Sustainable Management of Groundwater Resources in the Gash Basin, Sudan

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ABSTRACT

In the Gash Basin, Kassala State, Sudan; Domestic and horticultural irrigation water supplies depend entirely on groundwater. The basin is annually recharged from the Gash River which is shared with Eritrea, Sudan and Ethiopia. Recently, groundwater level has been significantly dropped in the unconfined Gash aquifer in Sudan due to over pumping. The objectives of this study were to determine the future safe utilizable amounts of groundwater under different developed scenarios by the year 2050, to investigate the sensitivity of the aquifers to changes in the recharging rates and to develop a sustainable operation plan. Datasets of 1194 discharging wells and 51 observation wells were collected and analyzed. A one-layer conceptual model was built for representing the unconfined aquifer based on the Modflow model. The calibration and validation of the model were carried out via the hydraulic heads of 12 observation wells (2008 – 2017). The results showed that due to the decreasing trend in the Gash River flows of 9% in the period 2000 –2018, the recharging rate experienced a decrease of 0.7%. The scenario “running the business as usual” stated a drawdown of 2m to 13 m relative to the year 2018. To stabilize the current head, annual recharge amounts of 228 million m^3 is required. Under the conditions that there is no recharge (no stream flows of the Gash River), a drawdown up to 20% will occur. Spatially, the upstream and middle parts of the River were the most sensitive part of the no recharging conditions. The described sustainable operation model of this study is recommended for managing groundwater resources in the Gash basin, Sudan.

Keywords: Groundwater; unconfined aquifer; Modflow model; Gash basin; Sudan

INTRODUCTION

Freshwater water resources have a paramount role in human beings' sustainable development. In which, groundwater is a cornerstone worldwide since it sustains the domestic and irrigation water supply to a large number of population, especially in arid and semi-arid areas (Pokrajac and Howard, 2010). However, groundwater has been rampantly jeopardized to overexploitation and pollution problems let alone the climate change impacts (van Engelenburg et al., 2018; Uddameri et al., 2017). Thus, groundwater has to be managed in a sustainable manner.

However, the sustainable use of groundwater remains a challenge due to limited available information and complexity in estimating the groundwater balance (Izady et al., 2017; Genthon et al., 2015; Zekri et al., 2015; Rödiger et al., 2014). The recent advance in groundwater modeling enables the provision of dependable information to pin the decision-making process (Rapantova et al., 2017; Johnston and Smakhtin 2014; Rejani et al., 2008). Among which the Modflow model has been successfully used worldwide, especially in 3D aquifers issues (Aghlmand and Abbasi, 2019; Khadri and Pande, 2016; Hogeboom et al., 2015).

Sudan is endowed with diverse water resources, namely surface water including Nile River, non-Nilotic rivers and streams, groundwater, and rainfall. While rainfall is characterized by its seasonality and variability, surface and groundwater sustain the country's water demand. However, the use of surface water is limited to areas in the vicinity of rivers, while the remaining parts away from rivers depend entirely on groundwater. National information pertaining to groundwater aquifers is very limited, resulting in groundwater's overuse problems (Abu Shora, 2012). Bearing in mind the diversity in aquifer's characteristics, of which the Nubian sandstone, *Umm Ruwaba*, *Gezira*, Alluvium and basement are the country's most famous aquifers. In the eastern part of the country, namely the Gash River basin, groundwater is extensively pumped for irrigation and domestic purposes without a piece of solid background information on groundwater balance in general, and on the annual recharge rates in particular. Ultimately, a severe reduction of 11 m in the groundwater table has been observed as shown in Figure (1) (Groundwater and Wadis Directorate, GWD, 2013).

The overall objective of this research is to recommend a sustainable management approach for groundwater use in the Gash basin, Sudan. The specific objectives of this study were to determine the future safe utilizable amounts of groundwater under different developed scenarios by the year 2050, to investigate the sensitivity of the aquifers to changes in the recharging rates and to develop a sustainable operation plan for the unconfined aquifer in the Gash basin, Sudan.

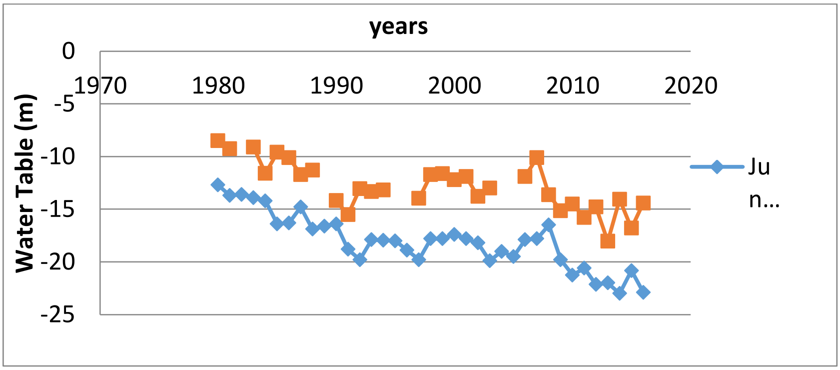

Figure 1, the drawdown trend at northern part of the Gash basin for two selected months

MATERIALS AND METHODS

Study Area:

The Gash basin is located in the eastern part of Sudan, specifically in the *Kassala* state (Fig. 2). The Gash River rises from the Eritrean and Ethiopian highlands as the River Moreb, 24 km south of *Asmara* city in Eritrea and ends in what is called the Gash Delta in Sudan. The river has an estimated catchment area of 21 000 km^2 (30-90 km wide by 250 km in length), shared by Eritrea, Ethiopia and Sudan (Hamid, 2011). The river is perennial for the first 175 km and then becomes an ephemeral river before it enters Sudan where frequent floods events have occurred during the rainy season (July and September) coupled with a long complete dry-out period for the remaining periods of the year.

Inside Sudan, the Gash basin can be divided into four sections: upstream, middle, downstream and delta parts, the aquifer characteristics that vary from a section to another (Table 1). In this study, only three sections were investigated, namely upstream, middle and downstream sections where the most extensive irrigation practices take place (Fig. 2). The Gash groundwater aquifer is alluvium consisting of intercalated unconsolidated beds of coarse to fine-grained sediments, gravel, sand, silt, and clay. The average saturated thickness of the alluvial sediments is 30 m and the depth to water gradually increases away from the Gash River, ranging in 5 - 30 m depth. Saeed (1969) estimated the storage capacity of the Gash aquifer in the Kassala area, the state's capital city, at 600 million m3coupled with Total Dissolved Solids (TDS) of 180-260 ppm, suggesting the excellent groundwater quality for both irrigation and domestic purposes. This limited capacity has experienced however a continuous water table drop of 1.5-11.5 m compared to the year 1980 (GWD, 2014). A monitoring report in the year 2010 has stated the lowering in water tables, especially during June, when more than 60% of monitoring wells (especially hand dug wells) have completely dried-out (GWD, 2010). Elkrail and Ibrahim (2008) recommended that the groundwater abstraction from the Gash basin should not exceed 156million km3 yr-1. However, Jochem (2015) recommended the use of the Modflow model for better sustainable management of groundwater resources in the Gash basin, Sudan.

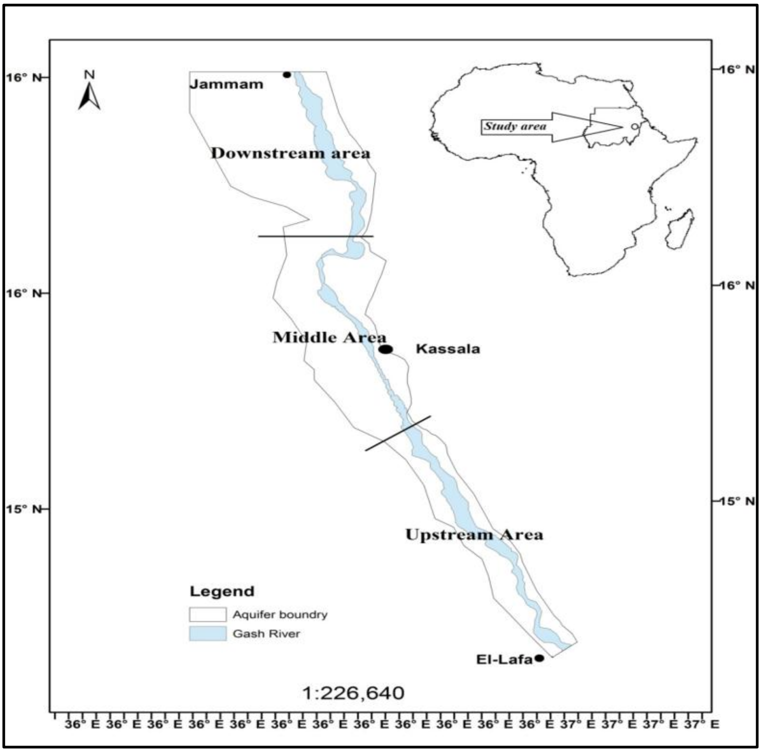

Figure 2, the studied area, the Gash River basin, Sudan

Table 1, Gash aquifer characteristics

Sub-area	Surface Area (m^2)	Saturated Thickness June 2017 (m)	Effective Porosity	Storage Capacity (m^3)
upstream area	53528748	19.83	0.20	212295014.6
Middle area	93323405	29.89	0.20	557887315.1
Downstream area	123021856	20.04	0.20	493071598.8
Total	269874009			1263253929

Methodology:

The Processing Modflow for Windows (PMWIN) model (Version 5.3.3 copyright (c) 1991-2001 W. -H Chiang, and W. Kinzelbach) was being used to simulate the groundwater system based on finite-differences (McDonald et al., 1988). Figure (3) summarizes the workflow of this study.

Datasets of 1245 wells (Fig.4) were collected from the groundwater official reports that prepared regularly by Kassala office- the Groundwater and Wadis Directorate, coupled with the collected field datasets for the research. Collected datasets were categorized into observational and operational ones. The observational sets were mainly collected from 51 observational wells while the operational ones represent datasets of 1194 discharging wells, which were mainly used for irrigation and domestic water supply purposes. Satellite-based actual evapotranspiration datasets (with an error less than 5%) were drafted from the Hydraulic Research Center, Sudan.

A one-layer conceptual model was built for representing the unconfined aquifer of the study area. The boundary conditions were determined with a cell size of 200 x 200 m covering a total area of 1232 km2 (44 km * 28 km). The top of the layer is the elevation surface of the ground while the bottom is the elevation of the basement complex rocks, derived from a DEM map enhanced by the field interpolator tools in the Modflow. The boundary conditions were assigned by simulating the actual boundary of the aquifer based on the geological and topographic maps. The active code was placed on all the cells inside the aquifer whereas the inactive ones (zero) were placed outside the aquifer, east and west, where no groundwater flows exist. The General-Head Boundary Package was used at the aquifer inlet i.e., Eritrean boundaries, and at the aquifer downstream outlet at the *Jammam* area inside Sudan. Data is entered in the model as shown in Table (2).

Table 2, Selected aquifer characteristics in Gash basin, Sudan

Property	**Before calibration**	**After calibration**
Horizontal Hydraulic Conductivity(m/day)	90 in upstream area	110 in upstream area
	38 in middle area	30 in middle area
	65 in downstream area	50 in downstream area
Effective Porosity	0.20	0.15
Specific yield	0.15 – 0.20	0.15
Storage coefficient	0.10 - 0.40	0.13
Average of annual recharge(m)	4.08	3.91
Annual abstraction (Mm3/year)	209	209
Evapotranspiration(m/year)	2.92	2.92

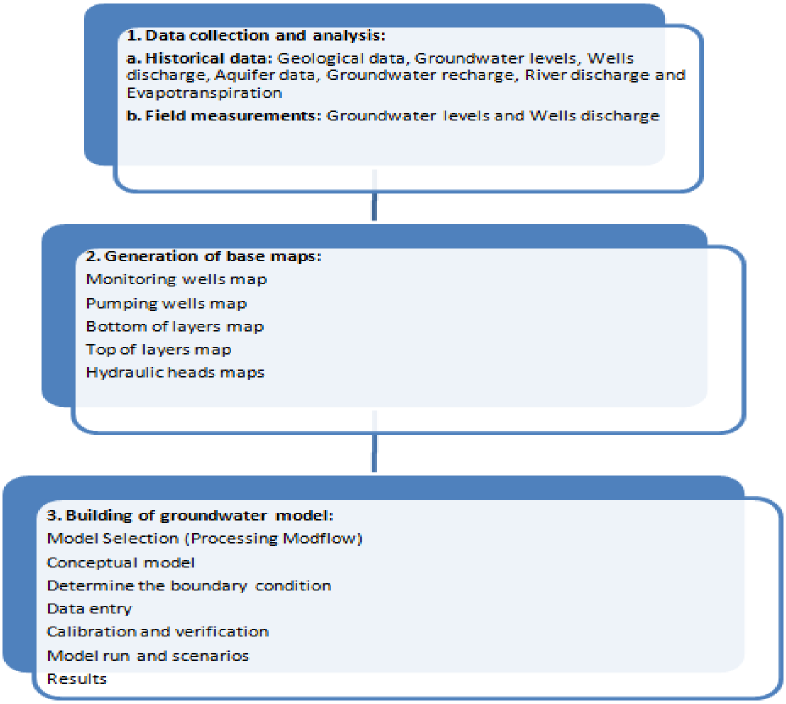

Figure 3, the workflow of the study

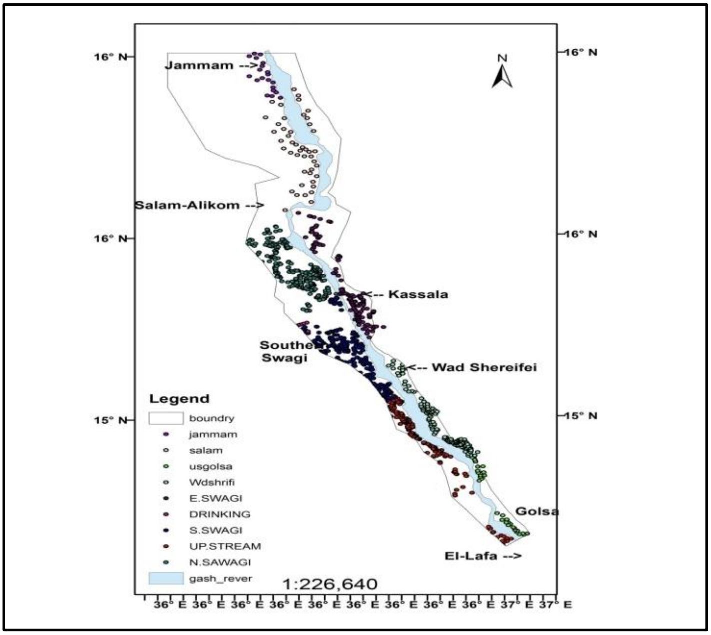

Figure 4, Studied Wells locations

Calibration and validation of the model:

The initial hydraulic heads data for June 2008; were used to cover the study area in an acceptable manner. Datasets of 12 observation wells of 9 years in length were used for the calibration and verification, based on a try and error iteration up to the year 2017
(Fig. 5).

Developed Scenarios:

The scenario tested in this study is to run the business as usual up to the year 2050. The sensitivity of this scenario to changes in the aquifer to recharge was tested under three conditions: 1. Estimating the groundwater recharge that is required for stabilizing current hydraulic heads with reference to the year 2018; 2. Effects of no recharge conditions of two extended periods (1 year and 2 years); and 3. What if the recharge increases or decreases by 10%.

The recharge was being estimated as follows:

$\text{Rv} = R\text{Aaq}E \qquad (1)$

Where R is the recharge (L), Rv is the volume of the recharge (L^3), Aaq is the aquifer area (L^2) and E is the effective porosity (L is a unit of length).

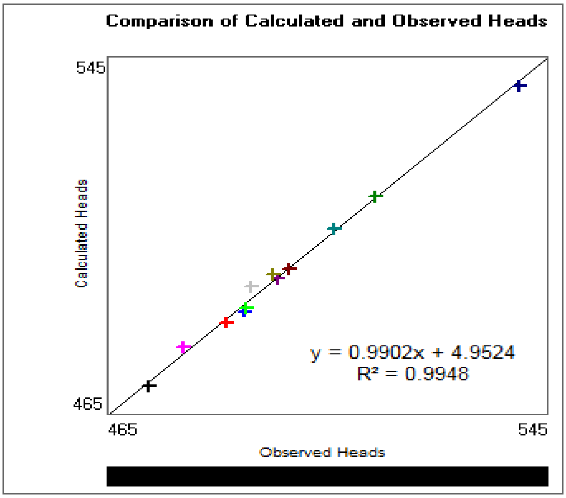

Figure 5, Comparison of calculated and observed heads (June 2017)

RESULTS AND DISCUSSION

Recharge from the Gash River:

Table (3) shows the estimated annual abstraction in the Gash basin, totaling 209 million m^3 yr^{-1}, this is coupled with a decreasing trend of 9% in the Gash River flows since the year 2000 (Fig.6). Consequently, a decreasing trend of 0.7% is observed in the annual groundwater recharge bearing in mind that the current recharge represents only 26.5% of the annual flows of the river, on average. Basically, the annual recharge amount is used to be estimated by the local authorities based on the aquifer area 270 $*10^6$ m^2 Table (1), the effective porosity and the rise in groundwater head during the wetting season (m). To predict the annual recharge amount based on the actual annual stream flows (2001-2016), a linear regression model was developed:

$$R = 0.255\mathbf{Q} + 7.33 \qquad (2)$$

Where R is the recharge amount (million m^3) and Q is the streamflow (million m^3). The limited datasets were enhanced by the Monte Carlo simulation (n = 1000), yielding a model's probability of 0.65 and a root mean square error of 68 million m^3.

Table 3 Estimated groundwater abstractions in the Gash basin

Area, use the division made in materials and methods	**Well operational Time (hr/day)**	**Annual abstraction (Mm3/year)**	**No. of wells**
Upstream area west	20	32	249
North Swagi	20	22	228
South Swagi	10-20	35	279
East Swagi	15-24	19	137
Upstream East (*Golsa*)	19	8	30
Wd shriefi	19	48	131
Slam alaikum	19	12	45
Jamam	19	13	20
Drinking wells	20	2	25
Urban water supply wells	20	18	50
Total		**209**	**1194**

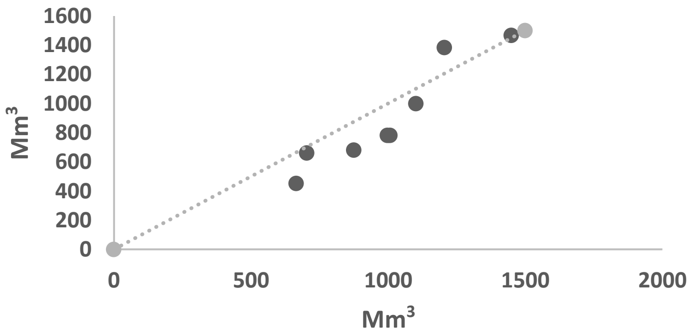

Figure 6, the trend in Gash River flows during the period 2000 – 2016, based on the partial trend index. The dot line is the 45^{o} line.

Developed scenarios:

Running a business as usual scenario:

Figure (7) compares the current hydraulic heads (545 – 465 m.a.s.l) with that of predicted ones by the year 2050 (545 – 470 m.a.s.l). Generally, the hydraulic heads are found to be a location-dependent, decreasing in the south-north direction (upstream-downstream). The middle part of the basin shows circular contour lines which indicate the high pumping rates because of the intensive irrigation schemes. This is coupled with drawdowns of 2, 13, and 11 m in upstream, middle and downstream parts, respectively relative to the head in the year 2018. These results advocate the negative balance between recharge and pumped water due to the over-pumping up to the year 2050, resulting in drying out of massive areas of the aquifer, particularly in the middle part. Thus, the current groundwater management practices have to be revisited, especially in the middle part.

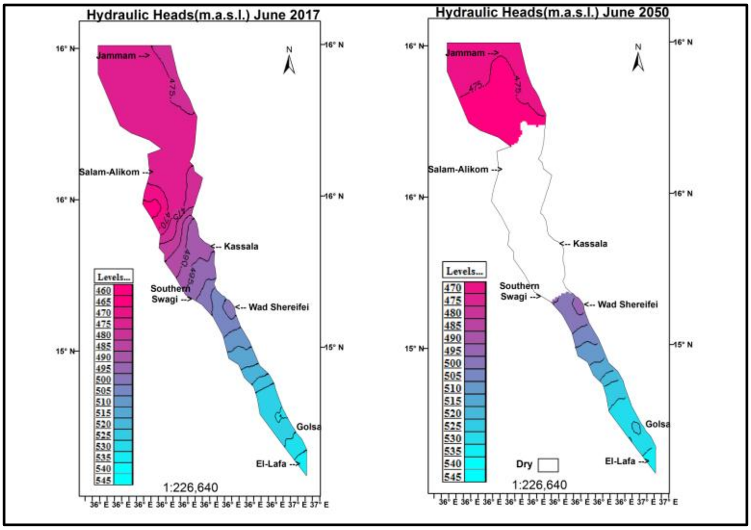

Figure 7, Hydraulic Heads in the Gash basin. The left hand is for June 2017 and the right one is for June 2050

The sensitivity of the aquifer to recharge:

As being said earlier, the groundwater in the basin depends entirely on the Gash River. The negative impact of no streamflows on the groundwater was investigated using the Modflow model under three conditions: 1. the recharge amount required to stabilize the current hydraulic heads; 2. there were totally none stream flows for 1-year and for 2-year; 3. the recharge experienced a change of ±10%.

Recharge amounts required to stabilize the current conditions:

The model was run up to 2050 to find the groundwater recharge required for stabilizing the hydraulic heads with reference to the year 2018. This has resulted in a recharge amount of 228 Mm3/year, based on a try and error iteration.

None stream flows (no recharge):

Figure (8) characterizes the aquifer's response to none stream flows conditions for 1 year and 2-consecutive years. The direct result was a drop of 0 – 19% and 0 -20% in the hydraulic head respectively. Spatially it turns out that the upstream and middle parts are most sensitive when there is no flow in the river (no recharge conditions). This reduction will have negative impacts on domestic water supply with a different intensity from one location to another.

±10% change in the recharge amounts:

Table (4) shows the drawdown in the groundwater under a 10% decrease and a 10% increase in the recharge. In line with the above results, the upstream and downstream sub-basins were the most sensitive to change in the recharge (Drawdown rate 0.06, 0.40 and 0.35 (m/year) in upstream, middle and downstream respectively at an average annual recharge (2008 to 2017) =211Mm^3).

Table 4, Percentages of change in the drawdown following ±10 change in annual recharge

Recharge (Mm^3)	Drawdown (%)		
	Upstream	middle stream	downstream
-10%	266	110	46
+10%	-133	-85	-57

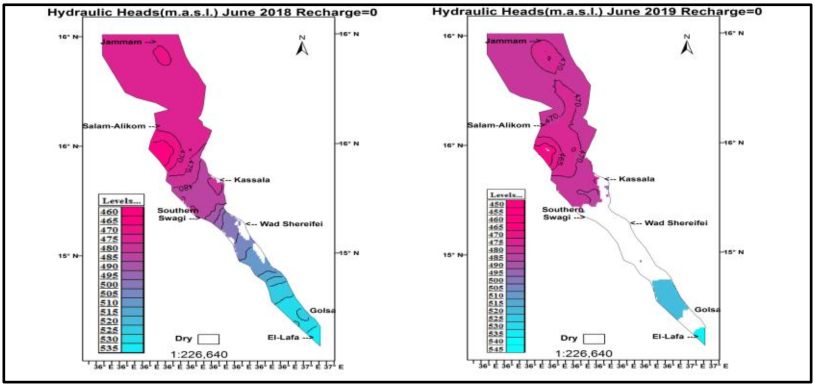

Figure 8, The response of the aquifer to zero recharge conditions for one year (left) and two consecutive years (right)

Sustainable wells operation program in the Gash Basin:

The future sustainable program (2050) was developed such that the abstraction from the wells shall be in balance with the recharge and the allowable drawdown for a reference year (2018) assuming that no new wells are drilled in the basin. The steps taken to develop this sustainable operational program in the Gash Basin were described below:

Firstly: Calculation of the recharge (Mm3/year) in the upstream, middle and downstream parts from the observation wells based on equation (1) above.

Secondly: Estimate the annual recharge required to maintain the water levels at its current state in the year 2018 (is 228 Mm^3yr^{-1} from results above).

Thirdly: Determine the wells' operation hours. This is controlled by the daily operating hours for agricultural wells without reducing that of the domestic water supply; thus, the annual recharge required for agricultural wells at the reference year = 228-20 = 208 $Mm^3\ yr^{-1}$

Fourthly: Determine the ratio between the current recharge and required recharge (228 Mm^3yr^{-1}) multiplied by the number of operation hours (19 hours); and thus obtaining the permitted hours for wells operation per day as follows:

$$= \frac{\text{Current Recharge(Mm3/year)} - \text{domestic water supply (Mm3/year)}}{228 - \text{domestic water supply (Mm3/year)}} * 19$$

Table (5) shows the resulted irrigation wells sustainable operation program in the Gash Basin, when the domestic water supply = 20 (Mm^3/year) and the recharge ranges in 100 -230 (Mm^3/year).

Table 5 Wells operation program in the Gash Basin

Current Recharge (Mm^3/year)	Permitted hours for wells operation per day (for 365 days)	Permitted hours for wells operation per year	Permitted days for wells operation per year (full 19 hr/day)	Permitted months for wells operation per year (full 19 hr/day)
100	7	2667	140	5
110	8	3001	158	5
120	9	3334	175	6
130	10	3668	193	6
140	11	4001	211	7
150	12	4334	228	8
160	13	4668	246	8
170	14	5001	263	9
180	15	5335	281	9
190	16	5668	298	10
200	16	6001	316	10
210	17	6335	333	11
220	18	6668	351	12
230	19	7002	369	12

CONCLUSIONS

The Gash basin aquifer exposes a very critical situation and serious deterioration and it needs special management to water resources in the basin as quickly as possible to remedy the problem.

There are no monitoring wells in the upstream and downstream areas, where limited measurements were carried out in this research (only two years), and this gives modest results in these areas.

The hydraulic heads generally sloping from the southeast to the northwest, and in some areas, there is a drawdown indicator in *Golsa,* *Wadshirifei, Auetla, Kassala, Northern swagi and Jammam* areas where contour lines are circular.

The Modflow model is found to be very effective in analyzing 3D groundwater complexity. In 2050, the basin will be dry in the *Kassala* areas as a result of the high pumping, which are the areas of population and agricultural density.

Current groundwater management practices will end up in a severe reduction in hydraulic heads which will have negative impacts on the groundwater and livelihood generation in the Gash basin; thus groundwater has to be managed in a sustainable manner.

There is a dire need for continuing the current monitoring programs.

Better coordination between the groundwater sector and the agricultural one is needed, particularly crop choices.

Conducting studies of artificial recharge methods is highly needed with continuous monitoring and evaluation programs as well as capacity building ones.

RECOMMENDATIONS

1. It is recommended that the developed sustainable operation program should be adopted by the decision makers.
2. Further research is recommended for studying potentials of artificial recharge.
3. Artificial recharge recommended for supplement the natural recharge in the gash basin.

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