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GROUNDWATER FLOW MODEL PART OF SOKOTO-RIMA HYDROLOGICAL BASIN, NORTHWESTERN NIGERIA

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ABSTRACT

The aim of this work is to model the groundwater system of Zamfara part of Sokoto-Rima hydrological basin, under three objectives which are to evaluate the water budget, assess the interaction between surface water and groundwater, and to predict the temporal and spatial distribution of groundwater head and groundwater flow. MODFLOW-NWT, which is a Newtonian formulation for MODFLOW-2005, was used in the study. The result of sensitivity analysis revealed groundwater (RCH), evapotranspiration (EVT) and hydraulic conductivity (HKZ) had the highest composite scales. The water budget of the calibrated model showed that groundwater recharge was 5,571,293 m^3 d^{-1}, contributing 65.7% of total inflow (8,478,903 m^3 d^{-1}) to the aquifer. Inflow from river seepage represented 30.7% of the total inflow to the aquifer by 2,597,995 m^3 d^{-1} while seepage from the general head boundary contributed 3.7% of the inflow to the aquifer by 309,615 m^3 d^{-1}. The outflow quantification of the aquifer showed that 75.8% (6,428,824 m^3 d^{-1}) of the total outflow was accounted to by evapotranspiration, the remaining 15 % (1,273,747 m^3 d^{-1}) outflow represented the river recharge, 8.6% (730,656 m^3 d^{-1}) to general head boundary (GBH), and 0.5% (45,678 m^3 d^{-1}) by pumping wells from the aquifer. Simulated groundwater level ranges between 202.9 m. asl and 688.5 m. asl, with an average level of 414.14 m. asl. Groundwater Flow model results indicated that the topography and geologic structures control groundwater flow in the study area and that base flow to river is an important factor moderating groundwater movement. This implies that the study area currently has sufficient groundwater resources to meet the demand, despite its fragile climate condition.

1.0 INTRODUCTION

Groundwater evaluation starts with gathering comprehensive data on the basin (physical and socioeconomic) and developing models of the physical systems (hydrology, geology and hydraulics). Analysis of the current governance and management then provides the basis for developing improvements in the socio-economic management of the resource which must be placed within the local governance and legal frameworks (Lanini *et al.,* 2004).

Water supply in Zamfara State is facing serious challenges that are driven by rapid urbanization, budgetary constraints, and social equity. An accurate assessment of groundwater resources of any place requires knowledge of not only the magnitude of rainfall, water loss to evapotranspiration, and water use priorities, but also how to manage the water is also very important.

Most of land area of Zamfara State is located within the Crystalline Hydrogeological Province within the Sudano-Sahelian Savannah Belt where potential evapotranspiration is higher than the rainfall, resulting in~~to~~ very scarce water resources. Thus, there is an urgent need for groundwater hydrological modelling of Zamfara State to bring into account the exact water budget of the area through a thorough evaluation of all hydrological components within catchment.

Groundwater reservoirs is an important water resource both for the maintenance of the natural environment and for human needs. Groundwater can be regarded as a renewable natural resource if there is a balance between recharge and abstractions of the aquifer (Voudouris, 2006). Groundwater recharge and discharge are critical to understand the hydrologic cycle and to manage water resources. Good groundwater resources management practices require developing a water budget approach on a

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regional scale for an entire aquifer or geographic region (Cherkauer, 2004).

The sustainable management of groundwater resources especially in basins depends on a detailed understanding of the regional hydrology and hydrogeological processes. In other words, understanding the groundwater reserve (potential and/or budget) is an essential pre-requisite for managing the groundwater system sustainably. Therefore, a well-known conceptual hydrogeological model of the basin is of great importance. The model plays a very useful role in the recharge estimation process (Scanlon and Cook, 2002). This model is used in the groundwater resources management plan.

The model approach, extent and model type may vary, depending on modeling objectives. Groundwater models can be applied as predictive, interpretive, or generic (Anderson and Woessner, 1992). Predictive models are used to predict the effects of a proposed action on existing hydrogeologic conditions or to assess the future change in groundwater head or solute concentration. Interpretive models are applied to investigate a certain case, to study system dynamics, and to evaluate groundwater flow or contaminant transport. Generic models are used to evaluate different scenarios of remediation schemes or water resource management and to identify the suitability of regions for some proposed action.

The aim of this research is to model the groundwater system of Zamfara part of Sokoto-Rima hydrological basin under three different set of objectives which is to evaluate the water budget, assessing the interaction between surface water and groundwater and to predict the temporal and spatial distribution of groundwater head and groundwater flow.

1.1 The Study Area

The study area is a component of Sokoto-Rima Hydrogeological Province of the northwest Nigeria, lies between Longitudes 5^{0}1'27.638″E to 7˚18'13.709″E, and Latitudes 13^{0}10'45.537″N ~~to~~ and 10˚49'4.152″N (Figure 1). The area is located in the Sub-Saharan Sudan belt of West Africa, in zone of Savannah-type vegetation. Rainfall is generally low; the average annual rainfall ranges from 600 to 1000 mm across the entire State (Nigeria Meteorological Agency, 2020). Much of the rain, falls between the months of May and September, while the months of October to April experience~~d~~ little or no rainfall. Temperatures are generally extreme, with average daily minimum of 18°C, during cool months of December and January and in the hottest months of April to June, an average maximum of 38°C and minimum of 24°C temperatures are recorded. Throughout the year, average maximum temperature is 36°C and average daily minimum is 21°C. Evaporation is high, ranging from 80 mm in July to 210 mm in April to May (Nigeria Meteorological Agency, 2020).

An average evapotranspiration of about 450 mm/annum represents 30 of monthly average precipitation into the catchment. The hottest months of April and May are periods of highest evapotranspiration. Relative humidity is low most of the year and only increases during the wet season of June to September. The vegetation is typically Sudan Savannah and is characterized by stunted and thorny shrubs, invariably of the Acacia species.

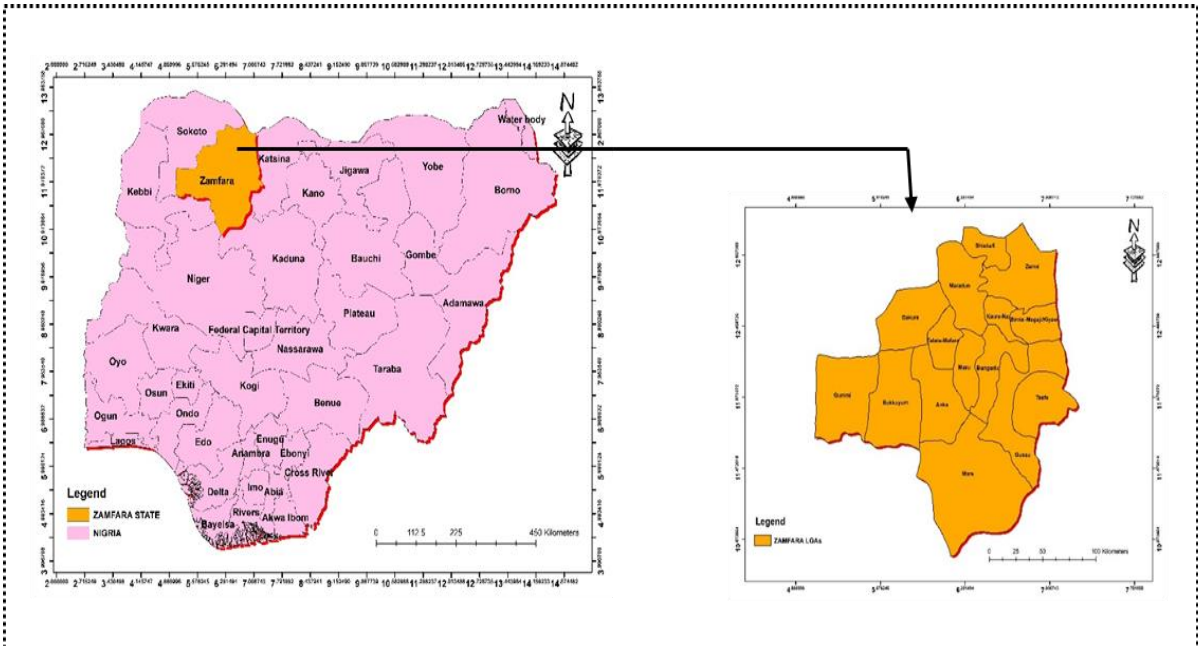

Figure 1: Location Map of the Study Area

2.0 Regional Geology of the Study Area

About 80% of the State is underlain by a variety of crystalline rocks of the basement complex of north western Nigeria described by McCurry (1976), as referenced in Obaje (2009), to be composed largely of migmatite, gneiss, schist, granites and granodiorite (Figure 2.4). The structural features commonly exhibited by the basement rocks include foliation, lineation, folds, rock-rock contacts, faults and joints. The rest of the state is overlain by the oldest sediments of the Sokoto (Illullemeden) basin, described by Kogbe (1976) and Oteze (1976). Groundwater in the basement rocks of the state can mainly be sourced from fractures and joints commonly (Yaya *et al*. 2001) and in the intergrannular pores of fine to coarse (white or light grey) sand or gravel (Oteze, 1976), in the sedimentary areas.

About 20% of the State is underlain by Gundumi Formation which consists of clays, sandstones and pebble beds thought to be lacustrine and fluviatile in origin. Its maximum thickness is reported to be up to 300 m near the Niger border. The base is marked by conglomeratic beds which are well preserved and exposed by the road side at Tureta and Ruwan Kalgo (Kogbe, 1976). These basal beds contain rounded quartz cobbles and pebbles and attain a thickness of about 3m. The formation is the oldest sedimentary rocks in the northern parts of the basin, lies uncomfortably on the Basement Complex.

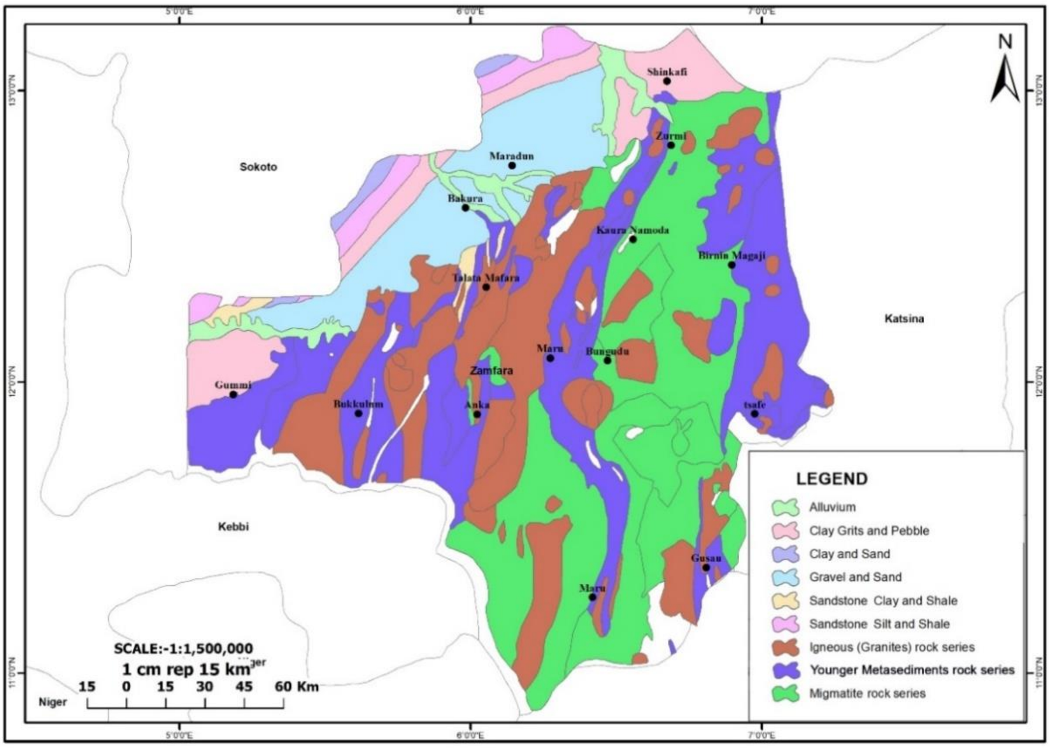

Figure 2: General Geological Map of Zamfara State (Nigeria Mining and Geological Agency, NGSA, 2006)

3.0 METHODOLOGY

The main methodology in groundwater modeling used in this study is shown in Figure 3. The objective of the model is defined as the first stage of modeling process. Data collection is a significant challenge in the modeling process. Another important phase in modeling exercise is conceptualizing the model, which is followed by building up the numerical model. Following model completion, model calibration and validation, as well as sensitivity analysis, can be undertaken. The final stage is to prepare and run simulations for forecast scenarios.

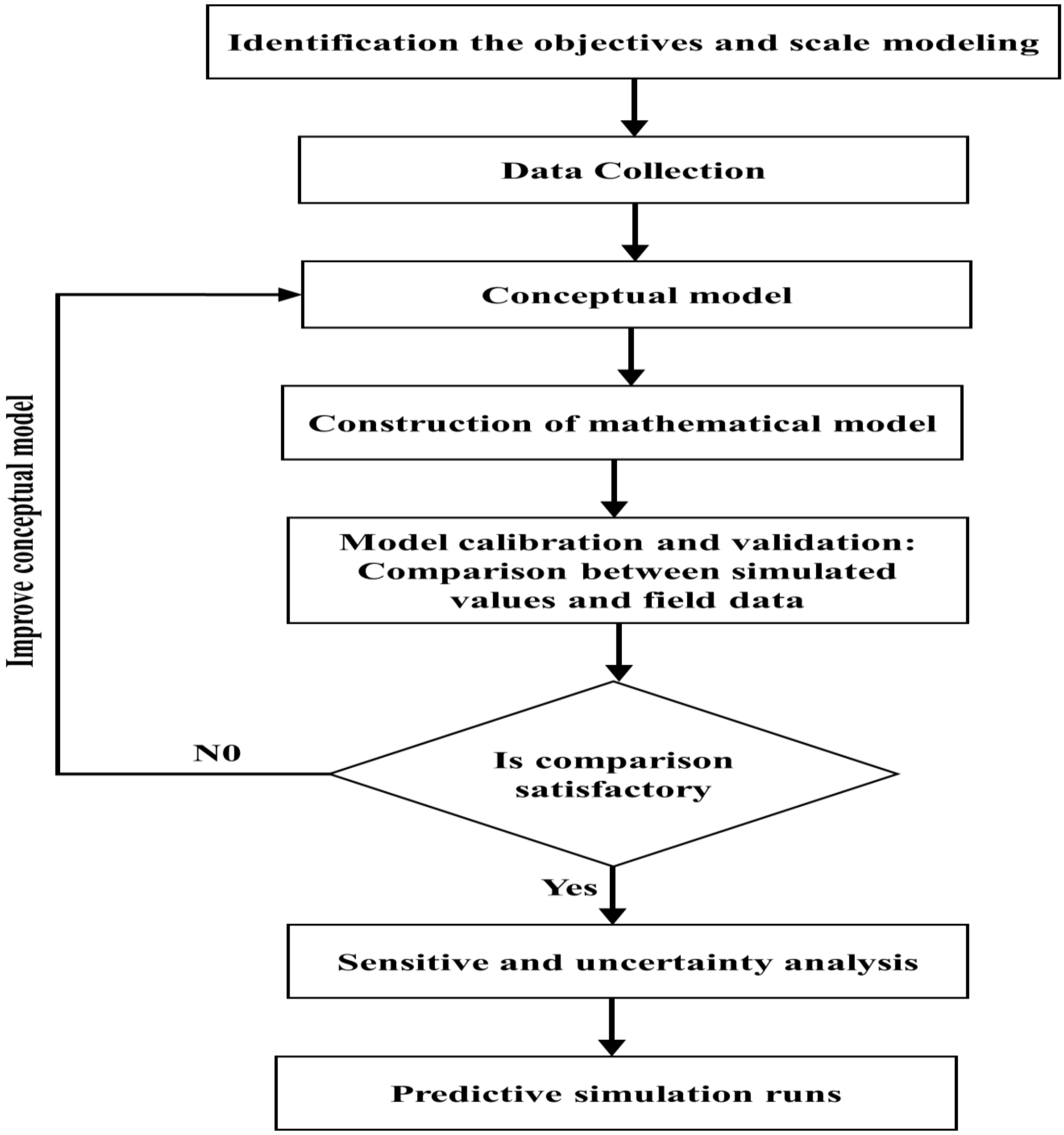

Figure 3: Flow diagram of stepwise methodology in groundwater modeling

3.1 Groundwater Data Acquisition: The following data was used to develop the groundwater flow model for the study area:

1) Static datasets, such as Digital Elevation Model (used as ground surface elevation), depth of groundwater from ground surface (used to estimate initial groundwater head), aquifer designation data, and soil type map (for horizontal permeability values), that are assumed to be static over the study period;

2) Observations of groundwater level (static well level data from 280 wells).

Conceptual model: The most significant aspect of groundwater modeling is a conceptual model, which is based on a knowledge of how a groundwater system operates. It entails comprehending the properties of the groundwater system as well as their spatiotemporal evaluation, as well as providing a descriptive representation of the hydrogeologic system. The groundwater system was conceptualized, using extensive knowledge of hydrology, geology, hydraulic parameters, and boundary conditions of the geometry of the rock formation of the area of study (Figure 4).

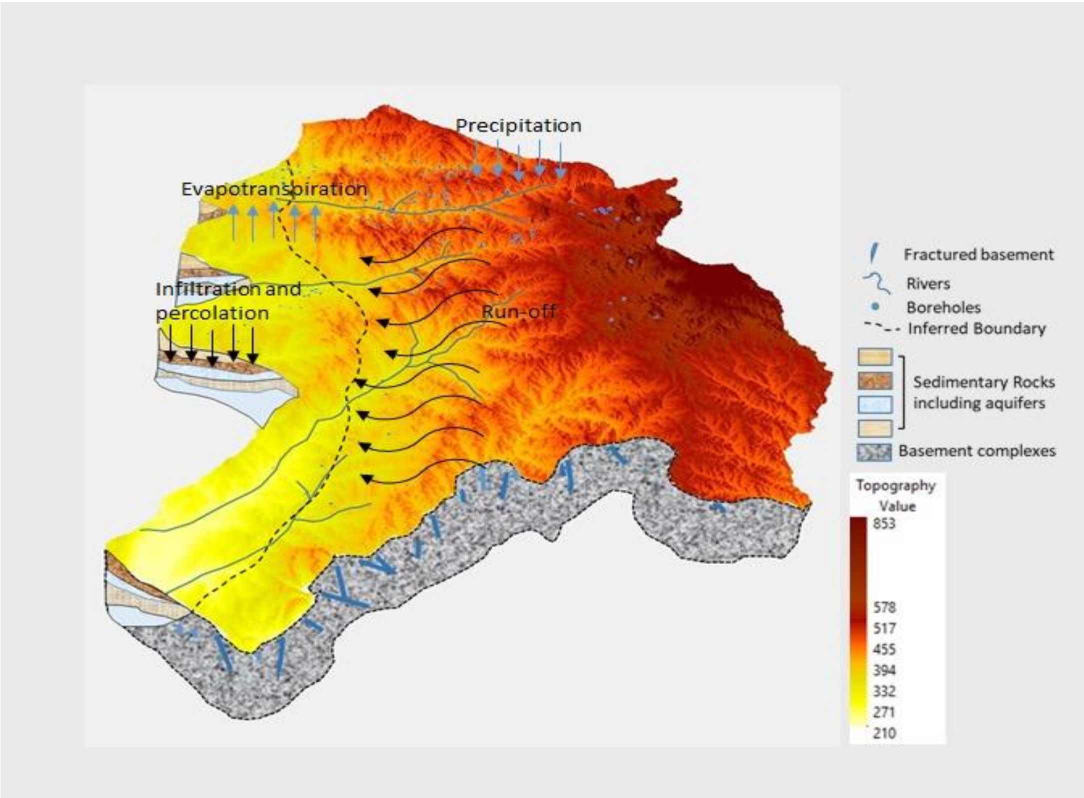

Figure 4: Groundwater Conceptualization Model

The conceptual model describes factors which include:

- Model domain and aquifer geometry
- Aquifer parameters, such as hydraulic conductivity, porosity, transmissibility, specific yield, specific storage
- Boundary conditions
- Evapotranspiration and groundwater recharge
- Identification of sources and sinks
- Water balance

Inputs to the groundwater system such as groundwater recharge from precipitation, rivers and streams seepage, lateral groundwater inflow, while the output from the groundwater system includes groundwater seepage to rivers and streams, lateral groundwater outflow pumping wells, and evaporation from groundwater were used to achieve the final output of the model.

Groundwater flow model setup: A fully distributed three-dimensional groundwater flow model MODFLOW-2005 (Harbaugh, 2005) was developed with the help of Modelmuse (Winston, 2009) as a graphical user interface. The partial-differential equation of groundwater flow used in MODFLOW is (McDonald and Harbaugh, 1988):

$$\frac{\partial}{\partial x}\left(K_x.\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial x}\left(K_y.\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial x}\left(K_z.\frac{\partial h}{\partial z}\right)+W = S_s.\frac{\partial h}{\partial t} \quad 1$$

where h (L) is the hydraulic head in the porous medium; Kx, Ky, and Kz (LT^{-1}) are anisotropic hydraulic conductivity for the porous medium in x, y, and z directions respectively, W (T^{-1}) is the volumetric flux per unit volume at sources or sinks of the porous medium, W < 0.0 for outflow of the groundwater system, and W > 0.0; Ss (L^{-1}) is the specific storage for the porous medium and *t* is time (T). In this study, MODFLOW-NWT (Niswonger *et al.,* 2011) with ModelMuse (Winston, 2009) as a graphical user interface was applied to simulate groundwater flow.

The groundwater flow system contained two layers, according to geological setting of the area and aquifer performance. The first layer represented weathered rock, with average thickness of 11.25 m, while the second layer is fractured crystalline aquifer, with average thickness of 65 m. The model Layer 1 and Layer 2 were defined as unconfined to confined. The model was discretized by a 500 m by 500 m grid, resulting in a domain of 516 rows and 484 columns, and 2 layers with a total number of 249,744 cells, 138,486 of which were active cells. Once the model was converted from conceptual to numerical by assigning the grid type, the model was translated and simulated with all the given inputs (including boundary conditions and observed wells).

The hydraulic properties were defined based on available 280 borehole log data. These include horizontal and vertical hydraulic conductivities, as well as aquifer storage properties. The Jacob's equation was applied to calculate the hydraulic conductivity for each aquiferous unit. According to boreholes data, the weathered layer consisted of two K-zones of hydraulic conductivity (Figure 5a), one for sedimentary area (20% of study area), with average hydraulic conductivity of 1 md^{-1} and the second for crystalline area (80% of study area), with average hydraulic conductivity of 0.4 md^{-1}.

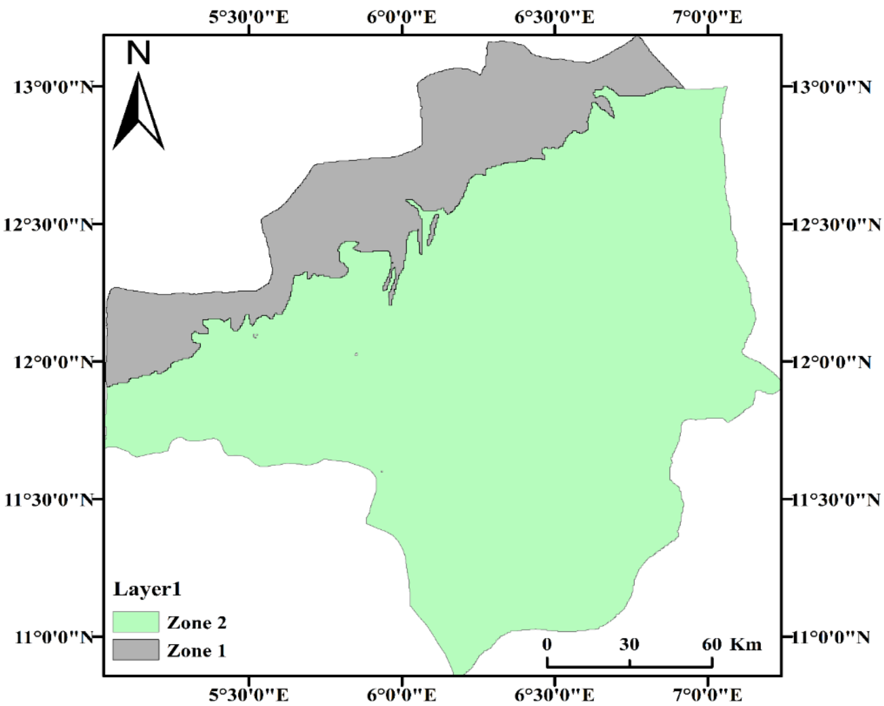

Figure 5a: Hydraulic Conductivity Zones for Layer 1

The fractured layer was characterized by four zones of older metasedimentary rock units, younger Metasedimentry rock units, Pan-African granites rock suits and Sedimentary units (Gundumi Formation), with average hydraulic conductivity of 0.22, 0.3, 0.48 and 0.57 md^{-1}, respectively (Figure 6b).

Although all the hydraulic parameters were determined in the field, because of limited spatial representativeness and the influence of modeling scale in accordance with Guimera *et al.* (1995), Zhang *et al.* (2006) and Zhang *et al.* (2007), they still had to be adjusted in the calibration process.

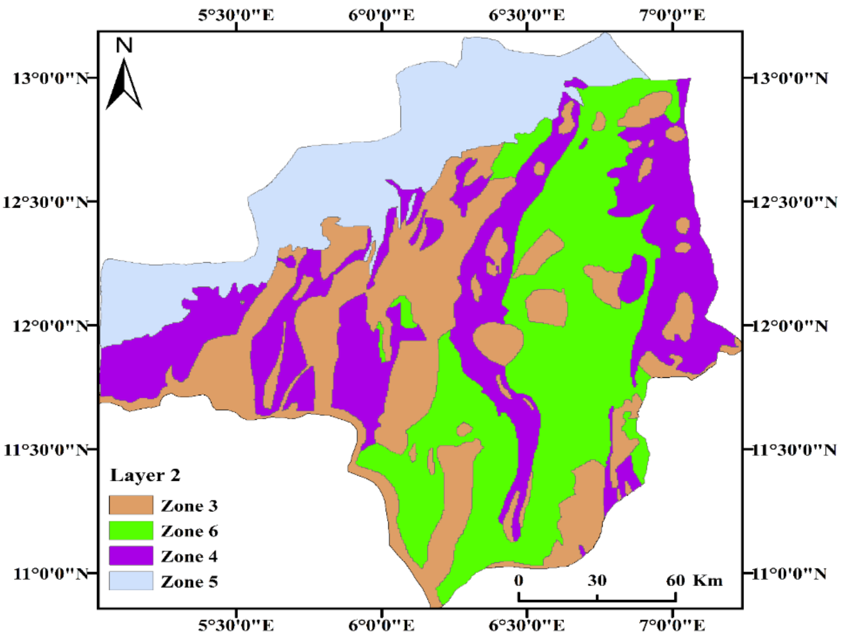

Figure 6b: Hydraulic conductivity zones for layer 2

Boundary conditions: Figure 7 shows the used boundary conditions in this study. In boundary conditions, the average groundwater level was assigned as the initial hydraulic head. The River Package is designed to simulate volumetric river interactions with groundwater. In this study, all rivers and streams were simulated by the river package. Flow between the river and the groundwater system for reach n is given by:

$$Q_{RIV} = C_{RIV}\,(H_{RIV} - h_a) \qquad h_a > h_{rivbot}$$
$$Q_{RIV} = C_{RIV}\,(H_{RIV} - h_{rivbot}) \qquad h_a \le h_{rivbot} \qquad (0\text{-}1)$$

Q_{RIV} is the flow between the river and the aquifer; C_{RIV} is the hydraulic conductance of the riverbed(L^2T^{-1}); H_{RIV} is the river stage (L); h_a is the head in the aquifer beneath the riverbed; and h_{rivbot} is the level of the river bottom. Therefore, when the head in the aquifer is higher than the river stage, the aquifer recharges water to the river, represented as a negative inflow to the aquifer. When the head in the aquifer is lower than the river stage, flow is recharge to the aquifer. This flow increases linearly as the head in the aquifer decreases, until the aquifer head reaches the river bottom the flow remains constant. Riverbed conductance, C_{RIV} $(\frac{m2}{day})$ can be computed as follows (McDonald and Harbaugh, 1988):

$$C_{RIV} = \frac{K.W.L}{d}$$

K is the hydraulic conductivity of riverbed sediments (L T^{-1}), w is the width of a river reach (L), L is the length of river reach corresponding to a volume of aquifer (L), d is the thickness of the streambed deposits (L). The conductance of the riverbed for the main and secondary streams were initially set to 0.3 and 0.2 m^2 d^{-1}, respectively, and adjusted during the calibration process.

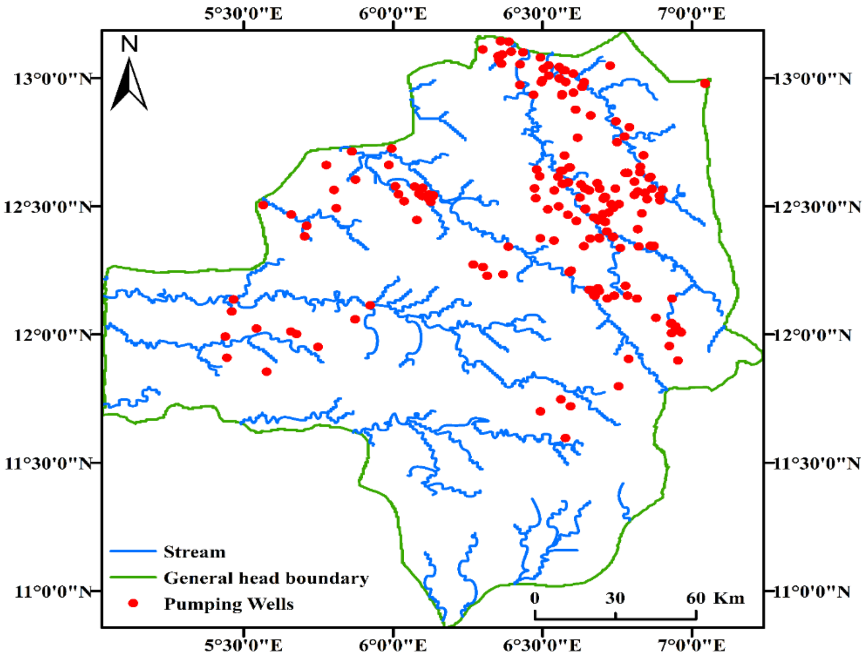

Figure 7: Boundary conditions

MODFLOW General-Head Boundary (GHB) was assigned to the northern, eastern, western, and southern boundaries to simulate lateral groundwater inflow and outflow of the system. The four sides categorized for three GHB, first one cut younger metasedimentry rock units, the second one the older metasedimentary rock units, and the third one the sedimentary environment. Initially, the conductance of GHB for younger metasedimentry rock units, older metasedimentary rock units, and sedimentary environment were set to be 0.5, 1, and 1.5 $m^2 d^{-1}$, respectively, based on geological boreholes and adjusted during the calibration process.

Recharge (RCH) Package: The Recharge (RCH) Package is designed to simulate a really distributed recharge to the ground-water system. Most commonly, areal recharge occurs as a result of precipitation that percolates to the ground-water system. Recharge is calculated using water table fluctuation method. The average daily recharge ranged between 0.0005 m/day to 0.0009 m/day, as ~~a~~ minimum and maximum values respectively, with an average value of 0.0006 m/day.

Evapotranspiration (ET) Package: The evapotranspiration (ET) Package simulates the effects of plant transpiration and direct evaporation in removing water from the saturated ground-water regime. The spatial distribution of evapotranspiration is imported in the form of a shape file into ModelMuse. The average daily evapotranspiration ranged between 0.0009 md^{-1} to 0.0018 m/day, as ~~a~~ minimum and maximum values respectively, with an average value of 0.0013 md^{-1}.

Well Package: The Well (WEL) Package is designed to simulate features such as wells that withdraw water from or add water to the aquifer at a constant rate during a stress period, where the rate is independent of both the cell area and the head in the cell. In this study, well packages (WEL) were applied to the pumping wells of 280 which are distributed in the study area with an average rate of 235 m^3/day.

ZONE BUDGET: ModelMuse can provide the overall volumetric groundwater balance, but it cannot produce the water balance for a specific region in the model or for each simulated layer alone. Harbaugh (1990) developed the ZONE BUDGET, which is capable of calculating the water budget for any zone

The Head Observation (HOB): The Head Observation (HOB) Package was applied to simulate the time series head records. For each piezometer, the required data are the piezometer name, the observed head, and the time step.

4.0 RESULTS AND DISCUSSION

4.1 Calibration of groundwater flow model: The model calibration process is aimed to match the model results with the measurements in the field within some acceptable criteria. The matching criterion is based on the modeling objective and the required accuracy. In groundwater models the simulated groundwater head and fluxes are forced to match the field measured values at observed points with a range of acceptable error. In this study, the steady-state and transient models were calibrated manually in a forward way because of its high complexity involving long simulation time when using optimization codes such as UCODE (Hill and Tiedeman, 2007) or PEST (Doherty and Hunt, 2010), and forward calibration procedure enables the modelers to understand model behavior. The calibration process was conducted mainly by adjusting the number of initially assigned K-zones, their areas and the associated hydraulic conductivities (Kh), groundwater recharge, and evapotranspiration boundary conditions. Some minor changes were made in the initially assigned riverbed conductance, and GHB conductance at the western boundary was slightly adjusted.

Several statistical indices have been recommended for assessing the performance of a model, of which Mean Error (ME), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE) are used as measures of groundwater head and lake stages calibration. They are mathematically presented as follows:

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i \qquad (0\text{-}1)$$

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|h_m - h_s|_i \qquad (0\text{-}2)$$

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i^2\right]^{0.5} \qquad (0\text{-}3)$$

where n is the number of observations; h_m is observed groundwater level, h_s is simulated groundwater level and $\bar{h}_m$ is mean observed groundwater level. ME provides a general description of model bias as both positive and negative differences are involved in the mean, the errors may eliminate each other, and thus decreasing the overall error (Anderson *et al.,* 2015). MAE measures average error in the model. RMSE is the average of the squared differences in observed and simulated heads. The model was calibrated using average groundwater heads from 51 boreholes. A good agreement between observed and simulated heads was achieved with R^2 =0.99 (Figure 8). The Mean Error (M.E) was calculated as -0.05 m, Mean Absolute Error (MAE) as 0.45m, and root Mean Square Error (RMSE) as 0.12 m. The calibrated parameters of hydraulic conductivity, river conductance, general head conductance, and groundwater recharge are shown in Table 1. The calibrated values of hydraulic conductivity result in six zones were 1.5, 0.75, 0.5, 0.9, 1.1, and 0.8 m d^{-1} respectively. The riverbed conductance for the main streams was 4.7 m^2 d^{-1}, and for secondary streams 2 m^2 d^{-1}. The conductance of the GHB boundary for was changed to 25, 40, and 60 m^2 d^{-1}. The calibrated groundwater recharge and evapotranspiration are 0.8 and 1.2 times of those calculated for groundwater recharge and evapotranspiration (Table 1).

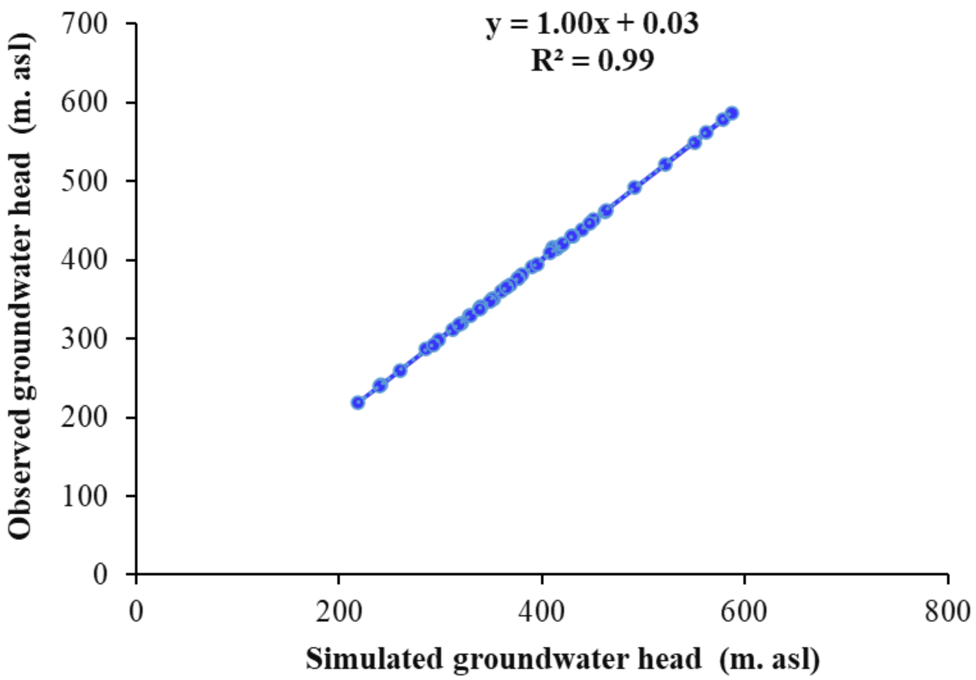

Figure 8: Scatter Plot between the Observed and Simulated Head

Table 1: Calibrated parameters for the calibrated model

Parameter	Value	Unit	Description
HKZ1	1.5	m d^{-1}	Hydraulic conductivity zone 1
HKZ2	0.75	m d^{-1}	Hydraulic conductivity zone 2
HKZ3	0.5	m d^{-1}	Hydraulic conductivity zone 3
HKZ4	0.9	m d^{-1}	Hydraulic conductivity zone 4
HKZ3	1.1	m d^{-1}	Hydraulic conductivity zone 5
HKZ4	0.8	m d^{-1}	Hydraulic conductivity zone 6
RCH	0.8 R	m d^{-1}	Groundwater recharge
EVT	1.2 ET	m d^{-1}	Evapotranspiration
RIVC1	4.7	m^2 d^{-1}	River conductance stream 1
RIVC2	2	m^2 d^{-1}	River conductance stream 2
GHBS1	25	m^2 d^{-1}	Conductance of general head boundary 1
GHBS2	40	m^2 d^{-1}	Conductance of general head boundary 2
GHBS3	60	m^2 d^{-1}	Conductance of general head boundary 3

4.2 Sensitivity analysis: Sensitivity analysis is a process of changing model input parameters through a reasonable range and evaluating the relative variation in model response (Kumar *et al.,* 2001) and measuring the effect of these variations on the model outputs. In this study, sensitivity analysis was achieved using computer code for universal sensitivity analysis, calibration, and uncertainty evaluation (UCODE) (Poeter *et al.,* 2006) with the help of ModelMate (Banta, 2011). It was applied to hydraulic conductivity (HK), which was divided into six zones, groundwater recharge (RCH), evapotranspiration (EVT), river conductance (RIVC), and general head boundary (GHB) parameters. The parameters of groundwater recharge (RCH), evapotranspiration (EVT), and hydraulic conductivity (HKZ6) had the highest composite scaled sensitivity values and were therefore the most sensitive parameters (Figure 8).

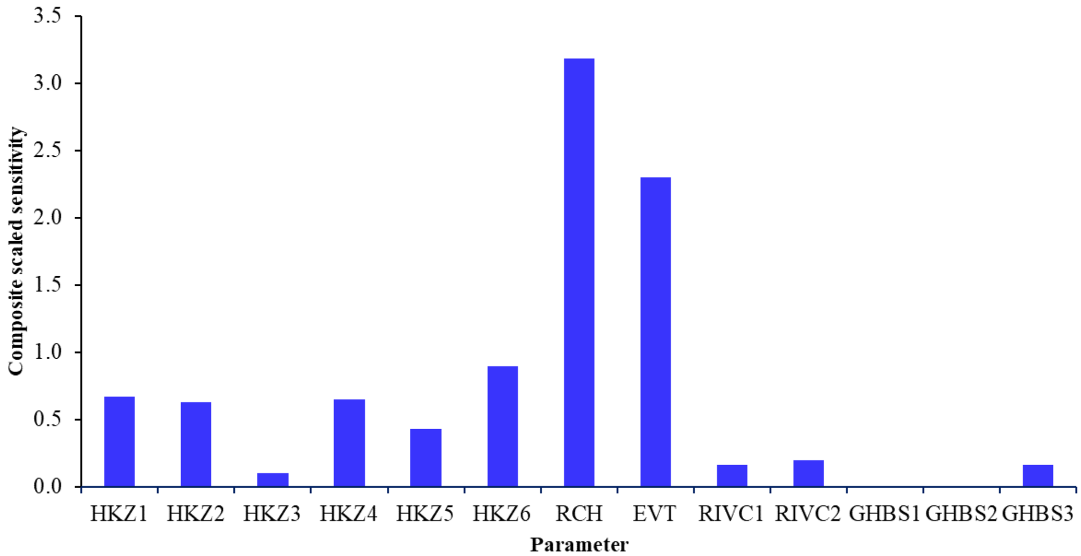

Figure 8. Composite Scaled Sensitivities with the Parameter Values.

Sensitivity analyses showed sensitivity to the change of the Kx value as a result of the major groundwater discharge flow pattern from E to the West (parallel to the longitudinal model extension). The aquifers are sensitive to the change of the longitudinal component of the hydraulic conductivity HKZ, with an average sensitivity value of 1.288 – 1.316. On the other hand, the model is sensitive to the groundwater recharge close to the southwestern part of the model that was estimated ~545.59 mm/year.

4.3 Water Budget

The water budget of the calibrated MODFLOW model is shown in Table 2. Results showed that groundwater recharge was 5,571,293 m^3 d^{-1}, contributing 65.7% of total inflow (8,478,903 m^3d^{-1}) to the aquifer. Inflow from river seepage represented 30.7% of the total inflow to the aquifer by 2,597,995 m^3 d^{-1} while seepage from the general head boundary contributed 3.7% of the inflow to the aquifer by 309,615 m^3 d^{-1}. The outflow quantification of the aquifer showed that 75.8% (6,428,824 m^3 d^{-1}) of the total outflow was accounted for evapotranspiration, the remaining 15 % (1,273,747 m^3 d^{-1}) outflow represented the river recharge, 8.6% (730,656 m^3 d^{-1}) to general head boundary (GBH), and 0.5% (45,678 m^3 d^{-1}) by pumping wells from the aquifer. Simulated groundwater level ranges between 202.9 m. above sea level (asl) and 688.5 m. asl with an average level of 414.14 m. asl (Figure 8).

Table 2. Groundwater Budget for the Whole Model.

Parameter	Inflow		Outflow		Inflow – Outflow
	m^3d^{-1}	%	m^3d^{-1}	%	m^3d^{-1}
Recharge	5,571,293	65.7	0	0	5,571,293
Evapotranspiration	0	0.0	6,428,824	75.8	-6,428,824
GHB boundary	309,615	3.7	730,656	8.6	-421,040
River	2,597,995	30.6	1,273,747	15.0	1,324,248
Wells	0	0.0	45,678	0.5	-45,678
Total	8,478,903	100.0	8,478,904	100.0	0

In order to calculate the groundwater budget for the layers; each single layer was assigned as a separate zone: zone 1 = layer 1, corresponding to weathered aquifer, and zone 2 = layer 2, corresponding to fracture. The final water budget for each layer is shown in Tables 3 and 4 respectively. It is much glaring that recharge into the upper layer is higher compared to that of lower layer; however, the effect of evapotranspiration is more exacerbated in the upper layer compared to that of lower layer.

Table 3: Upper Layer Groundwater Budget

Parameter	Inflow	Outflow
	m^3d^{-1}	
Constant	0	0
Recharge	5548700	0
Evapotranspiration	0	6417800
GHB boundary	311140	751740
River	2599700	1266900
Wells	0	43600
Zone 2 to Zone 1	2926600	0
Zone 1 to Zone 2	0	2906100
Total	11386140	11386140
Inflow – Outflow	0	
Percent Discrepancy	0	

Table 4. Lower Layer Groundwater Budget

Parameter	Inflow	Outflow
	m^3d^{-1}	
Constant	0	0
Recharge	22552	0
Evapotranspiration	0	26
GHB boundary	0	0
River	0	0
Wells	0	2001
Zone 1 to Zone 2	2906100	0
Zone 2 to Zone 1	0	2926625
Total	2928652	2928652
Inflow – Outflow	0	
Percent Discrepancy	0	

Analysis of the piezometric surface map of the aquifer in the study area shows a general flow pattern towards NW part of the study area (Figure 9). This map defines the equipotentiometric contour surface, which is like a topographical map but define potential energy in the groundwater system. However, water table configuration was depicted by thick contours of water table elevation above mean sea level (msl), as indicated by arrow. Groundwater flow down gradient, which implies that the water flows in the direction of the steepest gradient, meaning that it flows perpendicular to the equipotential. In the study area the groundwater that results from recharge flows towards stream and river channels, this indicated by arrows drawn perpendicular to equipotential lines and tends to diverge from the recharge areas (watershed) and converge towards the drainage channels. At some point around the Northern part where the hydraulic conductivity of the aquifer is much higher in one direction than other or dominated by fractures with particular orientations, then this can redirect groundwater flow askew to the maximum gradient.

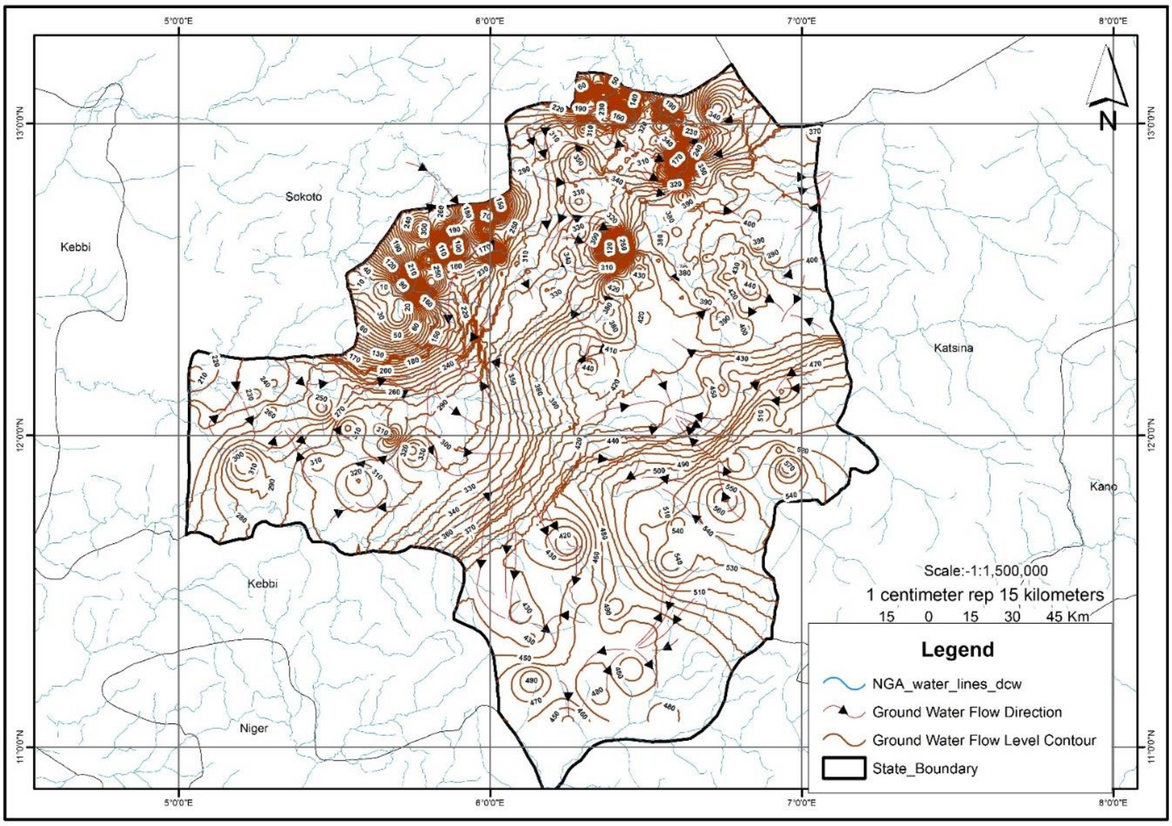

Figure 9: Groundwater Flow Pattern of the Study Area

5.0 CONCLUSION

Estimating groundwater recharge is challenging, particularly for arid and semi-arid regions, due to the spatial and temporal variability of climate data and a negative water budget. Therefore, implementing numerical modelling for groundwater and employing a sensitivity analysis approach can provide a better understanding of the hydraulic system and a more reasonable estimation of groundwater recharge. However, results are affected by the amount and quality of available data.

Groundwater model has been conceptualized and developed using the lithologic information and similar aquifer parameters applicable for the study area. The computed groundwater level contours have shown to replicate the trend of observed groundwater contours. It was found that the surface topography and geologic structures controls the groundwater flow conditions in the study area and that the general groundwater flow direction is NW, along the Pan-African orogenic structures.

The groundwater budget indicated that the study area is replenished particularly by groundwater effluence and rainfall. This is particularly important because the availability of water in the area is an important factor for the sustainability of the inhabitants of the area.

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