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Numerical Modeling of the Groundwater Flow in the Area Around Atbara Town, River Nile State, Sudan

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INFORMATION

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ABSTRACT

This paper emphasized on the numerical modeling of ground water as it is vulnerable resources to many environmental risks and is essential to sustainable development. The main geological units in the study area are Pre-Cambrian Basement Complex, Upper Cretaceous sedimentary formation, Oligocene Hudi Chert and Quaternary superficial deposit. 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 Atbara basin of Sudan. The model was calibrated using 3D Finite difference visual MODFLOW. The model calibration criteria such as absolute residual mean, root mean square error and mass balance error of water into and out of the system were adjusted to suitable values. Hence, model calibration seemed to be more acceptable with average of 0.756 m and average absolute residual mean of 0.633 m and average normalized root mean square of 2.45%. The contour maps of the simulated heads produced by visual MODFLOW show fair similarity with the contour map drawn using initial heads which confirm the reliability of visual MODFLOW application and acceptable model calibration for the problem. Therefore, numerical simulation indicated that, a sharp drop of hydraulic head can be observed at the center of the model area, east of Atbara River, generated cone of depression and a continuous decline of head with respect to the time as a result of heavy groundwater abstraction. The southwest part of the area between Atbara River and River Nile represents 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.

1. Introduction

The ground water problems related to water supply are normally described by one of equation, in term of hydraulic head (Drever, 1997). The resulting model providing a solution for this equation is related to as ground water flow model. The classical method of representing a complex geologic formation within a sedimentary basin for the purpose of simulating hydrogeologic behavior is to first decompose it into aquifers (layers of high permeability) and aquitards (low-permeability media) and then to represent the system schematically as multilayered (Hem, 1985; Anderson and Woessner, 1992; Hem, 1992). One or several of these layers may sometimes be discontinuous, as when an aquitard pinches out, which allows the overlying and underlying aquifers to form a single aquifer.

This schematic framework is based more on correlating major geologic and geophysical features between boreholes than on the petrophysical properties of the rocks. Once the geometric framework has been established, it is seldom modified. Instead, the layers are discretized further by means of a numerical grid, and each cell of the grid is assigned parameter values, such as permeability or transmissivity in the aquifers and vertical permeability in the aquitards (Frapporti et al., 1993; Malcolm and Soulsby, 2001). These parameters are derived from pumping tests, or sometimes, specific-capacity tests. The latter are viewed as local values, which must somehow be averaged over "homogeneous zones" or, preferably, interpolated by geostatistical methods such as kriging or cokriging correlated with other geologic or geophysical variables (Anderson and Woessner, 1992). The last stage in the modeling involves modifying the parameters, either manually or by some "inverse" method, so as to render the predictions of hydraulic heads and fluxes comparable with measured values (ElKrail and Salah, 2013; Sener and Davraz, 2013).

Vertical permeabilities of aquitards are usually estimated in this manner because they are rarely amenable to direct measurements, although they can sometimes be surmised from longterm pumping tests by using leaky-aquifer theories. For this study the visual MODFLOW software was selected as computer code to simulate groundwater flow model in the study area (Piper, 1944).

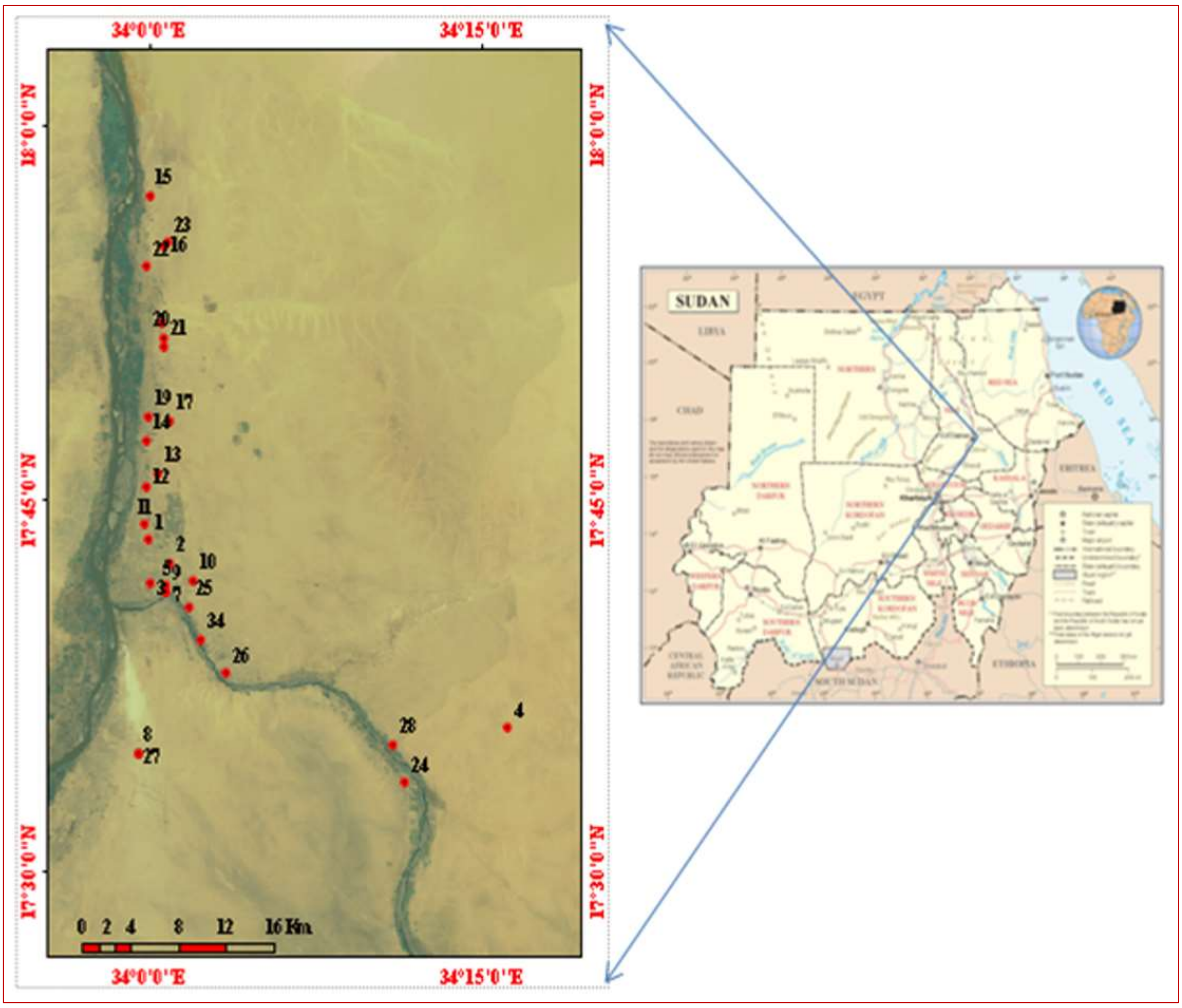

Fig. 1. Location map of the study area

2. The Study Area

Study area lies between latitudes 17° 34' -18° 00' N and longitudes 33° 55' – 34° 43' E covers an area of about 673 km2 (Fig. 1). It 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 lies in semi desert climate with long summer and low rainfall intensity (84 mm/year) and cold dry winter. River Nile and Atbara River and seasonal wades (e.g., Wady Mukabrab) are the main drainage system (Eltayib and Elkrail, 2018). The main geological units are composed of Basement Complex (Pre-Cambrian), upper

Cretaceous Sedimentary Formation (Nubian sandstone), Hudi Chert (Oligocene) and Quaternary superficial deposit in ascending chronological order (Mukhtar, 1999). The basement complex is composed of highly deformed metasedimnts and multi metamorphosed gneisses and schist, characterized by different types of structure and fracture systems. The Basement rocks are unconformable overlain by Cretaceous sedimentary formation of continental origin (Whiteman, 1971; Vail, 1978). Cretaceous sedimentary formation is mainly composed of sandstone, conglomerates intercalated by gravel, grits, iron-shale and mudstone (Mukhtar, 1999). These formations appear as an escarpment and isolated scattered inselbergs. Along river Atbara the Cretaceous sedimentary formations are characterized by thick layers of mudstone (300 m). Hudi Chert (Tertiary) formation occurs as fossileferrous (Gastropods) boulders mixed with quartz pebbles of gravelly and breccias form, consisting of cherty deposits or as bedded strata. The Hudi Chert rock overlying the Nubian sandstone formation covering large area in the southeast of the area at eastern bank of Atbara River near Elnikhela villages. Superficial deposits include dark clays and silt of the river terraces and unconsolidated layers of gravel, sand, silt and clays with kanker nodules as well as extensive sand dunes at southern part of the River Atbara (Sadam, 2019). The top surface blanket in the study area consists of fluvial and lacustrine facies. There are two aquifers' zones in the study area namely; alluvial (recent deposits) and Cretaceous sedimentary (Nubian sandstone) aquifers. The former one consists of pebbles, gravels, sands, silts and clays as well as kanker nodules in the most-top of the aquifer zone. It is an unconfined with high permeability and good water quality (Ophori and Toth, 1989). Aquifer zone, is characterized by good hydraulic properties and fresh water quality, except at the central part of the study area where poor hydraulic conductivity and bad water quality were encountered, confirming the poor interaction between surface water and ground water. The aquifers are partially hydraulically interconnected. The thickness of water potential zones varies between 90 to 220 m (Eltayib and Elkrail, 2018).

3. Methodology

Visual MODFLOW software was used for ground water modeling to provide an important tool for integrating and interpreting data that were compiled during investigation in the study area and it is the main subject in this study. Arc view software is one of the geographic information system GIS programs. This program presents the main components of the conceptual model such as well location, geological information's drainage system in the study area in form of base map. The hydraulic characteristics of the aquifer were estimated using the quietest for windows software. It is designed to give appropriate methods of analysis for different hydrologic condition it is used for calculation the hydraulic parameter of the wells of the study area.

4. Model Construction Calibration and Results

Forty-three pumping wells were used in this study evenly distributed throughout the model domain (Fig. 2). Twenty observation wells were used for monitoring groundwater heads during model simulations to reveal the water level distributions in model area (Fig. 3).

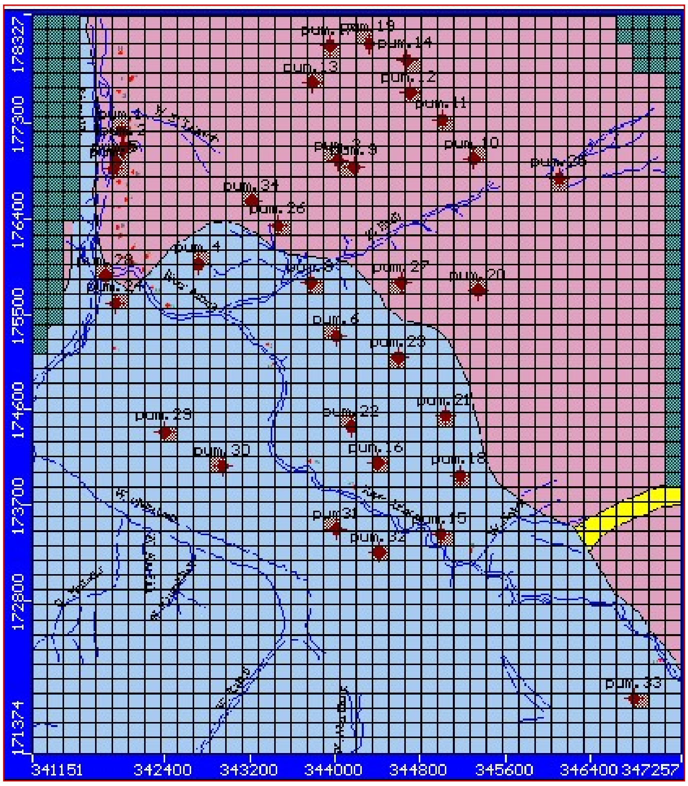

Fig. 2. The pumping wells distribution in the study area

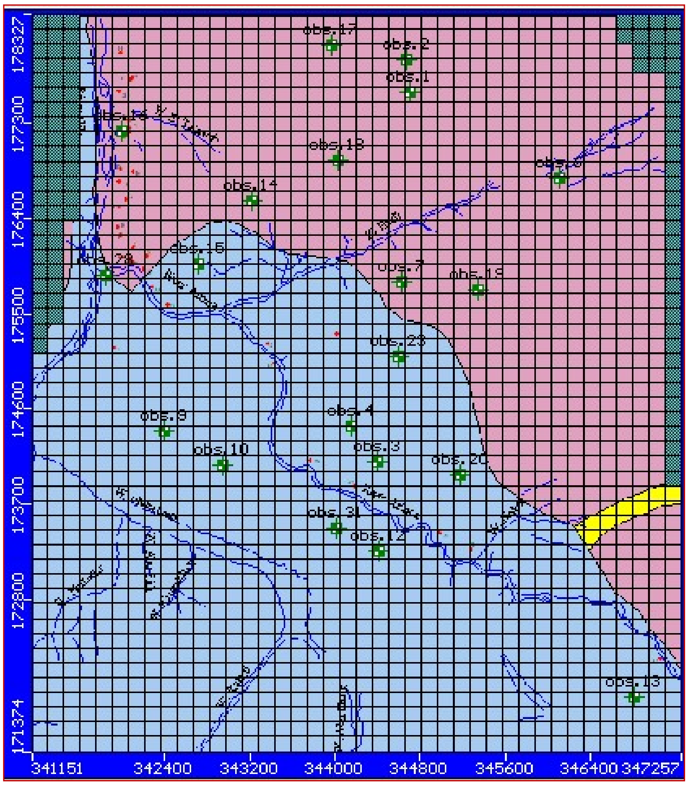

Fig. 3. The observation wells distribution in the study area

Groundwater abstraction and evapotranspirations were the main source of discharge. Therefore, groundwater pumpage represents the main source of discharge where 34 pumping wells were evenly distributed in the model domain. The main

Nile and Atbara Rivers were assumed to be the main source of recharge in the area, whereas the direct precipitation (41.9 mm/y) and natural base flow represent additional source of recharge. The hydraulic conductivity was calculated to be 27.12 m/d, in the area near the river Nile and Atbara river, whereas, the hydraulic conductivity of the rest of the study area was calculated as 2.36 m/d. The storage coefficient value of 5.12×10-2 for the area was 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. The hydraulic head of the year 2006 to 2009 were used as initial head distribution for the model simulation. The base of the aquifer and the eastern part of the area were considered as no-flow boundaries. Southern part of the model area was 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 which were considered as river boundaries. The model was initially constructed to constitute three layers, 50 rows and 40 column and 6000 cells. Model calibration targets and criteria have been adopted based on the discrepancies between the measured and the simulated groundwater heads at twenty groundwater observation wells. The main calibration targets are heads and mass balances.

Generally, the errors in the model area are considered randomly distributed throughout the model domain. During earlier stages of model calibration, an adjustment of the general head boundary, river stage, riverbed, conductance, pumping rates, and recharge was performed using trail-and-error procedure to minimize the discrepancy between the observed and simulated heads. The aquifer hydraulic conductivity, storage coefficient and specific yield considered to be constant of each zone for the entire period.

However, other hydrologic parameters are time dependent such as recharge, pumpage, evapotranspiration and constant head boundaries. 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. Since the stresses such as pumping rate, precipitation, lateral base flow 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 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 (Eltayib and Elkrail, 2018).

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 Root Mean Squired Error (NRMS) and mass balance percent discrepancy (Baalousha, 2006). The model calibration criteria such as MAE, RMS and mass balance error of water into and out of the system were adjusted to less than 1.3, 1.6 m, and 2.5% respectively. However, the calibration will be more acceptable with average RMS of 2.5 m and average MAE of 1.38m and average NRMS of (2.02%). The contour maps of the simulated heads produced by visual MODFLOW show fair similarity with the contour map drawn using initial heads which confirm the reliability of visual MODFLOW Code application and acceptable model calibration for the problem (Figs. 4 and 5).

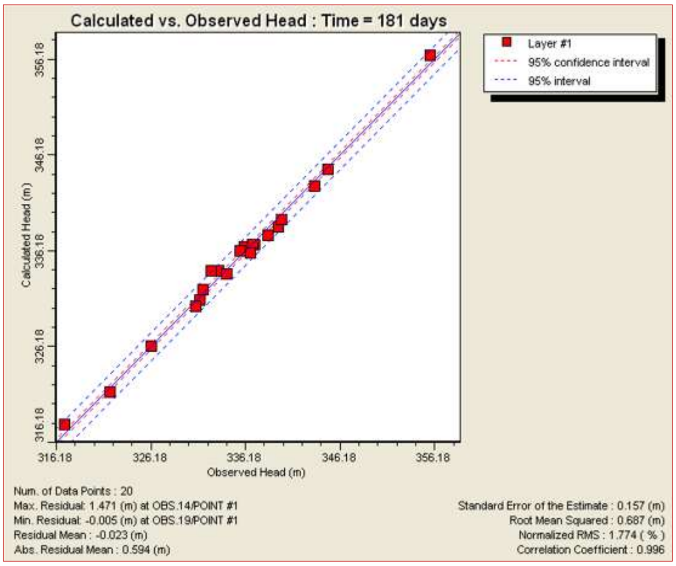

Fig. 4. Observed versus calculated head at stress period No: 1

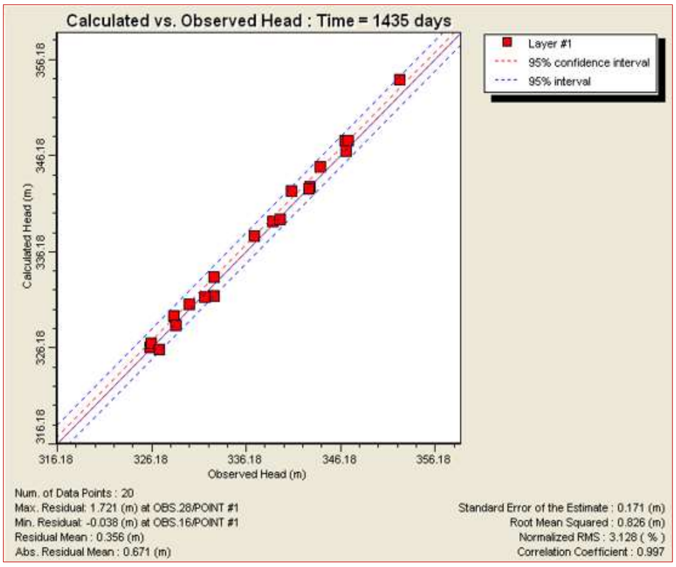

Fig. 5. Observed versus calculated head at stress period No: 12

The contour map of the simulated heads was drawn using visual MODFLOW post-processing tool representing one stress period length of 181 days, for the 20 observation wells. The contour lines elevation decreases towards the center of the area confirming that Atbara river and the main Nile are the source of recharge. Moreover, head decreasing towards the Eastern side of Atbara river generating cone of depressions in the center, South- East, North west and the top right of the study area due to heavy abstraction the natural depression in these localities (Figs. 6 and 7). At the middle of the study area the contour line become closely spaced causing steep hydraulic gradient towards the centers of the cone of depression at the model domain.

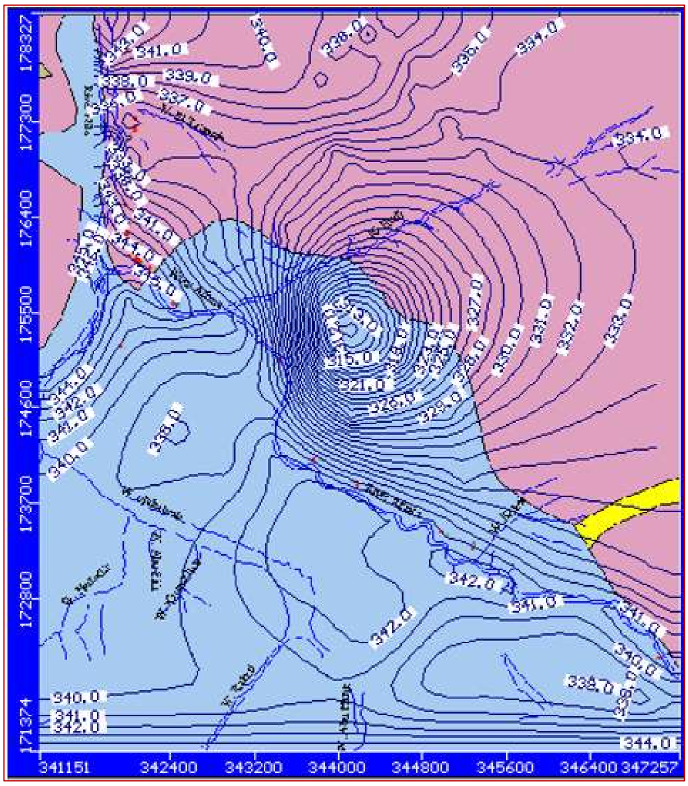

Fig. 6. Equipotential lines for stress period

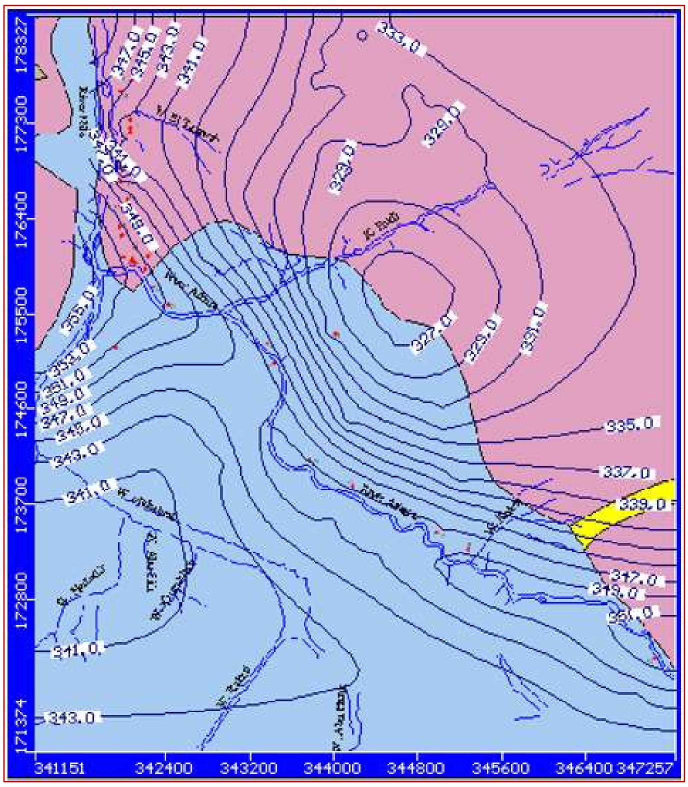

Fig. 7. Equipotential lines for stress period (1435) days

5. Zone Budget

Based on general hydrogeologic principles, a groundwater budget was prepared to estimate the amount of groundwater inflow, outflow and change in storage (Sener et al., 2009). 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 to streams, evapot-ranspiration and pumping. Recently a visual MODFLOW provide afacility for examining detailed water budgets (Eltayib, 2019). Ideally the error in the water balance is less than 0.1%, where an error of around 1% usually considered acceptable (Sadam and Elkrail, 2018). Generally, the visual MODFLOW computes flow-rate and cumulative budget balances from each type of inflow and outflow for each time step.

Moreover, it provides instantaneous budgets for user defined zones for individual layer and aggregated layers. The calculated zone budget components include, storage, pumpage, recharge, river losing, river gaining and general head boundary were evaluated. The volume of water in million cubic meters (mcm) 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 aquifer storage for two years varies from 60 to 27.40 million m^3.

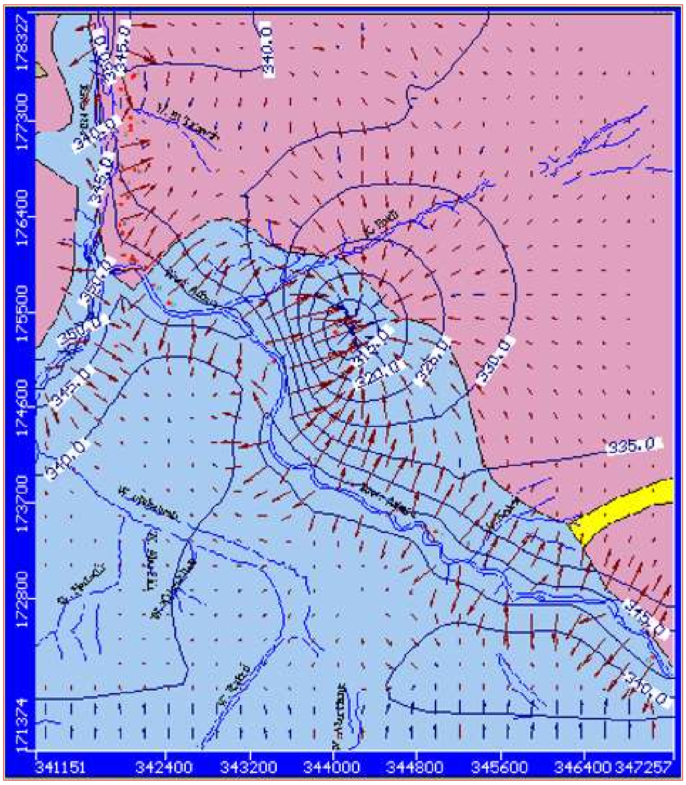

Fig. 8. Flow (velocity) direction in the model domain

The zone budget was calculated for all stress periods respectively (Table 1). The volume of water in million cubic meter per day (mcm/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 stress period is 43.15(mcm/d) and represent 74.49% from total inflow. Groundwater pumping rate in the entire area computed by the model was constant of 4.78 (mcm/d) throughout the simulation period, which represent 8.24% of the total outflow from the aquifer. The contour map of the simulated heads was drawn using the visual MODFLOW to the showing flow (velocity) direction in the model domain (Fig. 8).

Table 1. Groundwater zone budget components values

Time (day)	Component	In flow (mcm/day)	%	Out flow (mcm/day)	%
181	Storage	7	13.2	53.0	92.1
	Constant head	47	8.24	0.00	-
	Wells	0.00		45	7.8
	Recharge	234	4.05	0.00	
	ET	0.00		4	.08
	River leakage	43	74.5	0.00	-
	Total	57		57	-
1435-3326	Storage	100	34.27	212	72.6
	Constant head	1	0.54	310	1
	Wells	0.00	-	76	26.2
	Recharge	16	5.56	0.00	-
	ET	0.00	-	39	0.13
	River leakage	160	54.68	0.00	-
	Total	292	-	292	-

6. Conclusion

Visual MODFLOW software was used for ground water modeling to provide an important tool for integrating and interpreting data that were compiled during investigation in the study area and it is the main subject in this study. Arc view software is one of the geographic information system programs. The model was initially constructed to constitute three layers, 50 rows and 40 column and 6000 cells. The numerical simulation indicated that, a sharp drop of hydraulic head can be observed at the center of the model area, east of Atbara River, generated cone of depression and a continuous decline of head with respect to the time as a result of heavy groundwater abstraction. The southwest part of the area between Atbara River and River Nile represents 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. The contour maps of the simulated heads produced by visual MODFLOW show fair similarity with the contour map drawn using initial heads which confirm the reliability of visual MODFLOW application and acceptable model calibration for the problem.

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