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Groundwater Assessment using Numerical Flow Model: A Case Study in Gash Sub-Basin-Kassala State, Sudan

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The main objective of groundwater modelling in Gash River Sub-basin, is to investigate the effect of hydrologic, hydrogeological parameters and stresses on hydrodynamic behaviour through the implementation of a realistic three-dimensional groundwater flow model. Severe decline of water level due to uncontrollable heavy abstraction, exposes a water scarcity problem especially in summer seasons. The model was developed for four geological layers encompassing two aquifer zones. The improved three-dimensional visual MODFLOW Code was selected, implemented and run using WHS method to solve the finite difference equation using trail-and-error calibration procedure at Kassala Area. The transient model was successfully calibrated with acceptable results of model calibration criteria. The contour maps of the simulated heads were performed as potentiometric surface. The general flow direction of the groundwater is from southeast towards northwest part of the area and from Gash River course towards the east and west directions as detected from gradual decreasing of potential line's values in those directions, confirming the aquifer recharge from Gash River. The similarity of potentiometric surface contour maps of the two aquifers confirm the aquifers hydraulic interactions. It is found that the increasing pumping rate caused considerable increase in drawdown as detected from pumping rate incremental scenarios. Moreover, incremental pumping rate scenarios also reflected increasing river leakage into the aquifer system due to disturbance of water balance due to water level decline. The components of water budgets were calculated and its percentage was performed for the hydrologic balance. The difference between inflow and outflow of the water balance shows a deficit in most stress periods of the model simulations. Calibration fitness was accomplished at most of the observation wells suggesting that the groundwater model is an accurate representation of the actual historic groundwater system and confirm the validity of the model to forecasting purposes. It was found that the model is more sensitive to hydraulic conductivity and least sensitive to specific yield (Sy). Hence, precaution should be revealed for hydraulic conductivity in forecasting model usage.

Keywords: hydrogeology; numerical model; hydraulic property; boundary condition; aquifers

I. INTRODUCTION

Groundwater is one of the most important natural resources for potable water in many countries of the world in recent decades. In general, groundwater is an attractive source of water, because it is fresh and readily available (Behera *et al.,* 2022). Moreover, potable water is believed to be safe, free from pathogenic bacteria and from suspended matter (Jennings *et al.,* 2018). The rate of overdraft of groundwater is usually increasing continuously due to faster rate of population`s growth accompanied by agricultural and industrial development. In many regions of the world, groundwater and surface waters are hydraulically

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interconnected and an understanding of this interaction is fundamental to effective water-resource management (Winter *et. al.,* 1998; Sophocleous, 2002; Sophocleous & Devlin, 2004; Brodie *et. al.,* 2007; Kacem *et al.,* 2016). The assessment of groundwater motion in natural complex and irregular systems needs specific hydraulic, hydrogeological and geometric assumptions and simplifications (Anderson, Woessner & Hunt, 2015). Moreover, groundwater assessment, and its sustainable management options to understanding its dynamic behaviour can be carried out by resorting to aquifer modelling techniques, based on the use of different geo-informatics tools that allow for the proposition of possible scenarios of groundwater flow (Behera *et al.,* 2022). Groundwater models can describe the groundwater flow using partial differential equations based on certain simplifying assumptions (Elkrail & Ibrahim, 2008). These assumptions typically involve the direction of flow, geometry of the aquifer and the heterogeneity or anisotropy of sediments or bedrock within the aquifer (Kumar, 2004). Groundwater models can be used to refine different conceptual models, estimate hydraulic parameters, predict how the aquifers might respond to changes in pumping and climate change, evaluate irrigation strategies and to simulate different water management scenarios (Arenas *et. al.,* 2020; White, 2018; Regli *et al.,* 2003).

Visual MODFLOW computer code has been widely used to simulate the aquifer conditions, to estimate aquifer parameters, and to predict groundwater conditions (Anderson, Woessner & Hunt, 2015; Hashemi *et al.,* 2013). Generally, modelling is usually implemented during the planning and optimisation phases of groundwater system (Ringleb *et al.,* 2016).

The study area at Kassala state, east of Sudan, recently has received greater attention due to agricultural activities as well as industrial and domestic developments. Kassala town and its rural areas in Gash River Sub-Basin depends mainly on groundwater for human activities and other needs. The Gash River Sub-Basin surrounded by exposed and subsurface basement rocks covered by thin layers of sandy and sandy clay layers. The area recently subjected to severe continuous decline in water level that could be attributed mainly to an uncontrolled heavy abstraction of the groundwater (Anderson, Woessner & Hunt, 2015). The effect of heavy abstraction on groundwater level could be clearly understood and investigated through the implementation of numerical flow modelling using Visual MODFLOW software.

The study generally aims to investigate the effect of hydrologic, hydro-geologic parameters and stresses on hydrodynamic behaviour, through the implementation of a realistic flow model. Specifically, the study should delineate the geometry of the water-bearing formation; provide a complete description of the hydro-geologic framework of the aquifer system; design an appropriate conceptual model to fit a suitable groundwater flow model of the aquifer system; determine aquifers capacity and calculate the groundwater balance in Gash River Sub-basin.

The River Gash is a seasonal stream that originates in the highlands of Ethiopian Plateau and flows northwest across the flat plain and ending as an inland fan delta, which is the most important agricultural land in the area (Saeed, 1969; Abdalla Elshiekh *et al.,* 2011). Inside the Sudan, Gash River is braided ephemeral stream of the fluent type (Hago, 2014). The area can generally be subdivided into three parts: upper stream, middle stream, and downstream or Gash delta. The study area lies between longitudes (UTM) 854000 m (36°20′) and 874000 m (36°35′) E and latitudes (UTM) 1695000 m (15°10′) and 1720400 (15°25′) N (Figure 1), covering an area of 635 km². The study area represents part of Gash River catchment. The work is intending to evaluate water resources, supply and demand of River Gash Sub-basin within the area that extending from Al lefa to Alsalmu Alikum.

The study area is a flat peneplain spotted with scattered isolated hills and mountain at the southern and eastern part of the area such as J. Taka, J. Kassala, J. Mukram and J. Abu Gamul. The peneplain is crossed by the Gash River course and its seasonal tributaries from the south and south east toward the north and northwest and diminished out with a characteristic Gash inland-delta fan. The area is characterised by semi-arid climate with hot and dusty summer (April–October), where maximum temperature exceeds 45°C, and winter season (November–March) where the average temperature is about 25°C. The rainy season starts in July and continues to October with annual average rainfall of 350 mm.

From geological viewpoint, the area is composed of Pre-Cambrian basement complex, clay of the plain and alluvial deposits. The basement complex comprise meta-sediments intruded by scattered out-crops of granitic rocks. The area was subjected to extensive erosion that reduced the topography to the peneplain. The basement rocks include the biotite gneisses, hornblende gneisses, marbles, pegmatites, granites and secondary quartz veins. These rocks cropped-out as scattered isolated hills that rise on the plain. In some places, the basement complex was covered with Tertiary-Quaternary deposits (Elkrail & Ibrahim, 2008).

The clay of the plain overlies the subsurface basement complex, Cretaceous sedimentary series and Tertiary lavas. The clay of the plain is usually found on the river flood plain east and west of alluvial deposits. The clay of the plain consists of grey to dark grey laminated loose to compacted clay, silt, sandy silt layers (Bireir, 2002). The thicknesses of these layers range from a few meters to 20 meters along both sides of the alluvial deposits. The Pleistocene-Recent alluvial deposits were formed during the flood seasons. These deposits, overlain the above described two lithostratigraphic units (Andrew, 1948). The coarse material (sands and gravels) usually deposits upstream and the fine material (silt and clay) deposits downstream. The thickness of alluvial deposits is about 30 m at the upstream, where as it reaches up to 60 m downstream. The lithological data collected from four boreholes during field trips indicate that, the alluvial deposits are composed of intercalating beds of loose and friable coarse to fine-grained gravel, sand, silt, and clay (Figure 4).

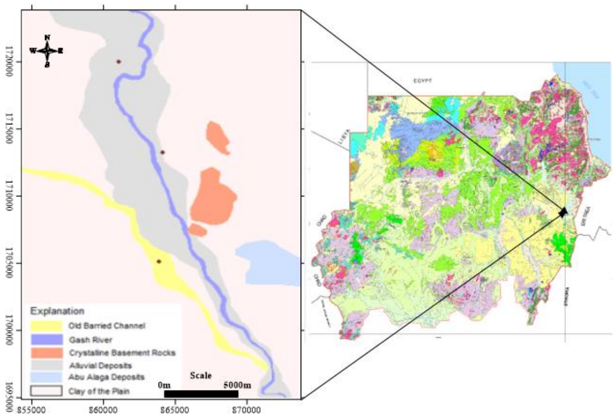

Figure 1. Location and Geological Map of Gash River Sub-basin

The Gash River and its tributaries represent the seasonal surface water resources in the study area. The flooding period of Gash River starts from June and reach its peak at the end of October. The flood plains may attain a width of 1 Km on either side of the Gash River (WAP, 1982). The Gash river forms an extensive inland delta near Kassala town. The major seasonal runoff is constituted by the Gash River drainage system (Figure 2). The systematic Gash River annual discharge measurements at El Gera gauging stations were performed during the period from 1907 to 2007 (Historical records at Gash River Technical Committee office, Kassala town). Accordingly, the annual discharge rate varies between 110-1780 million cubic meters (mcm) with average value of 615 mcm (Figure 3).

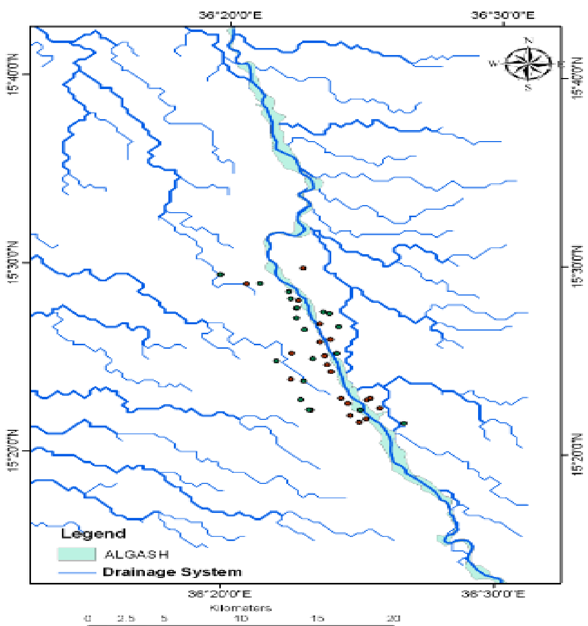

Figure 2. Drainage system of Gash River Sub-basin at Kassala Area (After Elshiekh *et al.*, 2011)

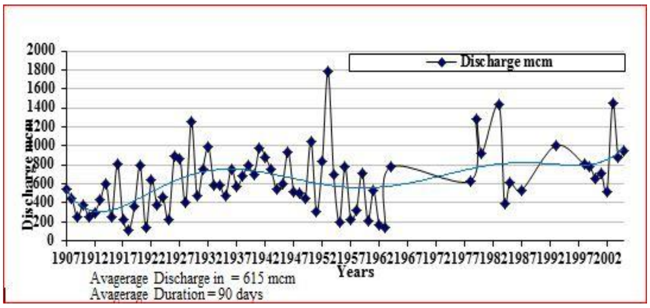

Figure 3. Gash River Annual Flow at El Gera gauging Station (After Elshiekh *et al.,* 2011)

From groundwater viewpoints, the main water-bearing formations in the Gash River Sub-basin are the medium to coarse sands, the gravelly sand of alluvial deposits and weathered basement layers. The thickness of alluvial deposits of Gash River Sub-basin varies from 25 to more than 50 m as detected from the drilled boreholes. In the study area, two main aquifers were determined, namely upper and lower aquifers as the results of wells' lithological logs interpretation and construction of cross-section for four boreholes drilled in Gash Sub-basin (Figure 4). The main sources of recharge of aquifer is due to infiltration from the Gash River's flood or direct precipitation from the rainfall. The average aquifers saturated thickness varies from 10 - 16 m (Figure 4). The groundwater occurs under confined, and semi-confined conditions due to the presence of a confining bed overlying the aquifers. Generally, the starting date of water level rise is usually mid to last June and the date of peak is usually ended in October to the beginning of November (end of river flow). These phenomena give the first indication that Gash River is the main source of recharge. The general flow direction in the study area is towards the north and northwest.

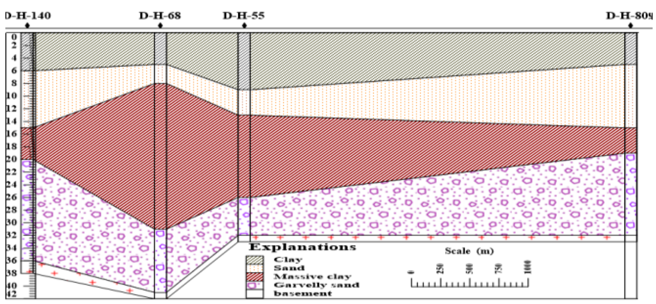

Figure 4. Lithological Cross-Section in Gash River Sub-basin

II. MATERIALS AND METHODOLOGY

The natural water system in Gash River valley will be investigated using appropriate methods and techniques. Appropriate data were collected to help define the hydrogeology of the study area and to assist in constructing a groundwater flow model. The collected data included groundwater observation wells locations, groundwater levels measurements and surface-water sites (Figure 5). Moreover, stream flow and stream stages were measured and aquifer tests were conducted to determine aquifers hydraulic properties of confined condition using Thies's and Jacob' methods. One needs realisations for a parameter set that can be implemented in a numerical model so that optimisation, cross-validation and testing set can be developed. GIS spatial technique was used to prepare the aquifer spatial geometry and the input data, to analyse the output and to present the results of the groundwater flow model. Strater Software (version 3) was used to construct the well lithological logs and prepare the cross-section to delineate vertical distribution of the water bearing-formations (Figure 4). The groundwater system in Gash River sub-basin can be simplified to build a conceptual model that visualises the field problem and organises the associated field data. The three-dimensional groundwater flow of constant density through porous medium can be described by the partial differential equation (McDonald & Harbaugh, 1996; Elkrail, 2004) as follows:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)\pm W=S_s\frac{\partial h}{\partial t} \quad (1)$$

Where

K_{xx}, K_{yy}, and K_{zz} are the hydraulic conductivity [L T-1], h is the hydraulic head [L], S_s is the specific storage, W is the volumetric flux per unit volume and represents source and/or sink of water (t-). W is positive for a source and negative for a sink. This equation constitutes a mathematical representation of a groundwater flow system and is the type of flow equation often solved in groundwater models such as MODFLOW. Visual MODFLOW code was used for the three-dimensional flow simulation. The groundwater flow model was developed and run using Waterloo Hydrogeologic Services (WHS) method to solve the finite difference equation in the form of a large number of simultaneous linear equations by iteration. The Kriging method was used to calculate the interpolated values during simulations in the model domain. The Root Mean Square Error (RMS), the Mean Absolute Residual Error (MAE), Normalized (RMS%) and mass balance criteria were used to check the calibrated model. The trial-and-error techniques was applied for adjustment of parameters. The base map, the depth to water table, and lithological cross sections have been prepared with GIS by creating point data or contour existing grids. The field data of pumping rate, evapotranspiration, recharge, head observations were prepared in ASCII or Excel files for the model input modules. The model domain encompassing the well fields was considered as one zone for estimating the groundwater balance.

A. Model Setup

The numerical model is based on the partial differential equation of water flow and generalisation of the conceptual model of groundwater system, and hypothetically describes the quantitative relation of groundwater system parameters. According to the mathematical model identification and verification, further validation of adaptability of groundwater system behaviour and function can be made and deepening understanding of groundwater system characteristics can be reached (Xue, 1986). The essential steps of groundwater model development are the conceptual model, analytical solution, numerical code selections and field data checkup (Elkrail & Ibrahim, 2008). Building a conceptual model is to simplify the field problem and organise the associated field data so that the system can be analysed more readily (Anderson & Woessner, 1992). There are three steps in building a conceptual model which are; defining hydro-stratigraphic units; preparing a water budget and defining the flow system (Elkrail & Ibrahim, 2008).

1. The model code selection and data availability

After the development of the conceptual model and hydrogeological characterisation of the site has been completed, the improved three-dimensional finite difference, block-centred visual MODFLOW computer code was selected to simulate the groundwater system in Gash River Sub-basin. Visual MODFLOW is the most widely used numerical groundwater flow model, originally developed by the U.S. Geological Survey and later by Waterloo Hydrogeologic Inc. (McDonald & Harbaugh, 1988; Wang *et al.,* 2008). Visual MODFLOW computer code can simulate steady and Transient state flow conditions in an irregularly shaped, heterogeneous and complex flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Conceptual groundwater flow model presented here incorporates the latest geologic and hydrogeological information available within the study area. The study area was simplified for developing an appropriate conceptual model to represent the physical properties of the groundwater system. The hydraulic properties of the rocks were estimated from available data and were modified by varying them in the model to obtain reasonable agreement between model-calculated and observed water levels.

2. Model input data

Pumping Wells: Groundwater outflow describes the water discharge out of the aquifers through wells abstraction, cross-formational flow, natural base outflow, evapotranspiration and evaporation. In Gash River Sub-basin, the groundwater pumpage represents the main source of discharge. Waters' production wells were used to simulate the groundwater abstraction in the area. Pumping rates of wells, which fall within one cell, were summed up and represented by a single well. A number of wells (more than 58) have been drilled (Figure 5) for extracting groundwater from Gash River Sub-basin, with pumping rate varies between 337 and 1080 m3/d. Evapotranspiration is an effective factor for groundwater discharge in the study area. Evapotranspiration rate of 165 mm/year was used for model simulation with extinction depth of 6 m below the ground surface.

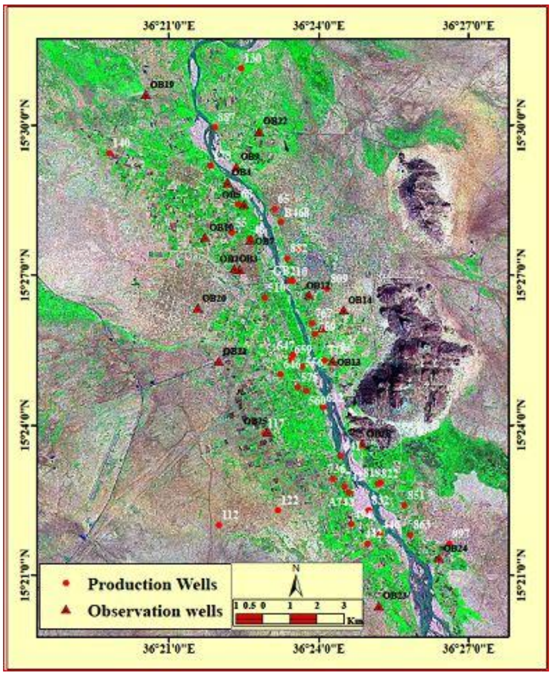

Figure 5. Pumping and observation wells in the study area

Observation Wells: Monitoring of groundwater level changes are observed from equipped observation wells in the model area. In Gash River Sub-basin, twenty-three observation wells (Figure 5), were used for model simulation. These observation wells were equipped with loggers to measure water level during the period from 2017 to 2018 (25 months).

Recharge: Precipitation, surface water infiltration and subsurface inflow through the porous or fractured media on high lands, represent significant source of recharge to groundwater. Aquifer's recharge may include precipitation, infiltrating from the river losses, irrigation return flow and vertical leakage from geologic units above the aquifers. In Gash River sub-basin, the upper layer is composed of fine-grained clayey sand through which considerable amount of precipitation recharges the aquifer system. The recharge from precipitation was assumed to be spatially uniform and assigned to the upper most part of the active cells in model domain. The average direct recharge rate of 160 mm/y was used for model simulation in the Urban Kassala area.

Evaporation and Evapotranspiration: The evaporation data from Kassala meteorological station shows that the highest value of evaporation is recorded in April to June (11 mm/d) while the lowest is recorded in January amounts to 6 mm/day (Hago, 2014). The average monthly evaporation in Kassala area is about 150 mm and the annual average value is 2900 mm. However, evaporation mentioned here is a potential value as it is valid for evaporation from water surface under the measured meteorological circumstances (Hago, 2014).

Hydraulic Properties: Transmissivity, hydraulic conductivity and storativity, could be statistically analysed for each hydro-stratigraphic unit. These hydraulic properties are most essential for groundwater flow modelling and helping to define the flow characteristics of the aquifer. Vertical hydraulic conductivity was estimated as percentage of horizontal hydraulic conductivity according to geological formations. The horizontal anisotropy was defined, discussed, and estimated. The main groundwater aquifers are the alluvial deposits of Gash River Sub-basin and the surrounding fractured-weathered basement aquifers. Two aquiferous zone were considered in the alluvial deposits namely; upper and lower aquifers. Hydraulic conductivity of the upper aquifer varies between 3.5 - 36 m/d where the lower value was assigned for the model simulation. The hydraulic conductivity of the lower aquifer varies between 8.5 - 58 m/d where the lower value was assigned for the model simulation. Total porosity (n_T), effective porosity (n_e) , specific storage (S_s) and specific yield (S_y) of the upper aquifer were assigned as 0.22, 0.16, 0.00005 and 0.18. The hydraulic properties of the lower aquifer was assigned as specific storage (S_s) of 0.00005, specific yield (S_y) of 0.20, effective porosity (n_e) of 0.22 and total porosity (n_T) of 0.25.

Initial Conditions: Initial conditions are defined as the head distribution everywhere in the system at the start of the simulation and known as boundary conditions in time (Anderson & Woessner, 1992). Initial conditions for steady-state simulations are important mainly to save computational effort in reaching a solution. The observed heads (static water level SWL) in the observation wells of the period between 2017 to 2018, which vary between 490.77 and 523.4 m, a.s.l in the model domain, were used for the model simulation.

Boundary Conditions: Boundary conditions are mathematical statements specifying the dependent variable (head) or the derivative of dependent variable (flux) at the boundary of the model domain (Anderson & Woessner, 1992). Water may enter or leaves a model domain either through sources and sinks within the interior of the grid or through boundaries as determine by boundary conditions. Hydrogeological boundaries include specified head boundaries (Drichlet conditions) for which head is given, specified flow boundaries (Neuman conditions) for which the derivative of head across the boundary is given and head dependent flow boundaries (Elkrail & Ibrahim, 2008). The model area is, therefore, located between no-flow boundaries assigned to the east and west. The upper surface of the aquifer represents a flow boundary, where water can enters and leaves the aquifer; through the unconfined layer, i.e. water table condition. The bottom of the aquifer represents a barrier boundary through which no flow enters or leaves the aquifer (Elkrail & Ibrahim, 2008). The specified boundary condition is the most appropriate boundaries to be assigned for the model simulation in Gash River Sub-basin. General head boundaries (GHB) were assigned at the most north and most south part of the model domain with boundary heads of 530 and 505 m, a.s.l, respectively with reference to heads at the nearest observation wells for aquifers model simulation.

3. Model design

Designing a calibrated model requires the formulation of mathematical approaches and the integration of various hydrogeological properties (Al-Muqdadi *et al.,* 2020). For model development in the study area, grid size and spacing, layer elevations, boundary conditions, aquifers' hydraulic properties, sources and sinks were performed for transient modelling conditions.

The physical and hydrogeological framework of the model grid were determined by using a base map to cover the extent of the model domain. A finite difference grid was superimposed over a coverage area of 600 Km2. Initially, 90 rows, 60 columns, 4 layers and 21600 cells were used to cover the model domain. Transient simulation model was developed with a total simulation time of 25 months (217-2018) representing 25 simulation stress periods of thirty daytime length. Visual MODFLOW allows the time step to increase during simulation with a geometric progression of ratios of 1.2 to 1.4 (Anderson & Woessner, 1992). The values of 10 and 1.2 were chosen as the input values for time step and time-step multiplier, respectively for the output obtained from trail runs.

Groundwater in the alluvial deposits distributed mainly along a narrow strip of Gash River valley (13 km wide). The water-bearing formations the study are medium to coarse sand and gravelly-sand layers of Quaternary deposits. The aquifers' thickness ranges from 10-16 meters with extreme maximum thickness of 28 m. Twenty-three observation wells were used for model simulation. The groundwater pumping wells represents the main source of discharge. During the flood season, the Gash river stage acts as losing stream, leads to subsurface water percolation and streambed infiltration. This phenomenon indicates that the river and aquifers are hydraulically interconnected.

In finite difference models, a pumping well is a point sink, which is represented by a node that denotes the finite difference cell (Anderson & Woessner, 1992). This point sink of water is extracted over the volume of aquifer represented by a cell that contains the point sink. A number of wells (more than 58) have been drilled (Figure 5) for extracting groundwater.

B. Model Calibration

Calibration is the process of adjusting model inputs until the resultant predictions give a reasonably good fit to the observed data. It is an iterative and very time-consuming process (Chen *et al.,* 1998). Calibration is needed in order to account for unmeasured, unknown, or unrepresented conditions or processes and uncertainty in measured input data (Banejad *et al.,* 2014). The calibration is performed to minimise the difference between field measured and model simulated head values, sometimes called the calibration criterion to acquire reliable modelling results (Wu *et al.,* 2017). A good calibration of a model ensures that the remaining data between the observed and the simulated data are as minimised as possible (< 1) and the uncertainties of the parameters are lower (Gan *et. al.,* 2018; Simmons *et al.,* 2017). Models are calibrated either by automated procedure or trial-and-error processes in which model parameters are adjusted within reasonable limits from one simulation to the next in order to achieve the best model fit (Praveena & Aris, 2010). Model fit is commonly evaluated by visual comparison of simulated and measured heads and flows or by comparing root mean square (RMS) errors of heads and flows between simulations (Yaouti *et al.,* 2008). Different criteria were used by visual MODFLOW such as Root Mean Squared error, Normalized Mean Squared error and Means Absolute Residual Error as a measure of the fit between the simulated results and the observed data and expressed by the equations:

Root Mean Squared error is defined by the equation:

$$RMS = \sqrt{\left[\frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)i^2\right]} \quad (2)$$

Normalized Mean Squared error %:

$$RMS\% = \frac{RMS}{(X_{obs})_{\max} - (X_{obs})_{\min}} \quad (3)$$

Means Absolute Residual Error :

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|(h_m - h_s)i| \quad (4)$$

where (n) is the number of calibration values, (h_m) measured heads and (h_s) is simulated heads, $(X_{obs})_{max.}$ and $(X_{obs})_{min}$ are results at selected data points.

Finite difference flow model was designed in three dimensions and calibrated to quantify the hydrological parameters of aquifers in the Gash River Sub-basin and provide the overall hydrological water balance in the aquifer system. 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 (Figure 7, 8 and 9). For transient simulation, storage parameters, initial condition, boundary conditions, and hydrologic stresses must be specified. Moreover, time and space must be discretised. During transient calibration head changes with time as a result of water release from or taken into the storage within the porous medium must be accomplished. When the transfer of water to and from the storage stops, the system will reach a steady state and head will be stabilised (Elkrail & Ibrahim, 2008). This property is known as storativity, and described by specific storage (S_s), storage coefficient (S) and specific yield (S_y). The model was calibrated using hydraulic heads for the period from January 2017 to December 2018 in Gash River Sub-basin. The minimal residual between observed and calculated heads was used to calculate the root mean squared error (RMS) and the absolute mean residual (AMR). During model calibration, model parameter values were adjusted so that simulated heads and mass balance would fall within the calibration targets (Elkrail & Ibrahim, 2008). After each run, differences between simulated and observed heads and their Kriging calibration values were calculated with the goal of every difference being minimal.

III. RESULTS AND DISCUSSION

In Gash River Sub-basin model simulation, the Root Mean Squared error (RMS), Absolute Residual Mean (ARM), Normalized (RMS)% and mass balance percent discrepancy were adjusted as the calibration targets (Figure 6). Specifically, the calibration was more acceptable with the average root mean square error (RMS) of 0.575 m, Absolute mean residual of 0.421 m, average Normalized Root Mean Squared (RMS %) of 2.33% and mass balance percent discrepancy of less than 0.01%.

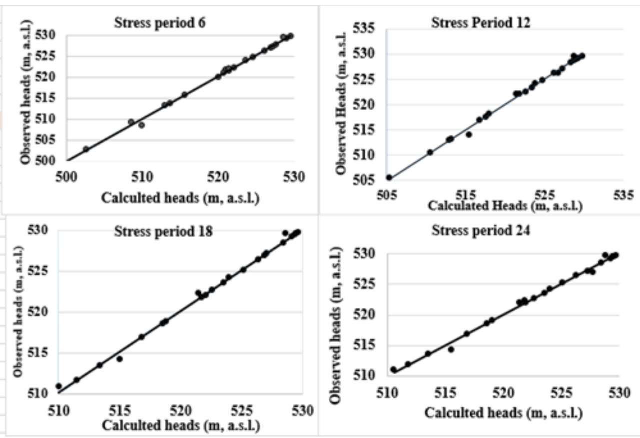

Figure 6. Observed versus calculated head for different stress periods (1:1 line)

The minimal differences between the measured and simulated heads at each observation well (Figure 6 and 7) and consistent results on hydraulic head distribution (Figure 8 and 9), confirmed model validation in the study area.

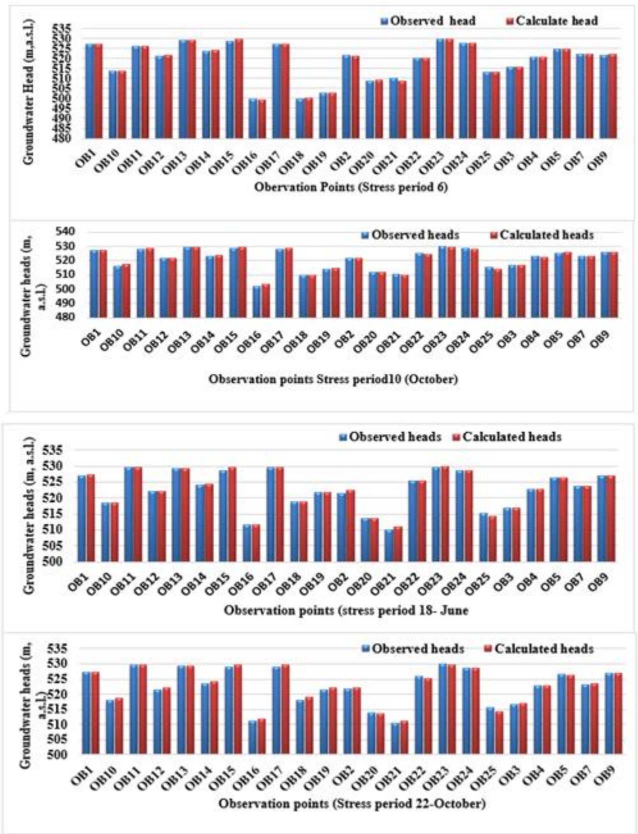

Figure 7. Comparison between Observed and calculated heads in Observation wells at different stress periods

The water level maps of the simulated heads were performed as potentiometric surface (Figure 6 and 7). Accordingly, the general flow direction of the groundwater is from southeast towards northwest part of the model area; and from the Gash River course towards the east and west directions as detected from gradual decreasing of potential line values in those directions, confirming the aquifer recharge from Gash River. Acceptable calibration was accomplished at most of the observation wells suggesting that the groundwater model is an accurate representation of the actual historic groundwater system (Figure 7) and confirm the validity of the model for forecasting purposes. The similarity of potentiometer surface contour maps of the two aquifers confirm the interaction surface and groundwater in the Gash River Sub-basin (compare Figure 8 and 9).

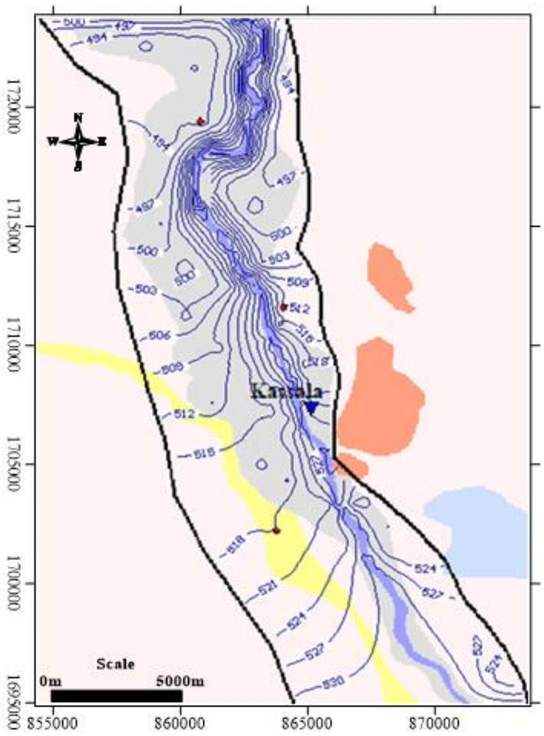

Figure 8. Simulated Peizometric Surface of upper aquifer in Gash River Sub-basin

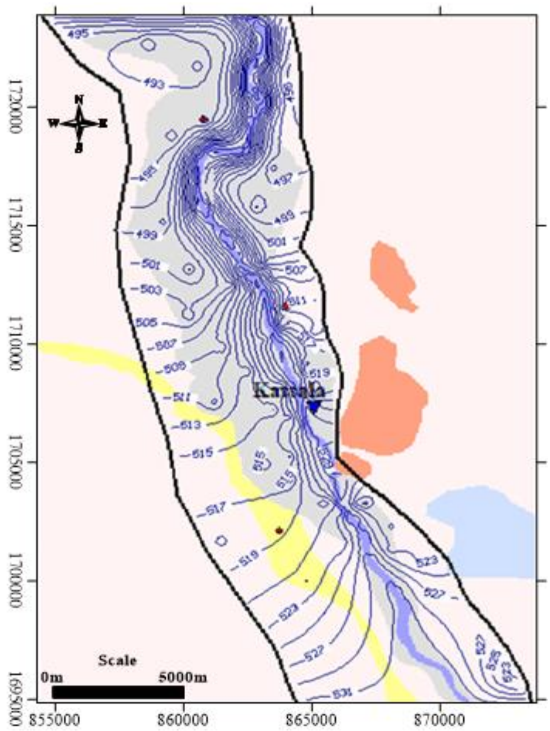

Figure 9. Simulated Peizometric Surface of Lower aquifer in Gash River Sub-basin

Effects of Wells' pumping scenarios were conducted to evaluation the resultant of drawdown and River leakage into the aquifer system (Table 1; Figure 10 and 11). Hence the total groundwater abstraction through the pumping wells was increased step wise as incremental percentage of 10, 20, 40, 50, 60, 80 and 100 from the original pumping rate (55059 m3/d; Table 1). It is found that the increasing pumping rate caused considerable increase in drawdown (Figure 10) indicating rapid decline of the water table. Moreover, increasing pumping rate also reflect an increase of the subsurface inflow as river leakage (Figure 11) to recharge the aquifers system and to offset the water table decline.

Table 1. Wells' Pumping Scenarios from the original rate (55059 m^3/d)

Incremental percentage %	Wells' Pumpage (m^3/d)	Drawdown (m)	River Leakage (m^3/d)
10	61177	13.64	70160
20	66738	15.66	81347
40	77861	20.39	80523
50	83423	22.05	81347
60	88984	20.82	78790
80	100107	21.31	84225
100	111230	21.74	88049

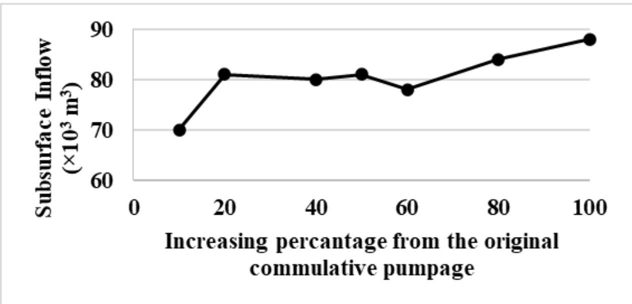

Figure 10. Effect of pumping Scenarios on Drawdown in Gash River Sub-basin

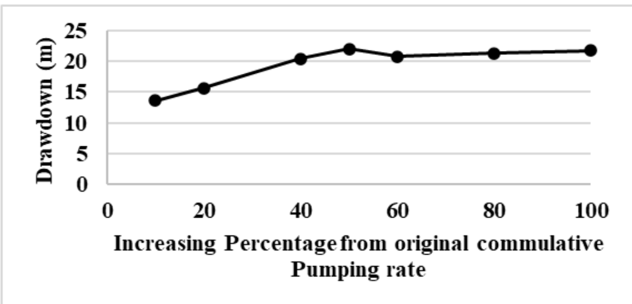

Figure 11. Effect of pumping Scenarios on River leakage into the aquifer system

A.Groundwater Balance

Groundwater recharge from precipitation, overland flow, subsurface baseflow along the boundaries, or recharge from surface water bodies represent the field-estimated inflows (Elkrail & Ibrahim, 2008). On the other hand; wells' pumping, baseflow to streams, evapotranspiration, spring flow and represent outflows. A water budget should be prepared from the field data to summarise 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 (Anderson & Woessner, 1992). In the visual MODFLOW statistical operations were used to report the cumulative budget for assigned zone in Gash River Sub-basin. Therefore, the four layers model simulations were used to investigate the water balance components during each stress period in the model area (Table 2). Groundwater budget was calculated for the whole model area as single zone. The calculated zone budget components include storage, pumpage, recharge, river leakage, general head boundaries and evapotranspiration (Table 2).

The zone budget was calculated for two years (2017 and 2018) each of twelve stress periods for the whole model area. The total volume of water as inflow is about 525.117 and 532.695 mcm for the first and second year, respectively. Accordingly, the total volume of the aquifer storage as inflow for the two years varies from 3.706 to 3.828 million cubic meters (mcm). It was found that recharge is the most important hydrologic component of inflow to the aquifer, which is able to offset the groundwater extraction from the aquifer. The annual net recharge volumes represent 47.01% and 46.34% of the total inflow for the first and second year, respectively (Table 2). The volume of water enter the model area as subsurface baseflow along the general head boundaries (GHB) represents 5% and 6.29% of the total inflow of first and second year, respectively. The cumulative water volume of river leakage as inflow, represents 47.32% and 46.64% of the total inflow of the first and second years, respectively (Table 2).

The total volume of water as outflow is about 525.124 and 532.763 mcm for the first and second year, respectively.

Groundwater pumping volume through wells in the entire area represents 23.68% and 23.41% of the total outflow of the first and second year, respectively (Table 1). The volume of water leaving the model area as subsurface baseflow through the boundaries represents 1.7% and 1.67% of the total outflow for the first and second year, respectively (Table 2). The cumulative water volume leaving the model domain as evapotranspiration represents 41.37% and 68.10% of the total outflow of the first and second years, respectively (Table 2).

The cumulative water volume discrepancies of inflow-outflow is negative in most stress periods. The water mass balance deficit is a sign of groundwater depletion with progressive time in the future under the same prevailing condition. Accordingly, good management of groundwater is mandatory for sustainable development of water resources in Gash River Sub-basin.

Table 2. Cumulative groundwater balance in Gash River Sub-basin

Time	Component	Inflow (mcm)	%	Outflow (mcm)	%
1st year	Storage	3.706	0.01	174.569	33.24
	Pumpage			124.359	23.68
	Recharge	246.864	47.01		
	River leakage	248.49	47.32		
	ET			217.264	41.37
	GHB	26.057	5	8.932	1.70
	Total	**525.117**	**99.34**	**525.124**	**99.99**
2nd year	Storage	3.828	0.01	36.384	6.83
	Pumpage	0		124.717	23.41
	Recharge	246.864	46.34	0	
	River leakage	248.49	46.64		
	ET			362.789	68.10
	GHB	33.513	6.29	8.878	1.67
	Total	**532.695**	**99.28**	**532.763**	**100.01**

B. Sensitivity Analyses

Model sensitivity is a function of groundwater response to changes in model inputs, such as groundwater aquifer hydraulic properties and recharge (Anderson *et. al.,* 2015; Al-Muqdadi *et al.,* 2020). In most entry hydrogeological parameters for numerical modelling, there is uncertainty in the boundary conditions, in measurement of abstractions and the estimation of recharge, in representation of natural processes within algorithms in standard software packages and in conceptualisation of the real system (Anderson *et al.,* 2015). Therefore, sensitivity analysis becomes important as the uncertainty in the key input parameters. Sensitivity analysis is a procedure for quantifying the impact on an aquifer's simulated response due to an incremental and decremental variation in a model parameter or model stress (Elkrail & Ibrahim, 2008; Hill & Tiedemann, 2007). Model sensitivity can be expressed as the relative rate of change of selected output caused by unit change in the input (Anderson *et. al.,* 2015; Batu, 2006). If the change in the input causes a large change in the output, the model is sensitive to that input (Anderson *et al.,* 2015). The most influential factor yielded parabolic-shaped sensitivity curves having deep troughs and steeply dipping sides (NRC, 2003). For Gash River Sub-Basin model, the sensitivity analyses were performed for changes in hydraulic conductivity (K), specific yield (S_y) and specific storage (S_s) 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 percentage change in root mean squared error (RMS) values were plotted versus percentage changes of parameter values. Hence, sensitivity analyses reflected that the model is more sensitive to hydraulic conductivity and least sensitive to specific yield (Sy) (Figure 12). Hence for prediction purpose, precaution should be gained to hydraulic conductivity (K) measurements and its distribution. Considering accurate hydraulic conductivity measurements, the model can successfully use for future prediction, although some technical limitations were encountered; such as accuracy of computations (hardware and software), model dependability on the various simplifying assumptions of the natural modelled system and approximations of the actual measurements and distributions of hydrologic and hydrogeological properties (vertical hydraulic conductivity).

Table 3. Parameters used for different sensitivity analyses

Control Parameters	K	S_y	S_s	RMS
	8.5	**0.2**	**0.000031**	**0.401**
K×1.2	10.2	0.2	0.000031	0.531
K×1.1	9.35	0.2	0.000031	0.444
K×0.90	7.65	0.2	0.000031	0.45
K×0.80	6.8	0.2	0.000031	0.589
S_y×1.2	8.5	0.24	0.000031	0.401
S_y×1.1	8.5	0.22	0.000031	0.401
S_y×0.90	8.5	0.18	0.000031	0.401
S_y×0.80	8.5	0.16	0.000031	0.401
S_s×1.2	8.5	0.2	0.0000372	0.421
S_s×1.1	8.5	0.2	0.0000341	0.410
S_s×0.90	8.5	0.2	0.0000279	0.404
S_s×0.80	8.5	0.2	0.0000248	0.402

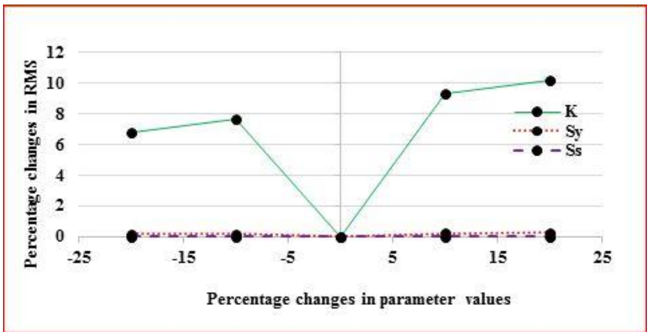

Figure 12. Sensitivity analyses on effect of hydraulic parameters on Root Mean Squire errors (RMS)

IV. CONCLUSION

The Gash River Sub-Basin recently subjected to severe continuous decline in water level that could be attributed mainly to an uncontrolled heavy abstraction of the groundwater. The main objectives are generally to investigate the effect of hydrologic, hydro-geologic parameters and stresses on hydrodynamic behaviour, through the implementation of a realistic flow model. The effect of heavy abstraction on groundwater level was clearly understood and investigated through implementation of numerical flow modelling using Visual MODFLOW software. The groundwater in Gash River Sub-basin was understood and investigated through application of numerical flow modelling using visual MODFLOW techniques. The improved three-dimensional visual MODFLOW Code was selected, implemented and run using the WHS method to solve the finite difference equation using a trail-and-error calibration procedure to evaluate groundwater flow regime of Gash River Sub-basin. Four layers of the alluvial deposits including two aquifers; namely upper and lower aquifers were detected in the model area. The transient model was successfully calibrated with acceptable results of average Root Mean Square error of 0.575 m, Absolute Mean Residual of 0.421 m, average Normalized Root Mean Squared Percent of 2.33% and Mass Balance Percent Discrepancy of less than 0.01%. The contour maps of the simulated heads, were performed as potentiometric surface. The general flow direction of the groundwater is from southeast towards northwest part of the model area; and from the Gash River course towards the east and west directions as detected from gradual decreasing of potential line values in those directions, confirming the aquifer recharge from Gash River. The similarity of potentiometric surface contour maps of the two aquifers confirm the aquifer interactions. From pumping rate incremental scenarios, it is found that the increasing pumping rate caused considerable increase in drawdown and increasing river leakage into the aquifer system due to disturbance of water balance generated from water level decline. The difference between inflow and outflow of the water balance show water deficit in most stress periods of the model simulations. Acceptable calibration results were accomplished at most of the observation wells confirming the validity of the model for forecasting purposes. Sensitivity analyses reflected that the model is more sensitive to hydraulic conductivity and least sensitive to specific yield (S_y). Hence, precaution should be gained for hydraulic conductivity in forecasting model usage.

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