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Numerical simulation of groundwater at Wadi El Hadu – East Nile, Khartoum state, Sudan

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Abstract— **The main objectives of this paper are to design a convenient, concise and more representative conceptual model for groundwater system to evaluate the groundwater potentiality, and to determine source of recharge and general flow direction using numerical model simulation. Arc GIS software was used for constructing the conceptual model components. Well sites were spatially located by GPS device. Aqua test software was used for measuring hydraulic characteristics of aquifers .Visual MODFLOW code was selected. Several model runs were done using trial-and-error technique. A good fitness between observed and calculated head was achieved with Root Mean Square Error (RMS), Absolute Residual Mean (ARM), and Normalized (RMS %) of 0.284 m, 0.226 m and 1.447 % respectively, indicating an acceptable model calibration. The contour lines simulated with visual MODFLOW model for upper aquifer (layer 2) and lower aquifer (layer 4) indicate down gradient flow from western part of the area towards north, confirming first the recharge sources from the Blue Nile and secondly the hydraulically interconnection of upper and lower aquifers in the study area. The volume rate for time step of inflow components such as constant head, recharge, river leakage, general head boundary were estimated to be 22 %, 63.7 %, 8.7 % and 5.8% of the total inflow respectively. On the other hands the volume rate for time step of outflow components such as constant head , wells, river leakage, general head boundary were 0.5%, 14.5%, 0.4% & 84.6% of the total outflow respectively.**

Index Terms— **Groundwater, aquifer ,flow model calibration, hydraulic properties, water balance.**

I. INTRODUCTION

Many aquifers in the world possess high storage capacity and good water quality, allowing them to constitute a prime source of water for human consumption and agricultural activities, even in dry seasonal periods when rainfall is scarce and surface water is fast depleted (Van Camp et al., 2010). Phreatic evaporation can form a significant component of the water balance of arid zone groundwater systems (Habermehl,1980; Sultan et al., 2007). Commonly, these groundwater systems provide the dominant water supply in arid areas and understanding their water balance is critical for the sustainable management of the resource (Danielopol et al., 2003; Habermehl, 1980). Understanding the spatial distribution of phreatic evaporation can contribute to many groundwater issues, such as mapping areas of soil salinization (Brunner et al., 2008), calibrating groundwater models (Li et al., 2009) and determining water balances of closed basins (Kampf and Tyler, 2006).The comprehensive basin approach allows one to correctly assess the results of both short- and long-term effects of interventions in the aquifers, and to carry out risk assessments associated with such actions. Groundwater is the main source of drinking water in the study area, and is also a major source of water for industrial and agricultural activities. Despite the huge groundwater resources, sustainable use of large water-extraction operations over large regions is only possible by considering the response of the groundwater system to human-induced forcing, i.e. considerable reduction of the groundwater level. The distribution of groundwater head in the study area was modeled using Visual MODFLOW. The groundwater flow model was applied to an area of 408.5 km^2 including four layers with two aquifer zones.

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II. GEOMORPHOLOGY, GEOLOGY AND HYDROGEOLOGY OF THE AREA

The study area lies at the eastern part of Khartoum state in semi-arid region. It is located between longitudes 32° 54□’ 00’’ - 32° 40’ 00’’ E and latitudes 15° 39’ 00 ‘’and 15° 27’ 00’’ N (Fig. 1) covering an area of about 408.5km^2.The study area is mainly a flat peneplain with an elevation which varies between 384 and 415 meters above sea level. The plain surface gradually slopes to the west in the direction to the Blue Nile. Seasonal wadies such as Wadi El Hadu represent additional source of recharge of the aquifers in the study area with flow direction toward the Blue Nile (Fig. 2). The study area is characterized by cold dry winter, very hot summer and warm rainy autumn. The annual average rain fall is 94 mm which occurs mainly in July and August, while the evaporation rate is 14.2 mm\day .The main geological units comprise Precambrian basement complex, Cretaceous Sedimentary formation Quaternary alluvial Formation and Recent superficial deposit (Whiteman1971). *The Basement Complex consists of a variety of gneisses, migmatites and schist with quartzite and marble at the north and northeast of the study area (Fig. 1). These rocks were subjected to different stages of deformation and metamorphism and later intruded by acidic (granite) and basic rocks during Organic activities (Vail 1978).The Cretaceous sedimentary rocks are lying uncomformably on the Basement Complex. They consists of conglomerate sand sandstone intercalated with lenses of mudstone and siltstone(Fig.1).Quaternary formation unconformably overlying the Cretaceous Sedimentary formation in very narrow strip along the right bank of the Blue Nile represents Gezira and Omdurman formations. They consist of* *unconsolidated sands and gravels intercalated with silt and clay lenses. The alluvial deposits consist of clays and poorly sorted sand and gravels of Quaternary to Recent age represent shallow aquifer of potential water storage.* The superficial deposits are the youngest geological units covering the area and composed of gravel, sand, clay and valley fills and the deltaic deposit which is seasonally transported by the ephemeral streams during rains. These sediments are in the form of narrow strip of variable thickness (5-20 m).Alluvial deposits and Cretaceous sedimentary formation represent the main water-bearing formations in the study area .Cretaceous sedimentary aquifers can be categorized into upper aquifer and lower aquifers. The *thickness of* upper aquifer *varies between 10-120 meters,* whereas that of the lower aquifer is more than 130 m.

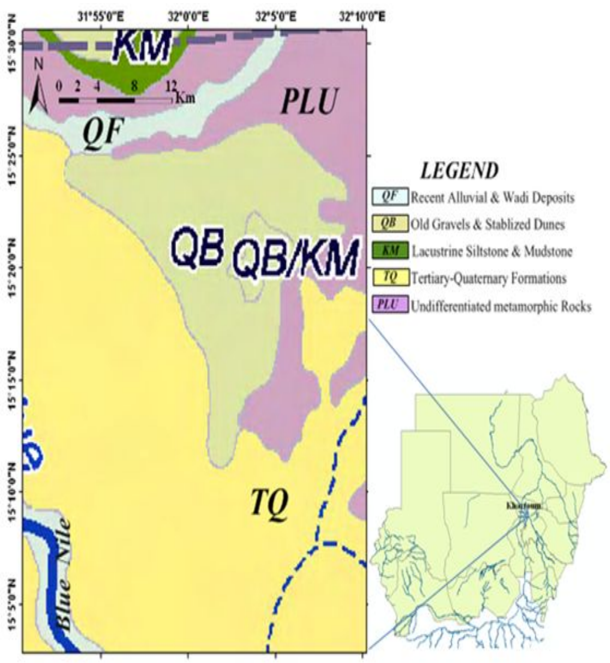

Fig. 1 Location and Gealogical map of the study area

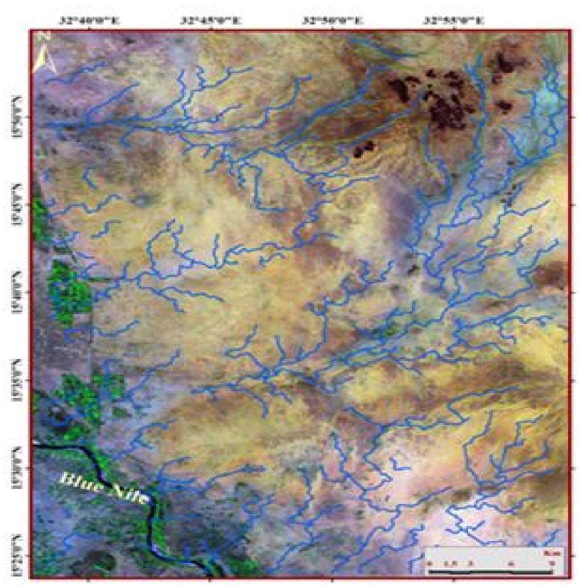

Fig. 2 Drainage system in the study area

III. Methodology

Rapid urbanization in the study area led to unprecedented population growth, resulting in the development of large areas of unplanned sub-standard housing and uncontrolled human activities. Many of these settlements rely on groundwater as their main source of domestic water supply, especially in the areas remote from the surface water courses. Assessment of groundwater system in the study area using numerical models then a crucial task to manage water for these development activities. Arc GIS software was used for construction the conceptual model components. Well sites were spatially located by GPS devices. The hydraulic parameters of the aquifer were calculated from pumping test using Aquifer Test Software. The groundwater flow model was run in visual MODFLOW computer code environment using trail-and-error calibration technique.

IV. Model Construction, Calibration And Results

A simplification of a well performed conceptual model was constructed, to represent the physical geometry, topographical features and hydrological properties of model domain. A finite difference grid of 80 columns, 80 rows and 4 layers, was then superimposed over the study area. Two main aquifers namely, upper semi-confined and lower confined aquifer represent the groundwater system. Georeferenced boreholes served as discharged wells and conjunctively some of them act as observation wells. Storage coefficient and horizontal hydraulic conductivities were measured based on well test results using aqua-test software. Vertical hydraulic conductivity was considered as 10% of the horizontal hydraulic conductivity depending on the type of formation (Batu 2006, Elkrail et al. 2004). The top of the model domain was selected as a variable head boundary. The Blue Nile at the southwestern part serves as river boundary. Static water levels in observation wells were used as initial head distribution for the model simulation. The base of the aquifer system of the area was considered as no-flow boundary. The eastern, southern and northern parts of the area represent general head boundaries (GHB). The western part represents constant head boundary. The top of the aquifer system acts as variable head boundary. Model calibration is the process of adjusting the model data to obtain a reasonable match between observed data and model calculation. The hydraulic conductivity of the upper aquifer in the study area was averaged to be20 m/d whereas that of the lower aquifer was taken as 20 m/d. The three dimensional finite difference flow model was run in visual MODFLOW code environment under steady condition using a trial-and-error calibration technique .The model calibration criteria were the Root Mean Squared Error (RMS), Absolute Mean Residual (AMR), Normalized (RMS%) and mass balance percent discrepancy. A good fitness between observed and calculated head was achieved with Root Mean Squared Error (RMS), Absolute Residual Mean (ARM), and Normalized (RMS %) of 0.284m, 0.226 m and 1.447 % respectively (Fig.3). The contour maps of the simulated head were drawn using visual MODFLOW post-processing tool (Fig. 4&5).The contour lines simulated with visual MODFLOW model indicated a down gradient flow from western part of the area towards the north and northeast with similar pattern in both aquifers confirming first the recharge sources as the Blue Nile and secondly the hydraulical interconnection of upper (layer 2, Fig.4) and lower (layer 4 Fig.5) aquifers in the study area. These results indicate that the calibration is acceptable. Moreover, the local trend of groundwater flow reflects a general flow direction toward the east and northeast. The water balance components over a period of time in the study area can be estimated by interrogating the water budget details of the robust numerical groundwater model, which replicate faithfully the main, recharge and discharge processes in a natural system (Table 1).Generally the visual MODFLOW computes flow-rate and cumulative budget balance from each component of inflow and outflow for each time step in the model domain. Accordingly, volume rate for time step of inflow and out flow components were tabulated as in Table 1. Hence, volume rate for time step of inflow components such as constant head, recharge, river leakage, general head boundary were estimated to be 22 %, 63.7 %, 8.7 % and 5.8% of the total inflow respectively. On the other hands the volume rate for time step of outflow components such as constant head , wells, river leakage, general head boundary, were 0.5%, 14.5%, 0.4% & 84.6% of the total outflow respectively.

Table 1. Groundwater Rates for Time Step

Component	Inflow(m^3/d)	%	Outflow	%	Difference
Constant head	51589.22	22	1125.41	0.5	
Wells	-	-	34129.06	14.5	
Recharge	149366.42	63.7	-	-	
River Leakage	19944.95	8.5	806.28	0.4	
General head (GHB)	13678.59	5.8	198512.88	84.6	
Total	234579.19	100	234573.63	100	5.56

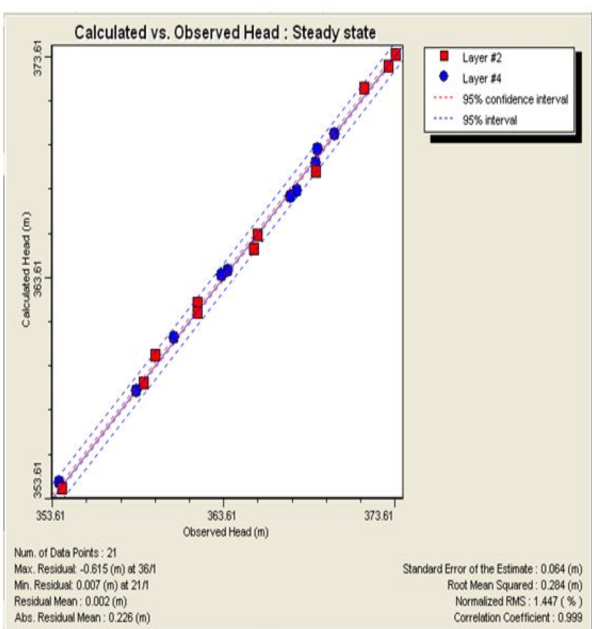

Fig. 3 Fitness between observed and calculated heads using visual MODFLOW

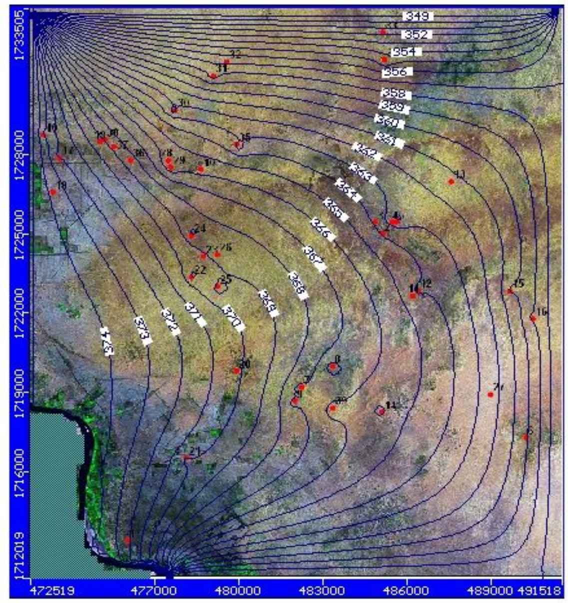

Fig. 4 Distribution of equipotential lines for the upper aquifer (layer 2)

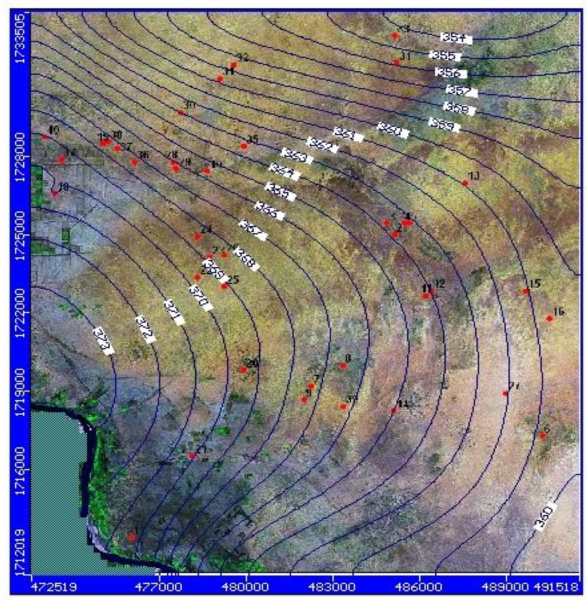

Fig. 5 Distribution of equipotential lines for the Lower aquifer (layer 4)

Model sensitivity can be expressed as the relative rate of change of selected output caused by unit change in the input (Batu 2006). Sensitivity analyses comprise two aspects namely the uncertainty of aquifer parameters and the geometry of the system (Elkrail2004). The less sensitive the model calibration is to deviations from the calibrated parameter values, the smaller the impact of uncertainty on the model predictions. The first sensitivity analyses were performed for changes in hydraulic conductivity (K), specific storage (S_s) and specific yield (S_y) with respect to root mean square error (RMS). The model was run four times for each parameter increment of 10 and 20 percent and decrement of 10 and 20 percent (Table 2). The corresponding changes in root mean squared error values were plotted versus the changes in the percentage of parameter values (Fig. 6). Sensitivity analyses showed that the model is more sensitive to Hydraulic conductivity and least sensitive to specific storage (Fig.5).

Table 2. Parameters used for different sensitivity analysis

	K	S_y	S_s	RMS
Control parameter	15	0.15	0.0004	0.284
K* 1.1	16.5	0.15	0.0004	0.434
K* 1.2	18	0.15	0.0004	0.656
K* 0.9	13.5	0.15	0.0004	0.453
K* 0.8	12	0.15	0.0004	0.858
S_y* 1.1	15	0.165	0.0004	0.284
S_y* 1.2	15	0.18	0.0004	0.284
S_y* 0.9	15	0.135	0.0004	0.284
S_y* 08	15	0.12	0.0004	0.284
S_s* 1.1	15	0.15	0.00044	0.284
S_s* 1.2	15	0.15	0.00048	0.284
S_s* 0.9	15	0.15	0.00036	0.284
S_s* 0.8	15	0.15	0.00032	0.284

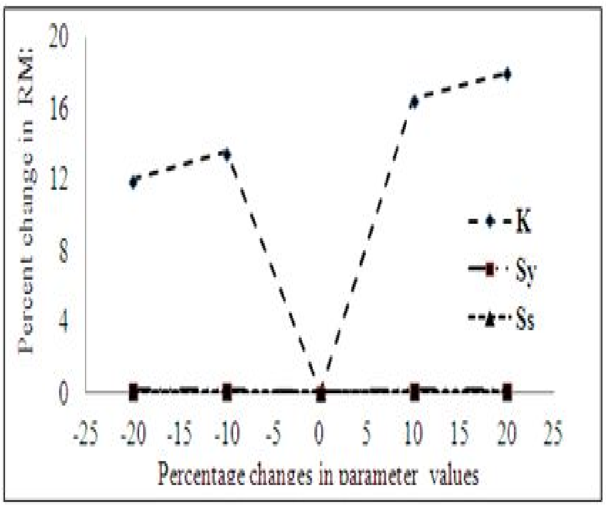

Fig. 6 Parameters used for sensitivity analyses

Conclusion

The three dimensional finite difference flow model was run in visual MODFLOW code environment under steady condition using a trial-and-error calibration technique. A good fitness between observed and calculated head was achieved with Root Mean Squared Error (RMS), Absolute Residual Mean (ARM), and Normalized (RMS %) of 0.284 m, 0.226 m and 1.447 % respectively, indicating an acceptable model calibration. The contour lines simulated with visual MODFLOW model indicated a down gradient flow from western part of the area towards north, confirming first the recharge sources as the Blue Nile and secondly the hydraulical interconnection of upper and lower aquifers in the study area. The volume rate for time step of inflow components such as constant head, recharge, river leakage, general head boundary were estimated to be 22 %, 63.7 %, 8.7 % and 5.8% of the total inflow respectively. On the other hands the volume rate for time step of outflow components such as constant head , wells, river leakage, general head boundary, were 0.5%, 14.5%, 0.4% & 84.6% of the total outflow respectively.

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