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Assessment of Effective Groundwater Management in Parts of Sokoto Basin, North-Western Nigeria

M. A. Popoopla [a], A. A. Adegbola [a], O. S. Oladeji [a] and O. S. Olaniyan [a*]

[a] Department of Civil Engineering, Ladoke Akintola University of Technology, Ogbomoso, Oyo State, Nigeria.

Authors' contributions

This work was carried out in collaboration among all authors. Author MAP designed the framework and conceptualize the model for the study area. Author AAA wrote the first draft of the manuscript and interpreted the groundwater modeling. Author OSO worked on the Geographical Information System used in the study. Author OSO worked on the hydrological and statistical analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

Aim: There is paucity of information on groundwater modelling within Sokoto basin. Groundwater levels, borehole records, precipitation, evaporation, hydraulic conductivity, storage coefficients and boundary conditions, were obtained from Sokoto Basin Authority.
Study Design: Parts of Sokoto Basin.
Place and Duration of Study: Sokoto basin, between April 2017 and April 2021.
Methodology: The time series rainfall data was input in MODFLOW-2000 software to compute Long Term Average (LTA) annual rainfall. Runoff values were obtained using recharge model and simulated annual average recharge values were estimated. The numerical model was calibrated and validated using groundwater flow data. Model sensitivity was assessed using volumetric and percentage numerical error
Results: The LTA and simulated annual average recharge for study area was 745 mm/year and 3.6 - 15.2 mm/year. The modeled recharge fluxes and groundwater heads ranged from 4.756×10^{-10} - 1.142×10^{-5} m/s and 0.1-10 m. The relatively volumetric and percentage numerical error varied from 0.03 - 0.06 and 0.004 - 0.01%.
Conclusion: Quantitative assessment of groundwater resources in part of Sokoto Basin was developed for effective utilization and sustainability of groundwater resources.

**Corresponding author: E-mail: osolaniyan@lautech.edu.ng;*

Keywords: Groundwater; hydraulic conductivity; precipitation; runoff; sokoto basin; storage coefficient.

1. INTRODUCTION

Groundwater is of fundamental importance in water resources planning, as it serves as both a storage and a release entity. Its exploitation has continued to remain an important issue due to its unalloyed needs. Though there are other sources of water in Sokoto which include streams, rivers ponds, none is as hygienic as groundwater because groundwater has good natural microbiological quality and generally adequate chemical quality for most uses [1,2]. Approximately 98 percent of liquid fresh water exists as groundwater, much of it occurs very deep in the Earth. Pumping is very expensive in Sokoto basin which prevents the full development and use of groundwater resources.

A well or borehole that is installed at a depth below the water table is likely to indicate a different level than the water table. This water level is called the hydraulic or piezometric head (or simply head), and is the most fundamental quantity in the analysis of groundwater flow. The hydraulic head expresses the energy (potential energy) of the groundwater per unit weight and thereby influences the direction of groundwater flow: flow occurs from regions of high hydraulic head to areas of low hydraulic head. Groundwater flow in Sokoto basin has many applications, among which are agricultural developments, domestic use such as supply of drinking water, irrigation, and a variety of water quality applications [3-5].

A groundwater model is any computational method that represents an approximation of an underground water system. While groundwater models are, by definition, a simplification of a more complex reality, they have proven to be useful tools over several decades for addressing a range of groundwater problems and supporting the decision-making process. Groundwater model is a simplified representation of a groundwater system. Numerical models are capable of solving the more complex equations that describe groundwater flow and solute transport. These equations generally describe multi-dimensional groundwater flow, solute transport and chemical reactions, although there are one-dimensional numerical models [6].

The specific objectives of this study includes: development of conceptual model for the study area; calibrate and validate the numerical flow model developed; carry out quantitative assessment of possible future impacts of management decisions for water resources sustainability and proffer management policies for water resources sustainability based on the scenario conditions.

Water occurs naturally as moisture in the upper part of the soil profile (atmosphere) as dew, on the earth’s surface as streams, rivers, oceans, lakes, and beneath the earth’s surface as groundwater [5]. The earth’s surface is composed of water from either, the seas, oceans, rivers, streams, ponds, or otherwise, yet none of these surface water sources is as much less vulnerable to contamination as groundwater [7-9]. The amount of freshwater available for human use is less than 0.08% of all the water on the planet [10]. The water demand within Sokoto basin increases geometrical due to their population explosion and which triggered domestic and agricultural need for water. There are no existing management policies for groundwater abstraction in the area. This study utilizes more geo-hydrological and climatic data in modelling. This guarantee having a reliable result from the groundwater modelling as compare to existing studies. For a proper assessment and management of groundwater resources, a thorough understanding of the complexity of its processes is quite essential [5], [9], [11].

1.1 Brief Description of the Study Area

The geographical location of the study area is presented on Fig. 1, and bounded by approximately latitudes 11˚00' - 14˚00' N, and longitudes 4˚00' - 7˚00' E. The major towns within the area include Gudu, Tangazar, Tambawal, Shagari, Gada, Kebbe, Dinga, and Dange. The Sokoto Basin in northwestern Nigeria is underlain by a sequence of semi consolidated sedimentary rocks, which in their surface expression form undulating plains broken by clay hills.

Characteristically, the hills are capped by resistant crusts of laterite or ironstone. Lowest elevations occur in the south near the River Niger, and the highest points are found on the ironstone-capped hills and the Dange scarp in the north. South and east of the Sokoto Basin, crystalline rocks form a dissected upland surmounted by isolated steepsided hills (inselbergs). Vegetation in the Sokoto Basin is that typical of the Sudan savannah and is characterized by sparse scrub, generally less than 20 feet high, and interrupted by large isolated trees.

The basin has a two-season climate, dry and wet. During the wet season, May to October, rains are induced by the northward movement of the moist Equatorial Maritime airmass from the Gulf of Guinea whose prevailing winds are from the southwest. The average annual rainfall during this season for 35 years of record is about 30 inches at Sokoto. It is somewhat greater in the south, up to 50 inches, but diminishes northward to about 20 inches toward the Sahara. During the largely rainless months from October through April, the dry dust-laden harmattan winds of the Tropical Continental mass blow in from the northeast. The coolest months in the Sokoto region are December and January when the average daily minimum temperature may decline to 60°F. The hottest month is April when 105°F is feet but also in the upper part of the Rima Group from depths of about 340 to 410 feet is the maximum and 76°F the minimum average daily temperature [12-14].

2. METHODOLOGY

The geo-hydrological data for this study were obtained from Sokoto Basin Authority. These were used for model set up, calibration and validation purposes. These data include geological maps, groundwater levels, borehole records, precipitation (1970 to 2018), evaporation, hydraulic conductivity, storage coefficients and boundary conditions. Runoff values were obtained using recharge model. River flow data were obtained from the daily river flow measurements at the widely distributed gauging stations on the Sokoto, Rima and the Zamfara Rivers**.** A nominal value of 1 mL per day of leakage from pressurized water mains was assumed to recharge the aquifer within the area of study. The current rates of groundwater abstraction from boreholes within the study area were used. A review of temporal variations of the abstraction rates was undertaken in order to obtain a time series of abstraction rate from January 1990 to 2018.

The hydraulic conductivity, storage coefficient, and static water values were obtained from the available field measurements and pumping tests, and subsequently interpolated to obtain values for each cell of the model. The thicknesses of the sub-surface stratigraphic layers were obtained from the geologic borehole logs. These values were used to represent the initial conditions of the model setup, and subsequently adjusted following the calibration process.

The methodology adopted in this work was to delineate the hydrogeological units, in terms of the boundaries conditions, inputs and outputs variables, as well as the associated structure and properties of the aquifers, aquitards and other geological units making up the catchment. Specifically, the catchment inflow variables considered are rainfall, leakages, rivers and its tributary, runoff, cross catchment transfer, while the outflows include river flows, abstractions for Public Water Supply, industrial, agricultural and private supply, as well as the infiltration.

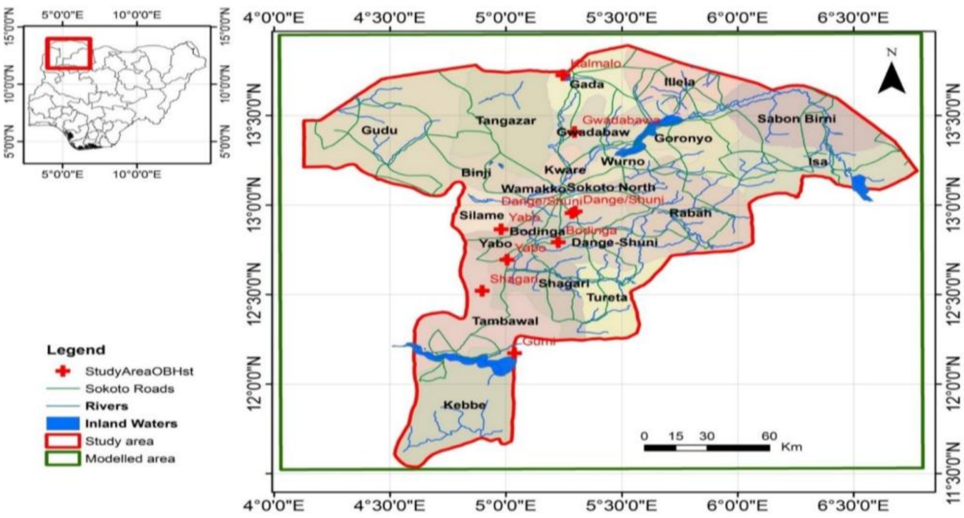

Fig. 1. Basemap for the Study Area

The numerical model was setup and calibrated under transient conditions approximately 7 years from October 1983 to December 1989, with average length of the stress period of 30 days, making a total number of 75 stress periods. Each stress period is equated to one-time step, corresponding to approximately 30-day time step. The model is set up as four layers representing the constituent aquifer horizons namely, Gwandu Formation (Sand), Sokoto Group (Limestone), Rima Group (Sandy) and Gundumi/Illo Group (Clayey Sandstone) Group. These layers represent model layer 1, 2, 3 and 4, respectively. The four layers are defined in the groundwater model as varying saturated thicknesses.

The initial groundwater heads and hydraulic properties within the aquifer horizons were obtained by interpolating the measured static water levels, as well as hydraulic conductivities (both horizontal and vertical), and the specific yield and specific storage across the entire model area. The interpolation technique used is based on the kriging approach. Where the river path exists, the initial groundwater head was set to equal to the river stage. These initial values were subsequently optimized during calibration process in order to obtain a good match between the field and calculated values.

The MODFLOW-2000 solver Package adopted for this work is the Preconditioned Conjugate Gradient 2 (PCG2). A detailed documentation of PCG2 is presented by [15]. The PCG type solution method is more robust when compared to other solver packages [16]. The maximum number of outer and inner iterations was set to 100 and 50 respectively. The convergence criterion for the hydraulic head observations was set to 0.01 m. These values were based on previous similar work in the literature [17-19]. Nine (9) of the groundwater levels monitoring data were used as targets for assessing the effectiveness of the calibration process. The observed and simulated data were compared, and the criteria considered for model acceptance are the residual between the simulated and the observed values, the user defined convergence criteria, and the matching trend between the observed and simulated data, based on the simulated equivalent produced by the Observation Process of the MODFLOW-2000 Package.

In order to be able to ameliorate the prevailing water resources problems as highlighted in the study area, the following water resources management scenarios were formulated to quantitatively assess probable impacts on the water resources regime and hence proffer management policies arising from observation from the model output. The formulated scenarios are:

Scenario 1:	Prevailing conditions where both the abstraction and recharge activities continue in the current rates for the next five years
Scenario 2:	Abstraction rates employed in Scenario 1 is reduced by 25%, at the prevailing recharge rates
Scenario 3:	Drought condition where the abstraction rate in Scenario 1 is sustained, but the recharge rate declined by 25%
Scenario 4:	Sequential policy that temporally progresses from Scenario 1 to Scenario 3, and completed with Scenario 2.

The initial condition of the flow model was represented by the calibrated model and the head distribution obtained from the calibration run was used as initial conditions for the predictive scenario model over the 5-year period.

3. RESULTS AND DISCUSSION

The notable inland waters within the area are located in Goronyo, Gada, Isa and Tambawal area. These include Gagare, Bunsara, Rima, Kware, Sheila, Zamfara, Gulbin Ka, Gayen and Gulbe. The initial water level used in the numerical modeling assumed the regional groundwater levels. The spatial distribution of the borehole locations, as well as the geological horizons within which the boreholes were completed are presented on Fig. 2. The information obtained from the boreholes was used to estimate the bottom elevations of the model layers.

Conceptually, the model is setup as a four-layer model, corresponding to the geologic horizons prevalent within the area of study. The Gwandu Formation constitutes the first model layer. This is underlain by the Gambu, Kalambaina and Dange Formations, which formed the second model layer. The third and the fourth model layers are constituted the geologic Formations, namely, Wurno, Dukamaje, Taloka, and Gundumi, Illo, respectively. The four model layers are underlain by the Basement Complex. The area is subsequently discretized into 600 columns and 500 rows. The boundary condition is represented by varying head condition. The summary of the conceptual model is presented on Fig. 3.

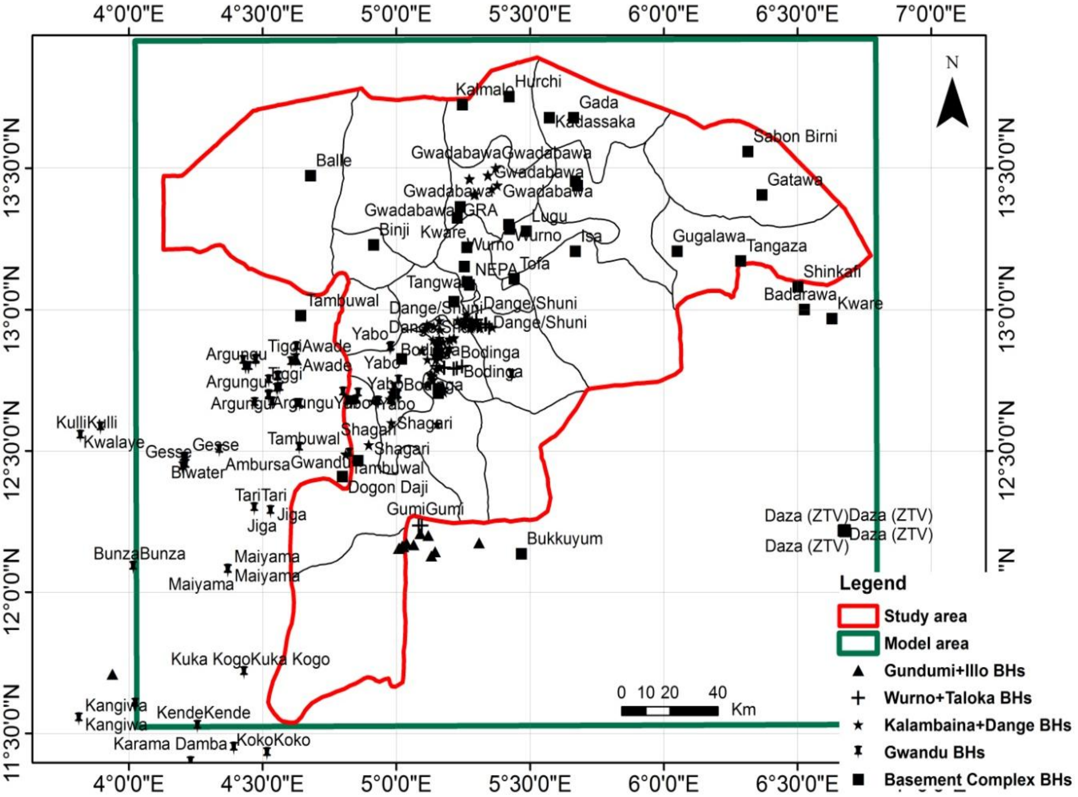

Fig. 2. Borehole Distribution within the Study Area

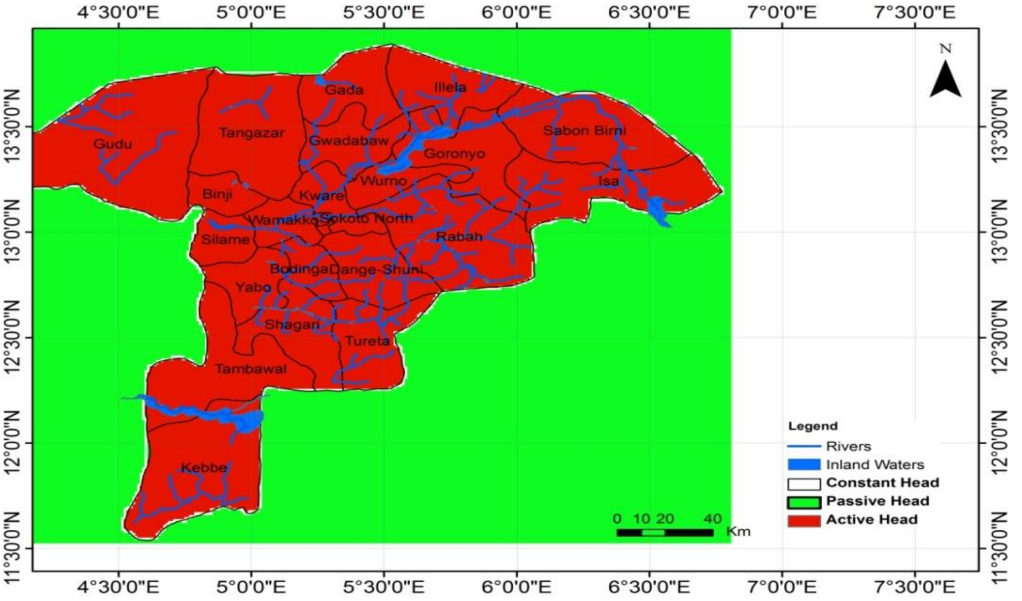

Fig. 3. Conceptual Model for the Study Area

The flow model was setup and calibrated over a 7-year period spanning October 1983 – December 1989. The model setup and calibrated results are presented in Table 1. The model refinement was carried out using trial and error approach, and the Observation Package of MODFLOW-2000 was used to calculate the simulated equivalents of the field observations. The hydraulic heads from five observation boreholes were used as the observed data during the model calibration process. The objective of the calibration process was to reduce the residuals between the observed and simulated hydraulic heads. A convergence criterion of 0.01m was set within the solver package, such that the solution is considered to converge either when the difference between two successive solutions for the calculated hydraulic heads is less than the convergence criteria, or when the difference between the simulated and observed values is less than the convergence criteria. The study area is divided into 5 recharge zones as shown on Fig. 4 based on the distribution of the different transmisivity values obtained in the literature.

The nine observation boreholes were used in the model calibration. Generally, a sufficient degree of match was obtained between the measured head observations and the simulated equivalents as presented on Fig. 5a and b. The simulated data are within ± 5 m of the observed data. The residual, as well as the percentage numerical error associated with the volumetric balance is less than 0.01% throughout the duration of the simulation. The volumetric budget and numerical errors for the model simulations are presented on Figs. 6 and 7. The groundwater heads in layers 1 at the end of the 7 years of simulation is presented on Figs. 8.

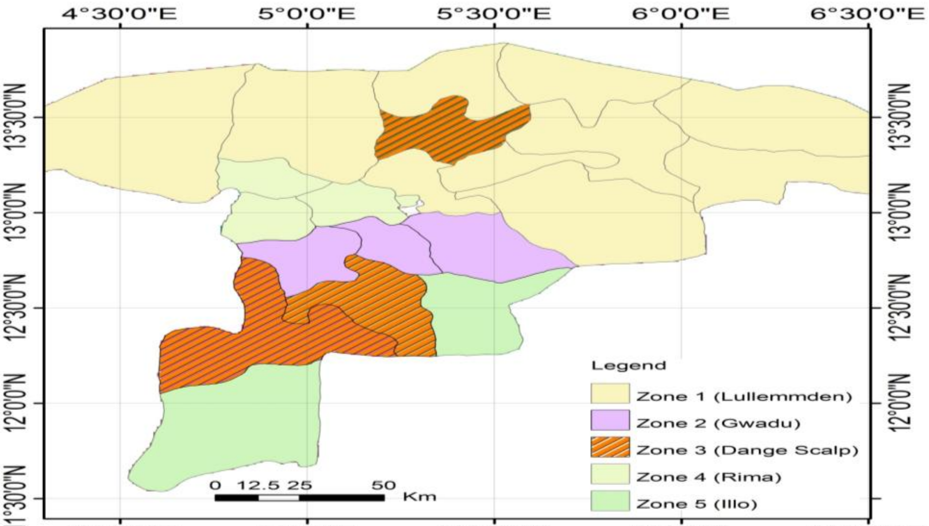

Fig. 4. Recharge Zoning Areas

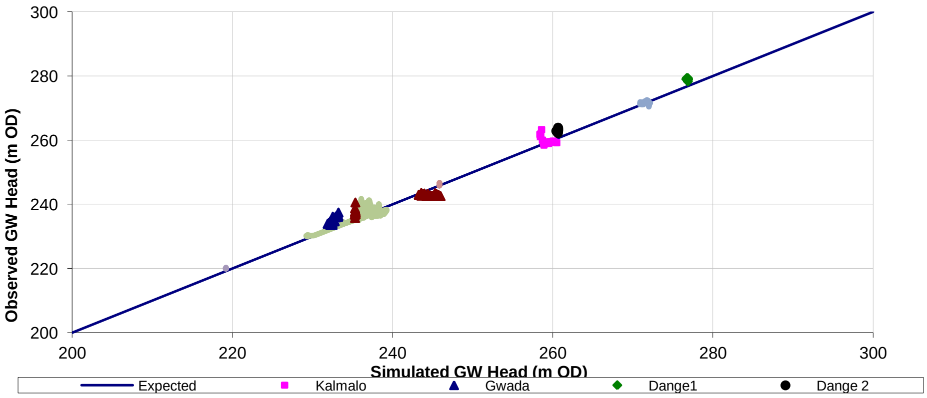

Fig. 5a. Observed and Simulated Groundwater Heads for all Observation Boreholes

Table 1. Summary of initial and final flow model data

S/N	Input Parameter	Initial Value	Final Value
1	Elevations (m)	Distributed values	Same as initial value
2	Boundary Conditions	Active head conditions	
3	Geometry	1: Gwandu Formation; 2: Sokoto Group 3: Rima Grp 4: Gundumi Fm + Illo Grp	
4	Spatial discretization (m)	No_ rows: 525; No_ cols: 600; $\Delta x=500$; $\Delta y=540$	
5	No of abstraction boreholes	50 – 123	
6	Abstraction rates (m^3/day)	Averaged at 130	
7	Observation boreholes and levels	9 boreholes, and 4.8 for locations and GW levels time series, respectively	
8	No of river reaches	13599	
9	River stage (m OD)	Varied	
10	River Bot (m OD)	Varied	
11	River bed condition	1.296×10^{-5} m/s	9.2593×10^{-9} m/s
12	Recharge rate (m/s)	Recharge rates for 5 zones: 1. Lullemmeden: 3.17×10^{-9} 2. Dange Scalp: 3.17×10^{-9} 3. Gwadu: 3.17×10^{-9} 4. Rima: 3.17×10^{-9} 5. Illo: 3.17×10^{-9}	Recharge rates for 5 zones: 1. Lullemmeden: 1.142×10^{-5} 2. Dange Scalp:4.756×10^{-10} 3. Gwadu: 4.756×10^{-10} 4. Rima: 4.756×10^{-10} 5. Illo: 4.756×10^{-10}
13	Horizontal hydraulic conductivity (m/s)	1: Gwandu Fm: $5.787\text{x}10^{-4}$ 2: Sokoto Grp: $2.315\text{x}10^{-5}$ 3: Rima Grp: $3.472\text{x}10^{-5}$ 4: Gun Fm/ IlloGp: $3.472\text{x}10^{-4}$	1: Gwandu Fm: $2.781\text{x}10^{-1}$ 2: Sokoto Grp: $7.515\text{x}10^{-2}$ 3: Rima Grp: $4.247\text{x}10^{-2}$ 4: Gun Fm/ Illo Gp: $5.022\text{x}10^{-2}$
14	Vertical hydraulic conductivity (m/s)	1. Gwandu Fm: $5.787\text{x}10^{-8}$ 2. Sokoto Grp: $1.157\text{x}10^{-7}$ 3. Rima Grp: $5.787\text{x}10^{-8}$ 4. Gun Fm/ Illo Gp: $5.787\text{x}10^{-8}$	1. Gwandu Fm: 1.668×10^{-2} 2. Sokoto Grp: 4.510×10^{-3} 3. Rima Grp: 2.548×10^{-3} 4. Gun Fm/ Illo Gp: 3.013×10^{-3}
15	Specific yield	1. Gwandu Fm: 0.12 2. Sokoto Grp: 0.10 3. Rima Grp: 0.12 4. Gun Fm/ Illo Gp: 0.12	1. Gwandu Fm: 0.15 2. Sokoto Grp: 0.12 3. Rima Grp: 0.10 4. Gun Fm/ Illo Gp: 0.13
16	Specific storage	1. Gwandu Fm: $1\text{x}10^{-4}$ 2. Sokoto Grp: $5\text{x}10^{-4}$ 3. Rima Grp: $1\text{x}10^{-4}$ 4. Gun Fm/ IlloGp: $1\text{x}10^{-4}$	1. Gwandu Fm: 6.00×10^{-3} 2. Sokoto Grp: $1.00 \text{x}10^{-5}$ 3. Rima Grp: 5.00×10^{-4} 4. Gun Fm/ Illo Gp: 6.00×10^{-3}

The flow model was subsequently setup as a predictive model for a 5-year period spanning January 2020 - December 2025. The December 1989 groundwater head output of the calibrated model were used as the initial water levels for the predictive modelling for the four layers, and under the four defined scenarios.

The predicted groundwater head for Layers 1-4 for scenario 1 ranged from -110 to 190 m as presented in Table 2. There is negative flux for layer 3 and 4 but layer 4 has the lowest value of -110m. The predicted groundwater head for layer 1-4 for scenario 2 varied from -60-240 m. The negative flux was only recorded at layer 4. Scenario 2 increased the predicted water head for all layers. Similarly, the predicted water head for all layers at scenario 3 decreased the heads. The heads varied from -120 - 180m. Scenario 3 also recorded a negative flux at Layer 3 and 4. This implies that Scenario 3 predicted a lower water head. Scenario 4 predicted a positive groundwater head for all layers. The predicted heads varied from 30 - 270m and there was no negative flux in any layer. The highest water head was recorded in the first layer while the lower was reported in layer 4. This implies that scenario 4 predicted the highest groundwater head and it is recommended in this basin. Scenario 1 to 3 and later to 2, which represent scenario 4 produced the highest water head in the basin. It must be noted that the predicted head is related to the nature of the hydro-geologic formation, which determines the transmissivity and yield of the formation.

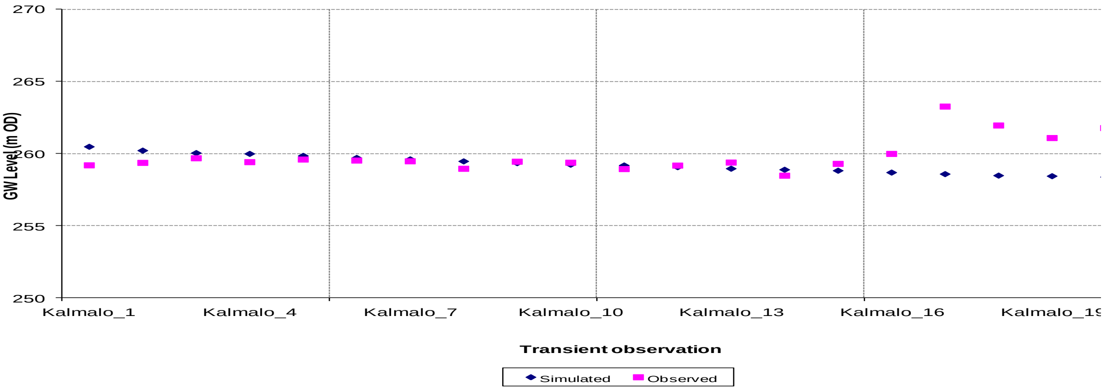

Fig. 5b. Observed and Simulated GW Heads Obtained at Kalmalo BH (S33 09)

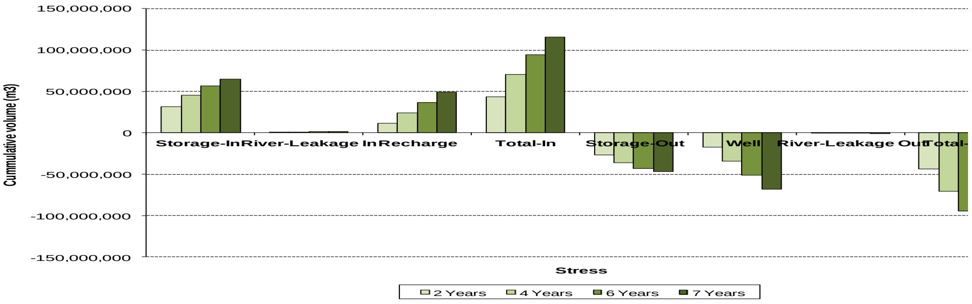

Fig. 6. Volumetric Budget of the Model Simulation

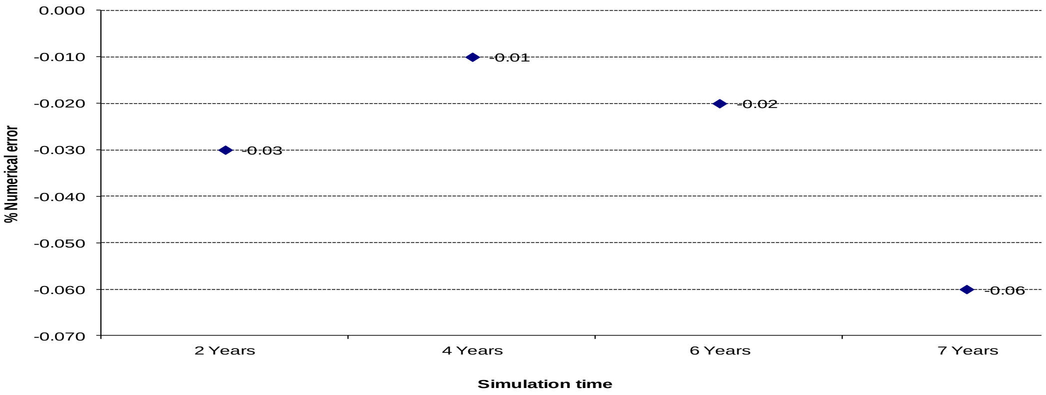

Fig. 7. Numerical Error of the Model Simulation

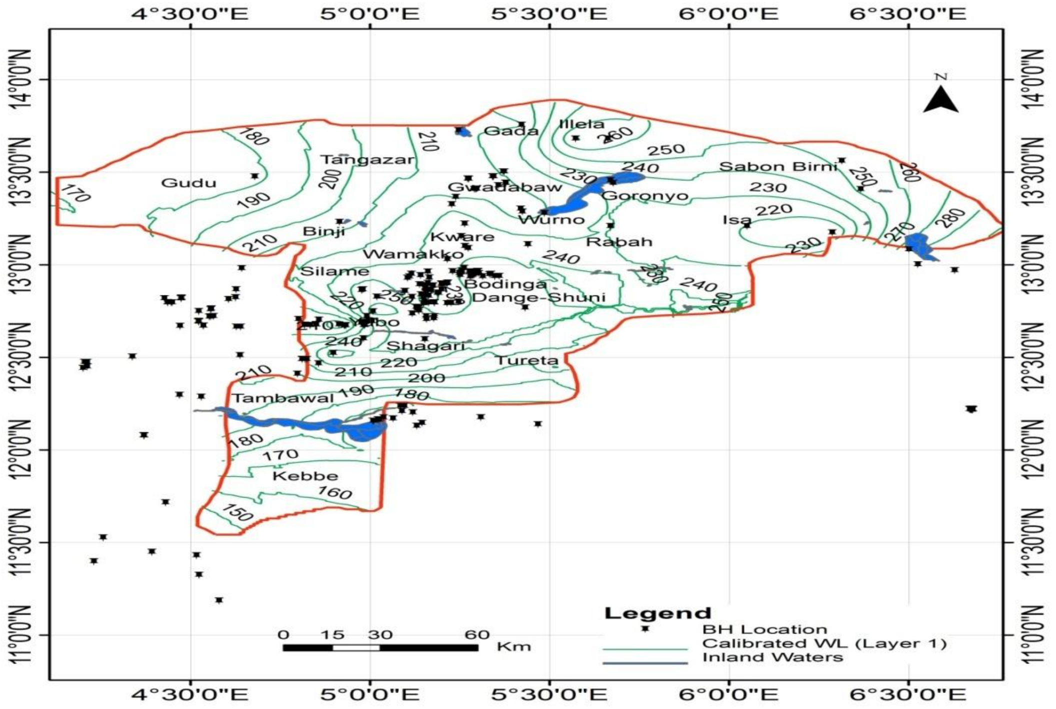

Fig. 8. Final Calibrated Groundwater Head in Layer 1

Table 2. Summary of predicted groundwater heads for different scenarios

	Heads (m)			
Layer	Scenario 1	Scenario 2	Scenario 3	Scenario 4
1	190	240	180	270
2	90	140	-20	170
3	-10	40	-20	70
4	-110	-60	-120	30

The final horizontal conductivity values are within the same ranges compared to the values obtained by [16], as well as [12].Furthermore, the final values for the specific yield were 0.15, 0.10, 0.12 and 0.13, and for the specific storage were 6 x10^{-3}, 1x10^{-5}, 5 x $10^{-4}$and 6x10^{-3}, respectively for Gwandu formation, Sokoto group, Rima group and Gundumi formation/ IlloGroup.. The values reported by [16], for the specific yield of the undivided Sokoto was 0.12, while [20] and [21] reported specific yield value of 0.15 for Gwandu formation. The values obtained in this work are similar to these referenced values.

4. CONCLUSION

The following conclusions were drawn from this study

(i) Due to the minimal effects on the depletion of the water resources within the area of study, scenarios 2 and 4 are considered deployable for effective and long-term sustainable management of the groundwater resources within the study area.

(ii) Scenario 4 represented a sequential management evaluation that integrated multiple scenarios

(iii) A developed wastewater treatment scheme using Solar energy (Solar powered wastewater treatment plant) should be located in the study area. This will cater for water demand such as irrigation, industrial and domestic usage.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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