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Groundwater Flow Modelling for Selected Parts of Port-Harcourt and Obi-Akpo Local Government Areas in Rivers State, Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. Author AAA designed the framework and conceptualize the model for the study area. Author OAK wrote the first draft of the manuscript and interprete the groundwater modelling. Author OSO re-worked on the first draft and interpret the result. All authors read and approved the final manuscript.

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ABSTRACT

Aim: There is a need to develop steady and transient state models for the hydro-geological system of Port Harcourt and Obio-Akpor areas to understand the groundwater system of the area.
Study Design: Port Harcourt and Obio-Akpor.
Place and Duration of Study: Port Harcourt and Obio-Akpor, between April 2011 and April 2021.
Methodology: Thirty-eight boreholes were selected randomly within the studied areas and examined to obtain their physcio-chemical properties which include borehole locations, chemical properties, water level, discharge, aquifer transmissivity, specific yield, and storativity. The data obtained were used to develop a base map for the groundwater model. A mathematical model (MM) was developed from estimated initial conditions (hydraulic conductivity and recharge). The MM was

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excited and its response was used to derive a Modular Three-Dimensional Finite Difference groundwater flow model. Groundwater Modelling System version 10.06 software was used to simulate and predict the groundwater flow. Root-Mean-Square=Error (RMSE) analysis was used to assess the relationship between computed and observed hydraulic heads.

Results: The mean values of aquifer transmissivity, specific yield, and storativity from the field data were 0.0600m²/min; 0.11596m³/min, and 0.00040, respectively. The developed base map spread between 4.4601ºN, 7.0498ºE, and 4.8156ºN, 7.5098ºE. The estimated hydraulic conductivity and recharge were 0.00004m/day and 0.00054m³/day respectively. However, based on Modular Three-Dimensional Finite Difference groundwater flow model, the hydraulic and recharge were 0.00055m/day and 2.27520m³/day, respectively.

Conclusion: The developed model for the selected parts of Port- Harcourt and Obi-Akpo has low sensitivity values compared with the estimated initial values for hydraulic conductivity and recharge. Results generated from the model cannot be used to predict future recharge and drawdown for the studied domain area but can serve as a baseline for further studies.

Keywords: Groundwater; aquifer; transmissivity; storativity; specific yield; MODFLOW; Port Harcourt.

1. INTRODUCTION

"According to the Stockholm environmental institute, one-third of the world's population lives in areas of moderate to severe water shortages. Large percentage of people in urban centers of developing countries do not have access to potable water. The provision of adequate water will go a long way in preventing water-related diseases such as cholera and dracunculiasis. Scarcity of water in Port Harcourt has left many people with poor or no access to potable water for domestic and industrial use" [1,2].

"Groundwater is a very important resource that supplies potable water for both industrial and domestic use. Port Harcourt city largely depend on groundwater because the surface waters in the areas are severely polluted by the direct and indirect discharges of domestic and industrial waste and oil spillage. Thus, making groundwater a very important resource for survival in Port Harcourt and environ" [3,4]. Groundwater plays a vital role in sustaining ecosystems and ensuring human adaptation to global environmental changes [5,6].

"The study of groundwater flow helps to increase the knowledge of the groundwater system, aquifer interaction, and accomplishment of proper management of their resources. Groundwater management and modeling address and solve various questions and problems from hydro-geological practice" [7]. In recent years, the rate at which groundwater resources potentially decrease compared to water supply demand is very alarming due to changes in climatic conditions, increase in population size, and advancement in civilizations [8,9].

"The study area inhabits a lot of companies and industries, especially in the oil and gas sector; these have led to the continuous influx of associate companies and people into the area, whose activities have led to the contamination and pollution of the available surface water resources by the discharge of effluents or pollutants in the runoff into the surface water. In regions with economically important resources like Port Harcourt and its environs, it will be helpful to use existing techniques to describe the hydraulic interaction between a borehole and its surrounding aquifer to determine the effect of changes in its water body" [10,11].

1.1 Brief Description of the Study Area

Port Harcourt is located within the Eastern Lower Niger Delta in South Eastern part of Rivers State of Nigeria. It is an urban city with a population of about 1.2 million people (Brinkhoff, 2010). It is located on the right bank of the Bonny River approximately 65 km (40 miles) inland from the Bight of Bonny. Fig. 1 shows the Basemap for the Study Area. The Southern part of the town stands largely on raised levees with silts and clay foundations. These afford dry and firm points within the zone of its freshwater swamps of the Niger Delta. It covers an area of 290sq.km. The boundary of the Port-Harcourt and Obio/Akpor Local Government Areas (LGAs) are assumed to be consistent with the physical natural boundaries. The main city of Port Harcourt is the Port Harcourt Township in the Port Harcourt City Local Government Area, consisting of the former European quarters now called the old Government Reservation Area (GRA) and new layout areas [12,13].

Port Harcourt City. the capital of Rivers State, consists of eight LGAs, which include: Port-Harcourt, Okrika, Obio/Akpor, Ikwerre, Oyigbo, Ogu/Bolo, Tai, and Eleme. Port Harcourt City has a climate with lengthy and heavy rainy seasons and very short dry seasons. December and January are the dry season months of the city. "Port Harcourt's highest precipitation occurs during September with an average of 370 mm of rain. December, on average, is the driest month of the year; with an average rainfall of 20 mm. The temperature throughout the year in the city is almost constant, showing little variation throughout the course of the year. Average temperatures are typically between 25°c and 28°c, in the city" [13-16].

2. METHODOLOGY

2.1 Meteorological and Field Data Acquisition

Meteorological data (precipitation, evapotranspiration, and temperature) were retrieved from Port Harcourt Meteorological station. Collection of fied data involved locating suitable wells within the study area. The coordinates and elevations of wells were taken using Gemin GPS. Well depths and water levels of were also measured using water level meter. Flow rates of the borehole logs were used to identify subsurface profiles. All potential monitoring wells were tabulated and a short list of the wells with adequate hydraulic parameters was selected. All relevant properties of the selected monitoring wells were then put into a database.

2.2 Groundwater Modelling

The groundwater flow model was simulated using the Groundwater Modelling System (GMS). GMS employs Finite Difference Method (FDM) in solving groundwater flow hydraulic conductivity and recharge. The groundwater flow model was set up as a one-layered, steady-state model. The boundaries of the model were determined such that it encompasses the entire area of interest and coincides with hydrological boundaries. Thirt-eight (38) boreholes logs were processed to determine the depth to the impermeable layer, which was subsequently interpolated to obtain the surface representing the bottom surface of the model layer. The top surface of the model was obtained directly from topographic map.

The predominant Benin Formation was utilized as a water table aquifer with an average bottom elevation of 90m below sea level. The aquifer problem domain was discretized into a finite difference grid of 100 rows and 100 columns in line with paucity of data modelling [2]. The model equations were based on the assumption that hydraulic properties were uniform within individual cells, or at least that meaningful average or integrated parameters could be specified for each cell. The numerical values of all the relevant coefficients and state variables were obtained from data collected from the Federal Ministry of Water Resources on Hydrogeological Investigation of the Eastern part of Nigeria; Messrs Badafash Nigeria Limited on Borehole Data Inventory and Pumping Test Analyses for Groundwater Development in Nigeria; Konsadem Associates Consulting Engineers, and the published literature.

The partial dferential equation for the three-dimensional flow of groundwater with constant density is given by:

$$\frac{\partial}{\partial x}\left\{Kxx\frac{\partial h}{\partial x}\right\} + \frac{\partial}{\partial y}\left\{Kyy\frac{\partial h}{\partial y}\right\} + \frac{\partial}{\partial z}\left\{Kzz\frac{\partial h}{\partial z}\right\} - W = Ss\frac{\partial h}{\partial t} \qquad (1)$$

Where:

K_{xx}, K_{yy}, and K_{zz} are hydraulic conductivity (LT^{-1}) along the x, y, and z coordinate axis respectively,
h is the potentiometric head (L);
W is a volumetric flux per unit volume (T^{-1});
S_s is the specific storage of the porous material (L^{-1});

and t is time (T).

2.3 Model Calibration

Each ground-water flow model of the aquifer model domains was calibrated using a trial-and-error method to get the best match between simulated hydraulic heads and measured water levels, and selected water-budget items. A total of eleven (11) observation wells were used in the model calieration of the aquifer-domainRoot Mean Square Error (RMSE) equation given below was used for the caliberation

$$\text{RMSE} = \left(\sum_{n=1}^{N} X_J^{\,2} / \text{N} \right)^{0.5} \qquad (2)$$

where $Xj = a_j - b_j$ (2a)

X_j = residual head obtained after calibration.
a_j = observed head.
b_j = simulated head.
N = number of observation wells used for the calibration process.

The Root Mean Square Error (RMSE) for the calibration process was computed using equation 3:

$$RMSE = (\sum_{n=1}^{N} X_J^{2} / N)^{0.5} \quad (3)$$

Sensitivity analysis was also performed to test the response of the calibrated models to a range of values for the initial hydraulic properties. This was done by varying the value of one input parameter while keeping all others constant. The Plot Wizard in Ground Water Modelling System (GMS), 10.0.6 Version was used in extracting data from the calibrated model for model verification.

3. RESULTS AND DISCUSSION

3.1 Observed and Simulated Heads

Table 1 shows the observed hydraulic heads from Eleven Observaton Wells. The heads as measured using vary from 14m-92m. Well Obs#1 has the highest head while well Obs#11 has the least head. The average hydraulic head of the well is calculated to be 47m. Fig. 2 shows the Steady Stated Simulated Head Model of Port Harcourt/Obiokor Domain. The simulated aquifer heads range from 2.0m - 102m. The northeastern part of the map has heads above 80m while the southwestern part of the map has low heads below 40m.

The model also presents calibration error between the observed and simulated heads as indicated by coloured bars. Green indicates all cases where the bar lies entirely within the target. Yellow indicates less than 200% error while red indicates greater than 200%. Three (3) of the examination wells, matched the computed heads within the calibration target limit, while one (1) well fell outside the target, but was within 200% of the observed value. Seven (7) wells were completely outside the specified range. The analyses of the results, in general, portray the degree of reliability of the calibrated model to duplicate reality. The center, top and bottom of the simulated model correspond to the observed value.

3.2 Observed and Simulated Heads Correlation

The correlation graphs in this study are presented in Figs. 4–8. The points located above the correlation line indicated an overestimation of simulated water level heads at the corresponding observation wells, with discrepancies equal to the vertical difference between the coordinate and the correlation line. However, points located below the correlation line indicate an underestimation of simulated hydraulic heads at the corresponding observation wells. The vertical difference between the points and the 1:1 correlation line depicts the degree of underestimation.

Residual versus Observed plot is presented in Fig. 6 which shows how well the entire set of observed values matched the model solution. On this plot is drawn a horizontal line along an error of zero, indicating what would be a perfect correspondence between observed data and solution values. One symbol is drawn for each inspection point at the intersection of the observed and residual (computed-observed) values for the point. The Error versus Simulation plot shown in Fig. 8 shows the Mean, Mean absolute, and Root mean squared error between successive solutions and observed data. Various simulations were run after changing model parameters such as hydraulic conductivity or recharge. The plot shows trends in the solution to present if model parameter changes were causing better calibration with measured field data. The differences, outside calibration targets, between simulated and measured values were perhaps due to an inaccurate distribution of pumpage to the individual wells, inaccurate estimation of the quantity and distribution of natural recharge, and/or inaccuracies in the reported water-level measurements.

The simulated water budgets at the end of the calibrated steady-state simulations were used to describe the flow characteristics in the domain. The water budgets of inflow (recharge to) and outflow (discharge from) in the aquifer model domain are shown in Table 2.

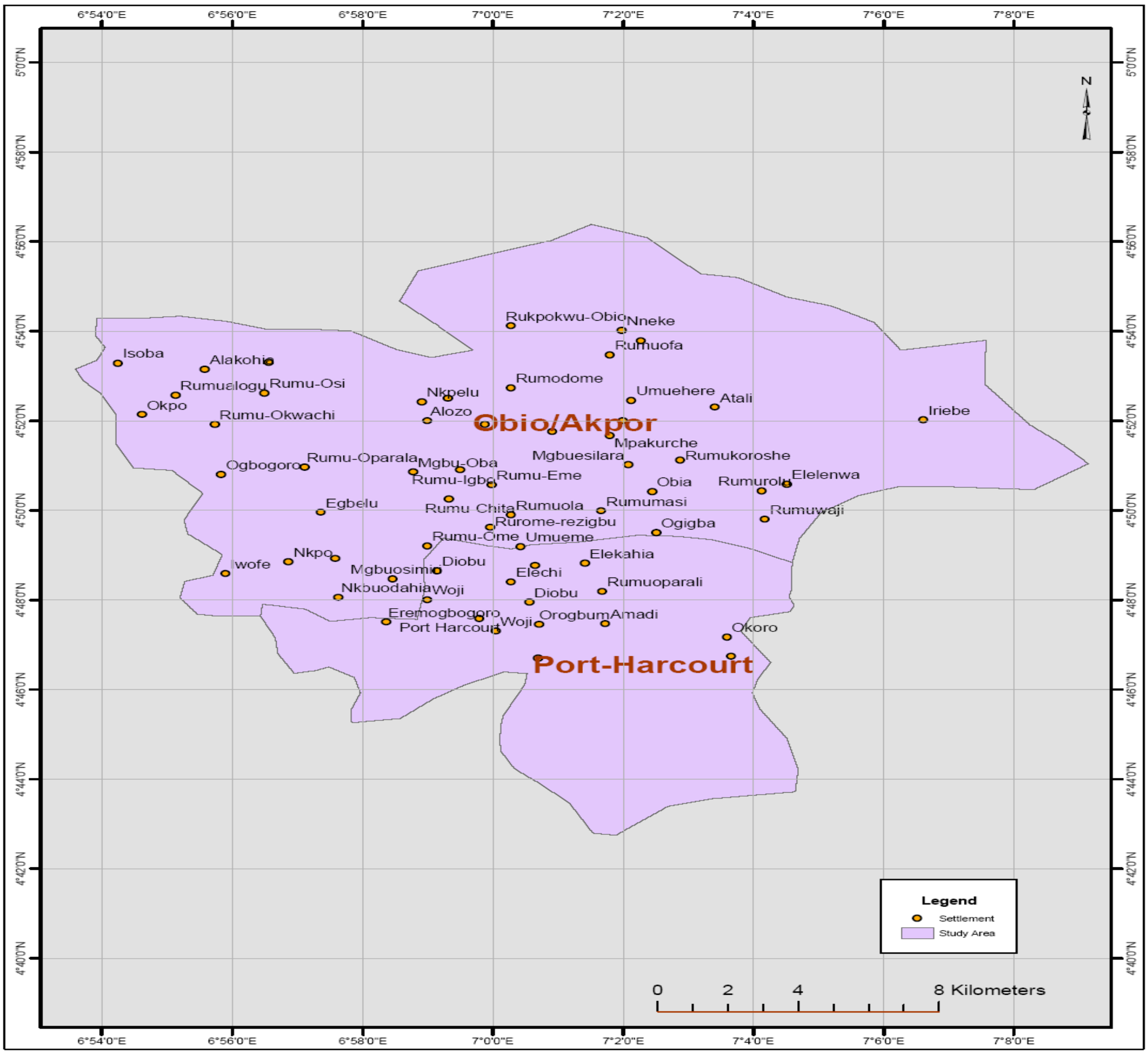

Fig. 1. Basemap for the Study Area

Table 1. Heads of Eleven Observations Wells

S/NO	X Coordinate (m)	Y Coordinate(m)	Observed Head (m)	Interval (m)	Confidence (%)
Obs #1	284420.0	537950.0	92.0	1.5	95
Obs #2	278980.0	534910.0	84.0	1.5	95
Obs #3	286450.0	533980.0	91.0	1.5	95
Obs #4	281650.0	532810.0	55.0	1.5	95
Obs #5	281720.0	530310.0	51.0	1.5	95
Obs #6	279280.0	529470.0	37.0	1.5	95
Obs #7	278220.0	529270.0	34.0	1.5	95
Obs #8	279520.0	528770.0	27.0	1.5	95
Obs #9	280320.0	528470.0	17.0	1.5	95
Obs #10	280380.0	527110.0	15.0	1.5	95
Obs #11	283190.0	524540.0	14.0	1.5	95

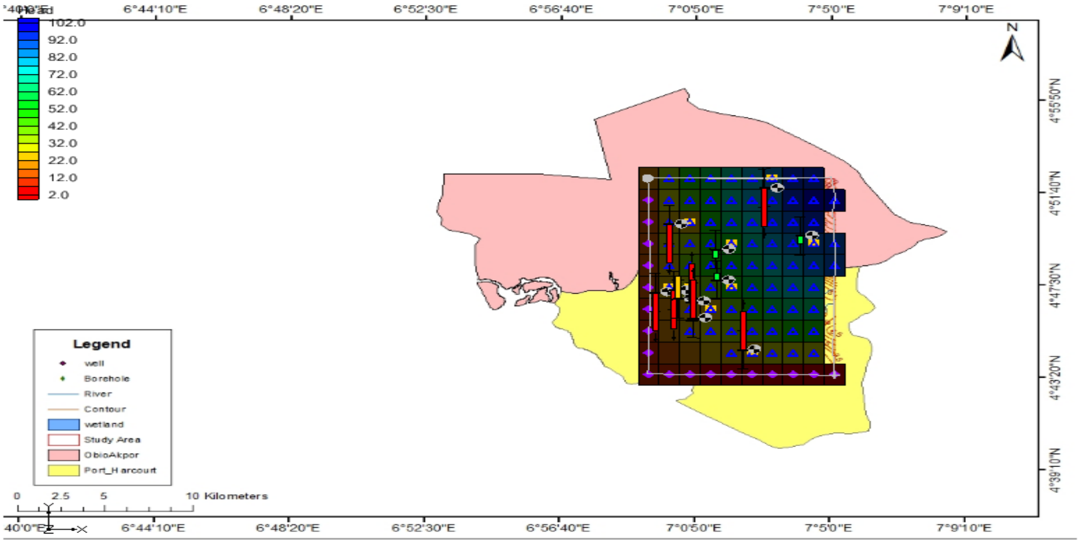

Fig. 2. Steady State Simulated Head Model of the Port Harcourt/Obiokor Domain

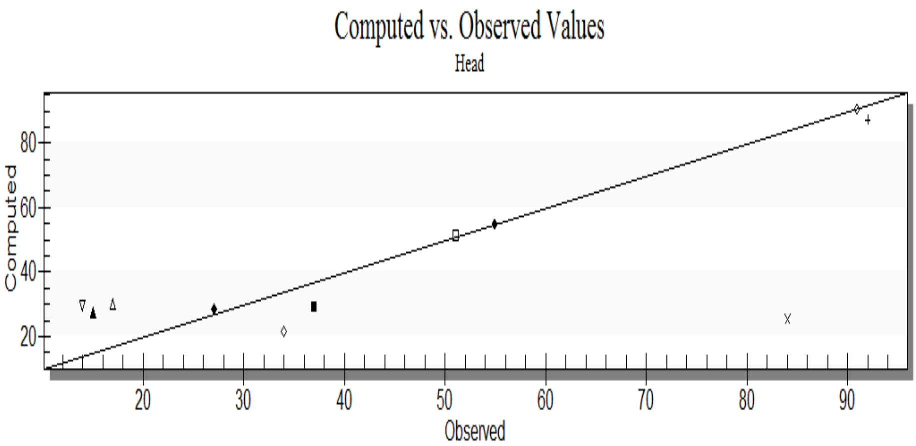

Fig. 4. Ratio 1:1 Line of Computed and Observed Heads for the Model Domain

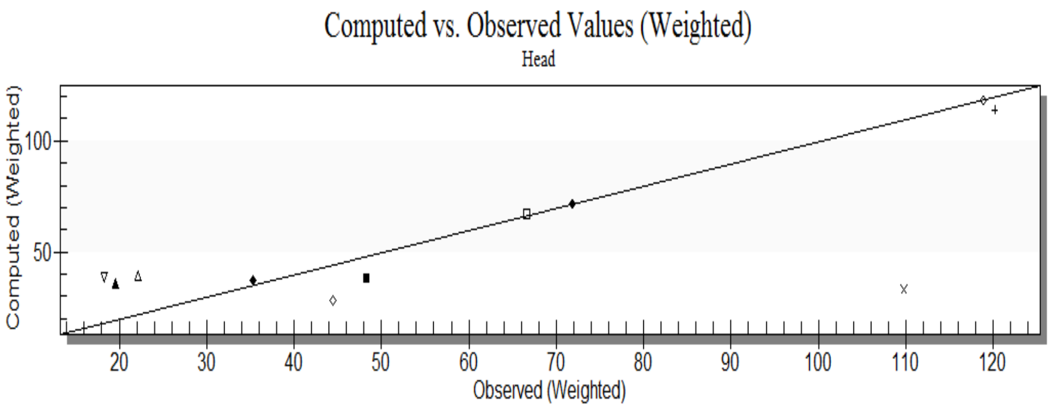

Fig. 5. Ratio 1:1 Line of Weighted Computed and Observed Heads for the Domain

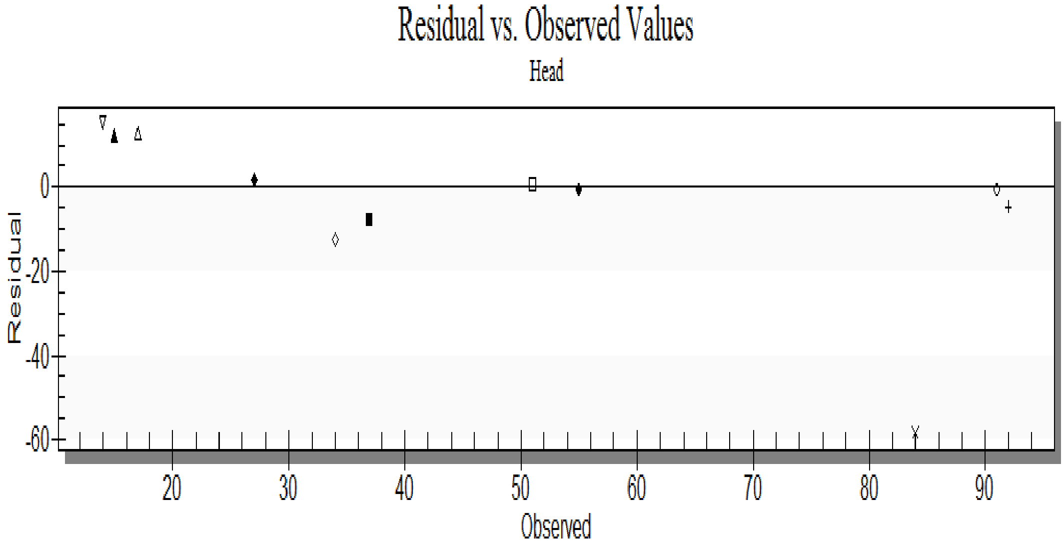

Fig. 6. Plot of Residual versus Observed Values for the Model Domain

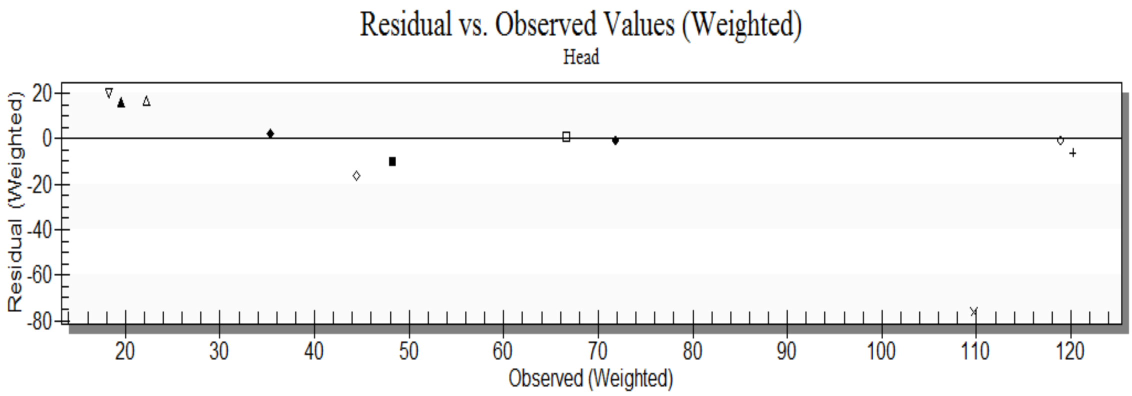

Fig. 7. Plot of Weighted Residual versus Observed Values for the Model Domain

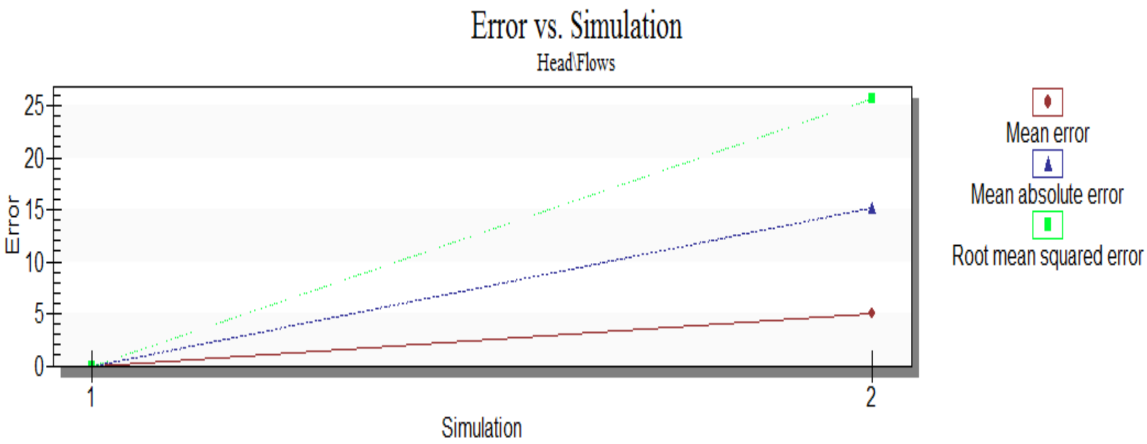

Fig. 8. Plot of Error versus Simulation for the Model Domain

Table 2. Water budget of inflow and outflow in the aquifer model domain

Sources/Sinks	IN	OUT
Constant head	0.0	-53079.84924316
Wells	0.0	-34261.70361328
Recharge	87341.555786133	0.0
Total source/sink	87341.555786133	-87341.55285645
Zone flow		
Flow right face	0.0	0.0
Flow front face	0.0	0.0
Flow left face	0.0	0.0
Flow back face	0.0	0.0
Total zone flow	0.0	0.0
Total flow	87341.555786133	-87341.55285645
Summary:	In	Out (% difference)
Sources/sinks	0.0029296875	0.0029296875
Cell to cell	0.0	0.0
Total	0.0029296875	3.35428826e-006
Flow budget for zone 1		
Constant head	0.0	53079.849243164
Wells	0.0	34261.703613281
Recharge	87341.555786133	0.0
Total	87341.555786133	87341.552856445
Summary		
In – out	0.0029296875	
Percent discrepancy	3.35428826e-006	

Table 3. Initial and Final Hydraulic Parameter estimate for Groundwater Flow Model Domain

S/No	Aquifer Parameter	Alluvium Formation	Alluvium Formation
		Initial Parameter (M/Day)	Final Parameter (M/Day)
1	Hydraulic Conductivity	0.0000451	0.000549
2	Recharge	0.000549	2.2752

3.3 Initial and Final Hydraulic Parameters

The summary of initial and final hydraulic parameter estimates for the groundwater flow model domain is tabulated in Table 3. Natural recharge in the aquifer domain was mainly due to the infiltration of precipitation runoff within the Alluvium drainage basin whch have high potential for groundwater storage and exploration. The initial estimate of natural recharge from precipitation runoff used to calibrate the steady-state models was 5.49×10^{-4} m/day. This estimate was increased to about 2.2572 mm/day after the calibration of steady-state simulations. The hydraulic conductivity and the recharge after calibration shows positive adjustment until computed heads fell reasonably close to the observed heads. There is therefore an abundance of groundwater reserve in the aquiferous formation of Port Harcourt City.

4. CONCLUSION

The following conclusions were drawn from this study:

(i) Port Harcourt/Obiokor Alluvium model shows that the aquiferous formation holds great potential for groundwater storage and exploration in the locality.

(ii) Four of the observation wells are within acceptable limits and seven outside the limits. The quality of the available data cannot be used to model beyond the preliminary investigation of groundwater flow within the aquifer domain.

(iii) The hydraulic conductivity and the recharge were positively adjusted until computed heads fell reasonably close to the observed heads in a matching exercise. This scenario indicated that there is an abundance of groundwater reserve in the aquiferous formation

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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