall that takes place in a basin would determine the water input into the basin (Gobo, 1988). However, the amount of annual rainfall in a particular area varies from year to year. Due to the lack of accurate meteorological data for the study area, the average annual rainfall over a ten-year period for the area with the closest meteorological station (Oyeleke, 2021) was used. The average rainfall was estimated to be 2728.28 mm/year. One thousand (1000) mm of this rainfall is lost to evapotranspiration and 37% (or 0.0018 m/day) of the subsequent effective rainfall value is the amount of water that recharges the aquifer while the remaining 63% flows directly into the stream (Akpokodje et al., 1996).

Hydraulic parameters

Hydraulic conductivity (K) values were also needed to represent the rock materials in the model. In this study, the hydraulic conductivity values used were assumed in correspondence with those of different sediment types as shown in Table 2.

FLOW SIMULATION AND CALIBRATION

After entering all the required parameters into the model, the MODFLOW code was run to create steady-state flow in the domain. The model was then calibrated by altering certain parameters such as recharge and hydraulic conductivity values in a systematic fashion such that the model, after being repeatedly run based on every change in parameters, computes a solution that matches values observed in the field within an acceptable level of accuracy. First, calibration was done using a set of head values

Table 2. Hydraulic conductivity standards for different sediment types (Bouwer, 1978).

Materials	Range of K (m/d)
Clay soils (surface)	0.2
Deep clay beds	$10^{-8} – 10^{-2}$
Loam soils (surface)	0.1 – 1.0
Fine sand	1 – 5
Medium sand	5 – 20
Coarse sand	20 – 100
Gravel	100 – 1000
Sand and gravel mixes	5 – 100
Clay, sand and gravel mixes	0.001– 0.1

observed in the field. Figure 3 shows how well the computed and observed head values correspond with the 45° line which is a line of perfect correlation. This similarity in values between the observed and computed heads shows the model is calibrated enough to be used for predictions and groundwater management plans at the study area. Further calibration was done based on the water budget, a tool used to quantify the amount of water flowing into and out of an aquifer, and calculated by the MODFLOW code. The code produced a percent discrepancy of - 0.48, which is close to zero, between inflow and outflow, validating that the model is sufficiently calibrated.

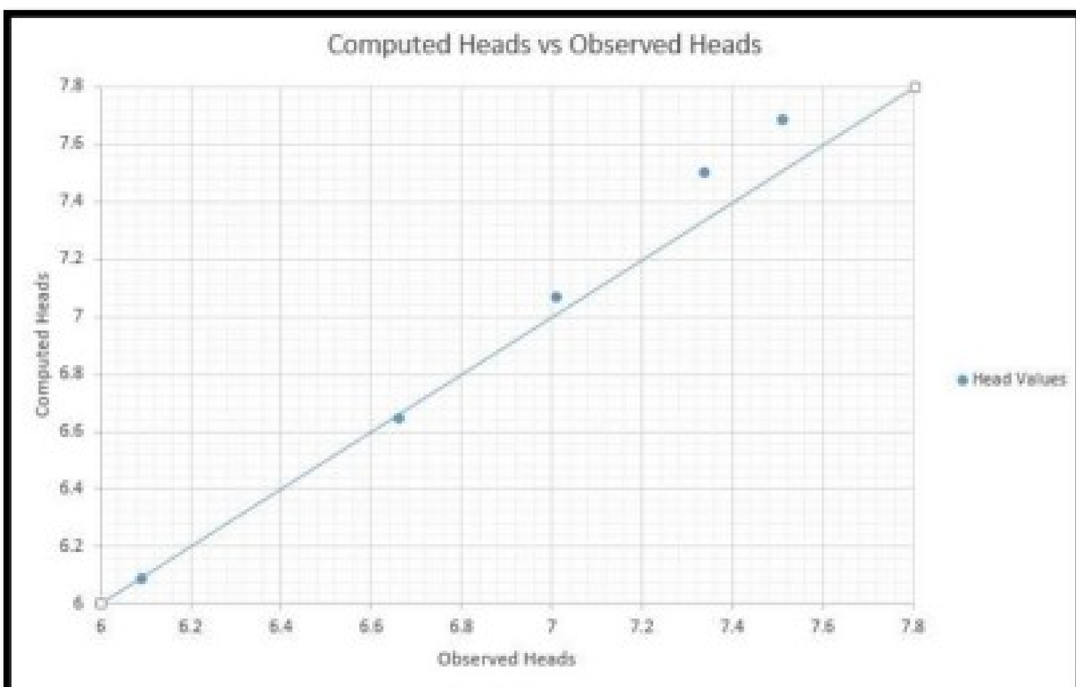

Figure 3. Plot of computed heads versus observed heads

RESULTS AND DISCUSSIONS

Groundwater flow

Figure 4 shows the head distribution across the model domain. It was observed that the head distribution follows the surface topography. The hydraulic heads range from 5.5 - 9.46 m, in line with those observed by Oseji and Ofomola (2010) at a nearby site in the town of Utagba-Ogbe. The flow vectors show that the flow lines follow the general slope of the land and flow tends towards the Ethiope River in the northern part of the model domain as water flows from regions of higher hydraulic head to regions of lower hydraulic head. An oblique view of the flow pattern also indicated active flow of water that percolates from the top layer into the bottom layer and subsequently towards the river. This shows that the Ethiope River is an effluent stream that is recharged by groundwater.

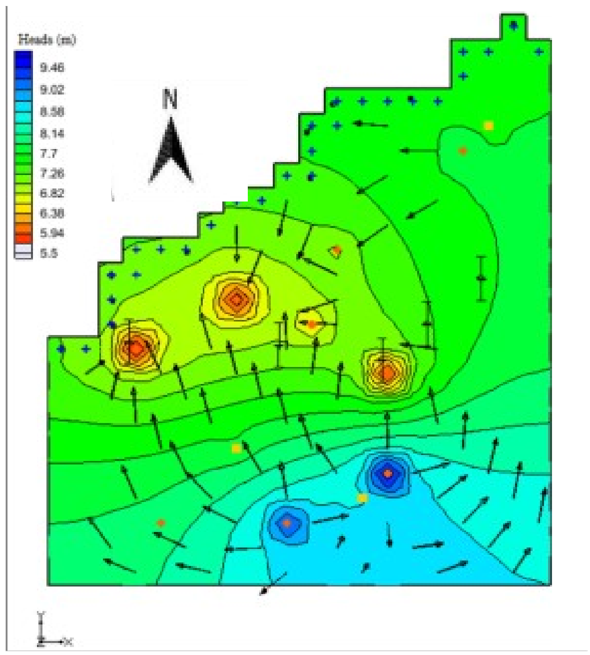

Figure 4. Calibrated model showing distribution of heads and flow directions

Sensitivity analysis

The model's sensitivity to parameters affecting the hydraulic heads of wells was assessed, and these parameters include the hydraulic conductivity, the pumping (discharge) rate, and the recharge rate. These parameters were tweaked to observe the model's response to their changes in value. The hydraulic conductivity, discharge and recharge values used in the model were increased and subsequently decreased by 50% simultaneously, and model runs were performed to observe any changes in head values. The result showed that the model was only slightly sensitive to these parameters. Increase in hydraulic conductivity values tended to slightly increase the hydraulic head in regions of lower elevation but slightly decreased the hydraulic heads in regions of higher elevation (Figure 5). The rate of pumping also affected the head values but only slightly. An increase in the pumping rate led to a slight decline in hydraulic head values while a reduction in rate of pumping led to a slight increase in the hydraulic heads (Figure 6). Changes in recharge rate affected the hydraulic heads more significantly than pumping rate. An increase in the recharge rate led to an increase in the hydraulic heads while a reduction in the rate of recharge led to a decline in the hydraulic heads (Figure 7).

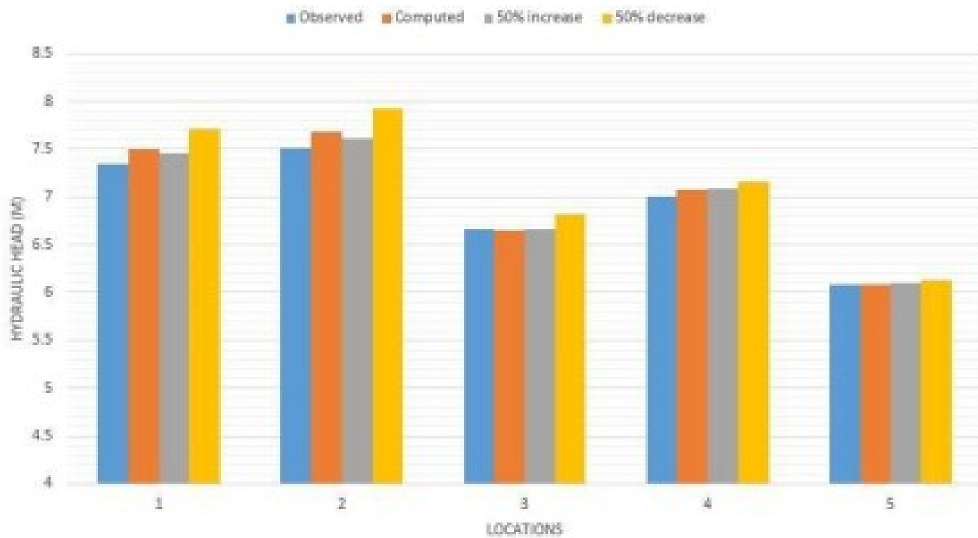

Figure 5. Relationship between changes in heads with changes in hydraulic conductivity.

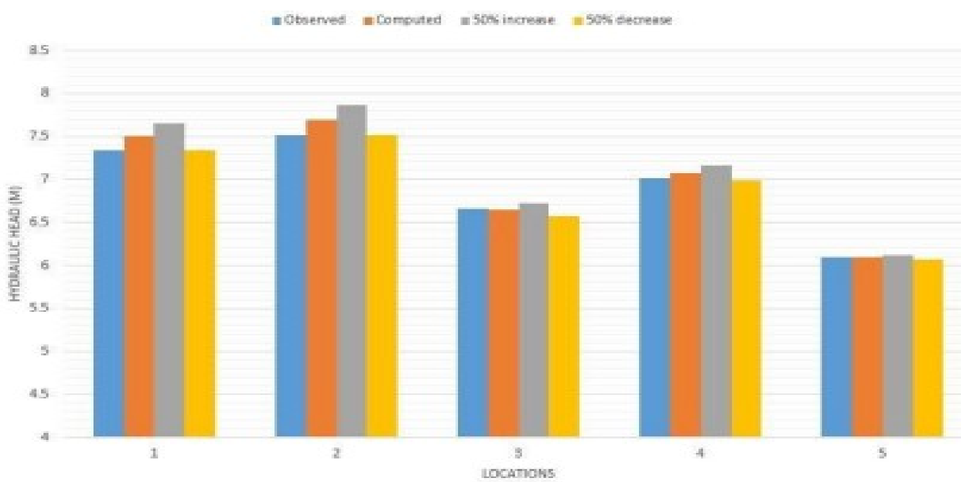

Figure 6. Relationship between changes in heads with changes in pumping rate.

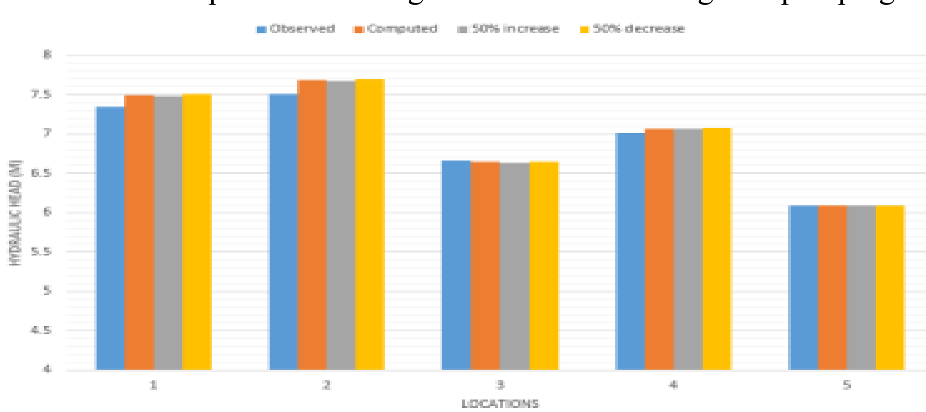

Figure 7. Relationship between changes in heads with changes in recharge rate.

RECHARGE SCENARIOS ON GROUNDWATER RESOURCE

Precipitation or rainfall is a major aspect of climate change that may have a significant impact on groundwater resource. Rainfall directly recharges an aquifer from the surface through percolation and infiltration. It could be assumed that every other hydrological condition being equal, higher rainfall may produce higher recharge and vice versa. The result of reduction in recharge rate by 20%, 50%, 80% and 100% as a result of possible decreases in rainfall are shown in Figures 8 and 9. The recharge rate used in the calibrated model was 0.001749 m/d. This value was reduced to 0.0013992 m/d, 0.0008745 m/d, 0.0003498 m/d and 0.00 m/d to represent decreases in rainfall. The results show a steady decline in hydraulic heads with reducing recharge rate but this decline is not enough to cause serious shortages in groundwater resource under the simulated conditions. Increase in recharge rate as a result of increasing rainfall will lead to slight increases in the hydraulic heads (Figure 10). The initial recharge rate value was increased by 50% and 100% to 0.0026235 m/d and 0.003498 m/d respectively to represent increase in rainfall.

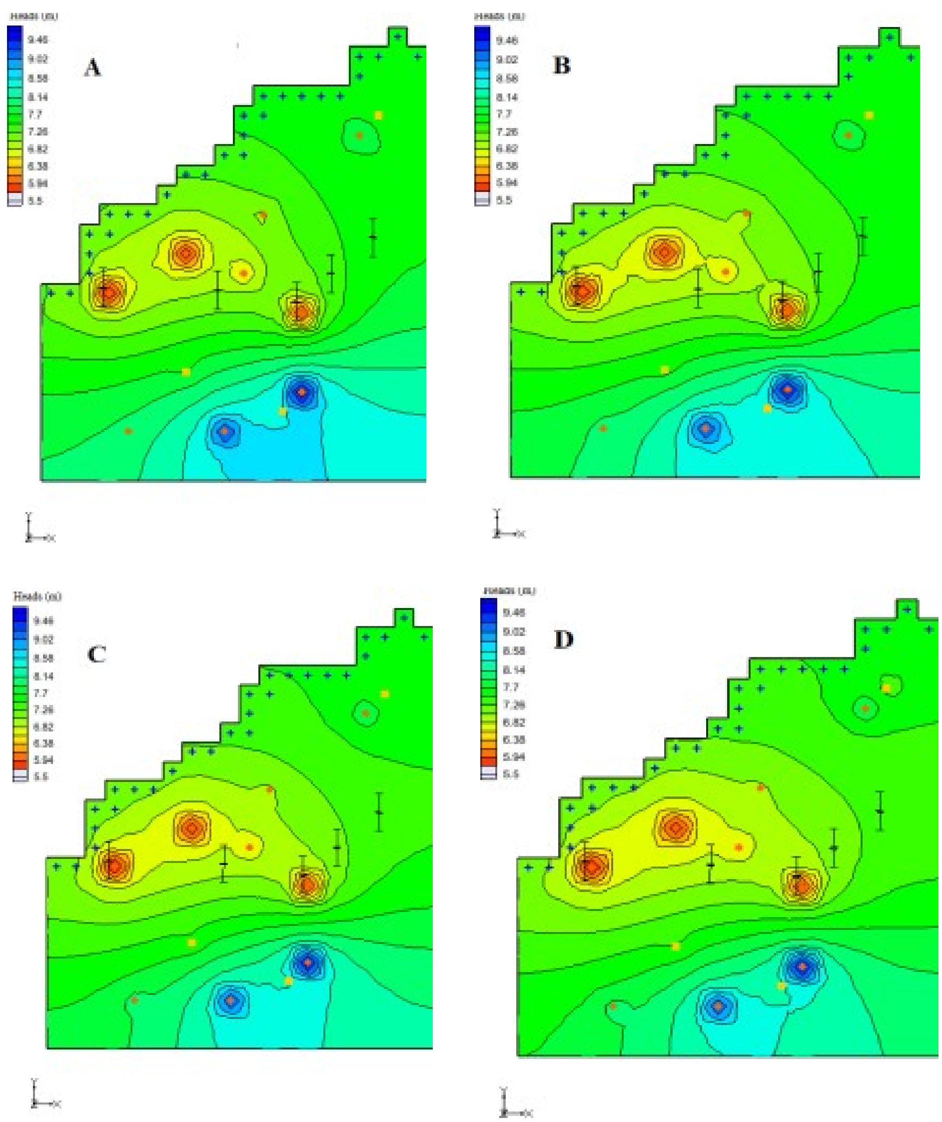

Figure 8. Head distribution at 20% (A), 50% (B), 80% (C) and 100% (D) decrease in recharge rate

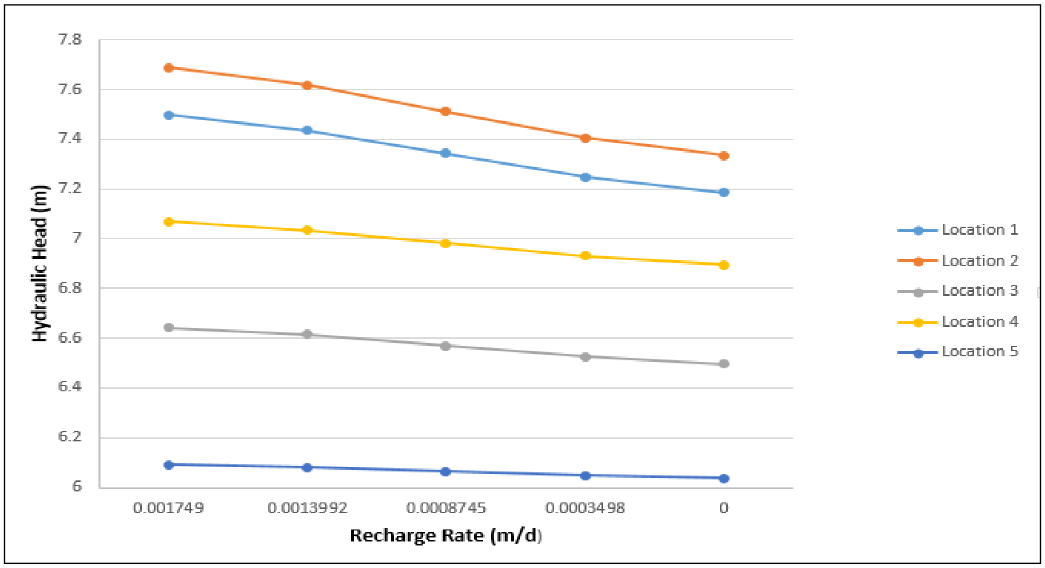

Figure 9. Head declines with decreasing recharge rates selected locations.

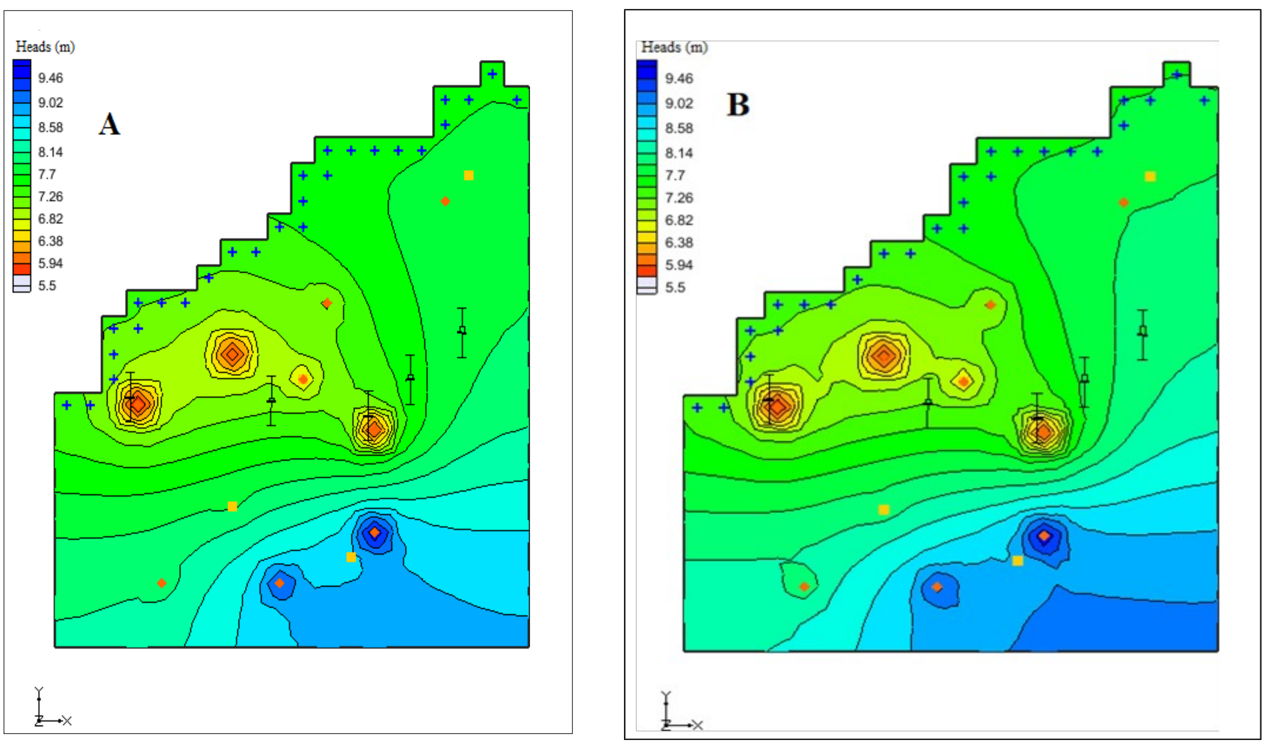

Figure 10. Heads distribution at 50% (A), and 100% (B) increases in recharge rate.

IMPACT OF PUMPING ON GROUNDWATER RESOURCE

Groundwater in the study area was assessed in potential scenarios of increasing demand. This was done by simulating pumping rates at five selected wells in the modeled area. The selected well sites and pumping rates were ascertained from the study by Ochuko (2015). The reported discharge rate was 313.92 m³/day. This discharge rate was entered into the model at the well sites as sink terms, and a model run was performed. This value was then increased by 50% and 100% to 470.88 m^3/d and 627.84 m^3/d respectively in subsequent runs to model the area with respect to possible future increases in groundwater demand. The results are shown in Figure 11, which indicates that an increase in water demand under the average recharge conditions will lead to a decline in the hydraulic heads of the region but this decline is not enough to cause a significant water shortage. The worse-case scenario was also assessed for the area with the discharge rate increased by 100% under conditions of drought. The result is shown in Figure 12, indicating a significant reduction in hydraulic heads, but not of huge consequences on the accessibility of groundwater resource.

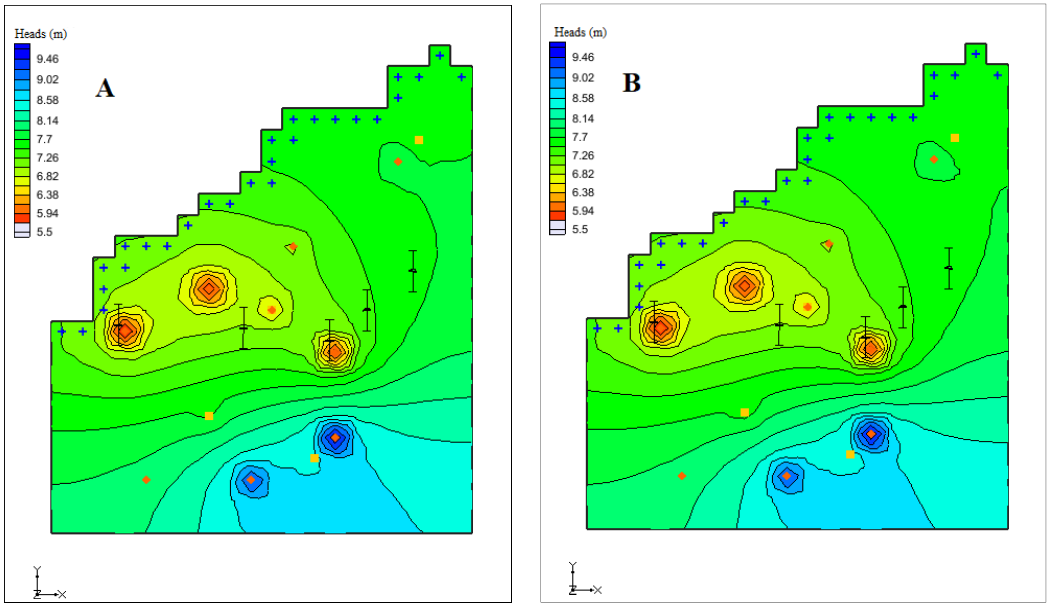

Figure 11. Heads distribution at 50% (A) and 100% (B) increases in pumping rate.

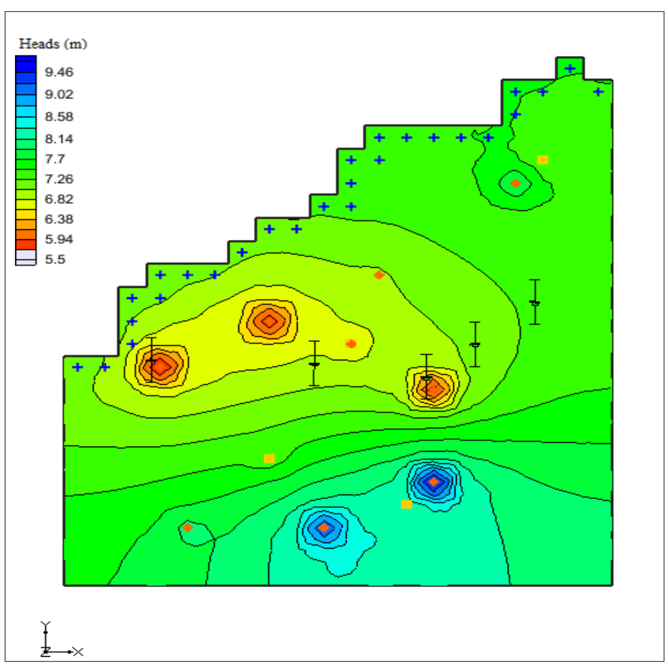

Figure 12. Head distribution at 100% pumping rate increase under zero rainfall conditions.

SUMMARY

A groundwater flow model was developed for the Eku area and its environs to access the impact of climate change on its groundwater resource. Precipitation as an index to climate change was used to estimate groundwater recharge rate for the aquifer. Understanding the climatic conditions of the area in terms of rainfall coupled with the geology of the area played an important role in the modeling process. After the collection of field data as well as research for climate variables, a contour base map was created for the area for the modeling process. The map explored the use of Google Earth Pro and QGIS software. The map was gridded into cells and layers with the boundary conditions outlined. Model parameters such as hydraulic conductivity, recharge rate, boundary heads, elevation and pumping rate were entered into the model. The model was calibrated successfully with field-measured hydraulic heads and model calculated water budget. The flow pattern suggests that groundwater in the area flows from south to north, with groundwater discharging into River Ethiope. A sensitivity analysis with the model showed that hydraulic heads were only slightly sensitive to hydraulic conductivity, pumping rate and recharge rate. The heads were directly sensitive to increases and decreases in these parameters. The model's response to changes in recharge rate was most significant. Thus, recharge rates were altered to access the level of groundwater in the aquifer under different rainfall scenarios, simulating climate change conditions. Decreases in recharge rates led to declines in hydraulic heads of the area. These declines were not significant enough to cause groundwater mining even in periods of drought and increased demands as simulated in this study. This modeling approach with MODFLOW and GMS appears to be a valuable tool for groundwater management.

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REFERENCES

Adelana, S.M.A., P.I. Olasehinde, R.B. Bale, A.E. Edet, and B. Goni. 2008. An Overview of geology and hydrogeology of Nigeria. In: Adelana, S., MacDonald, A., (Eds.), Applied groundwater studies in Africa. IAH Selected papers on Hydrogeol., Vol. 13, pp. 171-198

Akpokodje, E.G., J.O. Etu-Efeotor, and I.U. Mbeledogu. 1996. A study of environmental effects of deep subsurface injection of drilling waste on water resources of the Niger Delta *CORDEC*, University of Port Harcourt, Choba, Port Harcourt, Nigeria

Atakpo, E.A. 2009. Groundwater and Contaminant flow modelling in Olomoro Area of Delta State. Journal of the Association of Mathematical Physics, Vol. 15, pp. 205 – 212

Awosika, L.F. 1995. Impacts of global climate change and sea level rise on coastal resources and energy development in Nigeria. In: Umolu,J. C., (Eds.), Global Climate Change: Impact on Energy Development. pp. 83-88

Bear, J. 1979. Hydraulics of Groundwater. McGraw-Hill Book Co., New York Bouwer H. 1978. Groundwater Hydrology. McGraw-Hill Book Company, New York. p. 480

Doust, H., and E. Omatsola. 1989. Niger delta. AAPG Memoir 48, pp. 201-238

Freeze, R.A., and P.A. Witherspoon. 1966. Theoretical analysis of regional groundwater flow: 1. Analytical and numerical solutions to the mathematical model. Water Resources Research, Vol. 2 (4), pp. 641 – 656

Freeze, R.A., and P.A. Witherspoon. 1968. Theoretical analysis of regional groundwater flow: 3. Quantitative interpretations. Water Resources Research, Vol. 4 (3), pp. 581-590

Gobo, A.E. 1988. Relationship between rainfall trends and flooding in the Niger- Benue River Basins. J. Met., Vol. 13, pp. 132-139

IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of The Intergovernmental Panel on Climate Change, In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L. (Eds.), Cambridge University Press, Cambridge, UK and New York, NY, USA, 966 p

Irabor, O., and S. Olobaniyi. 2007. Investigation of the Hydrological Quality of Ethiope River Watershed, Southern Nigeria. Journal of Applied Sciences and Environmental Management, Vol. 11 (2), pp. 13 – 19

Kumar, C.P. 2013. Numerical modelling of groundwater flow using MODFLOW. Indian Journal of Science, Vol. 2 (4), pp. 86-92

Kumar, C.P., and S. Singh. 2015. Climate change effects of groundwater resources. Octa Journal of Environmental Research, Vol. 6 (2), pp. 264-271

McDonald, M.G., and A.W. Harbaugh. 1988. A modular three-dimensional finite- difference groundwater flow model. Techniques of Water-Resources Investigations, Book 6, Chapter A1; U.S. Geological Survey: Reston, VA, USA, p. 586

Nwajide, C.S. 2013. Geology of Nigeria's Sedimentary Basins. CSS press, Nigeria. 565 p

Obaje, N.G. 2000. Geology and Mineral Resources of Nigeria. Springer-Verlag Berlin Heidelberg, pp. 109 – 113

Ochuko, A. 2010. Hydrogeophysical and hydrogeological investigations of groundwater resources in Delta Central, Nigeria. Journal of Taibah University for Science, Vol. 9 (1), pp. 57-68

Okocha, F.O., and E.A. Atakpo. 2013. Groundwater Flow Modeling at the Source of River Ethiope, Delta State Nigeria. Pacific Journal of Science and Technology, Vol. 14 (2), pp. 594-600

Ophori, D.U. 2006. A preliminary analysis of regional groundwater movement in the Niger Delta, Nigeria. Journal of Environmental Systems, Vol. 32, No. 2, pp. 125-144.

Ophori, D.U. 2007. A simulation of large-scale groundwater flow in the Niger Delta, Nigeria. Environmental Geosciences, Vol. 14 (4), pp. 1-15

Oseji J.O., and M.O. Ofomola. 2010. Determination of groundwater flow direction in Utagba Ogbe Kingdom, Ndokwa Land Area of Delta State, Nigeria. Archives of Applied Science Research, Vol. 2 (4), pp. 324-328

Oyebanjo, O.M., G.E. Ekosse, and J.O. Odiyo. 2018. Mineral constituents and kaolinite crystallinity of the < 2 μm fraction of Cretaceous- Paleogene/Neogene Kaolins from Eastern Dahomey and Niger Delta Basins, Nigeria. Open Geosci. Vol. 10, pp. 157–166

Oyeleke, O.O. 2021. Analysis of Decadal Rainfall and Temperature Trend in Warri, Nigeria. European Journal of Environment and Earth Sciences, Vol. 2 (2), pp. 15-18

Pochat, S., S. Castelltort, V.J. Driessche, K. Besnard, and C. Gumiaux. 2004. A simple method of determing sand/shale ratiosfromseismic analysis of growth faults: An example from Upper Oligocene to Lower Miocene Niger Delta Deposits. American Association of Petroleum Geologists Bulletin, Vol. 88, pp. 1357 – 1367

Short, K.C., andA.J. Stauble. 1967. Outline of Geology of Niger delta. American Association of Petroleum Geologists Bulletin, Vol. 51, pp. 761-779

Stacher, P. 1995. Present understanding of the Niger Delta hydrocarbon habitat. In: Oti, M.N., and Postma, G., (Eds.), Geology of Deltas: Rotterdam, A.A. Balkema, pp. 257-267

Sule, B. F., and S.E Ayenigba. 2017. Application of GMS – MODFLOW to Investigate Groundwater Development Potential in River Meme Catchment, Kogi State, Nigeria. International Journal of Sciences, Vol. 6 (9), pp. 39-51

Tóth, J. 1963. A theoretical analysis of groundwater flow in small drainage basins. Journal of Geophysical Research, Vol. 68 (16), 4795 – 4812

Tuttle, M.L.W., R.R. Charpentier, and M.E. Brownfield. 1999. The Niger Delta Petroleum System: Niger Delta Province, Nigeria, Cameroon, and Equatorial Guinea, Africa. USGS Open-file report, 99-50-H, 65 p

Weber, K.J. 1986. Hydrocarbon distribution patterns in Nigerian growth fault structures controlled by structural style and stratigraphy. AAPG Bulletin, Vol. 70, pp. 661-662

Weber, K.J., and E.M. Daukoru. 1975. Petroleum geology of the Niger delta. Proceedings of the 9th World Petroleum Congress, Tokyo Vol. 2, pp. 202-221

Whiteman, A. 1982. Nigeria: its petroleum geology, resources and potential. Graham and Trotman, London, 381 p

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