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Evaluation the Aquifer Hydraulic Parameters of Wadi Nyala, South Darfur State, Sudan

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Abstract:
This study is a part of the study that focused on development of criteria for identification of potential water harvesting and artificial recharge sites. It takes into account the area of Wadi Nyala Aquifer. The study aims to investigate and optimize the existing hydrogeological parameters of the Aquifer.
The model was achieved from 2013-2017 with 20 observation wells. Initially, in order to obtain the data overview, the observation data were evaluated. Using existing hydro-geological and meteorological data, the model was developed and calibrated in one distinct vertical layer in unconfined Aquifer. A detailed comparison is made between two cases; using the Parameter Estimation Package "PEST" software in MODFLOW.
Results found that the optimization values of Hydraulic Conductivity (K_x) and Storage Coefficient (S_y) are 6.5 m/d, 0.00478 and 1.0 m/d, 0.058 in case-1 and case-2 with the average values are 3.75 m/d and 0.0314; respectively, whereas, the other parameters are stable during simulation periods in both cases. These improved values indicate that the recharge is good and the Aquifer has good potential of storage and will be increased by achieve the water harvesting in the area.
Keywords: *Groundwater; Numerical Simulation; MODFLOW; Parameters; Wadi Nyala Aquifer*

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I. INTRODUCTION

Groundwater is a vital source of water throughout the world because of its availability and general good quality [1]. It has faced huge challenges due to increased population, economics and water resources management problems. Numerous studies have been conducted in the last decades using professional groundwater software, such as Visual MODFLOW, GMS, FEFLOW, SEAWAT, GSFLOW and/or the integration of some ones. The most widely used numerical groundwater flow model is Visual MODFLOW in different geographical regions; arid, semi-arid and tropical areas. It is a well-known model in the field of groundwater [2]. According to Butler, the Theis method will yield estimates of Transmissivity (T) and Storage Coefficient (S) are weighted averages of near-well and far-field properties for heterogeneities, which are distributed radially symmetrical about the pumping well [3,4]. Butler and Liu concluded that constant-rate aquifer tests are not very effective for the characterization of lateral variations inflow properties [5]. Schad and Teutsch compared T and S values derived from several small-scale and large scale aquifer tests in a braided stream environment [6]. Meier et al. suggested that the straight-line method of Cooper and Jacob will provide a good approximation of the effective T in multi-lognormal and non-multi-log normal T fields when constrained to late-time data [7, 8]. Meier et al found that estimated Transmissivity values for different observation points tended to converge on a single value, which in a multi-log-Gaussian field corresponded to the geometric mean of the point T values [9]. Naff used a perturbation solution for three-dimensional radial flow in heterogeneous porous media. He concluded that the effective hydraulic conductivity (K) will be essentially constant at a distance greater than two to three length scales from the well bore and will have a value dependent upon the statistical anisotropy of the medium [10]. Wang and Anderson, Fetter, Anderson and Woessner and Mays provided information on the implementation of the numerical scheme, the conceptual model and grid design, boundary conditions, sources and sinks, or model calibration [11-14]. In Bangladesh, groundwater modeling software (MODFLOW) has been used for many groundwater studies [15]. A full description of the capabilities of MODFLOW can be found in [16, 17].

Located in the semi-arid region of western Sudan, Wadi Nyala (ephemeral water course) is the main water source for the rural and urban population there. Water is provided through the shallow wells dug in the alluvial aquifer. Therefore, the groundwater level observations are a vital input for modelling the groundwater of the Wadi. There have been a number of efforts in the past to model the Wadi aquifer. The first attempt was made by TNO-DGV Institute of Applied Geosciences within the framework of the Water Resources Assessment Program in the Sudan WAPS-2 [18]. Considering the limited computing facilities available at the time, a small part of the aquifer covering the town area was modeled with model parameters. Also, a simplified model was developed by Hussein in which all model boundaries were grossly idealized and assumed to be straight including aquifer top and bottom [19]. A groundwater model based on VISUAL MODFLOW (96) has been developed, where pumping test data was analyzed to determine the hydrogeological characteristics of the aquifer T and S using Theis Equation, Jacob solution method and Theis-recovery method Techniques. The problems identified by Ahmed and WRADM [19, 20], which causes the water problem in the urban and rural parts of the State to remain and exacerbated: (1) the pressure on the existing limited water resources (groundwater from Basement fractures and Wadi Alluvial), (2) the population pressure especially in the IDP camps where the dependency is on limited groundwater, (3) the high water demand required by the main livelihood practice, agriculture and animal raising, and (4) the poor reliability of the water harvesting systems, especially earth dams. The current research study is built on a recommendation by the WRADM project on the conflict affected regions in Darfur conducted by the Civil Engineering Department of University of Khartoum in the year 2010, which found that the water demand in Darfur represents less than 7% of the renewable water resources, while the supply represents only about 14% of the demanded volume, reflecting the crucial water supply problem in the region [20]. This study aims to apply the graphical design system for modular finite difference groundwater flow model (MODFLOW- 2000) to investigate and optimize the hydrogeological parameters of Wadi Nyala aquifer; specifically: 1) Transmissivity (T), 2) Storage coefficient (S) and 3) Hydraulic conductivity (K), taking into account the different climatic conditions.

II. MATERIALS AND METHODS

2.1 Study area:

According to the Groundwater and Wadis Directorate being originated at Jebel Merra, Wadi Nyala flows southeast to cross Nyala City at about the Kilo 45 [21]. It continues through Kundua area and Beleil depression till it reaches its outlet. Figure (1) shows the tributaries of the Wadi and the distribution of the wells within the Wadi course. The main tributaries of Wadi Nyala, i.e. Domai and Kalkandi, meet just before Nyala City. At the city, the Wadi course leaves the Basement Complex dissected rocky pediment and entering into a flood plain. The main two rock types are the quartzite and granites of Jebel Nyala that is located in the eastern part of the town [22]. The alluvium aquifer that underlies the Wadi channel in the city of Nyala area and further downstream is considered as the main aquifer and it represents the main sources of water supply for the city as well as for supplementary irrigation along the Wadi channel. The aquifer is recharged from the Wadi flood flows as well as from rainfall.

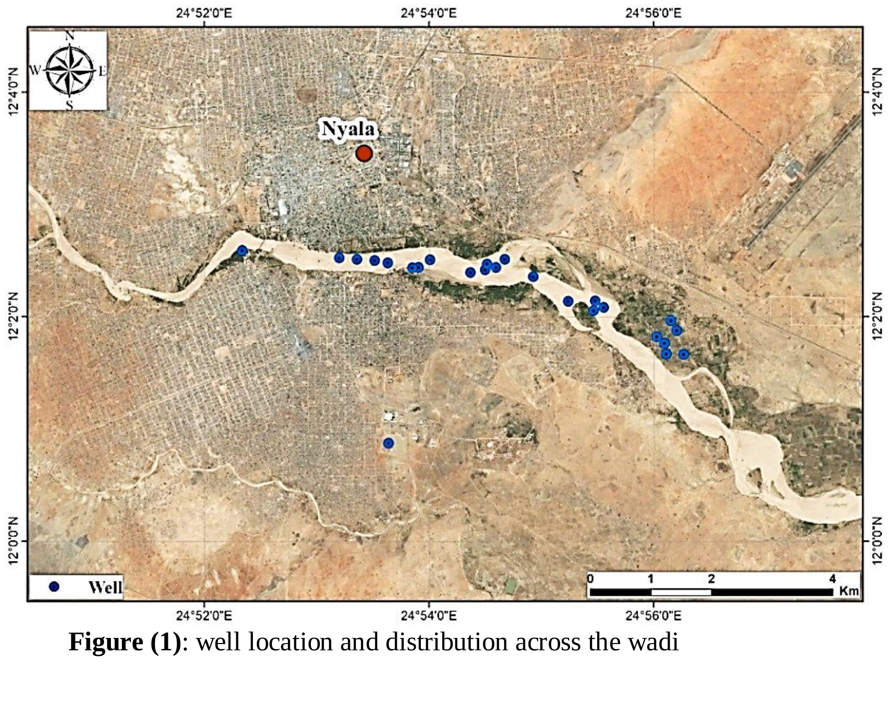


Figure (1): well location and distribution across the wadi

2.2 Acquired Data

Table no 1: Summary of the collected data and the purpose of its use

No.	Data Type	Source	Purpose
1	Daily Rainfall data	Meteorological station at Nyala Airport	calculation of the Wadi discharge, recharge and evaporation
2	Pumping rates of 20 wells and its observation.	Nyala Water Corporation	Investigating groundwater level
3	Wadi Aquifer properties (Specific yield (S_y), Porosity (n) , Hydraulic Conductivities (Kx, Ky, and Kz) and Transmissivity (T))	-Groundwater and Wadis Directorate in Khartoum -Ahmed, H.I 2008)	Initial values for simulation process
4	Thickness of the Aquifer	Water Research Center Report, University of Khartoum	To evaluate the Transmissivity

2.3 Procedure Methodology

2.3.1 Design of Model

In this study, the model was designed using the main and general groundwater flow equations including; Darcy's Law, Finite-difference forms of the general diffusion equation. The governing flow equation for three-dimensional saturated flow in saturated porous media, which have been developed [11, 17, 23, 24, 25, 26].

The computer program, used in this study is a graphical design system for modular finite difference groundwater flow model, commonly known as MODFLOW. It is the popular numerical model code MODFLOW- 2000 [16]

The current study involved 20 samples of pumping wells and simulating with 20 observation heads in the area. Using the observation data to see the groundwater level fluctuations during the study period. The Wadi aquifer properties were used with the result of developed model that done by in Wadi Nyala Aquifer. The thickness of the aquifer that used in this study ranges between 5 to 20 meters with an average saturated thickness of 10 m. Other input data such as wells diameters were considered as well [19].

2.3.2 Model domain area

The model domain covers an area of about 16 km×30 km extending from Nyala Bridge in the upstream to East Kundwa forest in the downstream Figure (2). The model domain was divided into 50 rows and 50 columns to form rectangle cells of equal sizes of 600 ×320 m dimensions, 12 stress periods (s) (during simulation process; namely 1440 days) in simulation with 10 time steps was applied. Model time unit is a day, and model length unit is meter. One model layer as the unconfined aquifer was considered with boundaries condition. The boundary conditions adapted for the groundwater modeling is no-flow boundaries in the north and south limits where the ranges provide natural barriers. A groundwater recharge (Infiltration) was considered as percentage of rainfall of 2017 and the recharge package was used to simulate the net recharge [20].

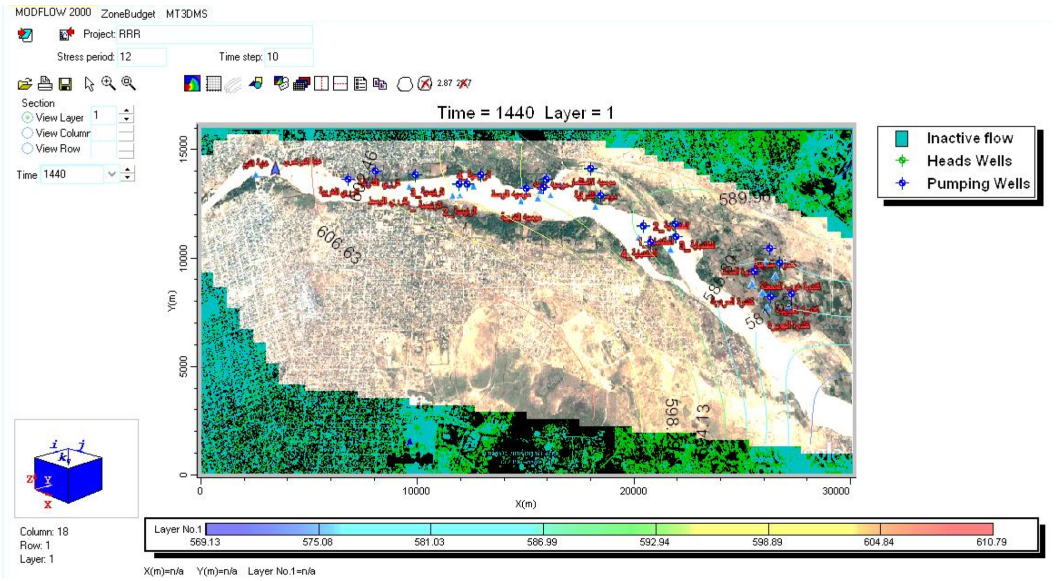


Figure (2): model domain and well locations

2.3.3 Calculation of Groundwater levels

The initial head data, the model hydrologic inputs and other parameters were consistent. The top elevation of the model is the surface elevation, which is taken from the Google Earth. The bottom elevation of the model is interpolated from the limited geological borehole data. One of the main parameters that is required during the process of solving the groundwater flow equation a modeled domain is the saturated thickness of the aquifer, which in reality changes with location and time from one point/cell to another. The saturated thickness was computed in the devised modeling process by subtracting the aquifer's bottom layer elevation from the hydraulic head values at any point in time. A transient flow model was constructed and simulated. The purpose of the transient model is to simulate seasonal variations of groundwater levels and Wadi flow caused by varying precipitation and Evapotranspiration values.

The annual average values of rainfall, ET, River conductance, and daily pumping rate from (2013 – 2017) were used and simulated. Initial head in two cases: 1) the ground elevation and 2) the specified heads from the observed head were achieved.

2.3.4 Determination of Water Table elevation

The elevation of water table is evaluated depending on the drawdown at an observation point. It is calculated automatically by the model using an initial (starting) head value and a calculated head value. If the initial observed head value at the observation point is not available, then the drawdown value at the observation point is calculated using the following formula.

$$s = \mathrm{h_i} - \mathrm{h_c} \quad (1)$$

Where, s = Drawdown at the observation point; $\mathrm{h_i}$ = Initial head at the observation point*; and $\mathrm{h_c}$ = Calculated head at observation point*(* *The calculated head and initial head values at the observation points are horizontally interpolated from the grid cell centers to the actual location of the observation point).*

If the observation point has an observed head value at time=0, then the drawdown value at the observation point is calculated based on the observed head value using the next formula (2) rather than using the interpolated initial head values at the location of the observation point.

$$\mathrm{s} = \mathrm{h_o} - \mathrm{h_c} \quad (2)$$

Where, ho = Observed head at the observation point at time t=zero.

2.3.5 Estimation of potential recharge

In the absence of detailed information, the estimated recharge and abstraction for the Baggara and basement complex within Wadi Nyala were obtained from the estimations given in WRC and Omer [28,29] by the ratio of the areas. The recharge estimate to the basement is still uncertain [30, 31, 32].

2.3.6 Optimization of Hydrogeological parameters

The optimization of parameters (hydraulic conductivities, specific yield and Transmissivity) were calibrated automatically during the model processing using the Parameter Estimation Package "PEST" software [33]. A trial and error approach improving estimates of the hydraulic conductivity in the x, y and z directions and storage parameters (S) while minimizing the error in head values. PEST adjusted the model parameters until the fit between the physical observations and numerical outputs was optimized.

III. RESULTS

In this study, investigation and optimization of the existing hydrogeological parameters of Wadi Nyala Aquifer; using MODFLOW-2000 as well as previewed studies have showed some important results.

2.4 Elevation and Groundwater levels

Groundwater levels were converted into the height of the water table above mean sea level with the calibration of the land elevation of wells; height of water column automatically by the Model. In this work, the input groundwater levels were used as initial groundwater heads in the transient model. Results show that almost all of the hydrographs of water head in all wells; (i.e. observed versus calculated heads) are decrease with time; as example in (Figure.3). This Figure illustrates the match of the calculated heads to the observed in five observation wells (i.e. Observation well No: 1-5) through 1440 days. The comparison between the observed and simulated head for 20 observation wells is presented in Figure 3.a and 3.b. the calculated head shows a good match with the observed data and each other (Figure.3.a). The root mean square error (RMSE) indicates a small error value appropriate for model elevation (RMES = 3.565 m), whereas the standard error of the estimation is 0.644, and the normalized RMS Vs time (head) (Figure 3.b) is 7.75%. The correlation coefficient describes a strong degree between the observed and calculated head data (R^2 = 0.984) with the 95% confidence interval.

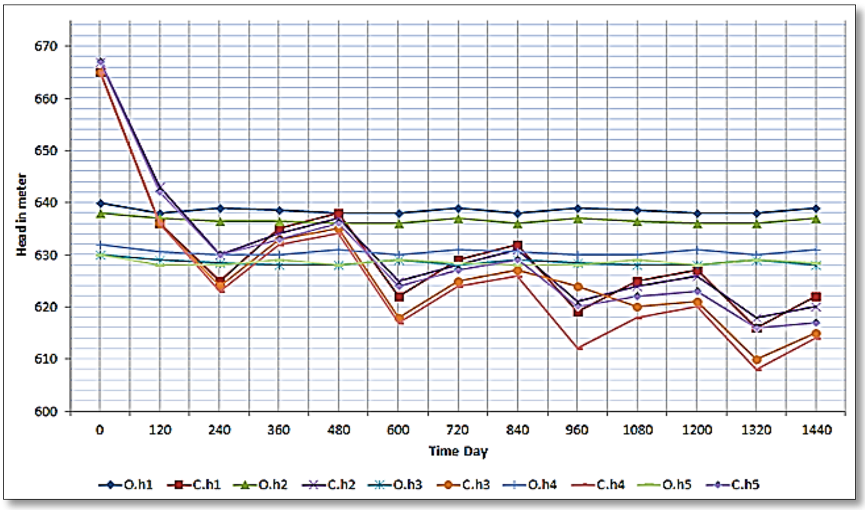
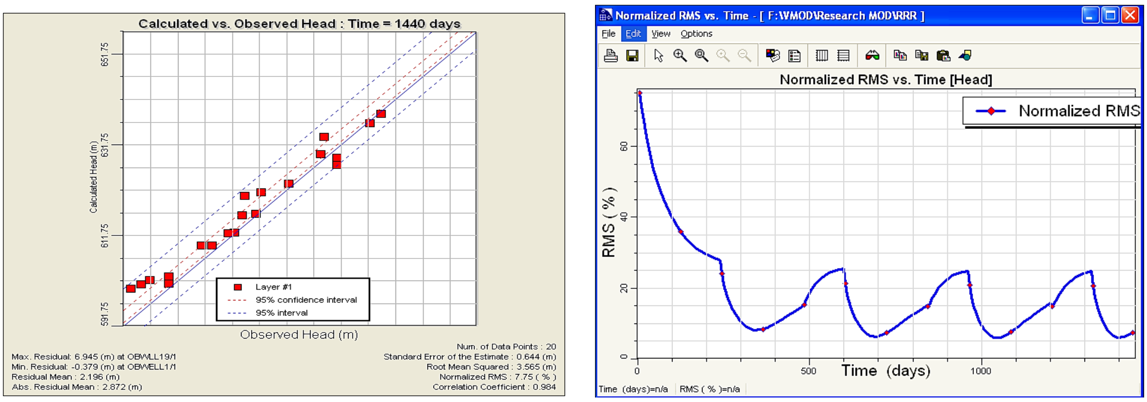


Figure .3: Observed vs. Calculated Heads for wells No: (1- 5), C.h **refer to calculated head whereas O.h refer to the observed head.**

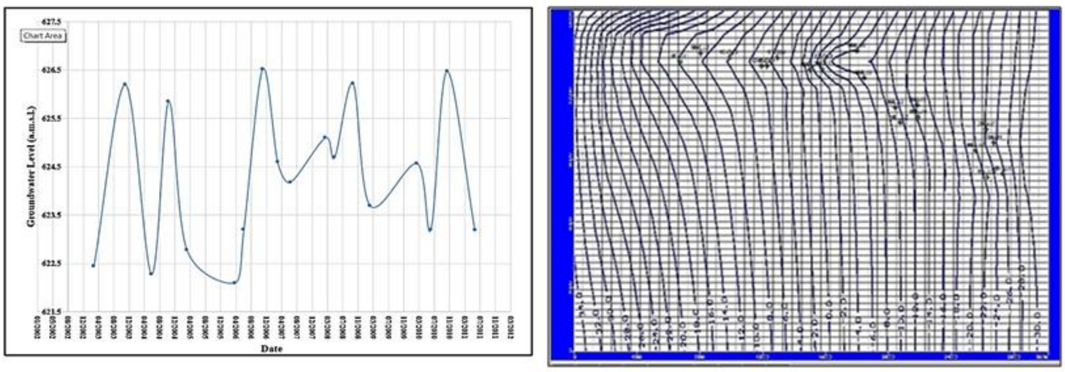


a) b)

Figure .3: Model results: a) Calculated vs. Observed Head (Time = 1440 days) b) Normalized RMS vs. Time (Head)

2.5 Elevation of Water Table

In the current study, the results show that the water table level ranges between 2 m to 32 m in some observation wells; the deeper level may due to continuity pump during 1440 days of model calibration as appear in the Figure. 4.b, which shows the contour of water table depth within the area (i.e. Wadi Nyala).



a) b)

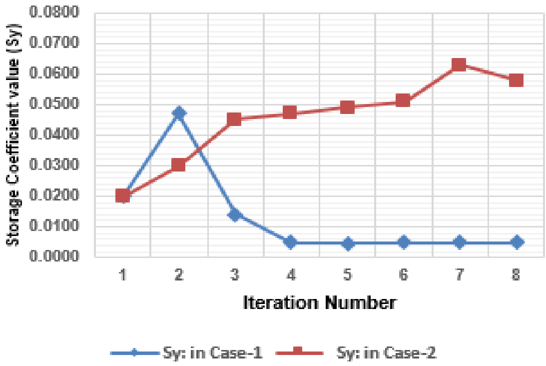
Figure 1: a) Groundwater Level Fluctuation in Wadi Nyala Aquifer (source 1]), b) contour of water table depth within the area (2 m to 32 m) (i.e. WadiNyala) from Mosku Bridge to East Kundwa

2.6 Recharge

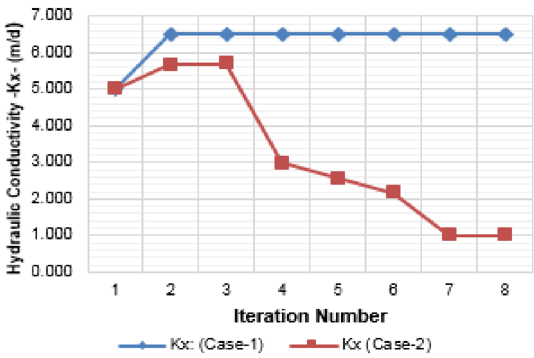
As part of a numerous recommendation of projects for water resource management and development in the region, the project recommended a study of Integrated Water Resources Development and Management of Wadi Nyala. It also revealed that with annual mean discharge of 41 x 106 m3, Wadi Nyala has a potential of 26 x 106 m3 annual discharge with 90% reliability. The runoff within the narrow Wadi carries an annual flow of about 50 MCM, thus replenishing the shallow Wadi Nyala aquifer. While direct recharge of the aquifer from rainfall is expected to be minimal, the overall recharge to the project area is attributed to the surface runoff in the Wadi, which is a function of the amount of rainfall in the region. It can thus be argued that the net aquifer recharge is also a function of the amount of rainfall in the region [20]. In this Simulation the net recharge has been considered from previews studies.

2.7 Hydrogeological parameters result

Estimating the values of the hydrogeological parameters of the Wadi Nyala aquifer is an essential step for the solution of the groundwater flow and hence the numerical model of the project area. The result found that the optimization values of Hydraulic Conductivity (Kx) and Storage Coefficient (Specific yield S_y); Figures (5.a and 5.b) are 6.5 m/d, 0.00478 and 1.0 m/d, 0.058 in case-1 and case-2 with the average values are 3.75 m/d and 0.0314; respectively, whereas, other parameters (i.e. Ky, Kz and Ss) are stable during simulation periods in all cases. A large value of Hydraulic Conductivity indicates good recharge, whereas large value of the Storage Coefficient indicates that the Aquifer will have good potential storage.



a)



b)

Figure 5: a) storage coefficient versus Iteration number, Figure 5.b) Hydraulic conductivity (Kx) versus Iteration number

IV. DISCUSSION

The numerical model successfully converged using the observational data from twenty observation wells within the study area, namely; Wadi Nyala course through Kundua area and Beleil. The previewed has documented that the water level data in an observation well within Wadi Nyala aquifer for the period (2003 – 2011) reveal that groundwater occurs within one to five meters below the ground surface during the rainy season (October-December) and three to nine meters below the ground surface in the dry season (March-May) [32]. The cyclic nature of the groundwater level (Figure. 4.a) underlines the significant impact of the rainy season on the aquifer recharge. Results do not reveal any decreasing or increasing trend between 2003 and 2011, thus reflecting the fact that aquifer did not exhibit any significant depletion at least until 2011. The analysis of the data shows that the groundwater flow follows the general trend of the topography of the ground surface. Also, the water quality in the aquifer is good with electrical conductivity (EC) ranging between 250-and 700 us/cm and the total dissolved solids (TDS) ranging between 200 and 500 ppm. However, groundwater at Nyala area is liable to pollution especially during the flood season due to the fact that the water table becomes close to the surface and therefore any surface contamination can reach the aquifer relatively quickly [31].

Estimated parameters (Hydraulic Conductivity, and Storage Coefficient) obtained from geotechnical sampling and testing is considered as unreliable for groundwater modeling. This is mainly due to the fact that laboratory results provide a biased single point result that is not representative of the larger aquifer domain. Aquifer pumping tests are the method of choice for obtaining reasonable estimates for the aquifer parameters. Results of a limited number of recovery pumping tests have been conducted in Wadi Nyala during previous studies. These studies report values of hydraulic conductivity ranging between 50 and 150 m/day. These values are considered by the study team as unrealistic and not representative of the true aquifer Transmissivity. The hydraulic conductivity of sandy clay or fine sand soils are expected not to exceed 5 or 6 m/day.

The THEIS solution technique, Jacob solution method and Recovery method also have been tested in Wadi Nyala to calculate Transmisivity (T) and Storage Coefficient (S) [19] , the study indicates that the average values of T & S are 0.0024 m^2/sec and 0.00114, respectively. According to the results of the modeling component carried out within the study, the storage coefficient of the modeled area of the aquifer ranges between 0.02 and 0.2 with an average of 0.11 [31]

In the current study, Model calibration parameters included the horizontal and vertical Hydraulic Conductivities and Storage Coefficient were used from the previous study [19] as references. These parameters were calibrated through the iterative calibration procedure using the optimization code PEST [32] in two simulation cases due to initial head: (1) case -1: the initial head was taken from ground elevation by Google earth, (2) case-2: the initial head was taken from the specified heads. Figures (5.a and 5.b) at the beginning the value of Horizontal Hydraulic Conductivity (Kx) was a noticeable increase during optimization iteration number (1-2; Fig 5.b), afterwards (Kx) is increasing gradually during iteration number (3-8) in case-1, whereas it dropped sharply during iteration number (3-8) in case.2.in the meantime the Storage Coefficient (Specific yield (S_y)) increases gradually while it dropped sharply during iteration period number (2-4) in case (1), afterwards it stables till to iteration number-8 . At the same time, in case -2 the Storage coefficient increases gradually to the end of the iteration period, these variation may have been due to different climate condition.

V. CONCLUSIONS

This study takes into account the area of Wadi Nyala Aquifer, which as a part of the study that focused on development of criteria for identification of potential water harvesting and artificial recharge sites within the Wadi Nyala watershed, South Darfur State. It aims to investigate and optimize the existing hydrogeological parameters of Wadi Nyala Aquifer; such as Transmissivity (T), Storage coefficient (S) and Hydraulic conductivity (K); taking into account the different climatic conditions, in order to show good potential of Storage of the Aquifer. Using MODFLOW-2000 as well as the previewed studies have showed some important results. Results show that almost all of the hydrographs of water head in all wells; (i.e. observed versus calculated heads) are decrease with time. The calculated head shows a good match with the observed data and each other. The root mean square error (RMSE) indicates a small error value appropriate for model elevation (RMES = 3.565 m), whereas the standard error of the estimation is 0.644, and the normalized RMS Vs time (head) is 7.75%. The correlation coefficient describes a strong degree between the observed and calculated head data (R^2 = 0.984) with the 95% confidence interval. The water table level ranges between 2 m to 32 m in some observation wells, this may have been due to continue pump during 1440 days of model calibration. The runoff within the narrow Wadi carries an annual flow of about 50 MCM, thus replenishing the shallow Wadi Nyala aquifer. The parameters were calibrated through the iterative calibration procedure using the optimization code PEST; in two simulation cases due to initial head. As general, the result found that the optimization values of Hydraulic Conductivity (Kx) and Storage Coefficient (S) are 6.5 m/d, 0.00478 and 1.0 m/d, 0.058 in case-1 and case-2 with the average values are 3.75 m/d and 0.0314; respectively, whereas, other parameters (i.e. Ky, Kz and Ss) are stable during simulation periods in all cases.

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REFERENCES

[1]. Zhang B, Song X, Zhang Y, Han D, Tang C, Yu Y, Ma, YHydro-chemical characteristics and water quality assessment of surface water and groundwater in Songnen plain, Northeast China. *Water Research.* . 2012; 46: 2737-2748.

[2]. Saleh A, Al-Hassoun., Thamer A M. Prediction of Water Table in an Alluvial Aquifer using Modflow. *Pertanika J. Sci. &Technol*. 2011; 19 (1): 45 - 55.

[3]. Butler JJ. Jr. Pumping tests in no uniform aquifers: the radially symmetric case. *J. Hydrol.* 1988; *101(1/4)*: 15–30.

[4]. Theis C.V. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage. *Eos Trans Am Geophys Union*. 1935; 16: 519 -524.

[5]. Butler JJ .Jr, and Liu W. pumping tests in no uniform aquifers: the radially asymmetric case. *Water Resour Res.* 1993; *29(2)*: 259–269.

[6]. Schad H, Teutsch G. Effects of the investigation scale on pumping test results in heterogeneous porous aquifers. *J. Hydrol*. 1994; 159: 61- 77.

[7]. Meier P.M, Carrera J, Snchez-Vila X. An evaluation of Jacob's method for the interpretation of pumping tests in heterogeneous formations. *Water Resour Res*. 1998; 34(5): 1011–1025.

[8]. Cooper H.H, Jr. and Jacob C.E. A generalized graphical method for evaluating formation constants and summarizing well-field history. *Eos Trans Am Geophys Union*. 1946; 27(4): 526 –534.

[9]. Meier P.M., Carrera J, Snchez-Vila X. A numerical study of the relationship between transmissivity and specific capacity in heterogeneous aquifers. *Ground Water*. 1999; 37(4): 611- 617.

[10]. Naff R.L. Radial flow in heterogeneous porous media: an analysis of specific discharge. *Water Resour Res* . 1991;27(3): 307- 316.

[11]. Wang H.F, Anderson M.P. *Introduction to groundwater modeling*. W. H. Freeman and Company, New York. 1982.

[12]. Fetter C.W. *Applied Hydrogeology*, 4th edn, Prentice Hall, New Jersey. 2001; Chp.3:66-112.

[13]. Anderson M.P, and Woessner W.W. 2002. *Applied groundwater modeling: simulation of flow and advective transport*. Academic Press, London.

[14]. Mays L.W. 2005.*Water resources engineering*. Ed. John Wiley & Sons.

[15]. Xu X., Huang G, Zhan H, Qu Z, Huang Q. Integration of SWAP and MODFLOW-2000 for modeling groundwater dynamics in shallow water table areas. *Journal of Hydrology*. 2012; 412 –413, 170-181.

[16]. Harbaugh A.W, Banta E. R, Hill M.C, McDonald M.G. MODFLOW-2000, The US Geological Survey modular groundwater model – User guide to modularization concepts and the Ground-Water Flow Process: US Geological Survey Open-File Report 00-92. 2000; pp.121.

[17]. McDonald M.G,Harbaugh A.W. *A modular three dimensional finite difference ground-water flow model.* US Geological Survey Techniques of Water-Resources Investigations, Book 6, Chapter A1, 586. 1988.

[18]. WAPS. 1985. *Water Resources Assessment Program in the Sudan WAPS-2*, Nyala Water Supply Study, Final Report, National Water Corporation. Sudan.

[19]. Ahmed H. I. Mathematical Modelling of Wadi Nyala Aquifer. 2008. Unpublished MSc. Dissertation, Department of Civil Engineering, Khartoum University, Sudan.

[20]. WRADM. *Water resources assessment, development and management in the conflict affected regions in Darfur, Western Sudan*. A project implemented by the University of Khartoum and funded by the UNESCO/Flanders Fund-in-trust (FUST). 2010.

[21]. GWD. Wadi Nyala water resources: An Approach towards Augmentation. Groundwater and Wadis Directorate. Water resources management project (WRM), Khartoum. 1993; WRM/T/ report/93/3.

[22]. HWNTIN 6 . Southern Darfur land use planning survey Annex-2 Water Resources & Engineering. 1974.

[23]. Darcy H. *Les Fontaines Publiques de la Ville de Dijon [The Public Fountains of the City of Dijon]*. 1856. Dalmont, Paris.

[24]. Remson I, Hornberger G.M, Molz F.J. *Numerical Methods in Sub-surface Hydrology, with an Introduction to the finite Element Method*. Wiley (Interscience), New York. 1971 ; p. 389.

[25]. Craig T.S, Henry Darcy (1803-1858). Immortalized by his scientific legacy. *Springer,Verlag*. *Hydrogeology Journal,* 2008;16: 1023–1038.

[26]. Barnett B, Townley L.R, Post V, Evans R.E, and Hunt R.J. *Australian Groundwater modeling Guidelines Sinclair Knight Merz and National Centre for Groundwater Research and traing.* Waterlines. Report .Series. 2012; No: 82.

[27]. Abdo G, and Salih A. Water resources management in Darfur. *U of K EJ*. 2011; *1(1)*, 41- 49. Available online: ejournal.uok.edu.

[28]. Abdo G. and Salih A. The Water Research Centre University of Khartoum (2017).

[29]. The Water Research Centre University of Khartoum (WRCUK). (2017). Detailed Wadi Nyala Aquifer Assessment and Water Resources Management (Aquifer Modelling). Final Report. April.

[30]. Doherty J, Brebber L, Whyte P. *PEST: Model-Independent Parameter Estimation; Watermark Computing*: Corinda, Australia. 1994.

H. I. Ahmed, et. al. “Evaluation the Aquifer Hydraulic Parameters of Wadi Nyala, South Darfur State, Sudan”. *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE),* 19(2), 2022, pp. 27-34.