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HRC SUDAN Hydraulics Research Center

مركز البحوث الهيدروليكية

Harnessing Floods to Enhance Livelihoods and Ecosystem Services in Gash Area, Sudan

Volume I:

Groundwater Management in Gash River Basin

Hydraulics Research Center (HRC-Sudan)

Ministry of Water Resources, Irrigation and Electricity

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1. Introduction

1.1 General

The Gash basin is one of the most famous alluvial basins in Sudan. The Gash river is an intermittent stream originating in the highlands of Eritrea, It flows northwest across a flat plain and ends as an inland fan delta. It forms one of the most important agricultural lands in this area. Groundwater basins are part of the ecosystem, therefore the studying and addressing any ecosystem problems in Gash basin requires the understanding of the present and future performance of aquifers within the basin. This study is to build a groundwater model of the Gash basin. Groundwater flow model is a valuable tool for better understanding groundwater flow in aquifers and helping to better manage groundwater resources. It is of the few tools available that can consider a complex array of aquifer variables (hydraulic properties, recharge, pumping, rivers, structure, and heterogeneity) and allow these variables to interact with each other. Exploring these interactions with a model can reveal how an aquifer behaves. Once a model is properly calibrated, it can be used for predictions to manage groundwater resources (Harbaugh, A. W. 2005). The groundwater flow modeling technique is introduced in this study to assess and evaluate aquifer system of Gash basin and predict the effect of increasing the extraction from aquifer for present and future development.

1.1.1 Climate

The region is characterized by semi arid climatic conditions. Two main seasons can be distinguished: summer and winter. The rainy period starts in July and continues to the end of September with an average annual rainfall of 150- 340 mm. The vegetation cover is governed by the intensity of the seasonal rains and it increases after the flood periods of the Gash River.

1.1.2 Physiography

The topography of the River Gash Basin is generally flat to slightly rolling with a gentle slope towards the northwestern part of the study area. The elevation ranges from 500 m in the southeast to 450 m in the northwest.

The total length of the river from its source in Eritrea to the apex of the fan north of Kassala is about 280 km. When entering Sudan, the flow direction of the river changes from west to the north and the river attains its characteristic appearance of a wide shallow stream with a sandy bed bordered on either side by extensive flood plains. The drainage pattern is characterized by several minor khors flowing from the east to the northwest joining the River Gash (Figure 1).

1.1.3 Geology

The rock units in Gash basin consist of Precambrian basement complex rocks, essentially made of granitic gneisses overlain by the clays of the plains, which are considered to be Tertiary-Pleistocene weathering products of basement complex rocks (Figure 2). These two units are overlain by the Pleistocene – Recent fluvial deposits of the Gash River. North of Kassala the River Gash forms an inland terminal fan- delta having a characteristic conical shape. The delta covers an area of 2000 square kilometers. The fluvial deposits extend between 3 and 4 km east and between 5 and 7 km to the west of Kassala. The thickness reaches more than 40 m in the west and northwest, and a maximum of 80 m in fan-delta. The fine to coarse sand and gravels dominates the deposits in Kassala area alluvial (Saeed, 1969).

Downstream of Kassala there is a progressive increase in fine sediments (silts and clays), which reaches a maximum in Gash fan-delta.

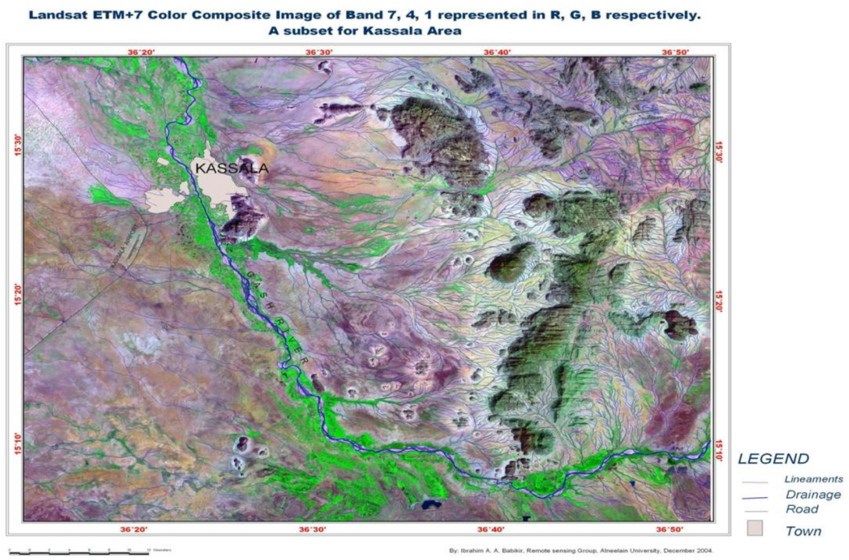


Figure 1: An image showing general physiography of the Gash basin area around Kassala (after Babikir, I, A, 2004)

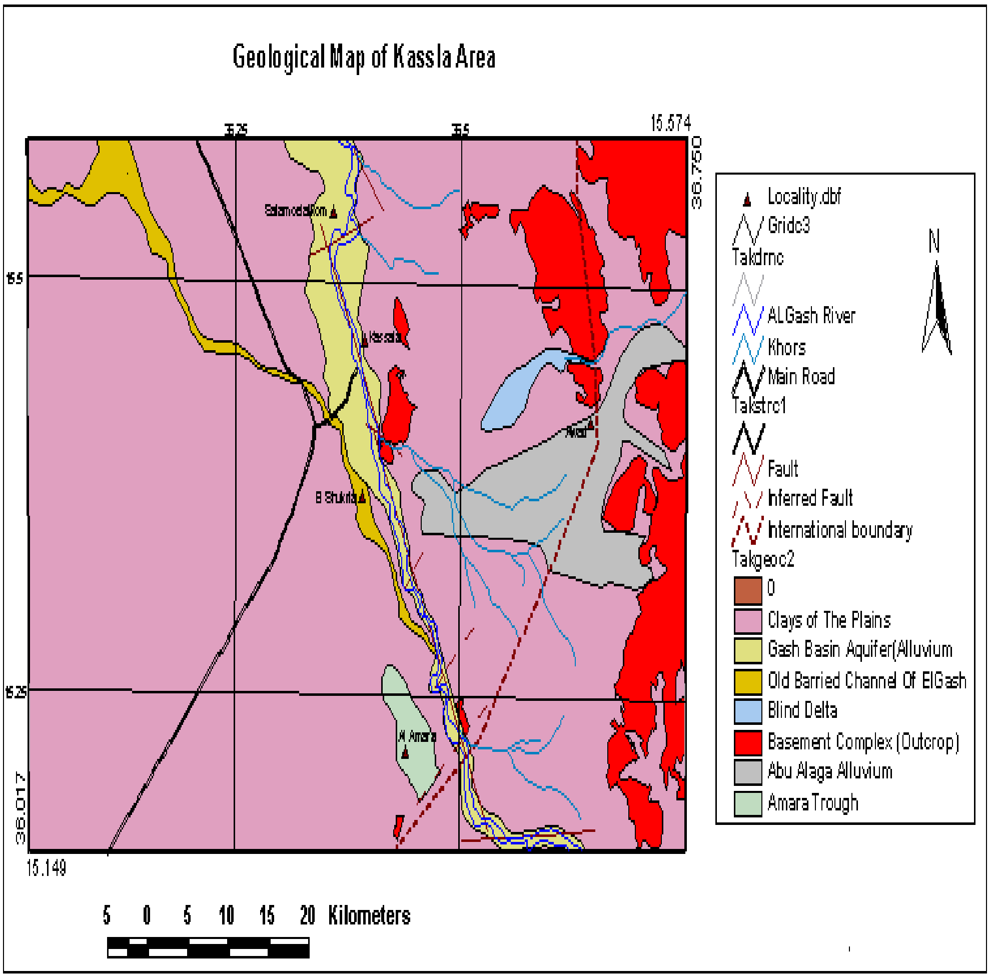


Figure 2: The geology of the Gash basin and Kassala area

1.1.4 Groundwater

Alluvial deposits of Gash River form an important aquifer in the region of Kassala. The headwaters of the Gash lie in Ertria, where flow is perennial. At Kassala the flow of the river lasts in average for 88 days per year and an annual average discharge is estimated to be of 483 million m^3, Kassala is situated at the apex of the river delta which extends northwards for 60 km, in a ribbon up to 15 km wide.

The alluvium of the Gash River consists of intercalated unconsolidated beds of coarse to fine-grained sediments, gravel, sand, silt and clay. The alluvium of the Gash is the only aquifer of significance in the area. The average saturated thickness of the alluvial sediments is 27 m and the depth to water increases away from the river, varying from 5 m to 30 m below surface.

Recent Reports of the Groundwater performance in the Gash basin indicates a general trend of groundwater level decline due to high pumping and the aquifer mis-management. Groundwater modeling is one of powerful tools to account for such a problem. It is used to simulate the behavior of a natural system by defining the essential features of the system in some controlled physical or mathematical manner. Mathematical model plays an extremely important role in the understanding and management of groundwater systems; therefore we attempt to apply it to simulate the groundwater situation in the Gash aquifer.

1.2 Objective

- Develop a strengthened conceptual foundation for local catchment and groundwater basins problems using an ecosystem approach.
- Increase ability to develop and demonstrate alternate management approaches for groundwater in the Gash basin.
- Increase ability to identify, engage, and communicate with stakeholders, women and youth to participate in groundwater management and awareness.

1.3 Approach

- Incorporates knowledge about functioning of the catchment ecosystem into planning and management.
- Focuses on managing groundwater and land resources within catchments.
- Recognizes the need to maintain catchment and groundwater basin ecosystem health.
- Incorporates ecosystem services to express value and influence behavior to address water security.

2. Previous studies

Different geological, hydrogeological, hydrogeochemical and hydrogeophysical studies were carried out in the study area. The earlier studies concentrated on geology of the area, static water levels and general hydrogeological studies. Then assessment, management and quantification of the resources came into consideration. Recently, studies on sustainability of these resources, the quality and evolution of groundwater and the general performance of the aquifer studies have been conducted. Karkanis (1961) comments on the general ground water conditions in the area, in his report he has given some data on static water levels in a few wells at Kassala town. Samuel (1962) described the geology of the area and classified the rock units as Basement Complex, Clay of the Plain, and Alluvial deposits. In his report he gives some static water levels for some wells in the area.

The first detailed studies for groundwater resources assessment in the Gash river basin were done by Saeed (1969 and 1972). He concluded that the groundwater level fluctuations depend on the recharge and discharge processes. However, later studies (Elamin, 1979) contradicted Saeed's findings, and from 1979 more land was put under cultivation in the Southern Sawagi (middle to upstream part) using groundwater, where more consideration of understanding the groundwater condition in the basin became necessary.

In the period August,1979 and ending in March,1982 a bilateral project between the Sudan Government represented by the National Rural Water Corporation (NRWC) and the Netherlands Government represented by The Netherlands Organization for Applied Scientific Research (TNO) was implemented to assess the groundwater resources of the Gash river basin and to develop a master plan for groundwater exploration for all purposes and promote the situation of regional water authorities in the alluvial basin. Most of information regarding this basin was collected during the implementation of this project. These include the geology, hydrogeology, the geometry of the aquifers, the engineering characteristics, the water quantity, water quality, recharge, discharge regime; the water uses and finally assesses the development and management of the basin. The statement of water Act was passed by a regional assembly in 1984 and as a result, Water Board and Technical Committee were established. The final report of the project (NAWR/TNO, 1982) and a later published technical bulletin (Enk and Mukhtar 1984) contains the results of the project’s investigations. From 1982 to 1984 monitoring of the water resources started using the existing network of 1982.

Samia (1987) identified an organic and bacteriological contamination in the area. Abdullatif (1989) discussed the channel-fill and sheet-flood facies sequences in the ephemeral terminal Gash River at Kassala.

The water resources management (WRM) project was formulated in September 1989. The work was carried out in three locations: The information center (IC) in Khartoum and two technical committees (TC), one in Kassala and another in Nyala. The final report of the project (WRM 1993) and the technical paper (Nurelmadina, 1993) contain the results of the project investigation. This phase concentrated on the management of the basin, where an attempt was made to develop a process for modeling the aquifers.

Mona (1993) studied water pollution in Kassala town and concluded that there is a bacteriological contamination in form of coliform within the town limit, mainly in the shallow parts of the aquifer.

Salama (1997) concluded that the Gash River has a relationship with the pre-existing basement shear zone in NW-SE direction and it belongs to the river Atbra basin. Mohammed (1998) conducted a geophysical study of the upstream part of the Gash river basin. He concluded that the basement complex is undulated forming a system of ridges and furrows represented probably by buried channels of the old Gash River, the same conclusion have been reached during the assessment phase of the bilateral project held by NRWC and TNO.

Bireir (2002) conducted a study on the geochemical evolution of the groundwater in Gash alluvial basin, using isotope hydrochemistry; he concluded that the periodical Gash river flow is characterized by light isotopic composition due to altitude effect is the main source of recharge. Artan et. al. (2007) presented a hydrologic model using Satellite-based rainfall estimates for flood forecasting to reduce the death toll associated with floods. They suggest that the remotely sensed rainfall estimates are an excellent source of rainfall data for modeling processes with monthly and longer time scales.

Elobeid (2007) conducted geophysical study to determine and configure the underlying basement complex and to assess it as potential zones for groundwater. The study found that, the fractured basement rocks plays as good zones for storage and movement of the groundwater in the area. Elkrail and Ibrahim (2008) constructed groundwater flow model to evaluate the groundwater potentiality and assess the effect of groundwater withdrawal to the regional water level and flow direction in the Gash River basin. They concluded that, to maintain the sustainable development, the annual abstraction rate as groundwater pumpage should not exceed 156 million m^3.

Elsheikh et. al. (2008) studied the subsurface geometry of the basin using remote sensing data, structural analysis, and geophysical surveys. They found that the river geometry and morphology is structural controlled and the paleo-river courses are parallel to the E-W fractures trend, while the current river course is parallel to the N-S fractures trend. Gadelmula (2008) conducted geophysical study for management groundwater as well as surface water. The study concluded two distinct paleochanells occur in the upstream of the Gash River. He also estimated the groundwater budget and found loss between the inflow and outflow.

Elsheikh et. al. (2010) estimated the groundwater budget of the upper and middle parts of the basin. He concluded that, the groundwater balance grants annual reserve storage in the aquifer. Nayl, K.E (2014), estimated the total annual groundwater recharge of the Gash basin. The total annual recharge is estimated as 380 Mm^3 and 235 by using equation and gauge stations methods respectively. Jochem, 2015 in his study to model the groundwater level in the Gash River delta, with a transient coupled surface-groundwater model in MODFLOW, concluded that the model provides a reasonable global overview of the important processes in the area and the sensitivity of the processes to changes in the groundwater levels. It is therefore recommended that the model should be improved to provide more accurate and reliable results. Crops are mainly responsible for the evapotranspiration. To increase the groundwater replenishment, the amounts of crops can be reduced or a crop with less water demand can be used. The first option is for practical reasons not realistic. It is likely that the duration of the period that the river flows is more important for the groundwater replenishment, close to Kassala, than the amount of discharge of the river.

3. Methodology

- Literature review and data collection:

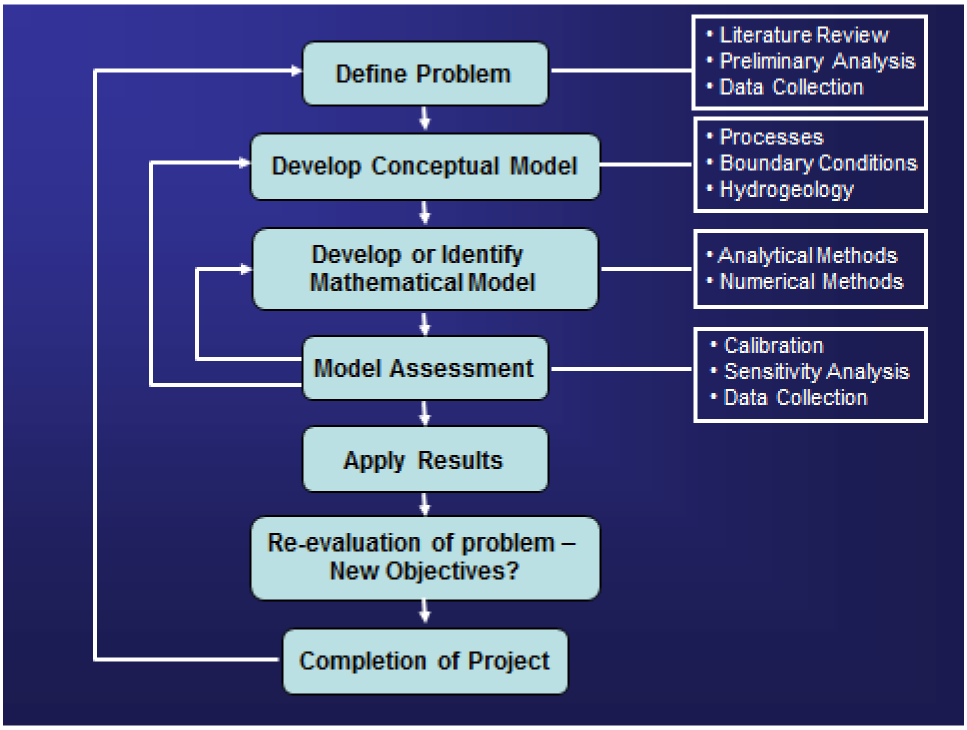
Information is collected from different resources, including reports, maps, sections and satellite images.

- Data processing:

Study the collected information to identify exactly the gaps.

- ❖ Reconnaissance field survey was done to clearly identify and understand the model area.
- ❖ Field survey was carried to collect the necessary required data especially from the downstream and Gash die area.
- ❖ The collected data was analyzed and necessary parameters was estimated.
- ❖ Groundwater modeling:

Modeling is an attempt to simulate the behavior of a natural system by defining the essential features of the system in some controlled physical or mathematical manner. Therefore, groundwater modeling is a tool used by scientists and engineers for solving groundwater problems. Modeling plays an extremely important role in understanding and management of hydrologic and groundwater systems. It follows the following steps as appears in the chart below.



- ❖ Data preparation for groundwater model:

1. Hydrogeological structure:

For each aquifer unit we define: top elevation, bottom elevation, thickness, and extent. Those data should be assigned to each model cell.

2. Aquifer properties:

For each aquifer unit we estimate: transmissivity and hydraulic conductivity, storage coefficient (specific storage), specific yield (for unconfined aquifer).

3. Boundary conditions:

For Flow Model we need to define:

- constant-head boundary
- no-flow boundary
- general-head boundary

- time-variant specified boundary

4. Recharge data:

Flow model needs to assign recharge rate by cell in each stress period and the layer to be recharged should be specified.

5. Discharge:

Discharge components were defined and calculated.

For Flow Model: discharge rate per stress period, pumped cell and layer should be specified.

6. Initial data:

For Flow Model we define initial hydraulic head.

- ❖ Develop the conceptual model.
- ❖ Enter data to model.
- ❖ Calibration and sensitivity analysis of the model.
- ❖ Run the model and development of different scenarios.
- ❖ Write the reports.

4. Groundwater

4.1 Aquifers/aquitards system

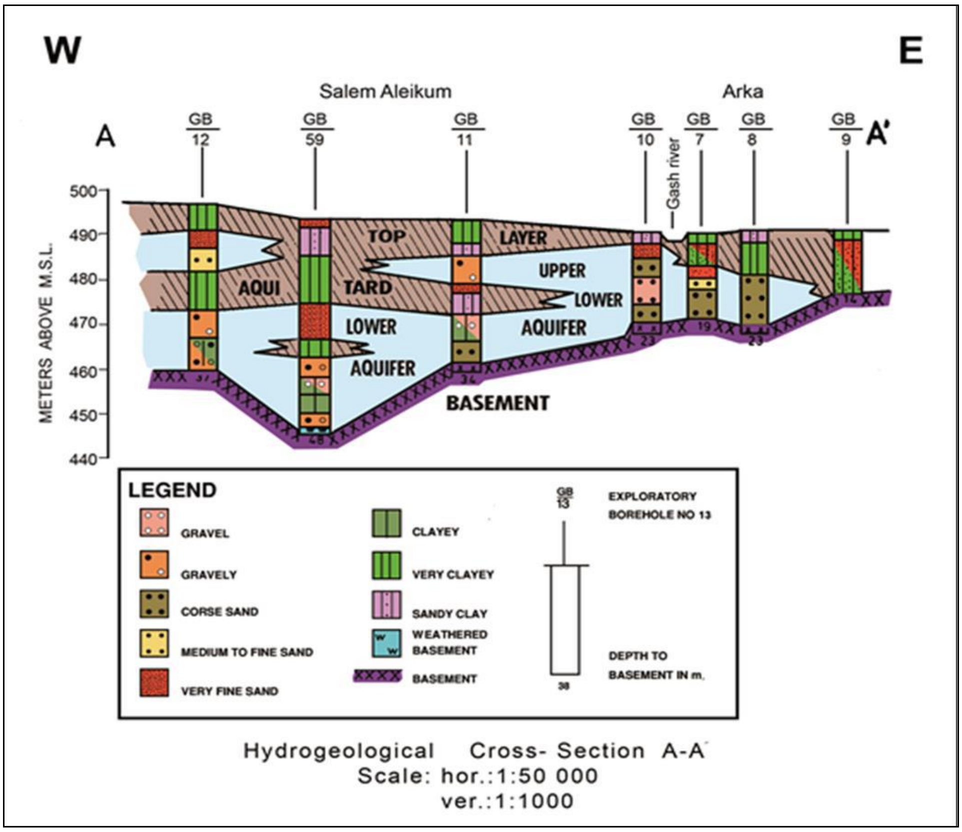
The most important aquifers found within the Gash alluvial deposits are divided into two main aquifers upper and lower aquifers generally separated by discontinuous aquitard (TNO, 1982). Where the aquitard is missing, the two aquifers form one unit, this case is clear in the upstream part. Therefore, the types of groundwater aquifers in Gash river basin are unconfined to semi confined.

Generally, the upper aquifer is composed of finer sediments than the lower one, which is mainly silt to fine-grained sand. It varies in thickness from less than 2 m to about 12 m while the average thickness amounts to about 7 m. The upper aquifer represents a water bearing unit in wide strip along both sides of the Gash River with average width range from 500 m to 1500 m in the upstream and around 4000 m in the middle and downstream parts (Bireir, 2002). The water table drops below the upper aquifer, especially at the end of the dry season. The upper aquifer is absent where the top layer and the lower aquitard form one unit in the upstream part and the eastern side of the basin where the basement is very shallow.

The lower aquifer is composed of coarser sediments than the upper one with thickness varies from 2 m to more than 20 m, locally near Kassala Bridge with average of 8.5 m. The depth to the top of the lower aquifer ranges from less than 5 m in the upstream area, to almost 40 m in the delta (Bireir, 2002) with an average depth of about 20 m. The depth to basement, which is considered the bottom of the lower aquifer ranges from 9 m to 60 m.

Two less pervious layers can be distinguished in the area. First there is a top layer, locally called "*badoba*" which consists of heavy sticky clay. These clayey layers are alternating laterally with rather permeable sand and or silty layers known locally as "*lebad*". The thickness of this layer varies from about 1m in the upstream to 17 m inside the Gash delta with an average of 6.5 m. The aquitard separating the upper aquifer from lower one is locally called "*sa*ra" and it consists of heavy clays alternating locally with argillaceous sandy layers.

The basement rocks are encountered to unconformably underlain the deposits. From the resistivity surveys conducted in the area and also from exploratory drilling and water well drilling, we estimate the depth to the basement rocks range between 9 m to 22 m, 27 to 50 m and 14 to 60 m in upstream, midstream and downstream areas, respectively (Figure 3).



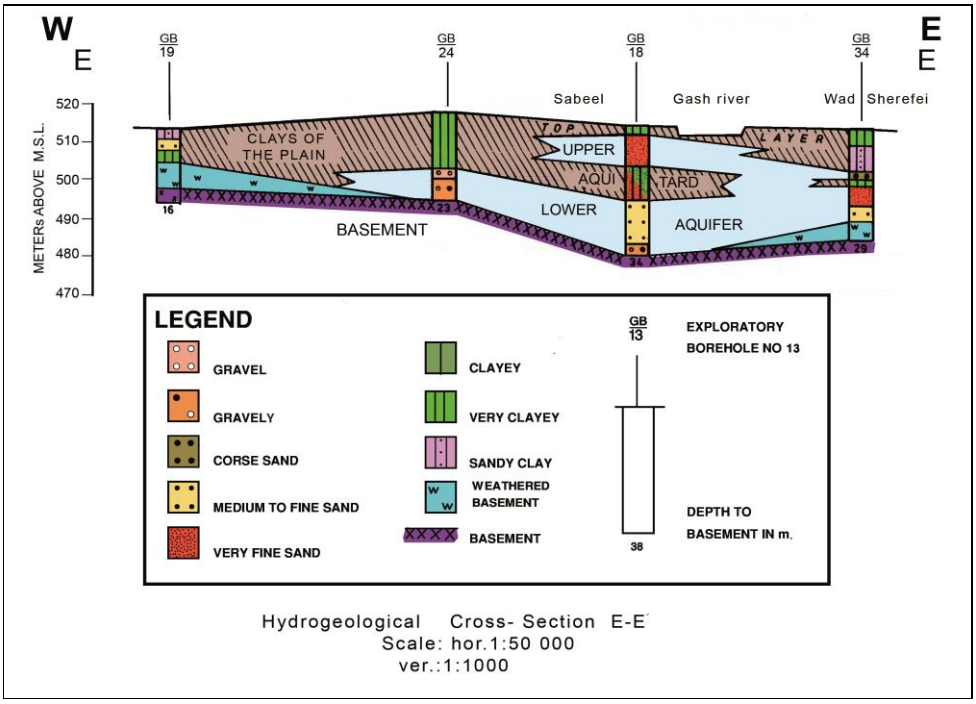


Figure 3: Example of cross-sections defining the aquifer geometry

4.2 Aquifer properties

The aquifer properties such as transmissivity, saturated thickness, hydraulic conductivity, aquifers storage capacity and groundwater velocity are discussed below.

4.2.1 Transmissivity

The transmisivity is defined as the rate of flow under a unit hydraulic gradient through a cross section of unit width and extending over the whole saturated thickness of the aquifer (T). However, using the semi-log (Cooper and Jacob, 1946) method and the semi-log Theis' recovery method, transmissivity of the aquifers in the most part of the basin is calculated (Table 1). As shown in this table, T is in the range of 1820 to 1141 m^2/d in the most upstream part where the two aquifers form almost one unit. Where the two aquifers are separate, T is 38 to 450 m^2/d for the upper aquifer and 216 to 2875 m^2/d for the lower aquifer. Hence the transmissivity values of the upper aquifer are clearly less than those of the lower one. This is mainly because in the upper aquifer silt and clay layers are more frequent. Where the lower aquifer is thin, the transmisivity values decrease relative to the rest of the aquifer (e.g. well no. 105). Very low values of T (less than 80 m^2/d) are found in other parts of the basin where fine sediments dominate and the aquifer thickness are thin; these are part of the aquifers near the clays of the plains and in the Gash delta.

4.2.2 Saturated thickness

The average saturated thickness in the most upstream part is 16 m, it ranges from 12 to 19.5 m in the lower aquifer with an average value of 10.5 m, where in the upper aquifer, the saturated thickness ranges from 8 to 12 m with an average of 9.5 m. Taking the two aquifers as one system, by the end of the wet season, the average saturated thickness of the Gash alluvial deposits is 20 m. However, by the end of the dry period where water table falls to the minimum values, the thickness of the saturated zone decreases. As observed during the field visit held in June 2015 (dry period) the saturated thickness of the aquifer in mid-stream and downstream parts falls down. In the Gash delta where the aquifer is artificially replenished by a system of dug wells scattered within earth-surrounded basins which filled with Gash river water during floods. The saturated thickness of the poor aquifer also drops during the dry period (Figures 4&5).

4.2.3 Hydraulic conductivity

Hydraulic conductivity (K), the capacity of material to transmit water, depends upon porosity, size and shape of pores, degree of sorting, the effectiveness of the interconnection between pores and the physical properties of the fluid. Small interconnecting tubes restrict the volume of the passing water and result in low hydraulic conductivity. In contrast, when the grain size is coarse, the connecting tubes are large relative to the pores and the hydraulic conductivity will be high. However, the hydraulic conductivity was calculated and the results are given in Table 1 where K ranges from 67.14 to 104.6 m/d; in the most upstream part; K is 31 to 53.3 m/d for the upper aquifer and K is 26.2 to 122.1 m/d for the lower aquifer. From these figures, it is clear that the lower aquifer is characterized by higher permeability than the upper one and the variability of K values reflect the anisotropy and heterogeneity of the system. The low values of K for the upper aquifer can be explained by the fact that hydraulic conductivity of the alluvial material tends to decrease with increasing degrees of deformation and consolidation and with increasing proportions of fine-grained material (Anderson et al., 1988), the case observed in the downstream and Gash delta.

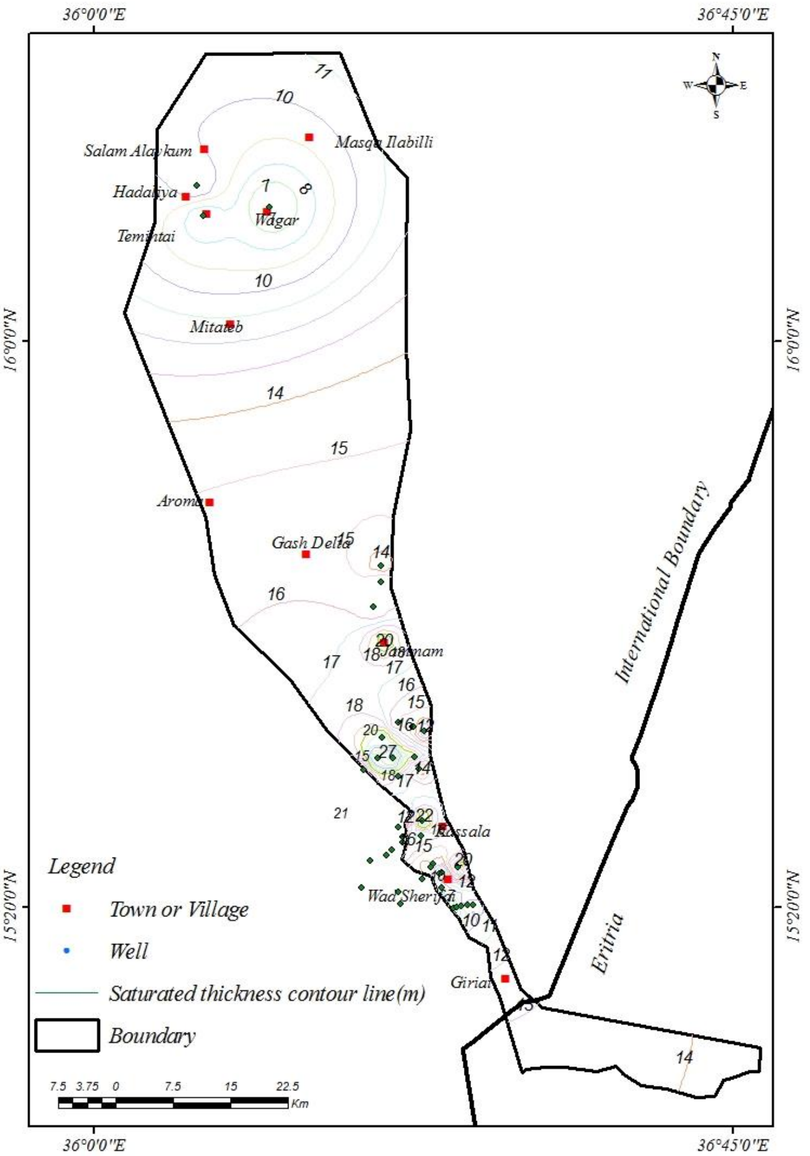


Figure 4: Aquifer thickness in the Gash basin

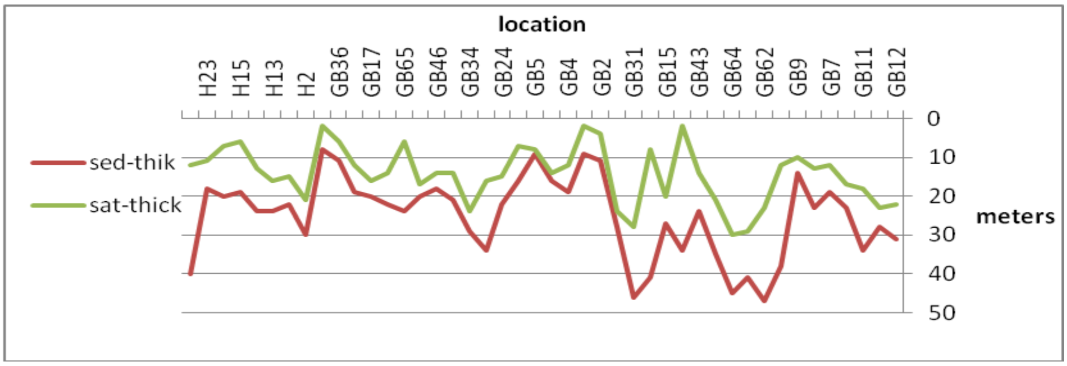


Figure 5: Alluvium sediments thickness and aquifer thickness in the Gash basin

Table 1: Transmissivity and hydraulic conductivity values for (A) most upstream part, (B) upper aquifer, and (C) lower aquifer and other part of the Gash basin

Well No.	**T (m^2/d) Jacob**	**T (m^2/d) Thies**	**T (m^2/d) Thies (Recovery)**	**T (m^2/d) (Logan)**	**T (m^2/d) (average)**	**Saturated Thickness (m)**	**K (m/d)**
A							
147		1200				12	100
120	1600	1600				15.3	104.6
Ellfa	1820	1680				19.5	86.2
126	1141.5	1141.5				17	67.1
B							
887	450	480				9	53.3
822	879	326				8	40.8
510	290	300				8.5	35.3
8	171	249				12	20.8
106	67	67				9	7.4
64	38	34				10.8	3.1
C							
10	2875	2075				17.0	122.1
6	2344	1318				19.0	69.4
127	1784.3	1858.7				13 .O	142.9
42	780	748				15.3	48.9
105	216	583				12.0	48.6
117	469	63 5				16.5	38.5
157	335	536				19.5	27.5
36	394.5	384.9				14.	26.
2	172	--	186	--	179		
147	--	--	1105	--	1105		
149	--	489	--	--	489		
196	39	37	--	96	57		
462	--	359	--	140	250		
520	335	--	536	535	469		
596	--	77	--	217	147		
842	--	90	--	421	256		
GB 6	2344	--	1318	923	1528		
GB 8	171	216	249	947	369		
GB 10	2857	--	2075	471	1801		
GB 11	229	--	220	351	267		
GB 18	879	--	326	385	530		
GB 13	--	--	--	19	19		
GB 26	151	--	--	241	196		
GB 30	191	--	404	121	239		
GB 31	5273	5095	5860	8861	6272		
GB 33	469	457	635	1304	716		
GB 34	--	--	--	77	77		
GB 35	67	--	67	368	167		
GB 39	352	383	474	881	523		
GB 42	780	881	748	332	685		
GB 44	16	--	19	351	129		
GB 45	26	13	24	199	66		
GB 46	2	--	1	4	2		
GB 64	38	--	34	91	54		
GB 69	216	--	583	229	343		

4.2.4 Ground water level fluctuations

The water levels fluctuated primarily in response to variation in recharge and discharge. The fluctuations are reflected by the water level changes in wells which provide information on the change in the groundwater storage.

The water levels in the Gash basin represent the main groundwater levels collected during the period of (1984-2015), from available data and during the field trip held in June 2015 (Table 2 and Figures 6-8). Fluctuations are reflected by the water level change in well, mainly due to the groundwater discharged from the Gash aquifer for many domestic purposes and irrigation uses through wells located in the basin area. The water table fluctuations during the wet and dry seasons were observed in the hydrographs constructed from these measurements. The records of the observation wells show that the groundwater table starts to rise as infiltration become greater during the flood period from July to September and drops during dry periods (Figures 9&10). The average difference between the maximum and minimum levels amounts to approximately 9 m (upstream) and 6 m in (middle stream). The Gash aquifers are recharged mainly by infiltratration from the Gash River when the stream flows during the flood season. This fact has been proved through the isotopic studies carried out by Bireir (2002). The direction of groundwater flow is towards the NW, and mainly towards the boundaries. Groundwater flows from area of high fluid potential in the south east to areas of low fluid potential in the north west. Saeed (1972) estimated a hydraulic gradient of 0.005.

Table 2: Location, well depth and ground water level in Gash Basin (June, 2015)

Well No.	**Lat. deg**	**Long. deg**	**Name**	**Depth (m)**	**Wl (m) f/G**
H1	15.6441	36.3405	Jammam		9.8
H2	15.6456	36.3405	Jammam	25	9.95
H3	15.6456	36.3405	Jammam (4 produc wels)	25	
H4	15.6683	36.3348	Propj		7.6
H5	15.6724	36.3391	Abdulla Kados		
H6	15.6694	36.3370	Jam (Ali Hashim Halngi)		9.2
H7	15.6663	36.3338	Jam (Mukhtar ElHadi)	15.5	11.3
H8	15.6652	36.3318	Dry well (boundary)		
H9	15.6873	36.3253	Darif (Rashid)	20	13.2
H10	15.2359	36.3286	Darif	20	16
H11	15.7133	36.3207	Dar ELmuk (Abd Munem Dafalla		14.6
H12	15.7157	36.3196	Dar ElMuk (Fissal El Taeeb)	23	16
H13	15.7173	36.3371	Karakoon	22	14
H14	15.7347	36.3372	Haggar	21	7 SWL
	16.1599	36.1090	Inter to Wager With PortSud Highway		
H15	16.1579	36.2067	Wager (Jedo)		11
H16	16.1579	36.2067	Wager (rech-basin, 3 basins 33 dug wells recharge artificially from basin filled by flood)	12	11.5
H17	16.1579	36.2067	50 m south of above		9.3
H18	16.1577	36.2072	Wager		11
H19	16.1514	36.2095	Wager		15.4

H20	16.1453	36.1297	West Wager (Tmentai)	11	10.5
H21	16.1456	36.1286	West Wager (Tmentai)	13.8	13.4
H22	16.1583	36.1197	Road, Entrance to Wager(Reco comp.)	60	34.6
H23	16.1826	36.1206	Hadalya (Abar Salamm Alikum)		10
H24	16.1828	36.1212	(Abar Salamm Alikum)	12	8.8
H25	16.1827	36.1206	Mussga 3(Osman Ahmed)	65	44
H26	15.5000	36.3773	Khor Shaigya(Wad Al Bula)	42	25(SWL)
H27	15.4972	36.3806	Khor Shaigya(Ali Moh. Issa)	38	29.2
H28	15.4959	36.3815	Khor Shaigya(Abu Baker Moh. Issa)	40	29
H29	15.4286	36.3996	Suagi El Haded		
H30	15.4285	36.3983	Suagi El Haded		
H 31	15.4241	36.4023	Awitra		
H 32	15.4185	36.4064			
H33	15.4373	36.3980			14.3
48	15.4621	36.3771	N.Swagi		20.82
65B	15.4719	36.3853	N.Swagi		Dry
163	15.4761	36.3718	N.Swagi		Dry
547	15.4233	36.3914	S.Swagi		Dry
556	15.4194	36.3944	S.Swagi		Dry
442	15.3600	36.4157	S.Swagi		Dry
446	15.3636	36.4203	S.Swagi		Dry
832	15.3716	36.4167	Wad Sharefee		8
851	15.3733	36.4286	Wad Sharefee		Dry
773	15.4217	36.4019	E. Swagi		pumped
882	15.4556	36.3894	GW Office		14.02
G2	15.4481	36.3903	Osman Degna		18.75

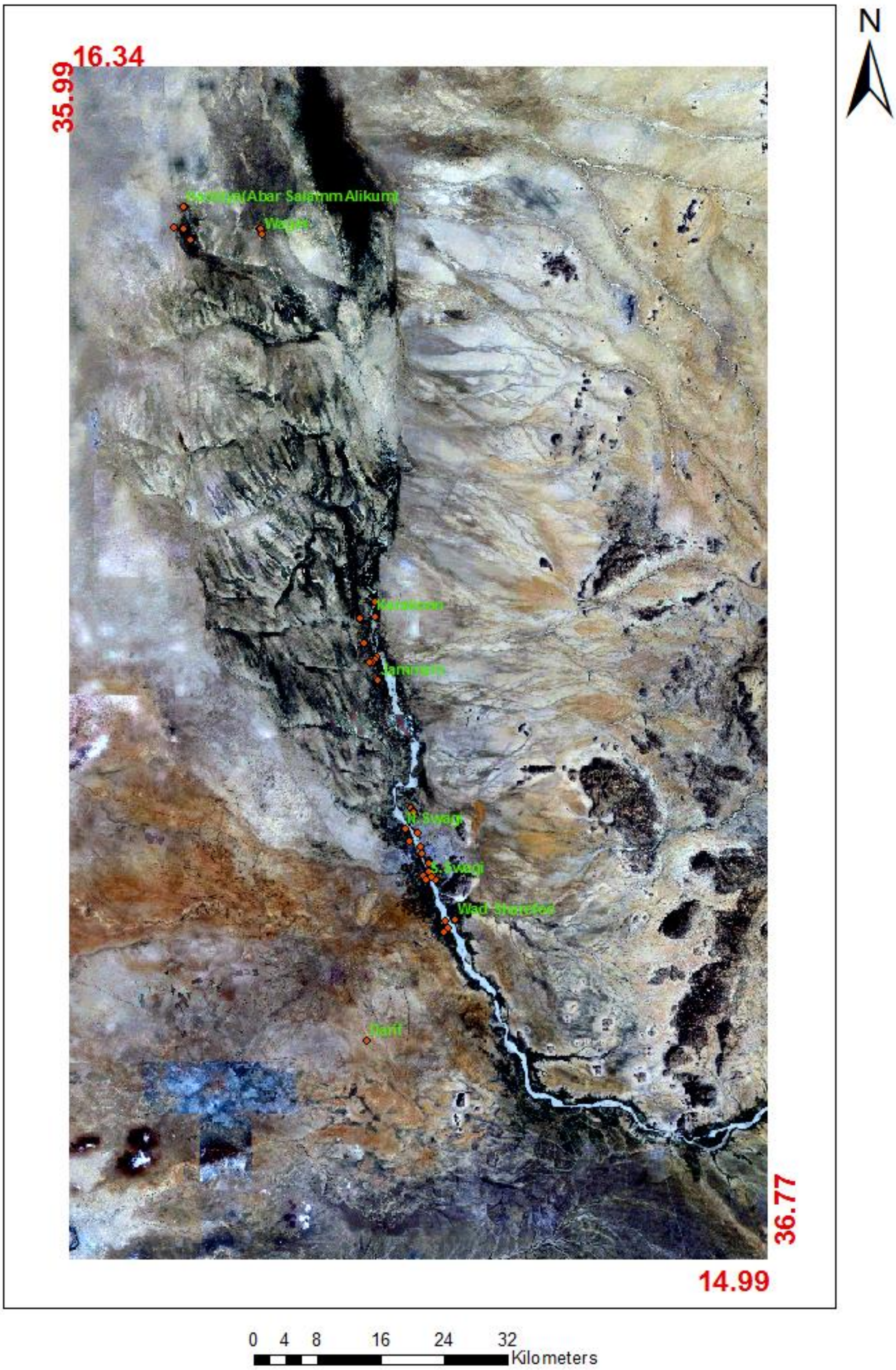


Figure 6: Location of wells monitored during field trip in June 2015

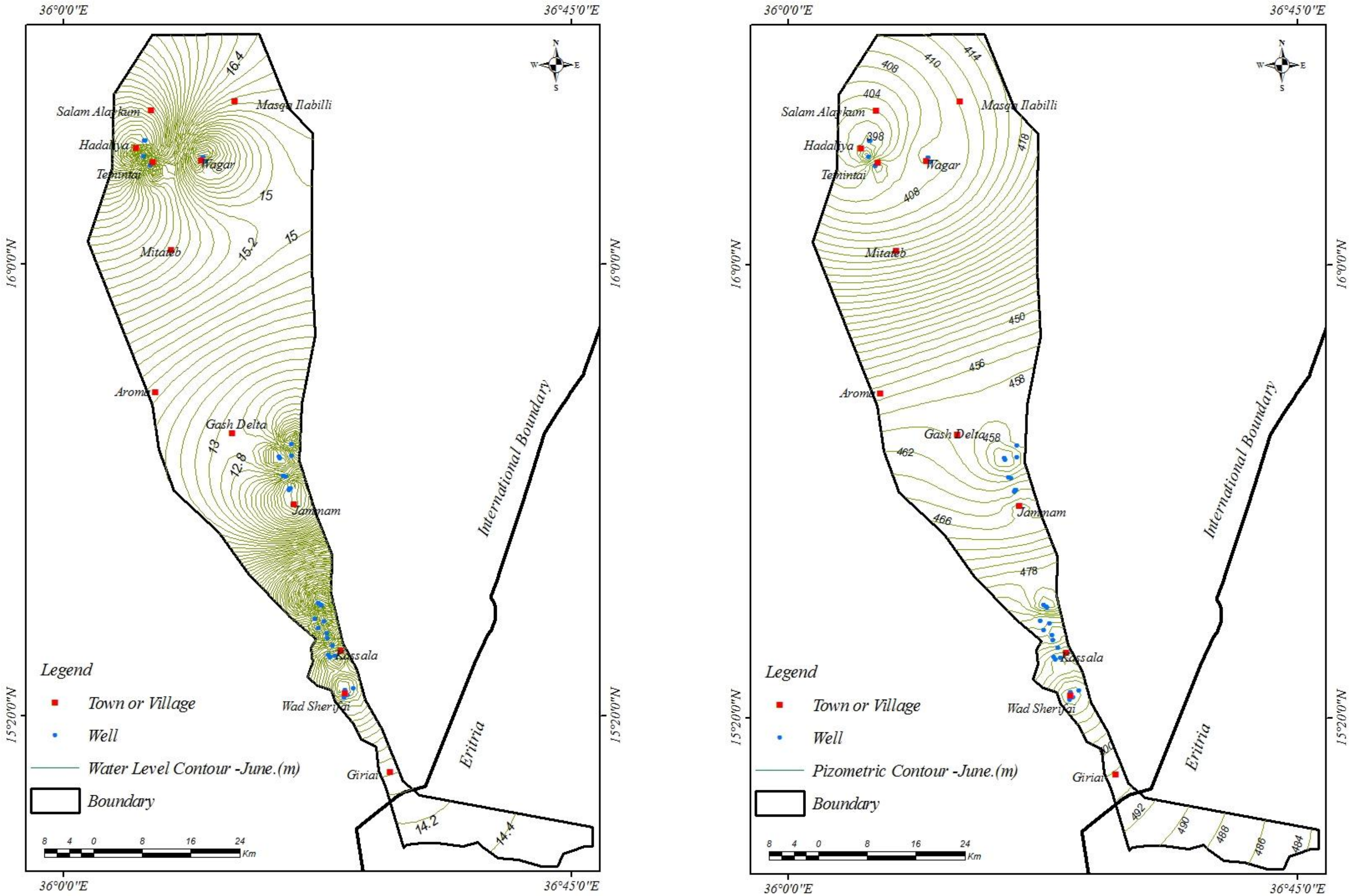


Figure 7: Water table depth from ground in Gash aquifer (left) and water table elevation in Gash aquifer (right) in June 2015

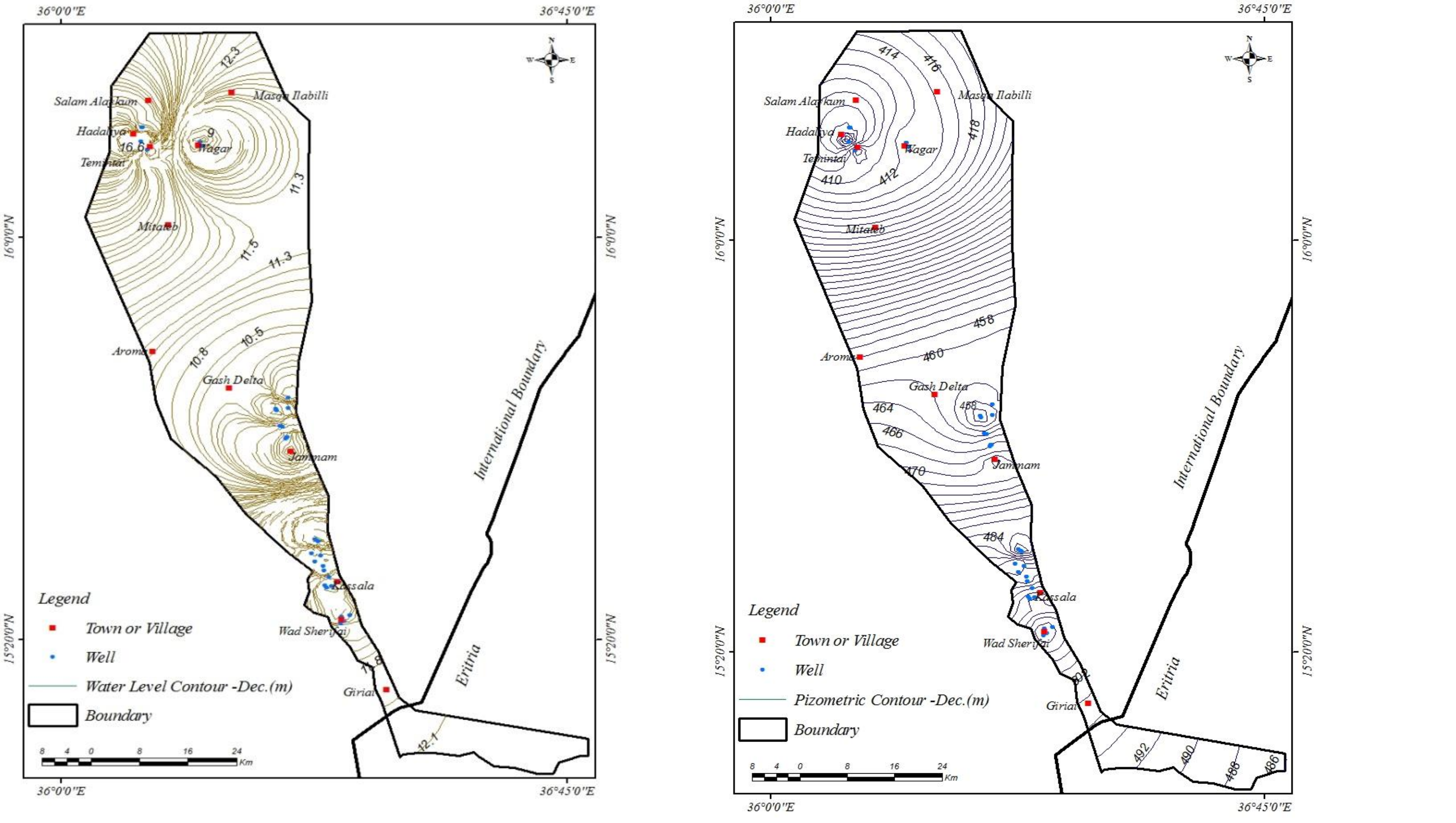


Figure 8: Water table depth from ground in Gash aquifer (left) and water table elevation in Gash aquifer (right) in December 2015

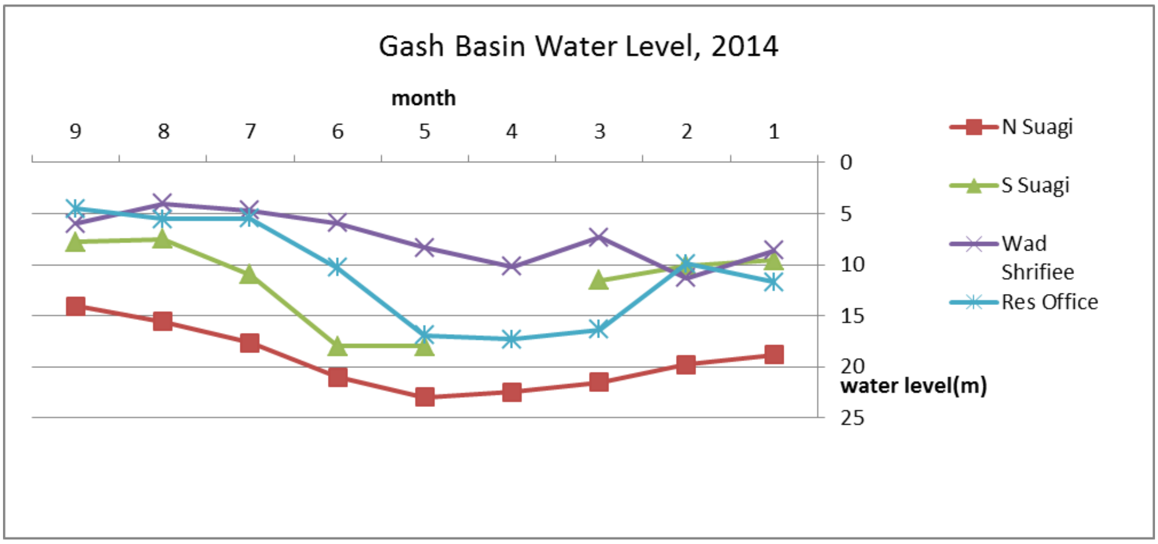


Figure 9: Fluctuation on water level in Gash aquifer

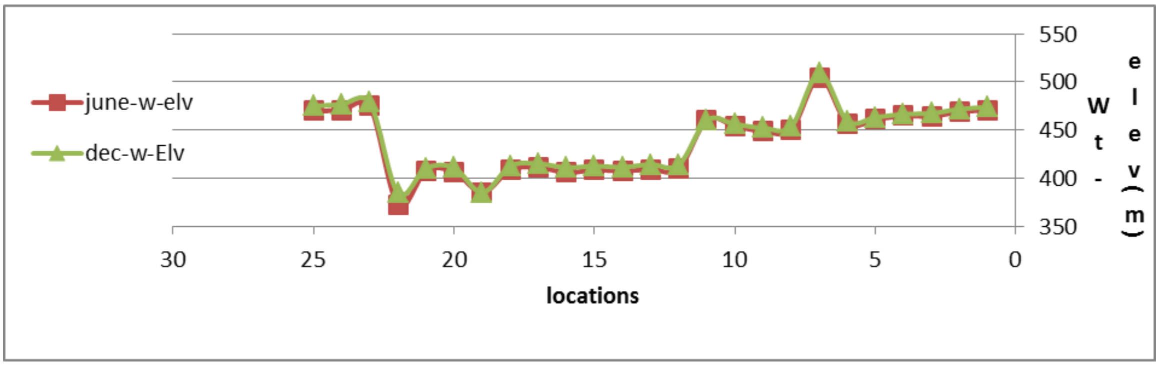


Figure 10: Water table elevation fluctuation for June and December 2015 in the Gash aquifer

4.2.5 Recharge of the aquifer

The expected sources of recharge of the Gash alluvial aquifer are:

- Infiltration from surface water runoff in the Gash basin.
- Infiltration from direct rainfall.
- Inflow of groundwater from the alluvial aquifer and through the fractures from the catchment areas.

Two methods for calculating the recharge were used, one is the losses between two gauge stations (one in the upstream (EL Gera) and the other in the downstream (Slam Allekim)). The other method by using equation, as described below:

<u>Equation method using difference in water level between dry and wet seasons</u>

$Q_R = A * \Delta h * Sy\%$

Where:

Q_R = Annual Groundwater recharge

A = Surface area

Δh = Difference in water level between wet and dry period

Sy = Specific Yield%

In this study the estimated total saturated area is about 824 km^2. The specific yield ranges in the study area from 20% in the upper stream zone to 15% in the middle stream zone - Kassala area (Elsheikh 2010, Gadelmula 2008 and Bireir 2002) and 5% in the most downstream and delta area (Table 3).

From the recent data observed by the monitoring observations network of GWWD, the fluctuations is calculated to be 3 m for upstream area, midstream area is about 6 m, the downstream area is about 4 m and about 4 m for the delta area. Table 3 presents the calculated annual recharge in the four sub-areas and also the total estimated annual recharge in the Gash basin. The estimated annual recharge is about 436 Mm^3.

Table 3: The estimated groundwater recharge in the Gash basin

Recharge (Mm^3)	**Difference in water level (m)**	**Specific Yield (%)**	**Surface area (km^2)**	**Sub area**
81.6	3	20	136	Upstream
180	6	15	200	Middle stream
102.4	4	20	128	Downstream
72	4	5	360	Most downstream and Delta
436			**824**	**Total**

<u>Discharge and gauge stations method</u>

Through the past years, Gash River water levels and discharges were measured at 4 stations located on the river banks in the upstream area of Gash River as well as the downstream. These stations are ELGira (upstream area), Kilo1.5 (Middle), Fota, and Salam Alikum (Downstream). The duration of the river discharge is depending on the period of rainfall in the source area (Eritrean Mountains). The flood period is usually from late June to early October. The most important source of recharge is the infiltration between ELGira (upstream area) and Salam Alikum (Downstream). To estimate the groundwater recharge, several things must be calculated.

Data from the Ministry of Irrigation in Kassala suggest that approximately 50% of the discharge of the Gash river is lost within the reach from El Gira station (upstream) and Kassala Bridge (25 Km from El Gira). These losses are attributed to infiltration and evaporation. It was assumed that there is substantial underflow, transmitted through a system of buried channels between El Gira and Kassala Area (Saeed, 1969).

Actual evapotranspiration is a complex phenomenon due to the interaction of climate, vegetation, soil and man (WAPS 1982). Evapotranspiration of water in the area includes evapotranspiration by irrigated horticulture zone and by natural vegetation. Yousef (2013) has calculated the total volume of water used by crop and natural vegetation to be about 346.23Mm^3, considered the area covered by crop equivalent and natural vegetation is about

152.04 km^2, while Elshekh (2010) has calculated the evapotranspiration as 355.8 Mm^3. Evapotranspiration is calculated according to following equation:

Actual evapotranspiration = E_o × *Crop coefficient* × *Cultivation period*

$$= 6 \times 0.8 \times 147000 \times 365 = 257.5\ Mm^3/year$$

Losses between two gauge stations:

Yousef (2013) discussed the procedure, which was used to estimate the flow discharge of Gash River at each gauging station (Geira upstream and Salam alykom downstream) as a conventional method applied from early time by Kassala Research Office (K.R.O) of the Ministry of Irrigation and Water Resources. In this study annual recharge of 2012 represented the ideal one because annual recharge of 2013 faced some problems in the cross sections (Gash River Training Unit – Kassala). The losses between the two gauge stations for year 2012 can be calculated as:

$$998 - 521 = 477\ Mm^3$$

The groundwater inflow from Eritrean boulder is calculated according to the following formula:

$$q = T*i*w$$

Where:

q = Groundwater discharge (m^3/d)

T = transmissivity (m^2/d)

i = hydraulic gradient (calculated above)

w = width of the aquifer (m)

The average transmissivity is 1400 (m^2/d), hydraulic gradient (i) is 0.005 and the average width of aquifers is 6 km, therefore the inflow is estimated to be:

Inflow = 1400 (m^2/d) × 0.005 × 6000 × 365 = 15330000 = 15.3 Mm^3/year

According to above calculations the groundwater recharge can be estimated using the following equation:

Annual Recharge values = Total loss between gauges (A - B) – ET

Where:

(A) = Annual discharge of ELGera station (calculated above)

(B) = Annual discharge Salam Alikum station (calculated above)

ET = Evapotranspiration (Estimated above)

The annual recharge can be calculated by subtracting evapotranspiration from losses between the stations as below

$$= 477 - 257.5 = 219.5\ Mm^3/year$$

The total annual groundwater recharge = Calculated annual recharge + the groundwater inflow i.e.

$$= 219.5 + 15.3 = 234.8\ Mm^3/year$$

4.2.6 Groundwater discharge

The discharge of groundwater Gash basin is through the daily abstraction by wells and evapotranspiration. The daily groundwater abstraction by wells is for irrigation and domestic water supply, mainly drinking purposes. In this study the abstraction by wells is calculated from water well discharge data collected during the field trip and from data collected from well inventory survey carried by Groundwater and Wadis Directorate, Kassala Office, in the year 2013. The estimated total daily abstraction is 303,745 m^3 and the annual abstraction is calculated to reach about 69,783,740 m^3 (Table 4).

Table 4: Abstraction of groundwater by wells in Gash basin

Sub area	Annual abstraction	Daily abstraction (m^3/day)	No. of wells	Remarks
North Swagi	5744000	28720	98	Irrigation (working 200 days/y)
South Swagi, sabeel and including western area	21899400	109497	370	Irrigation (working 200 days/y)
Upstream area	17786400	88932	230	Irrigation (working 200 days/y)
Down stream	4368000	21840	120	Irrigation (working 200 days/y)
Delta area	237250	650	130	Low discharge dug Wells
Drinking wells (western area)	2042540	5596	25	Drinking (working 365 days/y)
Urban water supply wells	17,706,150	48510	77	Drinking (working 365 days/y)
Total	**69,783,740**	**303,745**		

5. Conceptual model of the Gash basin

5.1 General

No groundwater model makes any hydrological sense if it is not based on a rational hydrogeological conception of the basin; therefore the first phase of groundwater model study consists of collecting all existing geological and hydrogeological data on the groundwater basin. This include information on surface and subsurface geology, water tables, precipitation, evapotranspiration, pumped abstractions, stream flows, soils, land use, vegetation, irrigation, aquifer characteristics, aquifer boundaries and groundwater quality. All the collected information is then used to develop a conceptual model of the basin, with its various inflow and outflow components.

Developing and testing the numerical model requires a set of quantitative hydrogeological data that fall into two categories, those define the physical framework of the groundwater basin and those describe its hydrological stress. Those sets are then used to assess the groundwater balance of the basin. Fortunately there exist enough data to describe the hydrogeological conditions at the site especially around Kassala, which is adequate to be used for developing the model.

5.2 Details of model conceptualization

Gash River is a seasonal river which flows only four months during the rainy season, it creates an area of agricultural activities as well as industrial and domestic developments in Kassala area.

The basement complex represents the oldest rock units in the study area, the main outcrops of the basement are the granitic biotitic gneisses of J. Kassala, and J. Mukram which rise on the plain. In other parts within the basin, the basement rocks were covered with Tertiary-Quaternary deposits. The depth to basement (the thickness of overlying deposits) ranges from 9 m in the upstream to 60 m in the delta. The clay of the plain overlies the basement complex, the clay of the plain is usually found above the river flood plain east and west of alluvial deposits. It consists of laminated loose to compacted clay, silt and sandy silt. Its thickness ranges from few meters to about 20 m along the west side of alluvial deposits. The boundaries (sides and bottom) of the model will be determined laterally and at depth by the impermeable basement rocks and the clays of the plains.

The alluvial deposits were formed by the action of Gash River during the flood seasons. The coarse material (sand and gravel) deposits are located upstream and the finer material (clay) deposits in the downstream. The thicknesses of alluvial deposits upstream are about 9-30 meters and reach up to 70 meters downstream. They are composed of intercalating beds of unconsolidated coarse to fine-grained gravel, sand, silt and clay. The aquifer is enclosed within these sediments. Therefore the Gash aquifer is composed of heterogeneous sequence of layers which is dominated by coarse sand, gravel, clayey sand and silts. The groundwater occurs under un-confined and semi-confined conditions. The saturated thickness of the aquifer ranges from 12 to 19.5 m in the lower aquifer with an average value of 10.5 m. In the upper aquifer, the saturated thickness ranges from 8 to 12 m with an average of 9.5 m. With the continuous pumping the confining effect of the upper bed may be reduced and the entire saturated portion will function as a water table aquifer (unconfined). In the construction of the model we consider the two aquifers as one unconfined layer. The entire aquifer will be assumed as one heterogeneous and isotropic aquifer with various hydrogeological properties (Transmissivity, hydraulic conductivity, and specific yield), the transmissivity and hydraulic conductivity values assigned for the aquifers decreases in downstream and delta areas.

The aquifer is replenished due to infiltration from the Gash River, only during flood seasons, from July to October. The general flow direction is towards the northwest. The aquifer discharge is through abstraction by the distributed wells and naturally by evapotranspiration. The Kassala town and midstream area recently suffers from the heavy exploitation of water for the irrigation and water supply aspects which cause a severe drop in groundwater level in the aquifer. Reasonable values for recharge and discharge estimated for specific years will

therefore be assigned for each sub area. Vulnerability of recharge and groundwater levels to amounts of flood is very high, and hence, water levels to groundwater extraction.
The main objectives therefore are to develop a conceptual model to suit the numerical model setup for assessing the groundwater potentiality, to determine the effects of stresses on the alluvial aquifer system, to evaluate the potential effects of abstracting additional groundwater in certain areas of the basin. To develop a groundwater flow model for the Gash basin, we will use the ModFlow2000 software using the Argose one interface, which is compatible with the developed thematic base maps build as shape files. The finite difference method will be used, where the model area will be divided into 1.5 km square cells.

5.3 Model description

The process starts by constructing a steady state model and then a transient model was built. The steady state model gives insight in the hydrogeological processes and it is less complex than a transient model. The steady state model can only simulate an average situation, which almost never occurs in the real system. The steady state model was used as basis for the transient model. When the steady state model gives good and understandable results the transient model will build. A transient model is representing the real situation better and can show the variation dependent on time. After the transient model was developed, the model was calibrated and a sensitivity analysis was performed, followed by a scenario analysis.

5.3.1 Domain and boundaries

<u>Domain</u>

The location of the domain border was determined, which was based on the geology, topography and the locations of the Gash River. The eastern boundary was placed over the basement complex rocks outcrops. The northern border is located in the northern end of the Gash delta (Gash die). The western boundary was located in the south-east boundary was put on the border with Eritrea (Figure 11).

<u>Boundary conditions</u>

The model boundaries were set where; two different boundary types were used. A no flow boundary (zero boundary) was set to model the impermeable layer and the groundwater divide. No flow boundary means: no groundwater can flow across the boundary. The second boundary type that was used is the specified head boundary. With this boundary, the head was set on a known head value.
A no flow boundary was implemented underneath the lowest layer because it was assumed that there was no flow in the basement rocks. No flow boundaries were also used for the model outside boundaries, because it is assumed that the domain border is located at the basement rocks outcrops and at a groundwater divide. An exception is a small part of the southern boundary, which is also the border with Eritrea. For this part a constant head boundary was implemented. The elevation of the constant head was estimated from the surface elevation and the groundwater depth measured from the ground surface. For the constant head an average height was estimated. The average groundwater level elevation was estimated by taking the average between the highest groundwater level elevation and the lowest one. Therefore, a constant head of 495 m was used for the constant head boundary. For

the transient model a transient specified head was used. The specified head was the water level elevations of June 2015.

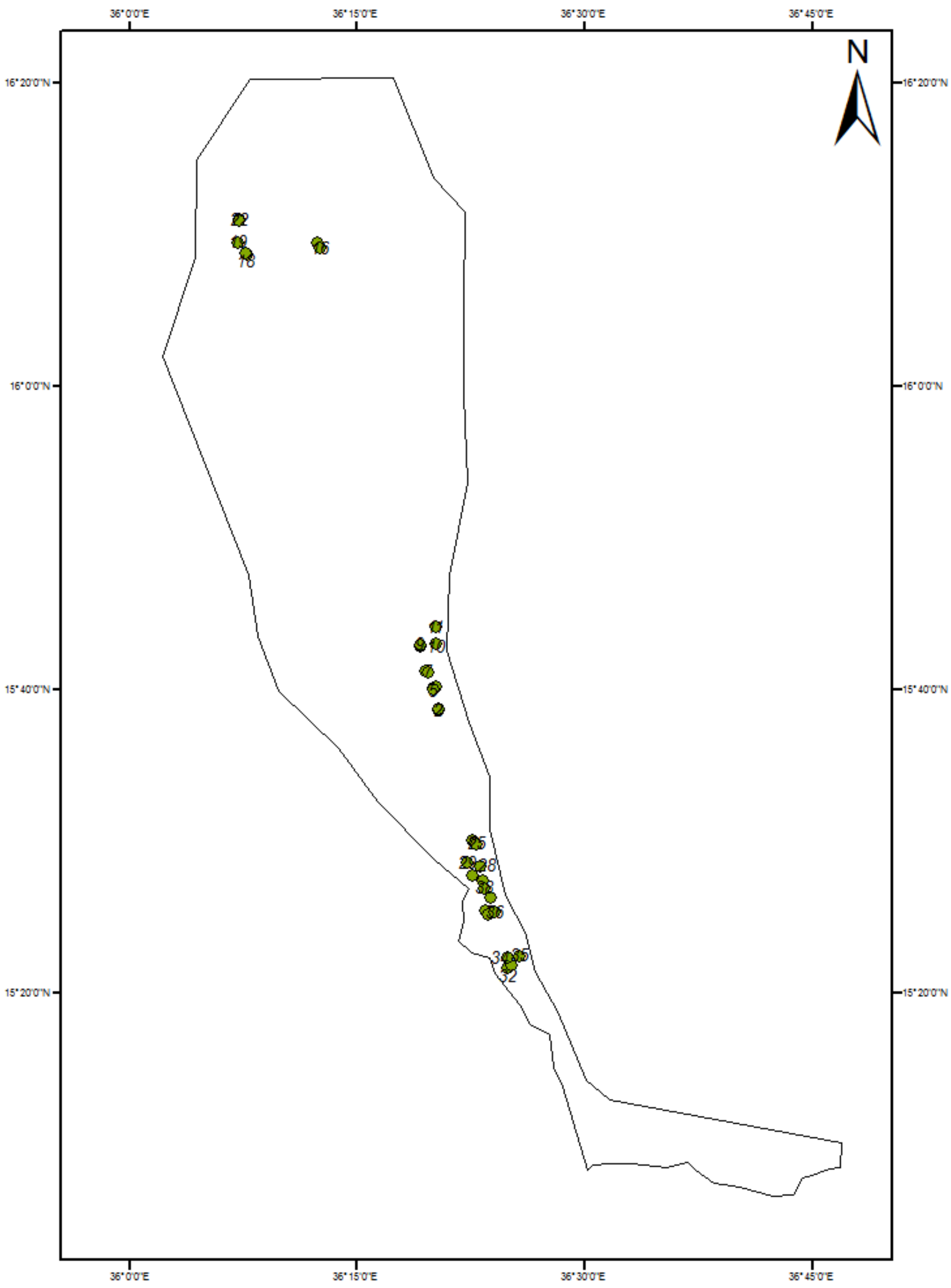


Figure 11: Boundaries of Gash Basin aquifer

<u>Discretization</u>

After the boundaries were defined, the model was discretized. Therefore, the grid sizes, the amount of layers and the thicknesses and heights of these layers were used in the model.

Grid sizes

The cells in the model are 1.5 by 1.5 km, which is a relatively coarse grid size. This grid size was used because the study area is large (824 km^2) and hence the large grid size will significantly reduce the simulation time. In addition, the available information was limited which means that there was no data to feed many detailed cells.

5.3.2 Alluvium aquifer

The river alluvium consists of four layers: two aquifers (upper and lower aquifer) and two aquitards. But for simplification the alluvium is considered as two layers, the upper layer started from the ground surface down to the water table (aquitered). The second layer (aquifer) started from water table to the bottom of the aquifer (basement rocks). The thicknesses of these layers were set in the model by using boreholes and cross sections. The boreholes and cross-section are based on drilling logs and geo-electric measurement. Only a limited number of drillings and geo-electric measurements were available in the downstream part and in the Gash delta. The alluvium thickness is variable through the aquifer, but the maximum depth is 60 m and the simulated average thickness of the aquifer is 40 m. It is assumed that the thickness is decreasing to zero at the end of the alluvial fan (Gash die).

5.4 Set parameters of model

5.4.1 Top and bottom

The initial model will have one horizontal hydrogeologic unit. This unit accommodates the prescribed head boundary condition that we place along the top of the model. This unit has a thickness of main aquifers in Gash basin (as one unconfined aquifer). To approximate hydrogeologic properties, the layer will be vertically isotropic with heterogeneous horizontal conductivity equivalent to that of the aquifers.

- The Top Elevation of the aquifer is the elevation of the hydraulic heads (water table elevation) as in shape file (Elev-wt-cont.shp)
- The Bottom Elevation of the aquifer are top basement elevation, (BASM_cont.shp)
- We set the following values as the aquifer values for each parameter.

5.4.2 Hydraulic conductivity

After discretization of the model, the conductance for each cell in the model, were defined. Different hydraulic conductivies (K) were assigned to the different model layers. The conductance for the river alluvium can be calculated from the KD and the saturated thickness. The assigned horizontal hydraulic conductivity as in shape file (Kmd-secon-2.shp).

5.4.3 Specific yield

Specific yield is assigned as 0.2 and 0.15 in the upstream and midstream and 0.1 and 0.07 in the downstream and the delta.

5.5 Model calibration

Model calibration is the process of adjusting the model data to obtain a reasonable match between observed data (calibration targets) and model calculation, i.e. implies a demonstration that the groundwater model is capable of producing field-measured heads and flows (Flow model). Repeated model data adjustments are usually required before the best fit of the model calculations. Different accuracy criteria can be used to compare the simulated and measured data during the calibration procedures. The most important criteria that used to check the calibrated model were Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE). Another way of checking the amount of residual error is to compare the total simulated inflows and outflows as computed by water balance.

A three-dimensional finite difference flow model was designed and calibrated to quantify the hydrologic parameters representing the hydrogeologic units of the Gash River Basin and provide the overall hydrologic budgets. Hydraulic heads in Gash River Basin were used to calibrate the model for the period from June 2015 to December 2015. The simulation time interval was divided into 6 stress periods each descritized to 6 time-steps. The model was run and calibrated using trail-and error techniques. The aquifer hydraulic conductivity, storativity, recharge, and constant head boundary (CHB) were adjusted during calibration to obtain acceptable match between calculated and observed heads and fluxes. The model was calibrated, to the selected input parameters against groundwater levels of 39 observation wells in the model domain under transient conditions. The objective of the calibration is to minimize the difference between the observed (measured) and calculated (simulated) values. The residual between observed and calculated heads was used to calculate the Root Mean Squared Error (RMSE) and the mean absolute error (MAE). During model calibration, model parameter values were adjusted so that simulated heads and mass balance would fall within the calibration targets. After each run, differences between simulated and observed heads were calculated with the goal of every difference being minimal. To check the hydraulic behavior of the alluvial aquifer in the model area the type model boundaries were altered in consecutive model runs. The calibration of flow model of Gash basin was realized through acceptable average (RMS) of 0.11 m, residual mean error of 0.09 m, and average normalized root mean square (NRMS) of 1.74 % (Figure 12).

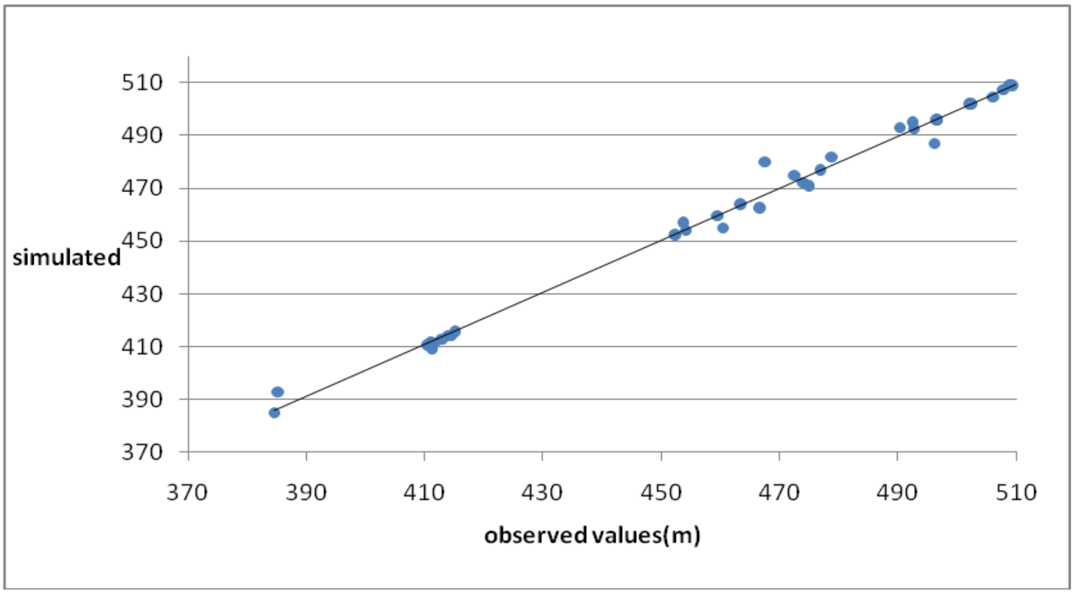


Figure 12: Observed against simulated water level elevations in Gash basin

6. Discussion and results

The model calibration of Gash basin was acceptable within the average Root Mean Square error (RMS), Residual Mean, and standard error of estimate to be of 0.11 m, 0.09 m and 1.74% respectively. The groundwater elevations and contour maps of the simulated heads show fair similarity with those generated from initial heads which confirm acceptable model calibration. The contour lines and flow lines show flow from the south east to the north-western sides of the basin indicating recharge parallel to flood path from the south east towards the northwest .The water heads decreasing towards the northwest and inside towards the center around Kassala, El Sawagi areas, and Jammam area forming cone of depression which is considered to be due to excessive pumping, where some wells go to dry by the end of dry season. The initial heads entered to model represent the end of dry season where water levels drop in all areas and also some wells go to dry at high excessive pumping areas. During the simulation period the aquifer is recharged and hence water levels rise relative to initial dry period's level. The model has predicted a maximum drawdown of 7 meters during simulation period of 6 months against a withdrawal rate of 303745 m^3 per day. The average values of pumpage and recharge of the aquifer during simulation time is calculated to be 69.784Mm^3 per year, and 418 Mm^3 per year respectively.

6.1 Scenarios results

Scenario 1: Minimum estimated recharge and actual abstraction of year 2015

The simulation for the period 18 months using recharge of 235 Mm^3 /year and discharge of 69.784 Mm^3 per year, reveals general pattern of the water level elevation similar to that of simulation period of 6 month, causing drawdown of 2-3 meters more than that of the of 6 months period (Figures 13&14). The difference in recharge rate is one of the factors affecting the water levels of the Gash aquifer and causing dryness of the pumping wells especially around the city. The test of the model have shown that drawdown in the basin is less sensitive to variations in hydraulic conductivity of the basin, it mainly corresponds with trends of aquifer thickness and buried channels in the area. The effect of rate of pumping and recharge proved to be pronounced in the basin.

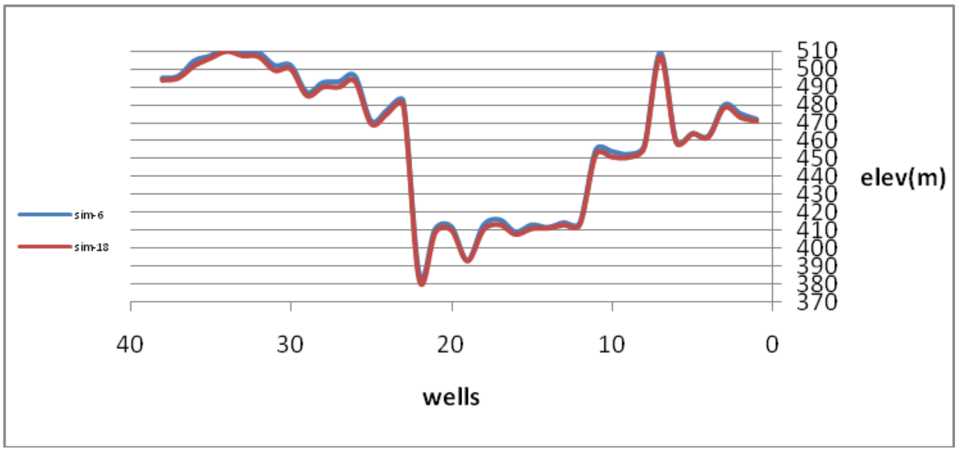


Figure 13: Water level elevation of 6 months and 18 months simulation periods

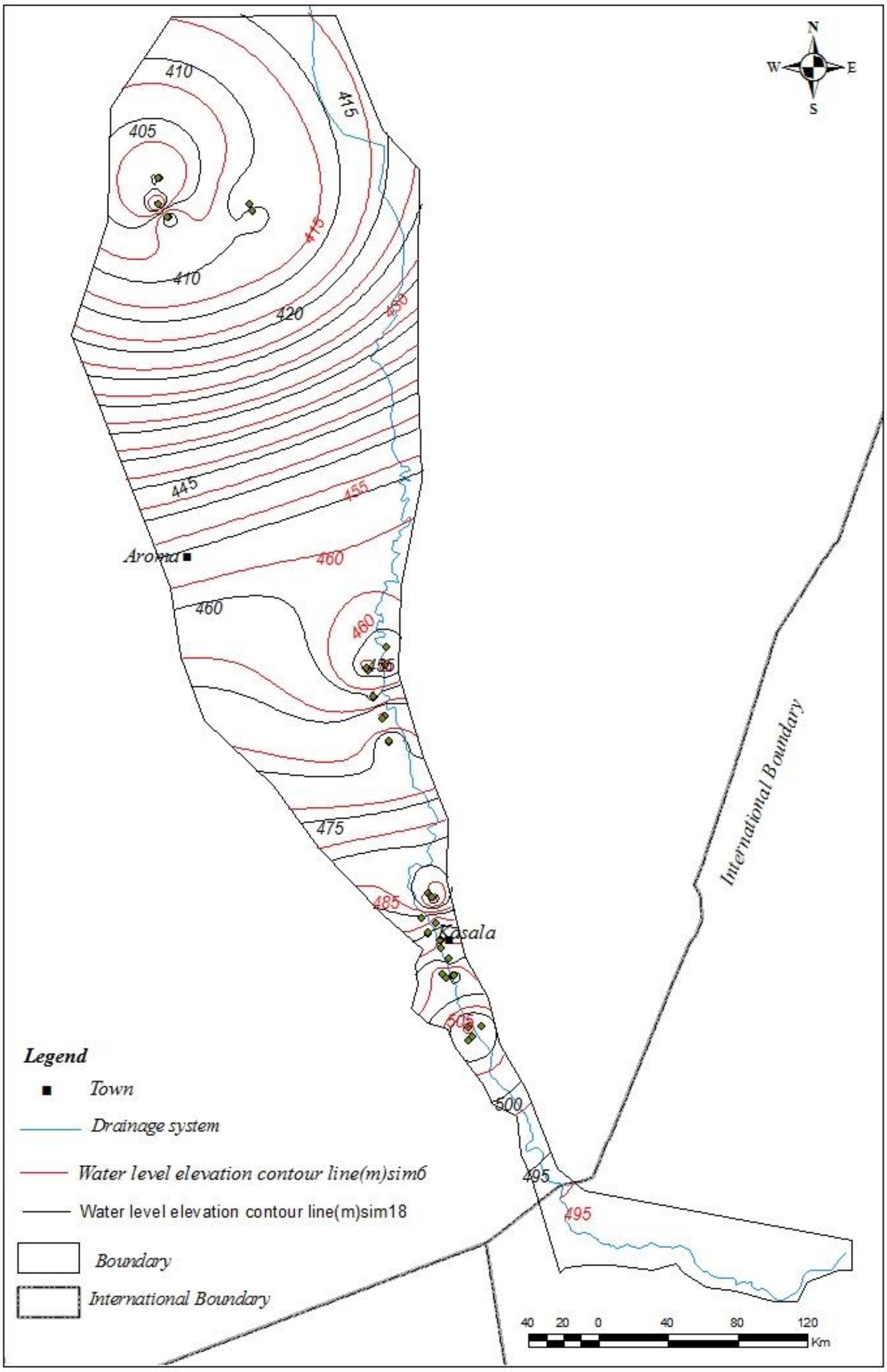


Figure 14: Water level elevation contour of 6 months and 18 months simulation periods

Scenario 2: Same minimum estimated recharge and half actual abstraction of the year 2015

The simulation for the period 18 months using recharge of 235 Mm^3/year but half of the actual discharge (35 Mm^3 per year), reveals general pattern of the water level elevation similar to that of simulation period of 6 month, but the water level elevation rises in range of 2 to 4 meters in the basin than that of actual levels measured in the same months (2015) causing rises of the same range (Figures 15&18). Figures 16&19 shows rise in water level between 2 to 6 meters and in some areas it may reach up to 8 meters, in wet months during and after recharge with respect to that of actual abstraction but the same recharge rates.

Water level elevations for half abstraction and the same recharge for June and December 2017 in the upstream and mid stream part of the basin are presented by Figures 17&20.

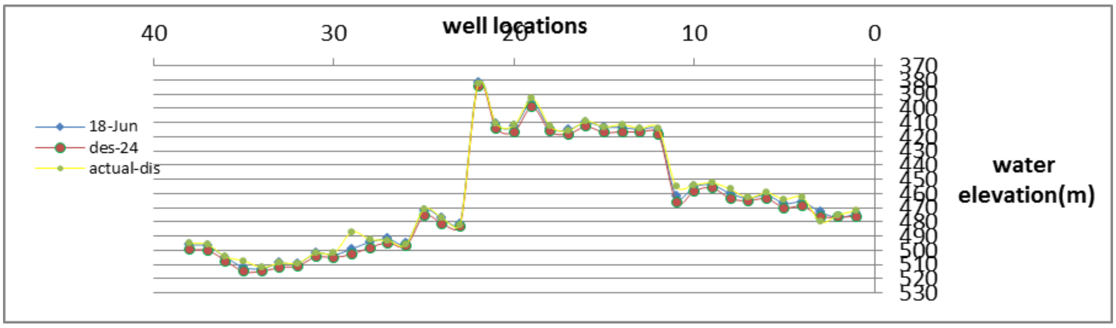


Figure 15: Water level elevations simulation for half abstraction and the same recharge (June & December 2017)

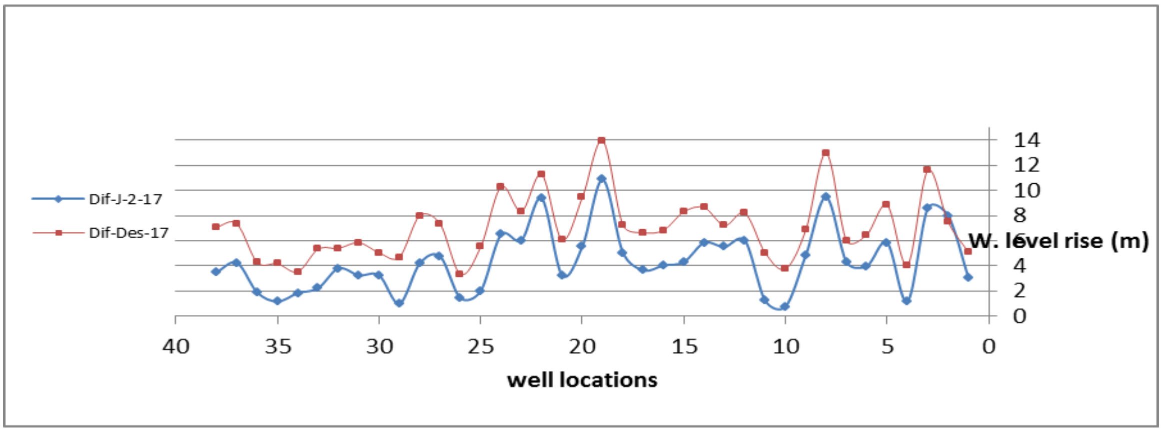


Figure 16: Difference in water level between June 2015 (using actual discharge) and simulated June and December 2017 using half of the actual abstraction but the same recharge

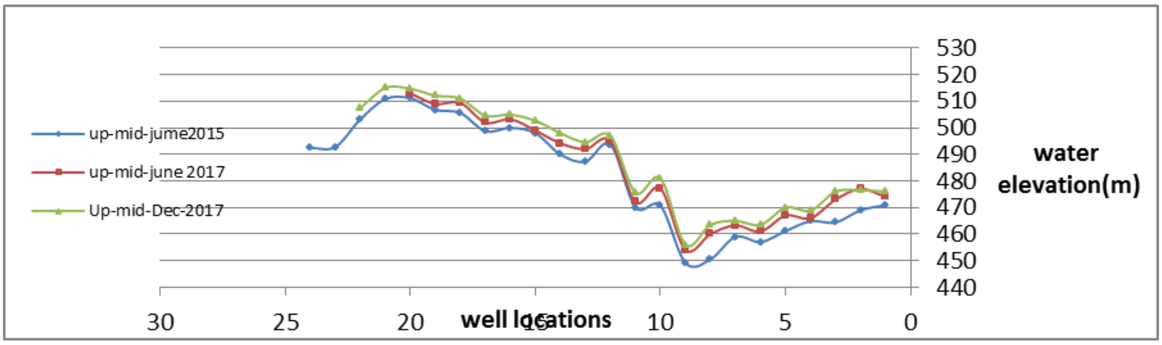


Figure 17: Water level elevations simulation for half abstraction and the same recharge (June and December 2017) in the upstream and mid stream part of the basin

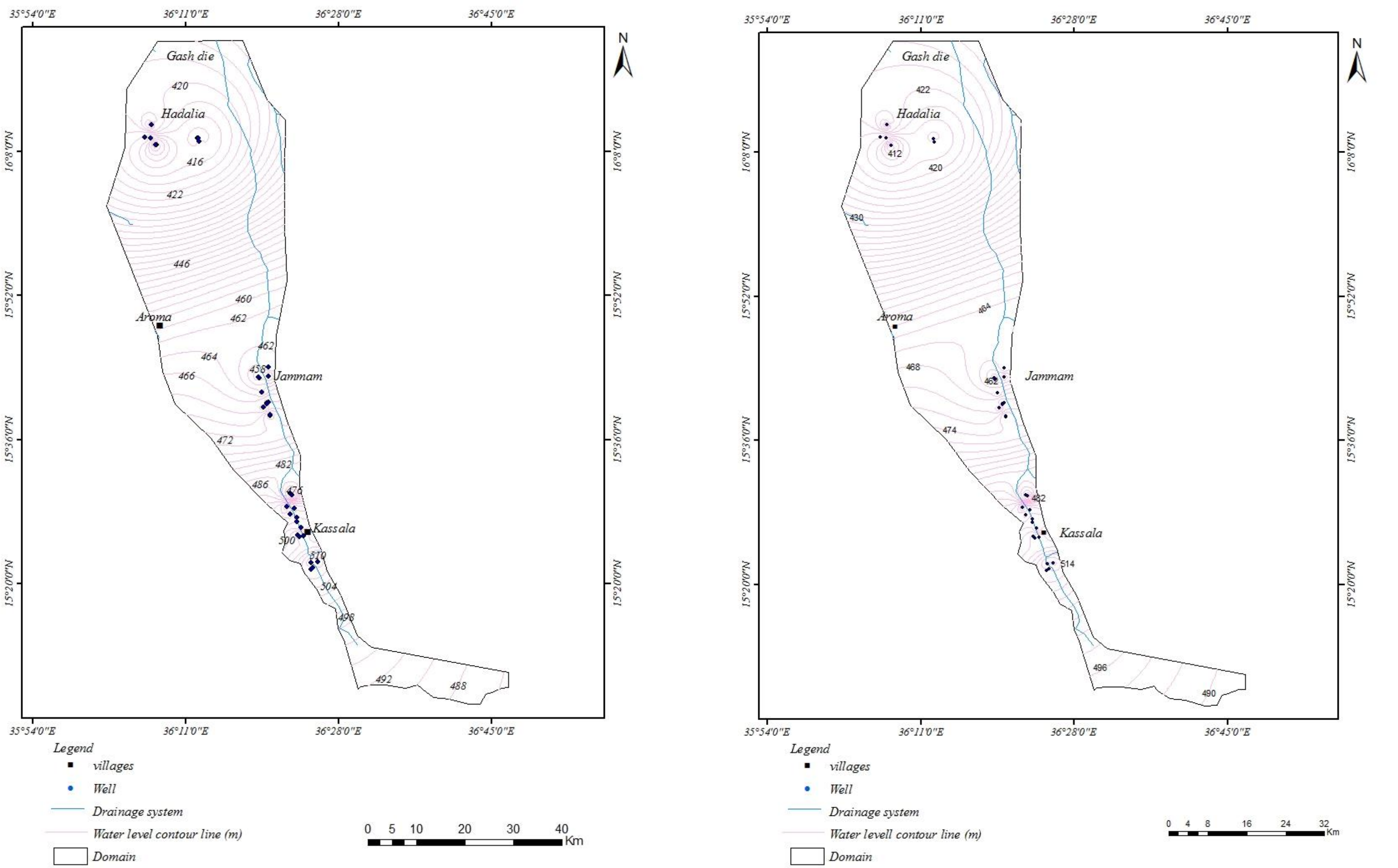


Figure 18: Water level elevations simulation for half abstraction and the same recharge on the left (June 2017) and water level elevations simulation for half abstraction and the same recharge on the right (December 2017)

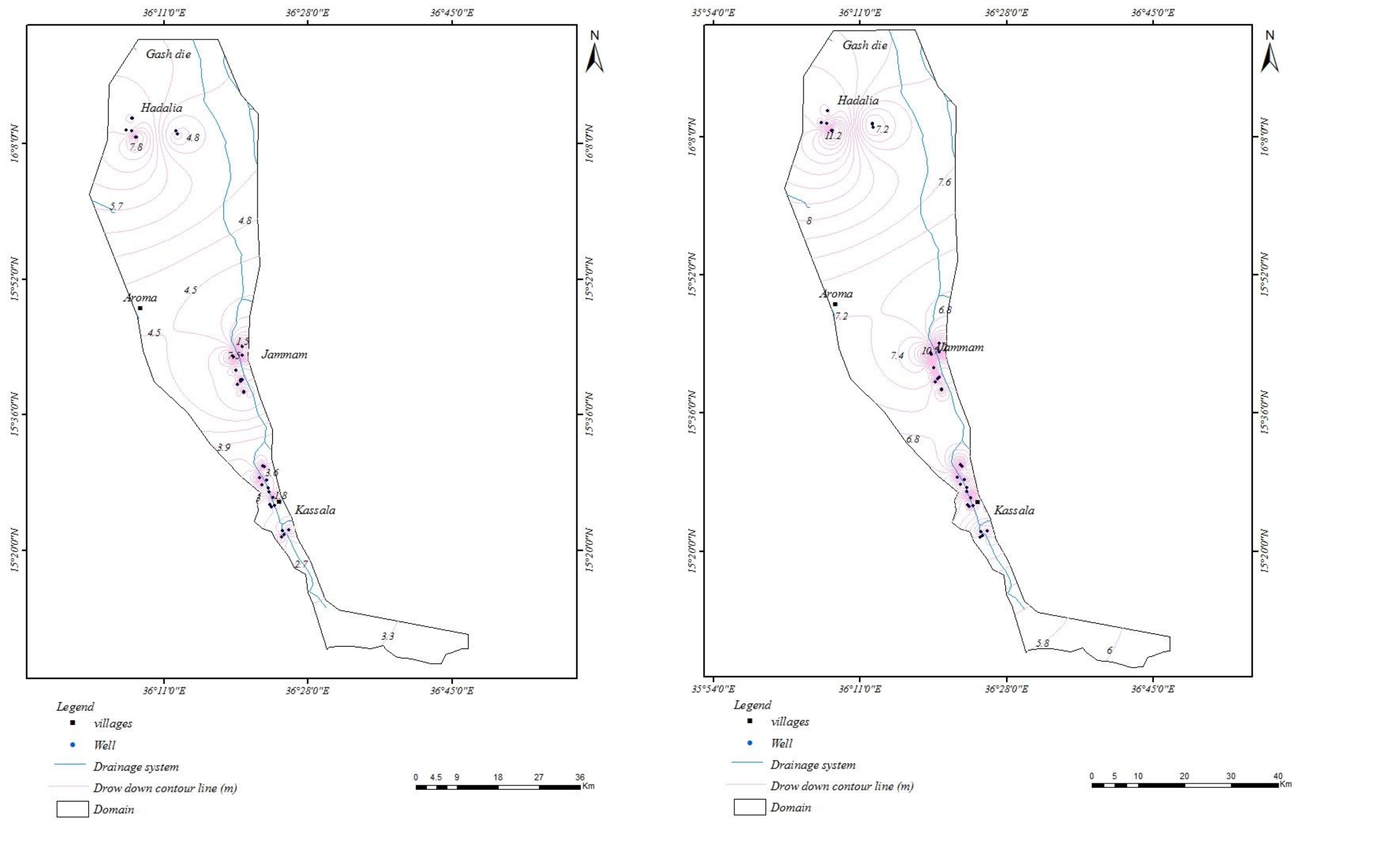


Figure 19: Rise in water level simulated for half abstraction and the same recharge for June 2017 (left) and for December 2017 (right) relative to that of June 2015 using actual discharge

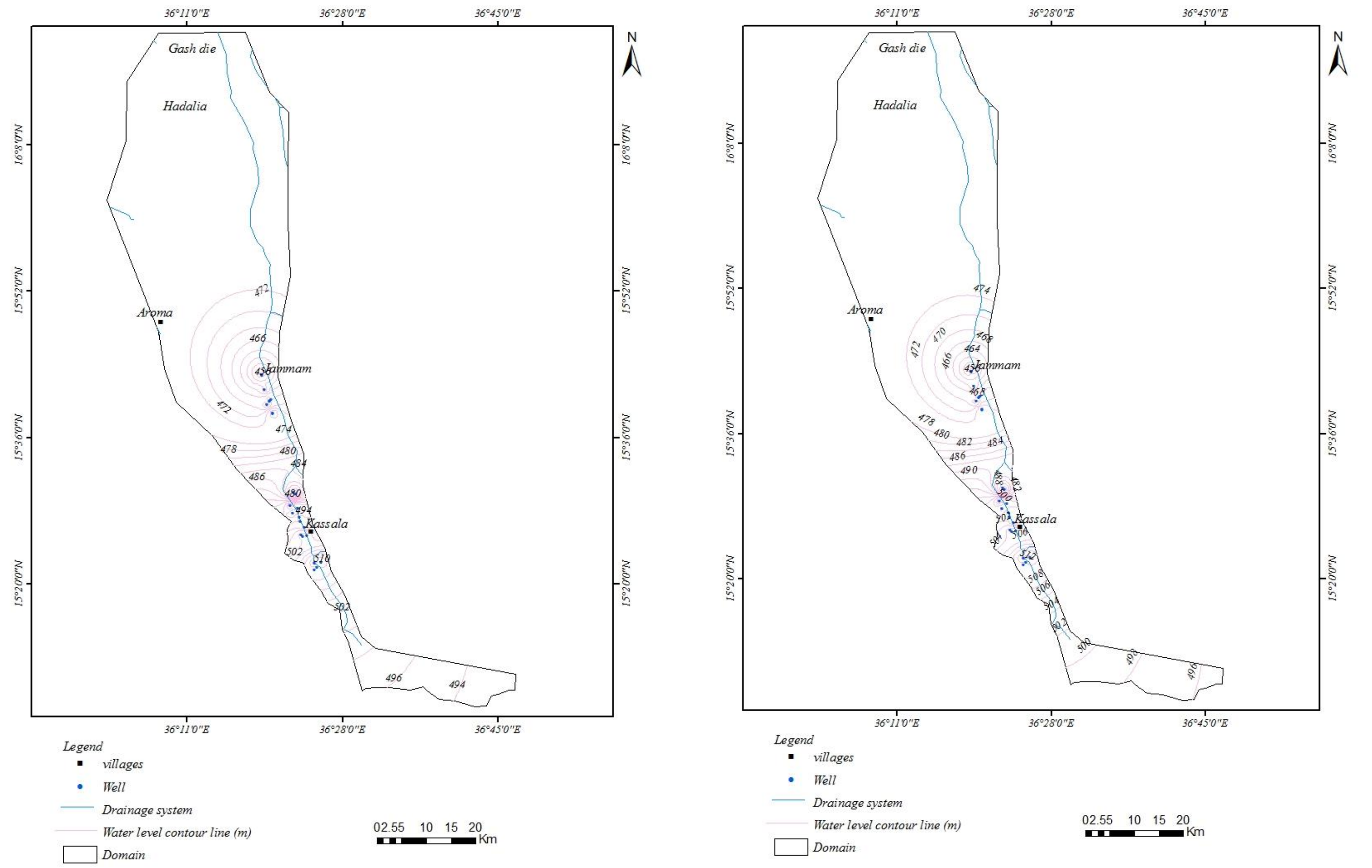


Figure 20: Water level elevations simulation for half abstraction and the same recharge (June 2017, left & December 2017, right) in the upstream and midstream parts

7. Conclusions

The Gash aquifer is highly depending on annual recharge of the River Gash seasonal flood. Therefore, the aquifer is replenished during the rainy season (July-October) and water levels starts to drop to reach condition of dryness in some wells in late summer.

The water level in the basin is highly sensitive to amount of recharge and to rate of pumping by wells for irrigation and drinking water supply uses. By receiving an annual recharge of 235 Mm^3 /year and abstracting annual amount of 69.784 Mm^3, which is the case of the year 2015, the water levels are undergo a severe drop and some wells may get dry like the case in and around Kassala town and Swagi area . However, by adjusting the annual well abstraction to level reaches half of the actual to become around 35 Mm^3, the water levels will improve to increase by 2 to 4 meters relative to that of respective month.

The natural discharge through evapotranspiration by citrus, mango, and other fruit trees in the midstream and Miskieet dense forests in the downstream and Gash delta, consumes about 30% of the aquifer recharged water.

The model shows that the basin can be grouped into the following parts considering the potential of the aquifer together with performance of the aquifer due to pumping (Figure 21).

- The area of the upstream from the Sudanese boarder with Eretria up to Wad Sharefaee is characterized by moderately groundwater potential, due to the relatively occurrence of thin alluvium deposits (9-14 m) and therefore thin aquifer (2-14 m).
- The area of the midstream, especially around Kassala town, El Sawagi north and south, Khor Esshigia, and Salaam Elekum, has high groundwater potential, considered the most productive zone in the basin. It is characterized by relatively big alluvium sediments (23-48 m) and aquifer thickness (10-30 m), high to moderate hydraulic conductivity. In the west central part of this area of the Gash basin, relatively high hydraulic conductivity zone can be inferred from widely spaced simulated equipotential (water level elevation) lines, this area was confirmed to be the most productive zone in the area. The eastern part of this area (midstream) has relatively moderate potential as compared to the western part, due to thin aquifer thickness (2-24 m).
- The area around Jammam has moderate groundwater potential due to an aquifer of wide and big thickness (15-20 m). The aquifer has good transmissivities and hydraulic conductivities as compared to the Gash delta in the north.
- The downstream part of the Gash basin (from north Jammam area to Gash Die) is characterized by aquifers of moderate to low potential. The Gash delta up to Gash Die is characterized by a highly heterogeneous sedimentation pattern which leads to the fragmentation of the aquifer into small pockets characterized by thin aquifer (4-12 m) with poor hydraulic conductivity.
- The water level depth and water table elevation in the aquifer vary seasonally, where they rise during and after the rainy season (July- December) and start to drop during dry season. The seasonal variation is between 3 to 7 meters depending on the location and pumping rate from the aquifer. Late in summer (May-June) some water wells become dry. The excessive drop in water table is observed in areas of high pumping rates around Kassala town and in South and North El Sawagi areas.

- The downstream parts of the aquifer around Jammam, the water levels vary between July to December 2015 in the range of 2 to 4 m.
- Delta area, the aquifer although poorly developed but the water levels vary between wet and dry season in the range 4 to 6 meters and also drop to dryness.
- The water table elevation although drops during dry summer but the general pattern is parallel and the groundwater flow direction will not change.

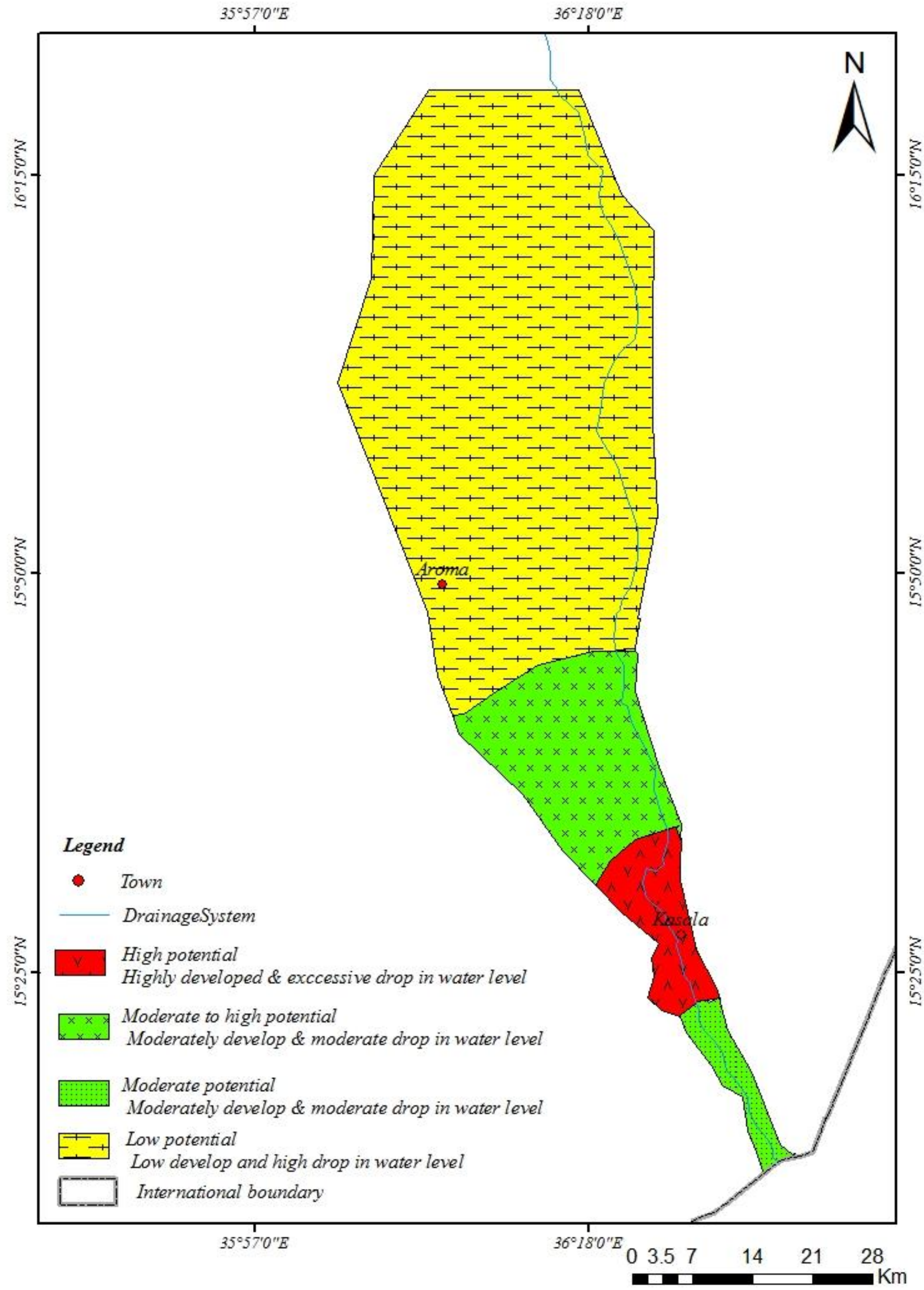


Figure 21: Utility map showing groundwater potential in Gash basin

8. Recommendations

To manage the basin groundwater resources wisely we recommend the following:

1. Reduce the amount of pumping by wells for irrigation purposes around Kassala and El Swagee areas in the midstream at least by one fourth up to half of the existing rate.
2. Priority is given to drinking water supply to serve the town and the villages of downstream. This can be achieved by utilizing aquifer around Kassala and Jammam areas.
3. Downstream parts should be utilized to drink the livestock.
4. The recharging of the downstream and delta aquifers can be supported by applying the artificial recharge techniques , the basin method which is used in some parts of the downstream and delta is highly recommended.
5. An integrated Water Resources management program is highly needed to be applied in the basin, including strong water regulations, construction of water Board for the development of the basin to be adopted and applied together with a big campaign of water awareness.
6. The community especially the women and youth should be highly involved in the water management process and in the campaign of awareness to support water conservation and wise use.

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