International Journal of Applied Science and Mathematics
Volume 5, Issue 5, ISSN (Online): 2394-2894

# Regional Groundwater Flow Modeling of Aldamer Area, River Nile State – Sudan

**Sadam. H.M.A. Eltayib [1*] & Adil B.M. Elkrail [2]**
*Corresponding author email id: sadam_h3@yahoo.com

*Date of publication (dd/mm/yyyy): 06/10/2018*

***Abstract* – The three-dimensional groundwater flow model was performed to evaluate the groundwater potentiality and assess the effect of groundwater withdrawal to the regional water level and flow direction in the Eldamer area central Sudan. Data used include periodic water level measurements, meteorological data, digital elevation data and well logs from scientific test wells and domestic water wells drilled in the study area. Transient visual MODFLOW model code was calibrated. Numerical simulation indicated that, a sharp drop of hydraulic head can be observed at the center and east of the model area, generated cone of depressions and a continuous decline of head with respect to the time as a result of heavy groundwater abstraction. The central part of the area, represent relatively high permeability zone and the model confirmed it to be the most productive region in the area and can be used for storing additional groundwater. Observation wells elaborate the reasonable match between the observed and calculated heads through the entire simulation period.**

***Keywords* – Groundwater, Simulation, Withdrawal, Transient Flow, Aquifer.**

## I. Introduction

The study area lies in the River Nile state in the North Central of Sudan Bounded between the River Nile at the west and Atbara River in the east and north and bounded in the south by the Mukabrab wady between latitudes 17˚ 4ˉ- 17˚ 20ˉ E and longitudes 33˚ 49ˉ – 34˚ 13ˉ N. it cover an area of 597 Km2, Figure (1). The area is extremely flat; the elevation ranges between 380 to347 meter a.m.s.l. It is dipping gently to the North West. Sand dunes and low ridges with scatter cobble, pebbles and boulders were covering the study area visualizing the undulated surface of the area. Many paved and unpaved roads were passing through the area; therefore, it is easily accessible to reach any point in the study area. River Nile and Atbara river and seasonal wades ( e.g. Wadi Mukabrab) are the main geomorphologic feature which drain the water to the River Nile and Atbara river which is flowing from south east to north west it is characterized by meandering drainage system depositing huge amount of sediments at the stream valley on the inside of beds. This process is clear in construction and maintaining a flood plain [18]. The geological setting of the study area is composed of Basement Complex (Pre-Cambrian) it is composed of highly deformed and multi metamorphosed gneisses and schist. The original rock are largely subjected to intensive deformation resulting in different types of structure and fracture systems and followed by erosional period creating of topographical relief [15] forming the base over which all other sediment were deposited and generally it appears as low bouldery outcrops at river Atbara, Nubian sandstone formation (upper Cretaceous) its mainly composed of sandstone in different color and cemented materials and it is intercalated by gravel, grits and mudstone which are older than early Tertiary lavas[18]. Nubian sand stone cover about 40% of Sudan and the bulk of formation is confined to the northern part of Sudan. In the study area the Nubian sandstone formation cover the area between the river Nile and Atbara River and northern part of the delta area. The Nubian sandstone is continental origin and it is classified into three cycles [2] namely; lower, middle, and upper and suggested more than twenty formations and proposed as Cambrian–Ordovician to Tertiary age. Hudi Chert (Oligocene) these rocks are named after the Hudi locality lying on the railway line between Atbara and Port Sudan, the place where they were discovered for the first time. They occur as boulders consisting of fossil (gastrobods fssils) and ferrous cherty deposits or as bedded strata. They are variable in texture, very hard frequently possessing a concoidal fracture, their surface is usually yellowish, brownish to reddish in color and also occur as gravelly and breccias form, which give a reddish brown appearance. Sometimes they occur as small mounds made of Chert, gravels and boulders mixed with quartz pebbles and reddish clayey sands. And superficial deposit (Quaternary) its include silt of the river terraces (Nile river and Atbara river) and unconsolidated layers of gravel, sand, clays and sandy clay with kanker nodules as well as extensive sand dunes that almost occupy the southern part of the River Atbara [5, 15, and 18].

## II. Methodology

The purpose of building a conceptual model is to simplify the field problem and to organize the associated field data so that the system can be analyzed more readily. Except for the groundwater recharge all the spatially distributed data, e.g., the initial groundwater level, the top and bottom surface of the layers, the bottom of the riverbed, etc., had been first mapped with GIS by digitizing point data, line or polygon features. Conductivity, transmissivity and vertical leakance had been mapped with GIS by using quaternary deposits map and geological and lithological cross sections. The natural water system in the study area was investigated in three-dimensions using visual MODFLOW model code to minimize the difference between the observed and calculated values, to determine the optimum groundwater pumping patterns to minimize the adverse effect of overdraft, to evaluate the potential effects of storing additional groundwater in certain areas of the basin based on the results of the storage calculations and to study the impacts of increasing groundwater production in the basin by 20%. A parameter set has been generated, while MODFLOW [17] is used for the flow simulation. The three-dimensional format of the groundwater flow model was developed and run using WHS solver method. For ground -

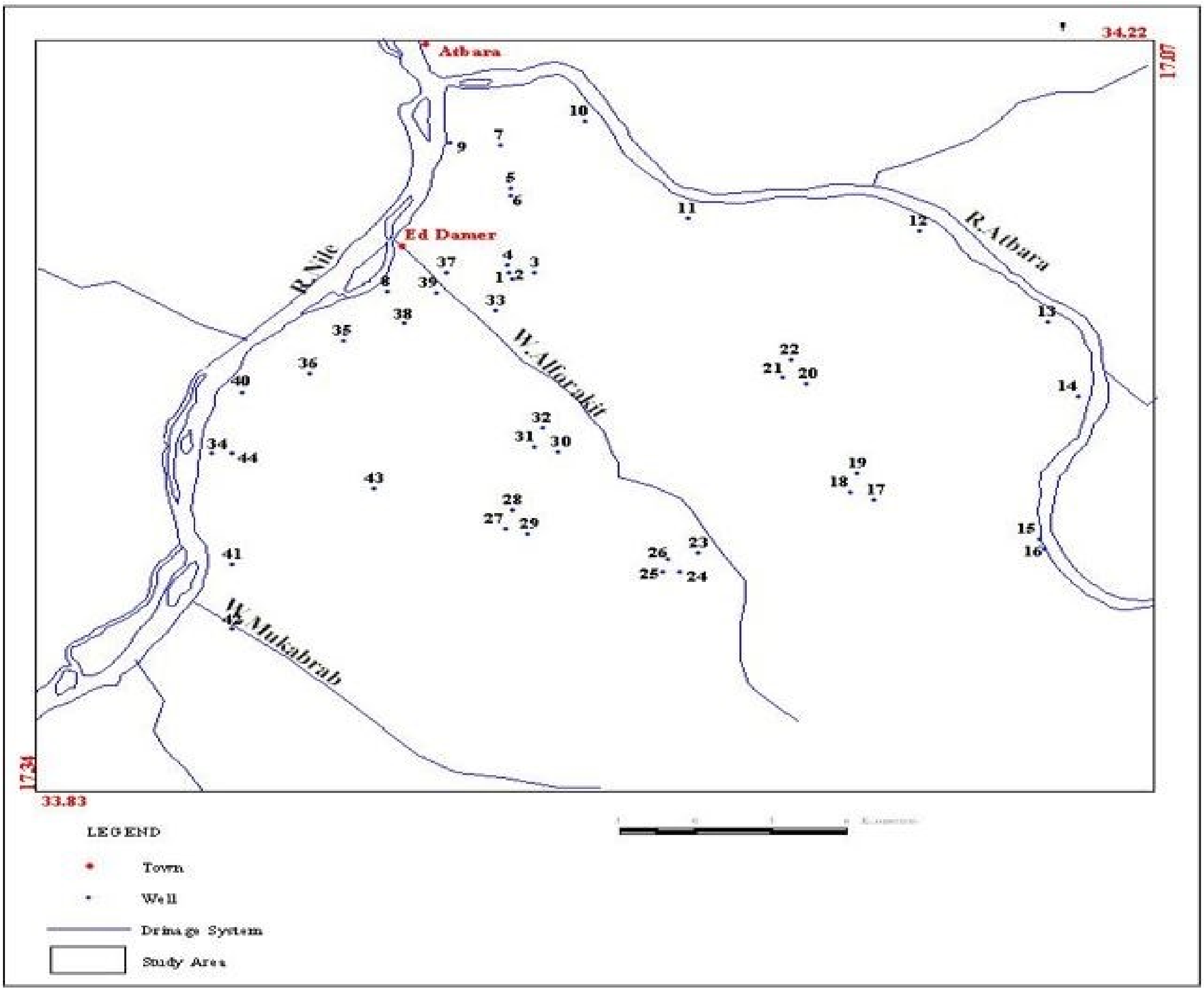


Fig. 1. Location map of the study area.

-water model calibration, the manual trial-and-error technique for adjustment of parameters was applied. The most important criteria that used to check the calibrated model are Root Mean Square error (RMS), the Mean Absolute error (MA), Normalized (RMS) and mass balance. The time dependent field data such as pumping rate, evapotranspirations, recharge, head observations and river stages were prepared in ASCII format files for the model input modules. The model domain encompassing the main well field was used for the zone budget model run to estimate the groundwater budget of the study area.

A. *Model Construction:*

In the recent years groundwater modeling has become a major part of many projects dealing with groundwater exploitation, protection and remediation. Continue to be improved and become more affordable, the role of models in highly quantitative earth sciences such as hydrogeology will increase accordingly. It is essential, however, that for any groundwater model, it should be interpreted and used properly, and its limitations should be understood. In addition to strictly “technical” limitations, such as accuracy of computations (hardware /software). The geographic boundaries of the model grid must be determined by using a base map. A finite difference grid was then superimposed over the whole area that designed and constructed, based on the simplifications of a conceptual model, to represent the physical properties of groundwater system. In plain view the blocks are made from a uniform grid or variably paced grids and a number of layers that can have varying thickness. Then a grid network, that composed numbers of rows, columns, layers and cells were used to cover the modeled area. Then initial conditions, hydraulic properties and stresses were specified for every model cell in the finite – difference grid. Then the program was run and results were obtained. In addition to technical limitations such as accuracy of computations (hardware and software), more problems were encountered in applying the model, because of its dependability on the various simplifying assumptions of the natural modeled system, approximations of the actual distributions of hydrologic and hydro geologic properties, that can never be determined most exactly, and the sets of algebraic equations replacing the partial differential equations are more or less accurate, suffering of lack scientific certainty, non-unique model problems and expensive data assembling costs and labor time. To overcome such limitations, it is important to understand the field behavior and all the assumptions that made to form the model, to avoid the misuse of the appropriate application of the concerned model based on the field situation. Model input data are essential to complete the model constructions and can be consisted of the parameter below. The aquifer was assumed to be confined, with thickness varies from 10 to 45 m. The upper surface of the aquifer (second layer) varies from 4 to33 m. The depth to groundwater table is about 9 to .34 m below the surface. Observation wells were used for monitoring groundwater heads during model simulations to reveal the water level distributions in the model area. There were fifteen observation wells used in the model area where the water level measurement taken at the years 2006 to 2008. Groundwater abstraction and evapotranspiration's were the main source of discharge. Therefore, groundwater pump age represent the main source of discharge. The main Nile and Atbara river were assumed to be the main source of recharge in the area whereas the direct precipitation (semi desert and the annual rain fall about 41.9mm /y and natural base flow represent additional source of recharge.

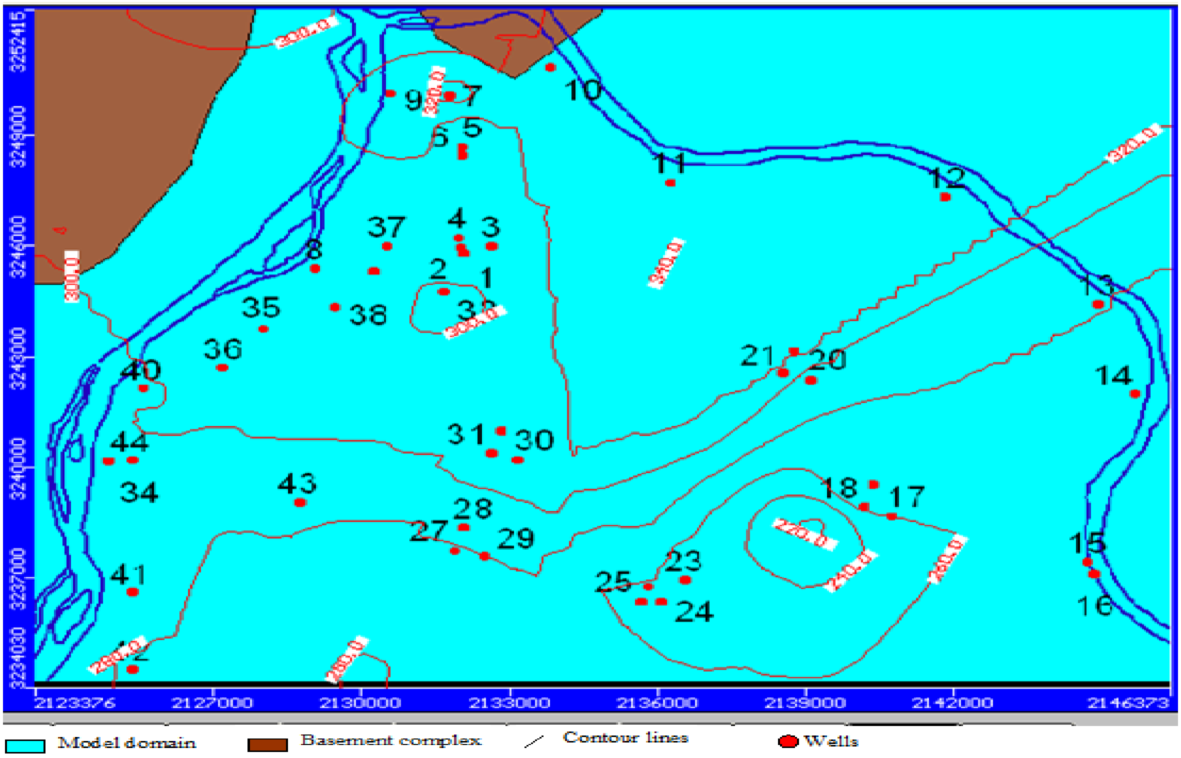


Fig. 2. Top elevation of the lower aquifer (layer 4) (m, a.m.s.l).

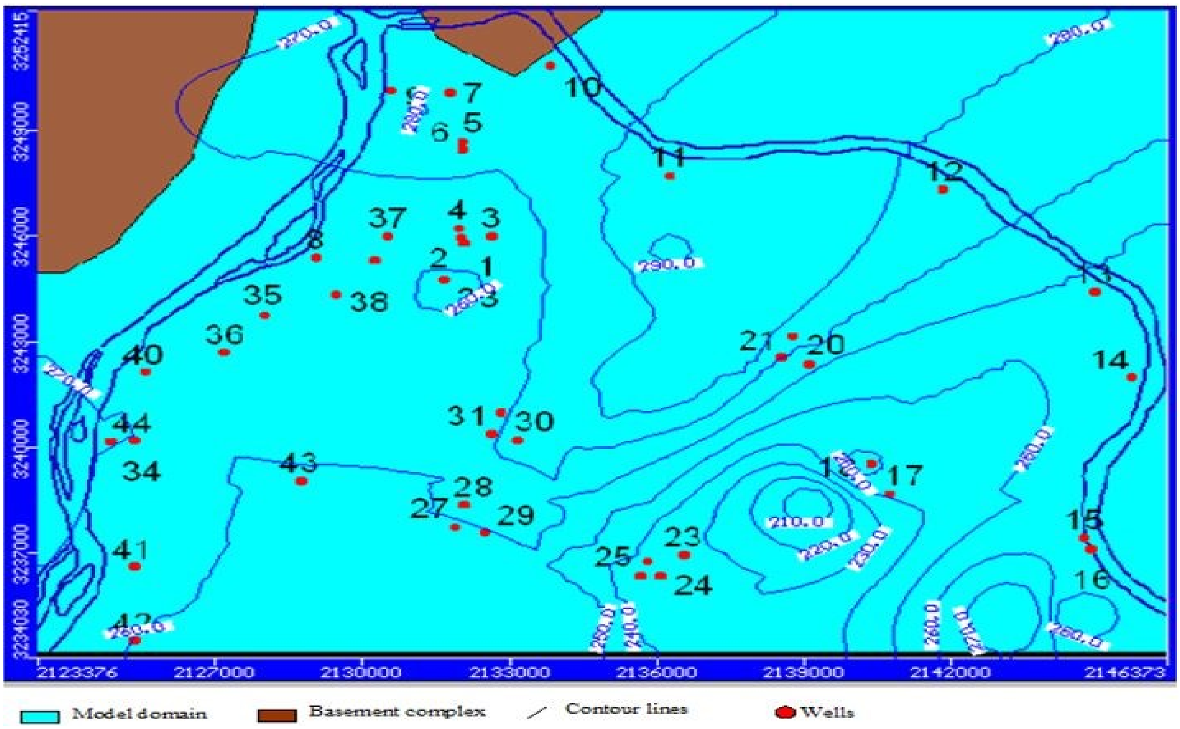


Fig. 3. Top elevation to the basement (m, a.m.s.l).

The hydraulic conductivity average value of 38.96m/d, in the area beside the river Nile in shape of film, and near the upper Atbara river comprise Manasir village 2 . The rest of the study area average 4.96 m/d. and the storage coefficient value of 2.59*10 - 5 for the first area and 2.61 for the second area were considered in the model simulation. The initial conditions are simply the values of the dependent variable (water head) specified everywhere inside the model domain or boundary at the time zero of measurements. The measured heads in the observation wells at the year 2006 to 2008 were used as initial head distribution for the model simulation. The bottom of the aquifer, the southern side of the model area was considered as general head boundaries. The eastern north-western north side and north of the model were taken as constant head boundary and the top of the aquifer as the variable head boundary, where flow may enter the model as a recharge from the main river Nile or Atbara River.

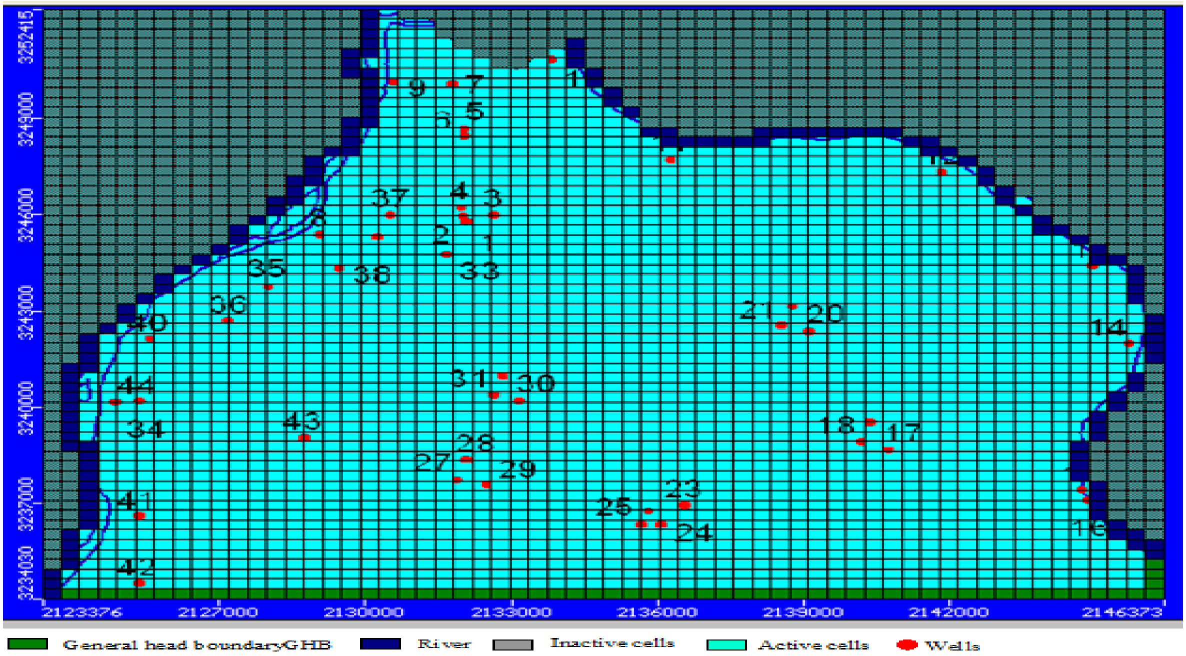


Fig. 4. Describe the model construction.

## B. *Model Calibration:*

Model calibration it's a process of finding a set of boundary condition, stresses, and hydro geologic paramete--rs, which produce the result that most closely matches the field measurements of hydraulic heads and flows. Calibration of every model should have the target of an acceptable error set beforehand. Its range well depend mainly on the model purpose. For example, a groundwater flow model for evaluation of a regional aquifer system can sometimes "tolerate" a difference between calculated and measured heads of up to several feet. This however, would be an unacceptable error in the case of a model for design of contaminant and cleanup of a contaminant plume spread over, say, fifty acres. In many instances the quality of calibration will depend on the amount and reliability of available field data. It is therefore crucial to assess these field data, or calibration data set, for their consistency, homogeneity and measurement error. Such assessment is the basis for setting the calibration target. Repeated model data adjustments are usually required before the best fit of the model calculations. Different accuracy criteria can be used to compare the simulated and measured data during the calibration procedures. The most important criteria that used to check the calibrated model were Root Mean Square error (RMS) and the Mean Absolute error. Another way of checking the amount of residual error is to compare the total simulated inflows and outflows as computed by water balance. Transient calibration was used to simulate time dependent problems. Transient head data can be displayed using a series of contour maps or hydrographs to show the transient variations of water level at selected nodes. For transient simulation, storage parameters, initial and boundary conditions and hydrologic stresses were specified. Time and space were descritized. During transient calibration, head changes with time as a result of water released from or taken into the storage within the porous medium. In performing transient calibration, parameters that describe the capacity of an aquifer to transfer water to and from the storage such as specific storage (Ss), storage coefficient (S) and specific yield ($S_y$) were assigned. Storativity is often assumed to be uniform within an aquifer or confining bed. The effects on the boundary should always be evaluated by checking the change in flow rates across specified head boundaries and change in head across specified flow boundaries. For specified head boundaries the flow across the boundary is the same for the initial conditions and for the final time step of the transient solution. If the resulting changes in the head solution are insignificant, the boundary does not affect the solution [9]. A three-dimensional finite difference flow model was designed and calibrated to quantify the hydrologic parameters representing the hydrogeologic units of the study area and provide the overall hydrologic budgets. Hydraulic heads in the study area were used to calibrate the model for the period from January 2003 to March 2005. The simulation time interval was divided into 27 stress periods each descritized to ten time-steps. The model was calibrated, only, using trail-and-error technique to the selected input parameters against groundwater levels of 15 observation wells in the model domain under transient conditions. The objective of the calibration is to minimize the difference between the observed (measured) and calculated (simulated) values, sometimes called the calibration criterion. The residual between observed and calculated heads was used to calculate the root mean squared error (RMS) and the mean absolute error (MAE). During model calibration, model parameter values were adjusted so that simulated heads and mass balance would fall within the calibration targets. After each run, differences between simulated and observed heads were calculated with the goal of every difference being minimal. To check the hydraulic behavior of the alluvial aquifer in the model area the type model boundaries were altered in consecutive model runs. Statistical analysis was performed by visual MODFLOW after manual Trial-and-Error adjustment to the selected input parameters. It involves regression analysis and the calibration of Root Mean Squared error (RMS) and Mean Absolute error (MAE). Moreover, Residual Mean and Normalized Mean Squared Residual were also used for calibration adjustment. A prior calibration targets and criteria have been adopted based on the discrepancies between the measured and the observed groundwater heads at the 15 groundwater observation wells (Fig. 2). During earlier stages of model calibration, an adjustment of the general head boundary (GHB), river stage, riverbed conductance, pumping rates, and recharge was performed to minimize the discrepancy between the observed and simulated heads. The aquifer hydraulic conductivity, storage coefficient and specific yields considered to be constant for the entire period. The main calibration targets are heads and mass balance. Since the stresses such as pumping rate, precipitation to the study area varies with the time (transient conditions), the heads distribution and mass balance vary from one stress period to the other. During calibration, the time dependent parameters' values were increased when the observed heads were higher than calculated head and decreased when the observed head was lower than the calculated heads. Hundreds of model runs were performed to achieve a calibration. A scatter plot of measured against simulated heads is one of the momentous ways of showing the calibrated fit. Deviation of points from the straight line (regression line) should be as minimal as possible. A scatter plot is helpful in detecting trends and demonstrating that all the points lie along the regression line.

## III. Model Results

The calibration of the three dimensional finite difference flow model of the study area was performed using the Root Mean Squired Error (RMS), Mean Absolute Error (MAE), Normalized (RMS) and mass balance percent discrepancy. The model calibration criteria such as mean absolute error (MAE), root mean square error (RMS) and mass balance error of water into and out of the system were adjusted to less than 0.132 m, 0.376 m and 0.05% respectively. However the calibration will be more acceptable with average (RMS) of 0.116m and average absolute mean error (AM) of 0.085m and average normalized root mean square (NRMS) of (1.516%).

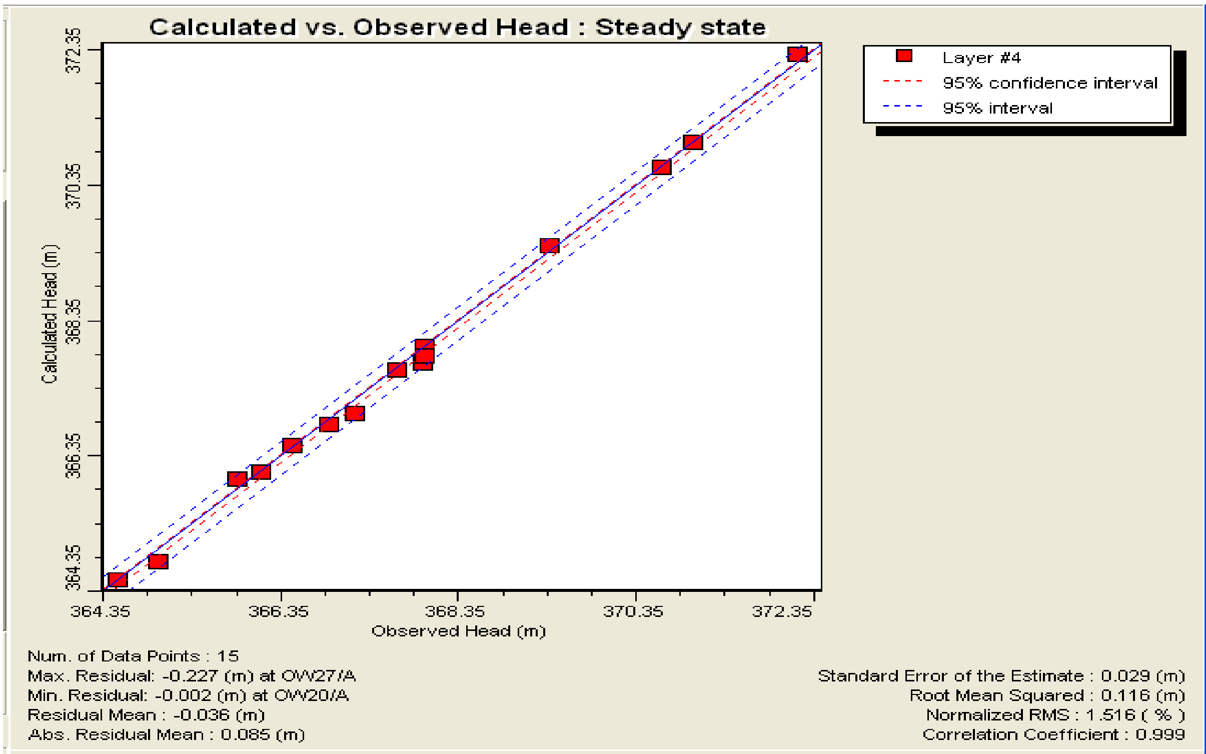


Fig. 5. Show the model calibration criteria.

The contour map of the simulated heads were drawn using visual MODFLOW post-processing tool representing one stress periods 730 days, for the 44 pumping well. The contour lines from the West and North West show the recharge from the river Nile with decreasing of head towards the East making cone of depressions in the top left of the study area East Aldamer. That cause of high pumping (discharge) in this area (Figure 6). Also three Anomalous cases in the south middle of the study area, the cause of this anomalous is heavy abstraction of the aquifer in that area. the contour line in South- East of the study area show the recharge from Atbara River towards North west making cone of depressions in the top right of the study area (Figure 6), the cause of depression is the discharge and the natural depression in that area, in the middle of the study area the contour line become more closer that causing steep hydraulic gradient towards the centers of the cone of depression at the model domain. At the eastern side of the model domain there is a sign of water divide where groundwater flows into two inverse directions (Figure 6).

*Groundwater Zone Budget*

Based on general hydro geologic principles, a groundwater budget was prepared to estimate the amount of groundwater inflow, out flow and changing in storage. The field–estimated inflows may include groundwater recharge from precipitation, overland flow, subsurface base flow along the boundaries, or recharge from surface water bodies. Outflows may include spring flow, base flow, evapotranspiration and pumping. A water budget should be prepared from the field data to summarize the magnitudes of these flows and changes in storage. Average recharge over a long period of time in the model area can be estimated by interrogating the water budget details of the robust numerical groundwater model, which replicate faithfully the main, recharge processes in a natural system. Generally the visual MODFLOW computes flow-rate and cumulative budget balance from each type of inflow and outflow for each time step for the whole area and does not report the cumulative budget for other individual zones, which are required for long–term estimation. Moreover, it provides instantaneous budget for user defined zones for individual layer and aggregated layers. However statistical operations were used to report the cumulative budget. Groundwater budget was calculated for the whole model area, the calculated zone budget components include river leakage, wells, and recharge and general head boundary (GHB).

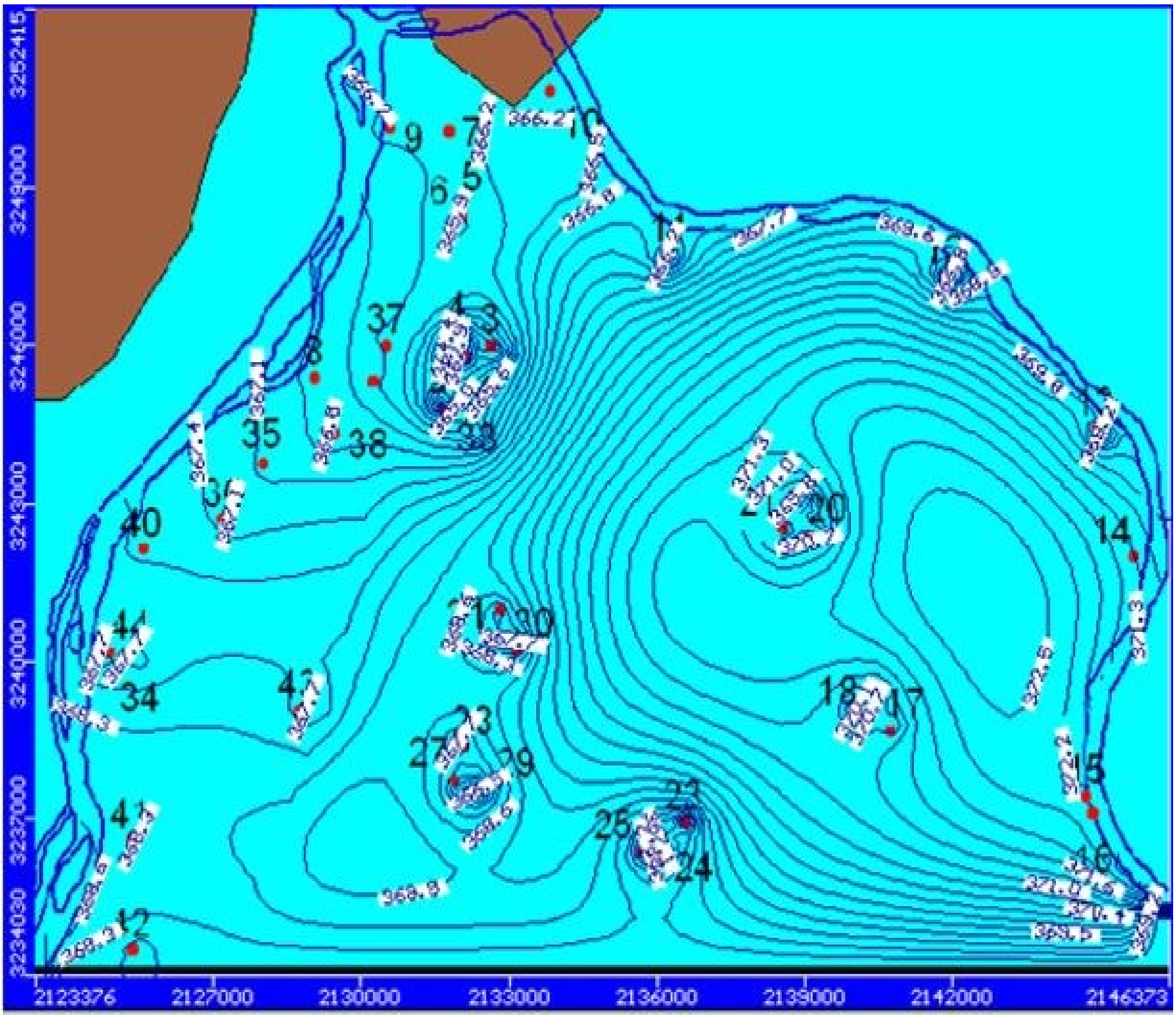


Fig. 6. Simulation head contour map of the study area.

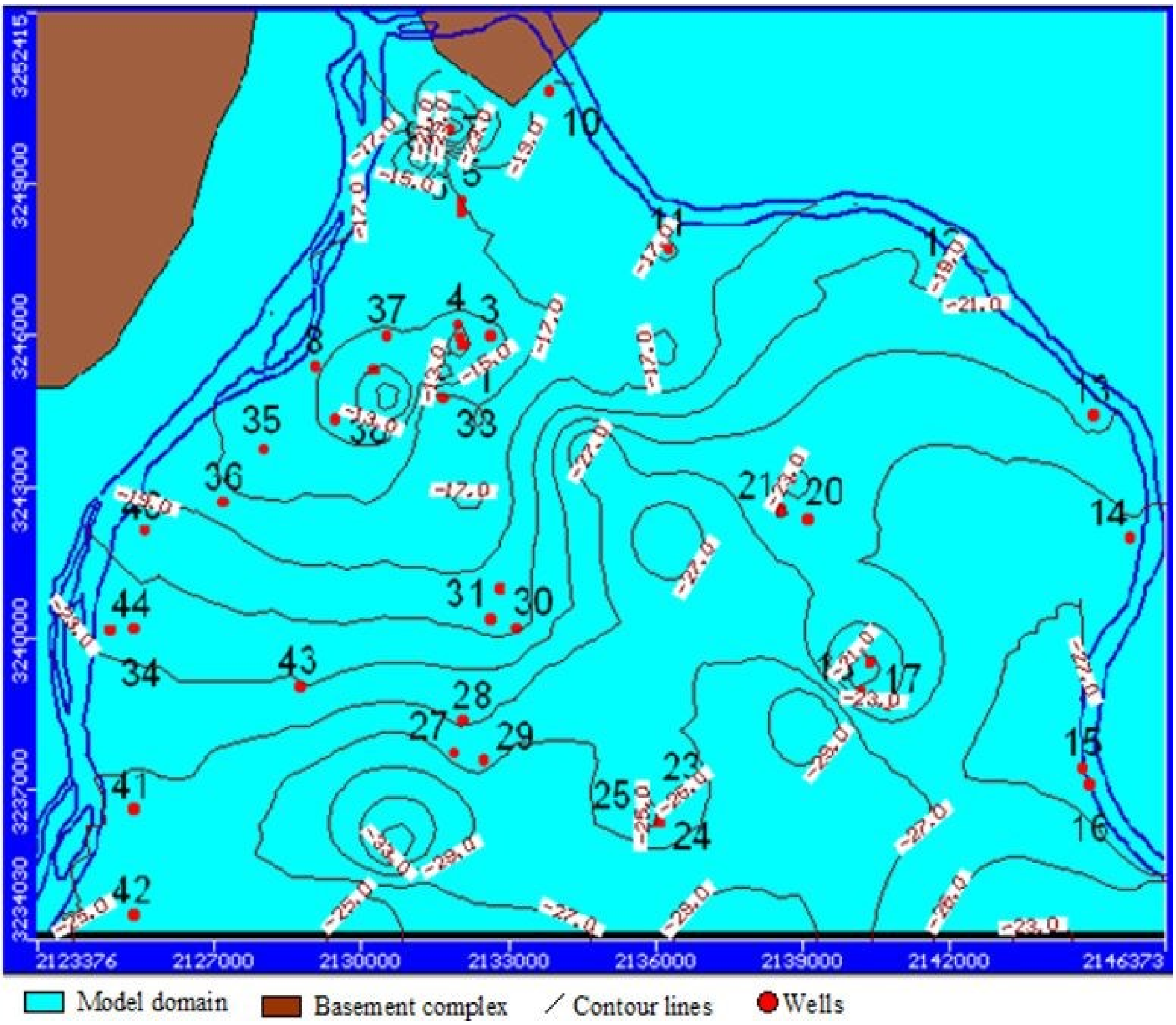


Fig. 7. Drawdown distribution of study area.

The zone budget was calculated for one stress periods respectively (table1). The volume of water in cubic meter per day ($m^3/d$) and its percentage was calculated for each component of the hydrologic budget. Recharge is the most important hydrologic component of inflow to the aquifer, which is able to offset the groundwater extraction from the aquifer. The total volume of the river leakage for the one stresses periods is 11433.00 ($m^3/d$) and represent 20.77% from total inflow. Groundwater pumping volume in the entire area computed by the model was constant of 35493.00 ($m^3/d$) throughout the simulation period, which represent 64.51% of the total outflow from the aquifer The general head boundary flow 174.82 and the out flow 12136.00 ($m^3/d$) represents 22.06% from the total out flow. The recharge water volume was 43434.00 ($m^3/d$) and represent 78.91% of the total inflow.

Table 1. Show the budget percentage.

| Component | Inflow (m3/day) | % | Outflow (m3/day) | % |
|---|---|---|---|---|
| River leakage | 11433.00 | 20.77% | 6072.60 | 11.03% |
| General head boundary | 174.82 | 0.317% | 12136.00 | 22.06% |
| Wells | 0.00 | - | 35493.00 | 64.51% |
| Recharge | 43434.00 | 78.91% | 0.00 | - |
| Et | 0.00 | - | 1310.80 | 2.38% |
| Total | 55042.00 | - | 55012.00 | - |

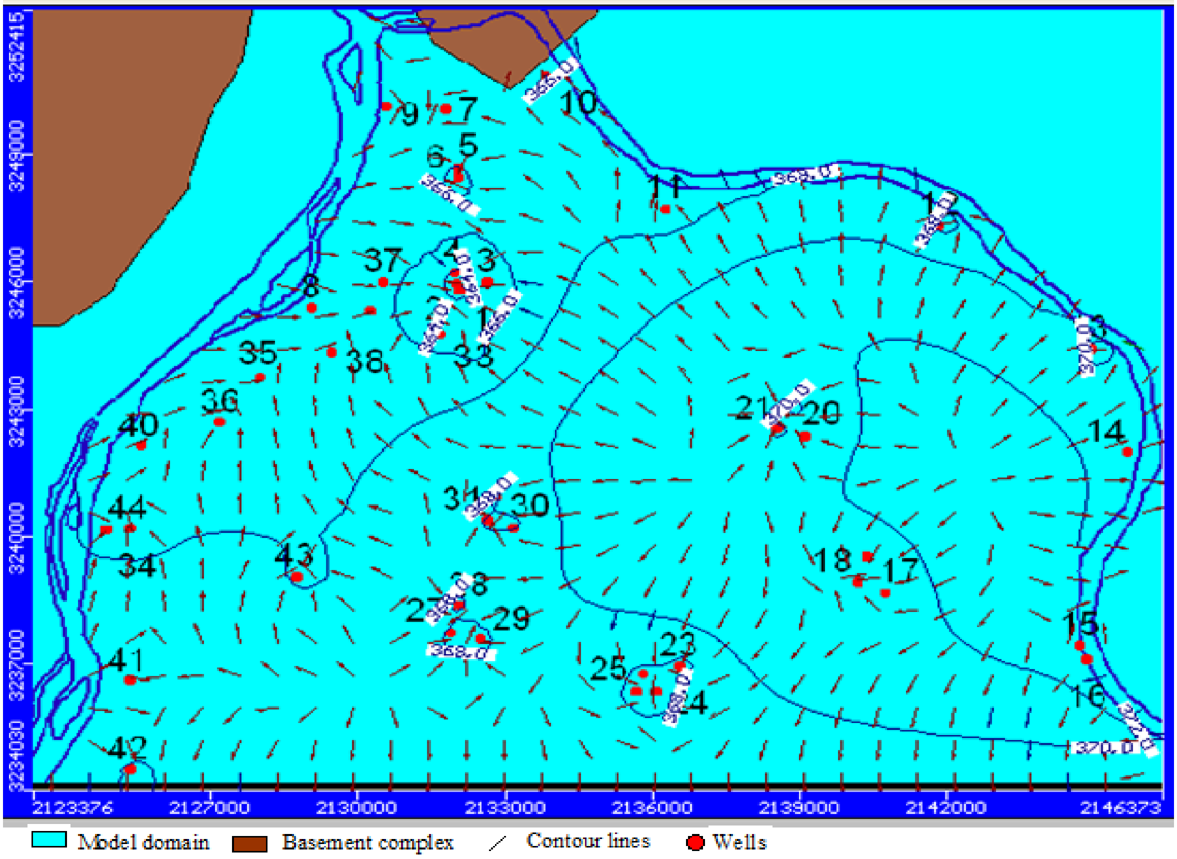

Fig. 8. The flow direction in the study area.

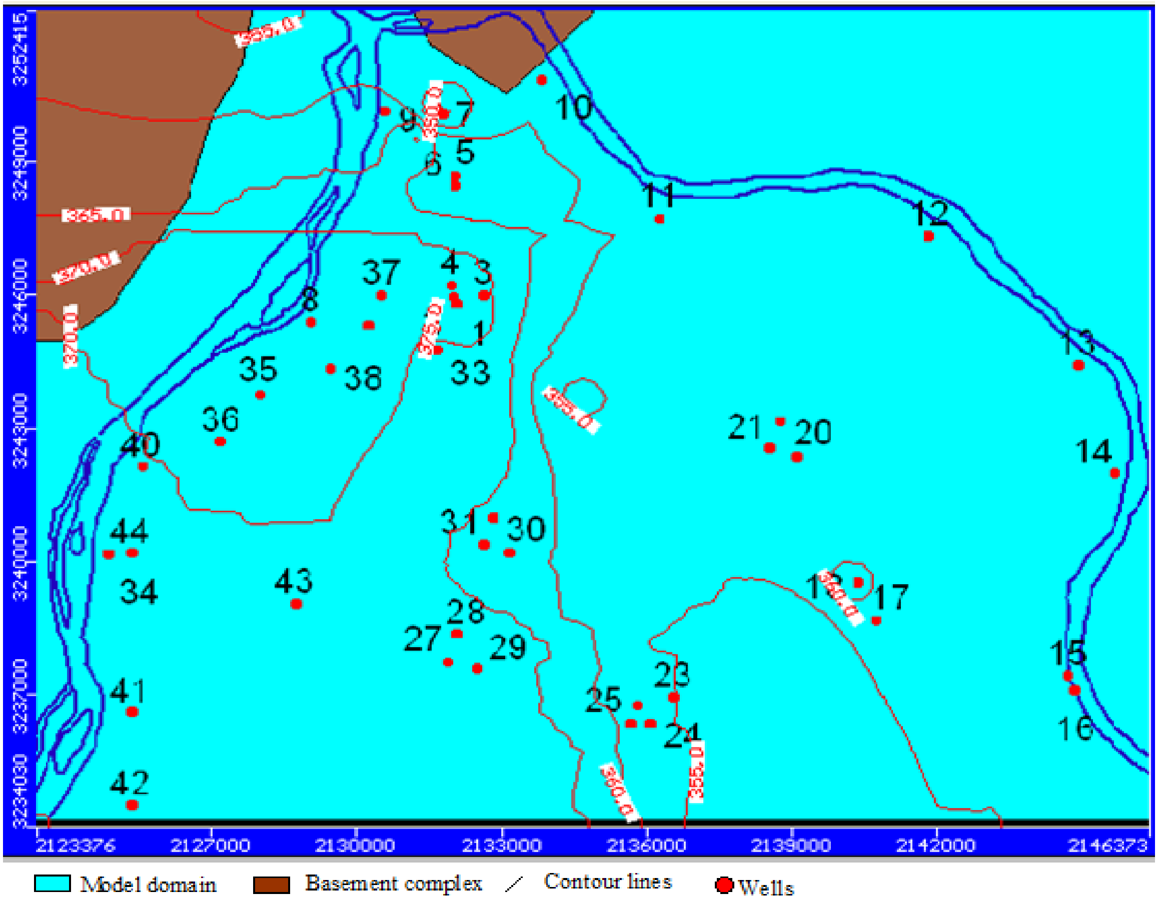

Fig. 9. Topographic elevation in the study area.

## IV. Conclusions

The calibration of the three-dimensional finite difference flow model of Aldamer area was conformed, and the calibration was more acceptable with the average root mean square error (RMS) of 0.7m, residual mean of – 0.045 m and average absolute mean error of 0.1 m. The Normalized Root Mean Squared (RMS) value was measured at 2.3% and well within the 10% norm. The contour map of the simulated heads, drawn using visual MODFLOW post-processing tool bears a fairly close similarity to the map of potentiometric surface of the initial head drown from measured data elaborating acceptable model calibration. In the west central part of the area, relatively high permeability zone can be inferred from widely spaced simulated equipotential lines. Hence, this area was considered as having quite an enhanced permeability and confirmed to be the most productive region in the area and recommended for storing additional groundwater even the production was increased by 20%. Therefore, to maintain the sustainable development, the annual abstraction rate as groundwater pumpage should not exceed 156 million m3 under the prevailing conditions.

## Acknowledgement

Authors were indebted to Non-Nile Water Corporation, Atbara Branch for providing most of hydrogeological data and direct support during field work in the study area; and also thanks to the International University of Africa and Al Neelain University for generous support which helped to improve the manuscript.

## References

[1] Afaa, A. E.Osman; (2005) Assessment and simulation of ground water potential in the area east of the river Nile Khartoum state.
[2] Ahmed and Abdrahman; (1996) studied the capacity of ground water wells around Atbara area and the use of ground water for different purposes.
[3] Anderson, M.P. & W.W. Woessner; (1992) Applied ground water modeling, Simulation of Flow and Advective Transport, pp.1-27.
[4] Awad; (1982). General survey for natural resources in central north including Kenedra basin.
[5] Ayed, M.A.; (1994) Assessing ground water using electrical resistivity technique to delineate the contact of Nubian and basement in Atbara basin.
[6] Bakker, M. 1999. Simulating groundwater flow in multi-aquifer systems with analytical and numerical Dupuit-models. Journal of Hydrology, 222: 55-64.
[7] Book 6, Chapter Al. Technical Report, US Geological Survey, Reston, Virginia, USA.
[8] Chen, X.H., Migration of Induced – Infiltrated Stream water Into nearby Aquifers due to Seasonal Groundwater Withdrawal. J. Groundwater, 39 (5): 720 – 728.
[9] De Marsily, G., 1986. Quantitative Hydrogeology, Academic Press, 440 p.
[10] Edwards, W. N. (1926) Fossils plants from the Nubian Sandstone of eastern Darfur – Q. J. Geol. London 82, p. 94-100.
[11] Groundwater flow model. US Geological Survey Techniques of Water resources Investigation.
[12] Guifer, N. and T. Franz, 1997. User's manual for Visual MODFLOW. Waterloo Hydrogeologic Inc.
[13] Hggaz .Y and other ;( 1990) Ground water in north and West Africa (natural resources/water series no.18)
[14] Himmelsbach, T. and R. Buter, 2001. Conceptual hydrogeological model to assess groundwater resources of the heterogeneous fractured aquifers at Tsumeb (Northern Namibia), In: New Approaches Characterizing Groundwater flow, Seiler and Wohnlich (Eds), Balkema Publication, 1: 245-249.
[15] Kheiralla; (1981) has carried out comprehensive study of ground water resources of the northern Sudan.
[16] Konikow L.F. and J.D. Bredehoeft, 1978. Computer model of two-dimensional solute transport and dispersion in groundwater. US Geological Survey Techniques of Water Resources Investigation Book 7, Chapter C2.
[17] McDonald, M.G. and A.W. Harbaugh, 1988. A modular three-dimensional Finite-difference
[18] Mukhtar, M ;( 1999). Evaluation of ground water in Atbara basin by resistivity methods.
[19] Province, Sudan. - Bull. Geol.Surv. Sudan, 18, 76 pp., Khartoum.
[20] Refsgaard, J.C. and H.J. Henriksen, 2004. Modeling guidelines, terminology and guiding principles, Advance Water Resources, 27: 71-82.
[21] Sadam Hassan M.A. (2011): Hydrogeological Assessment Based on Ground Water Flow Modeling Around Atbara Town. Msc. Thesis, Sudan Academy of Science Engineering Research and Industry Technology council.
[22] Saeed, E.M., 1969. Groundwater Appraisal of the Gash River Basin at Kassala, Kassala Province. Bulletin No. 17 pp. 6-26.
[23] Scarborough, J. B. 1966. Numerical mathematical analysis, John Hopkins Press. Baltimore.

## Authors Profile'

**Sadam. H.M.A. Eltayib**
Assistant professor at International University of Africa, Dept. of Petroleum Geology Faculty of Minerals & Petroleum, –Khartoum, Sudan
Cell Phone: ++249900541522
Email: sadam_h3@yahoo.com

**Adil B.M. Elkrail**
Professor of hydrogeology at department Of hydrogeology, Faculty of Petroleum &Minerals, Al Neelain University, Khartoum – Sudan
Postal Code: 11121, P. O. Box: 12702;
Cell Phone: ++249918268272
Email: adilmagboul321@yahoo.com