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Numerical simulation of groundwater flow in southeast of el Damer town, river Nile state – Sudan

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Abstract

The use of groundwater flow models is prevalent in the field of hydrogeology to predict the effects of the external stresses exerted on aquifer system for risk evaluation purposes. In this paper, the authors develop a groundwater flow model in Atbara basin, southeast of Atbara town by using Visual MODFLOW. The purpose of this paper is to investigate the aquifer potentiality with emphasize on groundwater flow and head distribution as well as zone budget using suitable modeling techniques. Hydrological parameters have been calibrated based on the available data observed. The model calibration criteria such as absolute residual mean (ARM), root mean square error (RMS), normalized (RMS) error and mass balance discrepancy of water into and out of the system were adjusted to produced good fit between observed and calculated hydrogeological parameters. Accordingly the calibration is more acceptable with absolute residual mean(ARM) of 0.085m, root mean square error (RMS) of 0.116m, normalized (RMS) error of 1.516% and mass balance discrepancy of 0.05%. The groundwater level decreases from the western side (River Nile) and Eastern side (Atbara River) towards the center of the study area, indicating potential contribution of both rivers in recharging the groundwater aquifers. The calibrated results show that the computed water heads reflect good fit with the measured data, which indicate that the conceptual model and the parameters used in the model can reflect the actual physical system of the study domain. Hence, the model can be applied further to predict the changes of groundwater levels and mass balance under different exploitation scenarios considering the future water demands in the study area.

Keywords

Numerical Model, Groundwater, Simulation, Atbara Basin

1. Introduction

Groundwater model is regarded as the best tool to conceptualize the hydrogeological situation in the groundwater basins [1], [2] and to predict the potential environment and socioeconomic impacts of the groundwater abstractions. Groundwater flow models have been extensively used for such problems as regional aquifer studies, groundwater basin analysis, and near-well performance [3]. Simplification of the complex natural processes, the high spatial and temporal variability, and the limited availability of observations and identification of the model parameters are difficult tasks. Even physically-based models require parameter adjustments due to differences between the observation and modelling scales, and to a limited observability of certain variables and processes. Understanding the general role of parameters in models and the impact of varying model parameters on the response of prediction models is a relevant subject in various fields of science and engineering [4]. Conceptual models require model calibration to estimate parameter values [5], [6], [7]. Model parameter values determined through inverse modeling are products of their relation to the input data and different sets of calibration data will yield different parameter estimates, although each may fit the calibration data equally well [8].

The purpose of this paper is to design an appropriate groundwater model with suitable modeling techniques for investigating the aquifer potentiality with emphasize on groundwater flow direction and head distribution and groundwater budget in Atbara basin.

2. Characteristics of the Study Area

The study area is part of Atbra basin, lies northeast of El Damer town, River Nile state, between latitudes 17° 40' 12" -17° 20' 23" N and longitudes 33° 49' 47" – 34° 13' 11" E (Fig.1). It covers an area of about 597 Km2. The area is, extremely flat, gently dipping to the northwest. Sand dunes and low ridges with thin blanket cover of scatter cobble, pebbles and boulders characterize the undulated surface of the area. The area is in the zone of semi desert climate with long summer and low rainfall intensity (84 mm/year) and cold dry winter. River Nile , Atbara River and seasonal wades are the main drainage system [9].

The geological setting is composed mainly of Pre-Cambrian Basement Complex, Cretaceous Sedimentary formation, Tertiary Hudi Chert and Quaternary deposit (Fig. 2). The *basement complex* is composed of highly deformed and metamorphosed gneisses and schist. Subsurface fissures, fractures and joints generated from shearing activities in addition to weathered basement may stored considerable amount of groundwater. The *Cretaceous sedimentary* formation is mainly composed of sandstone, mudstone, shale and conglomerates where the total drilled thickness was over 400 m [9]. This formation is characterized by thick layers of mudstone up to 300 m. The Tertiary *Hudi Chert* occurs as unconsolidated boulders and cobbles characterized by fossilferrous chert deposits. *Quaternary Alluvial deposits* (Umm Ruwaba Formation) at east and northeast of the area varies from 90 to 220 meters, dominated by intercalations of friable sand, gravel, clay and silt layers. Kanker nodules occur in the upper zone within gravel and sand sheets particularly in the east central part of the area. Fluvial and lacustrine fancies are not uncommon.

The Cretaceous sedimentary formation and Quaternary alluvial deposits represent the main water- bearing formations. Mainly two aquifer zones were recognized namely; shallow semi-confined to confined alluvial aquifer (3 - 30 m thick) and deep confined Cretaceous sedimentary aquifer (>55 m thick) characterized by very good water quality. The hydraulic conductivity of the shallow aquifer vary between 3-39 m/d whereas average hydraulic conductivity of deep aquifer was found to be 4.5 m/d and the maximum storage coefficient is 3.697% .

3. Methodology and Model Construction

To design and construct equivalent but simplified conditions, extensive information is required on the natural system. Simplification is necessary because a complete reconstruction of the field system is not feasible. Theoretically, the closer the conceptual model approximates the field situation the more accurate is the numerical model. Hence, the groundwater system in Atbra Basin was simulated at steady condition using three dimensional finite difference flow model with visual MODFLOW code to investigate the aquifer potentiality with emphasize on groundwater flow direction, head distribution and groundwater mass balance. ArcGis software was used as spatial analyzer for constructing the conceptual model. Grid network, that composed of 60 rows, 60 columns, 4 layers and 14400 cells were superimposed on the conceptual model to cover the modeled area. The initial conditions, hydraulic properties and stresses were specified for every model cell in the finite difference grid. The aquifer hydraulic conductivity, storage coefficient and specific yield considered constant of each zone for the entire period. Other hydrologic parameters are time dependent such as recharge, pumpage, evapotranspiration, and general head boundaries. Then the three-dimensional format of the groundwater flow model was developed and run using WHS solver method. Four geologic units encompassing the two aquiferous zones were used. Fifteen observation wells were used for water level measurement (Fig.1). Numbers of production wells were used to exploit the groundwater from variable depths in the two aquifer zones (Fig.1). The measured heads in the observation wells for two years were used as initial head distribution for the model simulation. Boundary conditions were performed through the river package, General head (GHB) and variable head boundary surrounding the model domain.

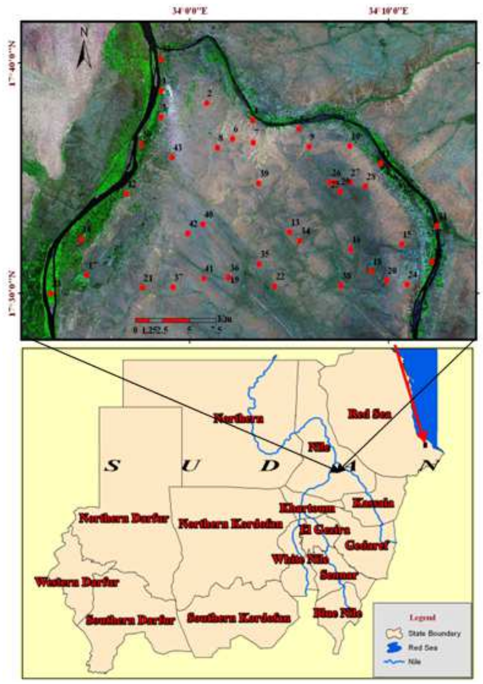

Fig 1. *Locality & Well location map of the study area.*

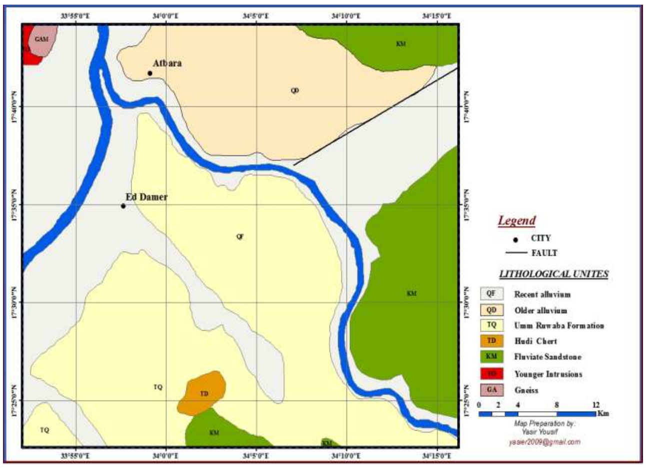

Fig 2. *Geological map of the study area.*

4. Model Calibration, Results and Discussion

Calibration is a process of finding a set of boundary conditions, stresses, and hydro geologic parameters, which produce results most closely matches field measurements of heads and fluxes. The main calibration targets are heads and mass balances. Calibration was performed by adjusting the hydrologic parameters until the model approximated field-measured values of head and pumping rates using the trail-and error procedure. The results of each model execution were compared to the calibrated targets. Hundreds of model runs were performed to achieve a calibration. A scatter plot of measured against simulated heads is one of the ways of indicating the suitable fitness. Deviation of points from the straight line should be as minimal as possible.

The model calibration of the study area was performed using the absolute residual mean (ARM), root mean square error (RMS), Normalized (RMS %) and mass balance discrepancy of water into and out of the system. These calibration criteria were adjusted to 0.085m, 0.116m, 1.516% and 0.05% respectively (Fig. 3, Table 1). The model results show that the computed values are in good-fitness of the measured data(Fig.2), which indicate the conceptual model is reasonable and it can be applied further to predict the changes of groundwater levels and mass balance under different exploitation scenarios considering the future water demands in the study area.

Simulated spatial distributions of groundwater level are presented in figure 4.

The groundwater level decreases from the western side (River Nile) and Eastern side (Atbara River) towards the center of the study area, indicating potential contribution of both rivers in recharging the groundwater aquifers. Cone of depressions were appeared at the central north and central south of the study area due to local heavy abstraction through the pumping wells. The hydraulic gradient is gentle at western part compared to steep gradient at the eastern part as reflected from contour spacing. This may ascribed to heterogeneity and anisotropy of aquifer characteristics.

The volume of water in cubic meter per day (m^3/d) and its percentage was calculated for each component of the hydrologic budget.

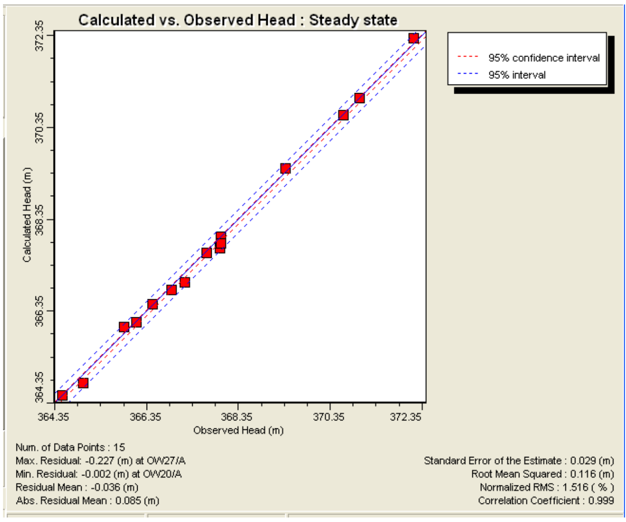

Fig 3. *The fitness of computed and observed water head.*

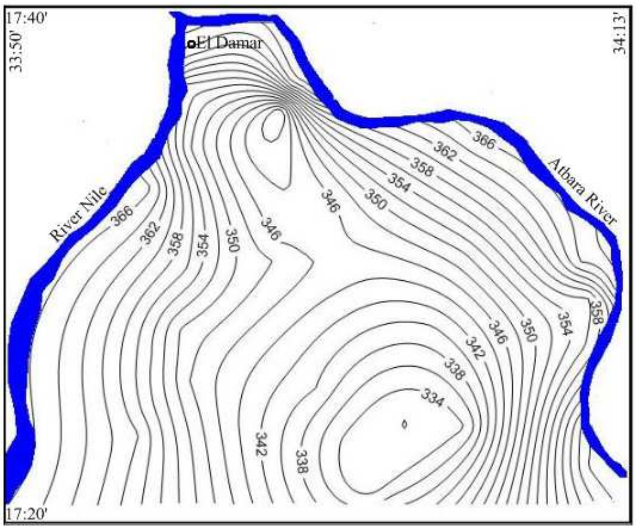

Fig 4. *Groundwater level (m) in the Atbara aquifers simulated with visual modfow.*

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 is 11433.00 (m^3/d) and represent 20.77% from total inflow. Groundwater pumpage in the entire area computed by the model is constant of 35493.00 (m^3/d) throughout the simulation time, which represents 64.51% of the total outflow from the aquifer. The general head boundary inflow is 174.82 whereas outflow is 12136.00 (m^3/d) represents 22.06%from the total outflow. The recharge water volume is 43434.00 (m^3/d) representing 78.91% of the total inflow (Table 1). The discrepancy between inflow and outflow was estimated to be 0.05%.

Table 1. *Calculated groundwater budget in the model domain.*

Components	Inflow (m^3/d)	%	Out flow (m^3/d)	%	Discrepancy	%
River leakage	11433.00	20.77	6072.60	11.05		
General head boundary	174.82	0.317	12136.00	22.06		
Well pumpage	0		35493.00	64.51		
Recharge	43434.00	78.91	0	0		
Evapotranspiration	0		1310.80	2.38		
Total	55042.00	100	55012.00	100	29.741	0.05

5. Conclusion

The groundwater system in Atbra Basin was simulated in three-dimensions in steady condition using visual MODFLOW model code to investigate the aquifer potentiality with emphasize on groundwater flow direction, head distribution and groundwater mass balance. Calibration was performed by adjusting the hydrologic parameters until the model approximated field-measured values of head and pumping rates using the trail-and error procedure. The model calibration of the study area was performed using the absolute residual mean (ARM), root mean square error (RMS), Normalized (RMS) and mass balance discrepancy of water into and out of the system. The groundwater level decreases from the western side (River Nile) and Eastern side (Atbara River) towards the center of the study area, indicating potential contribution of both rivers in recharging the groundwater aquifers. Cone of depression were appeared at the central north and central south of the study area due to local heavy abstraction through the pumping wells as well as heterogeneity and anisotropy of aquifer characteristics. The model results show that the conceptual model is reasonable and it can be applied further to predict the changes of groundwater levels and mass balance under different exploitation scenarios considering the future water demands in the study area.

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