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The Effects of the Newly Established Atbara/Setit Dam on Groundwater Storage, Upper Atbara River, Eastern Sudan

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Abstract: The study area lies in the Kassala and Gedaref states, eastern Sudan. It is located in arid/semi-arid climatic zone with average annual rainfalls (≈400mm). River upper Atbara and River Setit are flowing from Ethiopian highlands during the rainy seasons. The assessment of the effects of the newly established dam on groundwater storage is the main issue for the current investigations. The methods of investigation include the collection and analysis of the pre-existed data and field hydrogeological investigations. Different computer analyses were applied; to portray maps, established the geological sections, identification of the hydro-geological parameters and delineation of groundwater flow. The main geological units in the River Atbara watershed include; the old basement, Sandstone, basalt and alluvial sediments. The dam is directly constructed on the permeable layers of sandstone which formulate direct link with groundwater basins. Groundwater levels in the upstream area are increasing by about 10-15 meters during the last years after the construction of the dam. Huge amount of Dam Lake water storage is subjected to considerable amount of seepage to groundwater system upstream. While at the middle and downstream areas, the link between surface water storage and groundwater is insignificant due to the existence of less permeable layers. Two sedimentary depression were identify; the first one at the Southeastern part (Wald Elhelow basin) which is hydro-geologically of direct connection with the dam lake. The second one is an isolated basin from the river system at the western part (Gedaref basin).

Keywords: River Atbara; groundwater; Atbara/Setit dam; Eastern Sudan

1. Introduction

Groundwater Recharge from surface water bodies is the main sources of recharge to the water basins for succeeding recovery to groundwater conservation against the impacts of climate changes, (Sherif, et al., 2023). The climatic changes is the most common environmental hazard that contributes to food insecurity and poverty, (Tullu, 2024). The sustainable water supply is acting on, deduction of poverty, economic improvement and conservation of ecosystems for a sustainable life, (Kumar and Mazumder, 2019). Groundwater recharge and discharge in semi-arid area is very significant issues for water resources assessment and management as well as to magistrate the groundwater contamination, (Elsheikh and Ahmed, 2025).

The study area lies in the eastern Sudan in Kassala and Gedaref states, the eastern part of the study area situated in Kassala state while the western part of the study area located in Gedaref state. It bounded by latitudes 14.961004° N to 14.134170° N and longitudes 35.962208° E to 35.536336° E., (Fig.1).

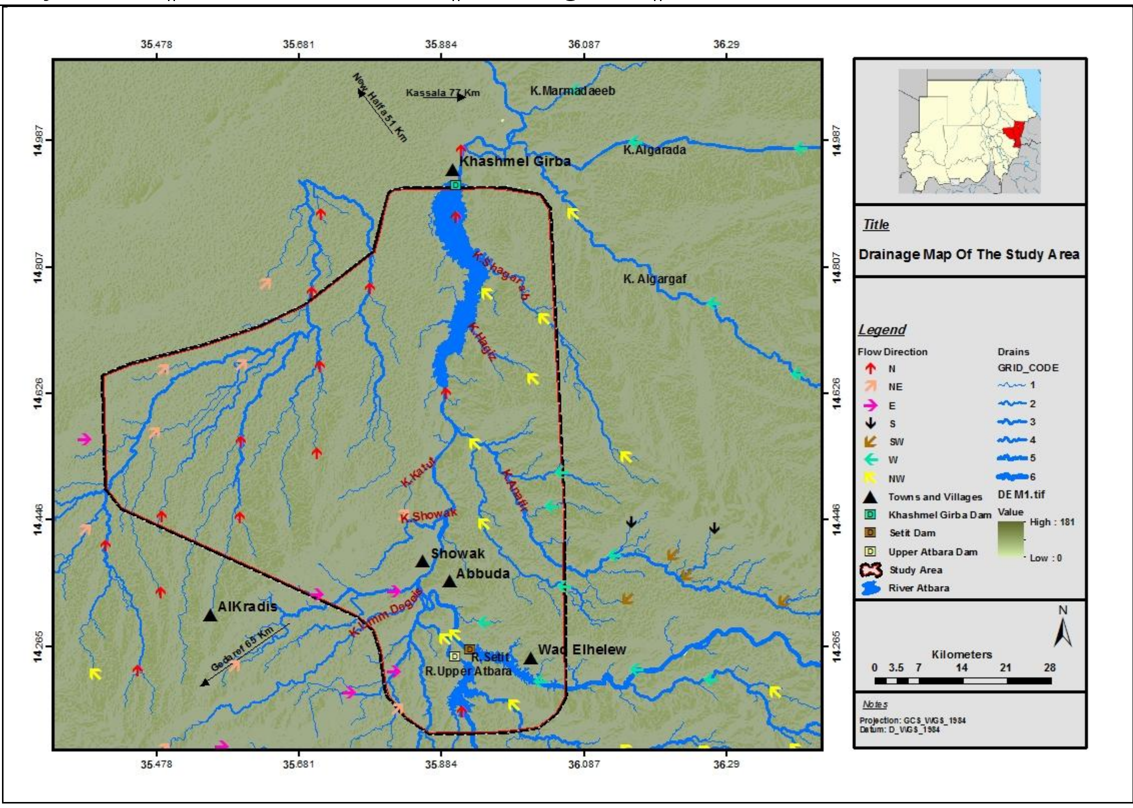


Figure 1: Location and drainage map of the study area.

The study area is located in arid and semi-arid climatic zone with average annual rainfalls is of about 400mm. The climate is characterized by long hot summer (April-October) with relatively short cold winter (November-March). Most of the natural vegetation has been replaced by Mechanized Farming of sorghum and sesame which they covers large area of the gently sloping land. However, remaining Accacia species scattered at some sites in the area. The decrease in rainfall in recent years has produced species more tolerant to dry climate conditions, (Gloverand Edinam, 2005; Fadull et al., 1999).

Geo-morphologically the study area can be divided into two parts; one is located near the River Atbara and River Setit on the both sides. This part characterized by rugged topography with a special land platform called Karab formation. The second part represented the plain area, which is gently sloping towards the River Atbara and their tributaries with general slope from Southeast to Northwest directions. The general elevation is varies from less than 490m.a.s.l. in the north to more than 535m.a.s.l. in the southern part of the study area.

River upper Atbara and River Setit are the seasonal rivers that flowing in short period during the rainy season, that is before the construction of Tekezi dam on River Atbara in north Ethiopia, in the present day the River is flowing all over the year. They are originated in Ethiopian highlands; they joined to the south of Showak town, where the newly constructed River Atbara/Setit Dam is located. The River Atbara flows about 805 Km until it joins the main Nile River at Atbara town to about 310 Km north of Khartoum capital. The River Atbara provides about one – third of the Nile's total volume of water ($\approx 11 \times 10^9 m^3$ annually). It also brings down more than 25 million tons of silt per year (Zaghloul et al., 2009).

The construction of the new dam was started in 2010 and completed in 2017. The water storage in the dam lake beginning in March 2015 at a level 513m above means sea level (amsl), the filling of the lake was accomplished in 2023 at level 521m (amsl). The planned total storage capacity of the dam lake is estimated to be equal to about 3.7 Billion cubic meters.

The study objective: The assessment of the effects of the newly established dam on groundwater storage is the main issue for the current investigations.

2. Material and Methods

The material and methods of the study were planned to achieve the research objectives. They include the collection and analysis of pre-existed data, enhancement of remotely sensed data and hydrogeological field surveys.

Most of the previous data such as reports, research papers. etc, were reviewed and investigated thoroughly. The collected data from groundwater and Wadies Directorate, Kassala & Gedaref States and from the Dams Implementation Unit, Ministry of Irrigation and Water Resources, Sudan where used. These include; climatic & hydraulic data, well logs, water levels fluctuations and others Hydrogeological data.

Four monitoring field trips were conducted to the study area specifically for to locate boreholes (of about 92 boreholes), measuring of Static Water Levels (S.W.L) and for measuring other's hydro-geological parameters through pumping tests conductance. The monitoring measurements were conducted for the piezometric and observation wells which are situated at the vicinity of the Upper Atbara/Setit dam, part of it they have been collected from Dams Implementation Unit (D.I.U).

Different computer and laboratory works were applied; to portray maps & display spatial data analysis through remote sensing and GIS techniques, established the geological cross sections, identification of the hydro-geological parameters and to delineate the general groundwater flow. The Arc-GIS 10 platform which it licensed (dongle license) by Arab Consult for Geology and Environment (ACGE) office was used for maps preparation. While GMS 10.5 software from Aquaveo (https://www.aquaveo.com) were used to conduct the boreholes lithological layers in 2D view through the (ACGE) office .The Microsoft office Excel software was used to perform hydrographs.

Various methods were applied to analyze the pumping test data through free sources software, the assumption and conditions for application for pumping test data were mentioned by Kruseman & Ridder, (1994). The most important calculated parameters from the pumping test data are; Transmisivity (T), Hydraulic conductivity (K), Storativity (S) and Hydraulic gradient.

3. Results and Discussions

The findings results from the geological, Hydrogeological and related issues were acquired, manipulated and analyzed as in the following.

3.1. General geology of River Atbara / Setit watershed

The Upper River Atbara and River Setit watershed from the Ethiopian and Eritrean highlands to El Girba dam to the north, the River Atbara and Setit passes through different geological units, (Nayl, et al., 2022; Eisawi & Schrank, 2009; Salama, 1985), (Table 1).

Table 1: The geological units of the Rivers Atbara and Setit watershed

No	Geological term	Age
5	superficial deposits	Recent- Quaternary
4	Basalts	Oligocene/Miocene-Pliocene
3	Sedimentary rocks	Jurassic- Cretaceous
2	Granites and quartz diorites	Lower Paleozoic and Precambrian
1	Metamorphic rocks	Precambrian (Upper Proterozoic)

Based on the regional geological survey and from the literature review, the basement complex consists mainly of slates, schist, granitic gneisses, quartzite and pegmatitic rocks. These rocks generally crop out in the form of scattered hills east and west of the River Atbara.

The Sedimentary rocks covered a large area of the southern part the study area, which occurred as hilly out crops distributed between Wad Elhelew town and Zahana village on the eastern side of River Setit. The sedimentary rocks sometimes intruded locally by Cenozoic basalts. Gedaref basin considered as tectonic depression filled by continental deposits which make up the Gedaref sandstone formation, (Adam, 1987; Almond et al., 1984; Kheir, 1980). Theformation is a succession of sandstone and mudstone previously thought to be of Jurassic to Cretaceous age, (Eisawi & Schrank, 2009).

The superficial deposits are the Quaternary clayey soil (black cotton soil) covering the flat plains, in addition to the valley fill and the deltaic deposits which covered the drainage basins and mainly composed of silts, sands and pebbles. The Neogene to Pleistocene sediments occur on the top of the succession which they represent the lands of River Atbara and Setit valleys (Known as Karab Formation), (Elubid, 2012; Hassan, 2011, Fadull et al., 1999).

3.2. Hydrogeological situation

The intervention between groundwater and surface water are a topic gaining increasing attention (Kluge et al., 2012). The groundwater plays a significant role in the ecosystem of the arid and semiarid regions. It is the vital local water source for human needs (Ghazavi et al., 2012). Groundwater forms the fundamental water supplies for many Africa countries and their development with increasing demands (MacDonald et al., 2021).

Groundwater in the study area is almost affected by the surface water regime in River Atbara water system and by the newly constructed dam. The established Dams are expected to raise the groundwater, especially surrounding the lake. In the past times, Rivers Atbara and Setit are the only source of water supply for all population living in the study area. During the flow period of the rivers (June – October), people are use the river water directly for all domestic purposes even without treatment. In the dry season they dig shallow wells at the river bed. Recently, after hydro-geological investigations, boreholes were drilled on both sides of River Atbara and Setit to secure the water supply for the local communities.

The Cretaceous sedimentary rocks that consist of sandstone, siltstone, conglomerate and mudstone comprise the major aquifers in the upstream area. The River Atbara sediments consist of sands, silt, clay, and gravelly layers characterized the main aquifer in the middle and downstream areas. The Cenozoic basalt occurs as thin layers intruded within the sandstone formations; the fractured basalt with the Karab sediments are usually they represent water bearing formations near the rivers, (Nayl et al., 2024; Elsheikh et al., 2014).

3.2.1. Boreholes cross-sections

The boreholes cross - sections, seems varies in the geological sequences in the study area, the boreholes logs recognized the existence of sandstone, basaltic rocks, the River Atbara sediments and Karab formation. The above sequences are overlain the basement rocks. The logs sections evident that the undulation of the basement complex, lateral and vertical sedimentary facies changes and variations in thickness of the intruded basaltic rocks, (Figs. 2, 3).

The boreholes logs data (Fig. 3), evident that the upstream area were the dam is existed, is lies in sedimentary basin, consist of alternative layers of sandstone and mudstone inter bedded with the basaltic volcanic layers with relatively deep basement rocks. At the middle and the downstream areas the basaltic volcanic rocks are the dominant strata overlain the shallow basement and covered by recent alluvial and clayey sediments.

This hydro-geological condition let the groundwater in the upstream area is closely related to the surface water storage in the River Atbara/Setit Dam, in which the dam is directly constructed on the permeable layers of the sandstone as a part of the Umm Gargoor basin to the west and Wad Elhelew groundwater basin to the east, (Fig. 4). The local groundwater recharge is reflected through the water table rises in nearby observation wells, (Sefelnasr et al., 2022).

Based on the revealed data presented above, huge amount of the dam lake surface water storage is subjected to considerable amount of seepage to groundwater system upstream. While in the middle and downstream areas the link between surface water storage at the Dam Lake and groundwater is insignificant due to the existence of less permeable layers over the basement rocks.

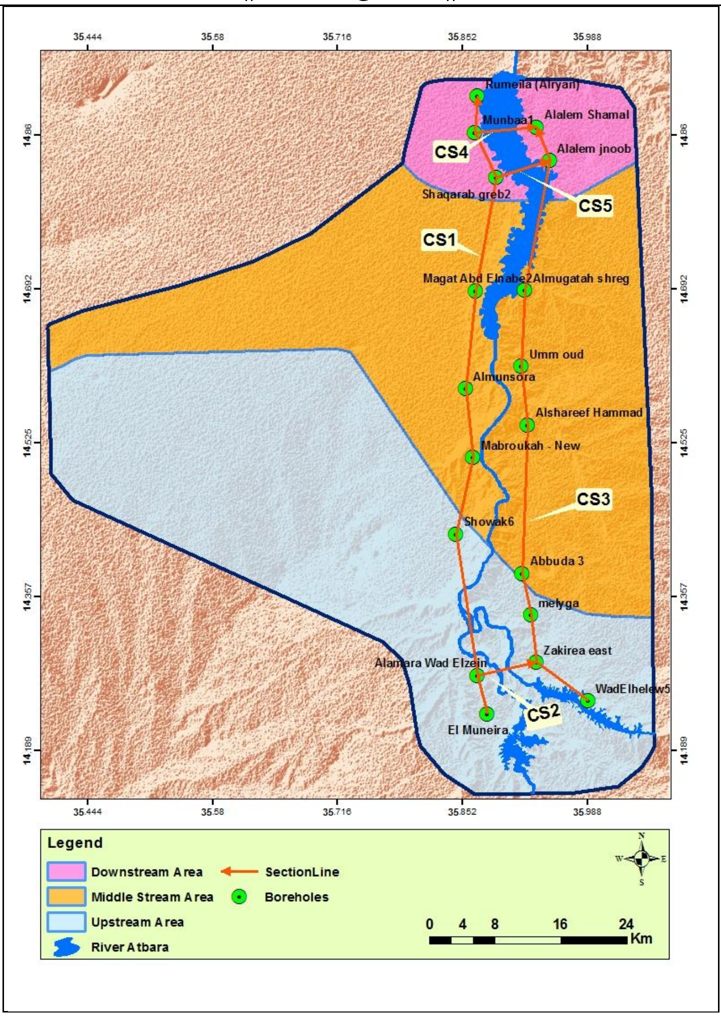


Figure 2: Distribution of the boreholes crosses sections in the study area

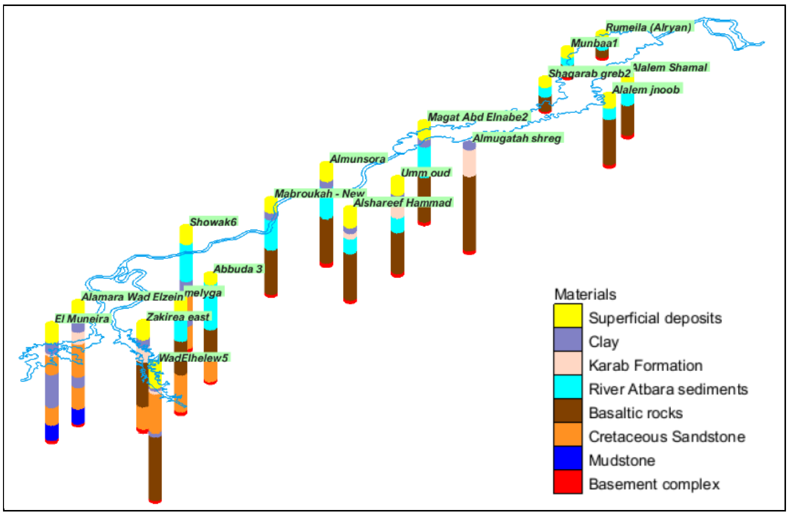


Figure 3: Boreholes logs cross section distributed in the study area.

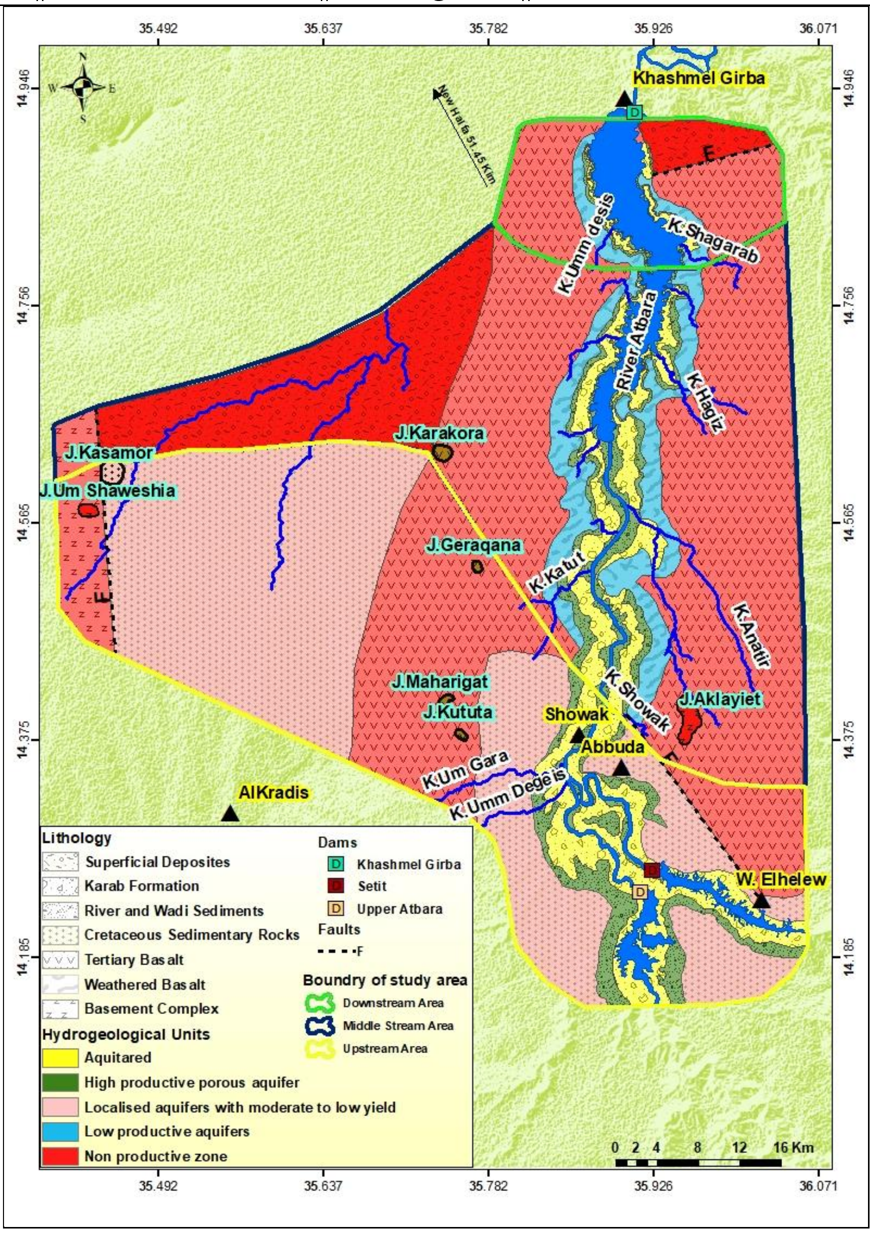


Figure 4: Hydrogeological map of the study area

3.2.2. Hydrogeological parameters

The pumping test methods were used to define the hydro-geological parameters for the aquifers. The pumping tests commonly used to determine the capacity of the wells and the hydraulic properties of the Aquifer. These parameters include; transmissibility, storability, specific yield and hydraulic conductivity, (Fetter, 2001). The groundwater flow in porous media is based on Darcy's law principles which are conclude that;

$$\upsilon = Q/A \quad (1)$$

$$\upsilon = -k\,\Delta h/\Delta l \quad (2)$$

$$\upsilon = -k\,dh/dl \quad (3)$$

$$Q = -k dh/dl\,A \quad (4)$$

$$Q = -KiA \quad (5)$$

Where:

υ is the average velocity, Q is the discharge and A is the cross-sectional area, k is the hydraulic conductivity and i is the hydraulic gradient (dh/dl).

A total of (22) pumping test data were collected from the productive and observation wells, which were distributed through the study area. From these data the aquifer parameters were calculated, considering types of aquifers and the hydrogeological conditions (Fetter, 2001; Kruseman and Ridder, 1994), (table 2).

Table 2: The Hydrogeological parameters of the aquifers in study area

Area	Average Saturated thickness (m)	Transmissivity (T) (m^2/d).	Hydraulic conductivity (K) m/day	Specific Yield%
Upstream	35	596	40	20
Midstream	25	328	33	18
Downstream	15	232	6.6	18

3.2.3. Groundwater level fluctuations

The fluctuation in the groundwater levels is an important indicator of the ecology and hydrology of the arid regions (Jolly et al., 2008; Hayashi, 2002).The elevation of the water table is a dynamic equilibrium with atmospheric pressure of the aquifer. Accordingly any natural or artificial phenomena that change the pressure on the groundwater or atmosphere will cause groundwater level to change (Elsheikh et al., 2011; Bireir, 2002).The water levels fluctuated primarily in response to variation in recharge and discharge. The depth to water table depends on the topography of the area, geological conditions and hydraulic gradients.

A number of 74 wells have been used to observe the groundwater levels fluctuations in the study area. Thirty three (33) wells are situated on the western bank and twenty four (24) wells were located on the eastern bank of the River Atbara, Seventeen (17) observation wells are located on Dam's area, (Fig. 5). The result is reflected in figure, (6).

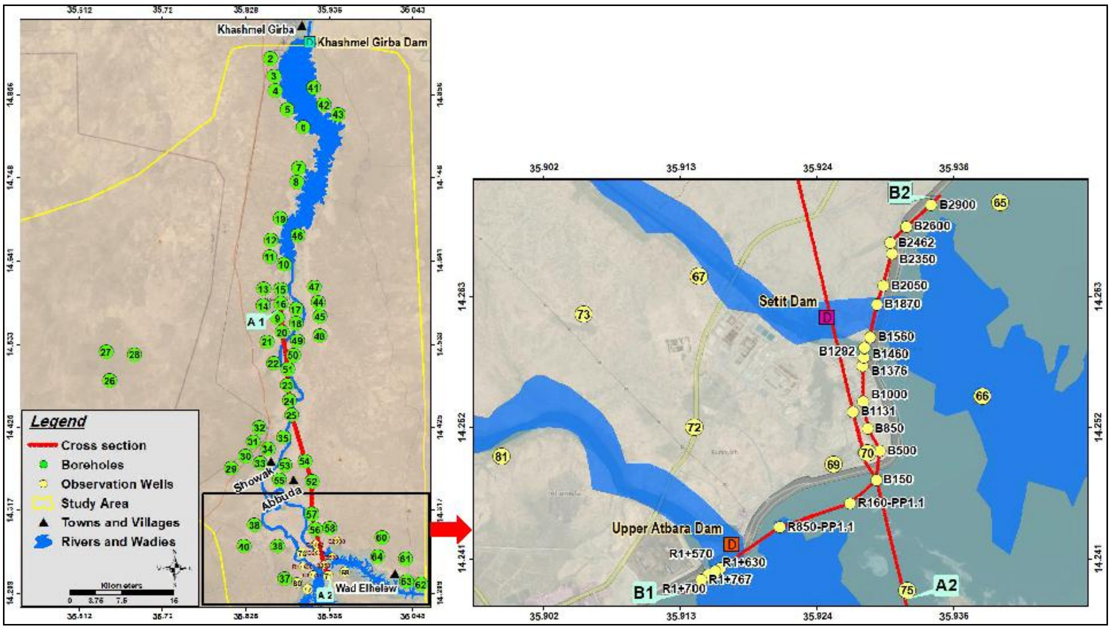


Figure 5: Location of the monitoring wells in the study area

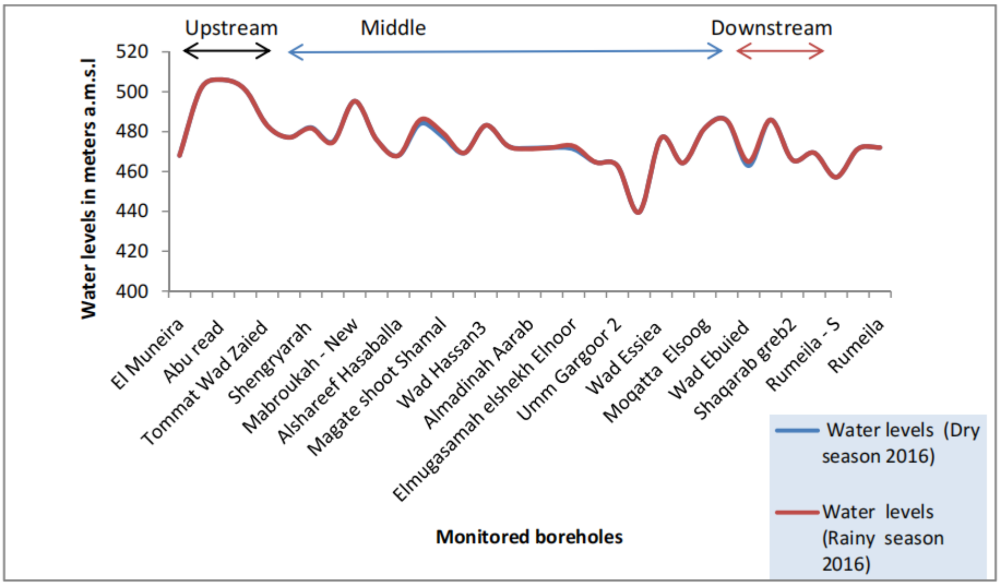
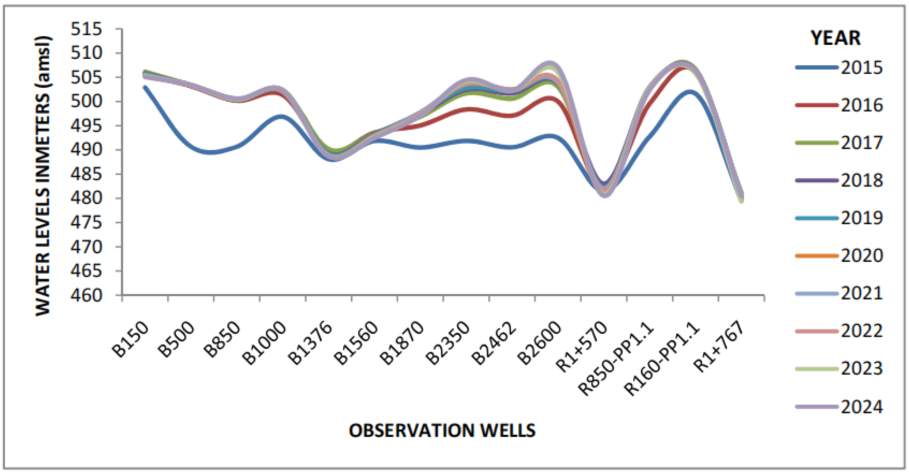


Figure 6: The average static water levels in selected boreholes in the area

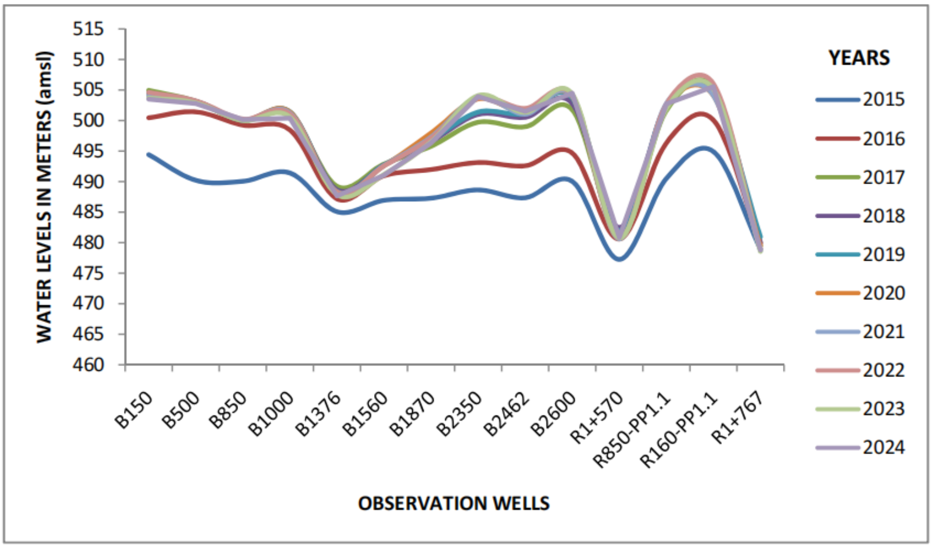
At the upstream area the groundwater levels are at shallow levels compared to that at the middle and downstream areas. That is referring to the rate of recharge, which is higher at the upstream area due to the direct link of the permeable strata to the recharge source from the rivers and the Dam Lake. Surface water storage is expected to be strongly subjected to the infiltration of water into the aquifers.

The groundwater fluctuated between the wet and dry seasons which reflect the possibility of recharge from the surface water sources in the river drainage basin and from the storage water in the lake which increase during and after the rainy seasons.

The monitoring data regards the measurements of water levels direct after the rainy season (October) and in dry season (June) which they reflect a clear continuous water rising after the construction of the Dam which reflect the direct recharge related to the Dam Lake in which the groundwater levels in the upstream near the lake is increasing by about 10-15 meters during the last years after the construction of the dam, (Fig.7, a& b). There is no specific difference in water levels variations between wet and dry seasons that is due to the saturation of the groundwater aquifers as results of the effects of the river lake on recharge. This reflects strong influence of the dam lake on groundwater system, in which the dam was constructed on permeable sedimentary rocks at the up-stream area. For the N-S water levels profile (Fig. 8) passing from upstream to the mid and downstream areas, it is not shows significant variations except at the upstream area near the dam, hence the mid and downstream areas is dominated by less permeable sedimentary layers over the basement rocks that make the link with storage dam lake is not achievable.



a



b

Figure 7: Groundwater levels fluctuations- wet season (October-a) & dry season (June-b) in upstream area (E-W Profile)

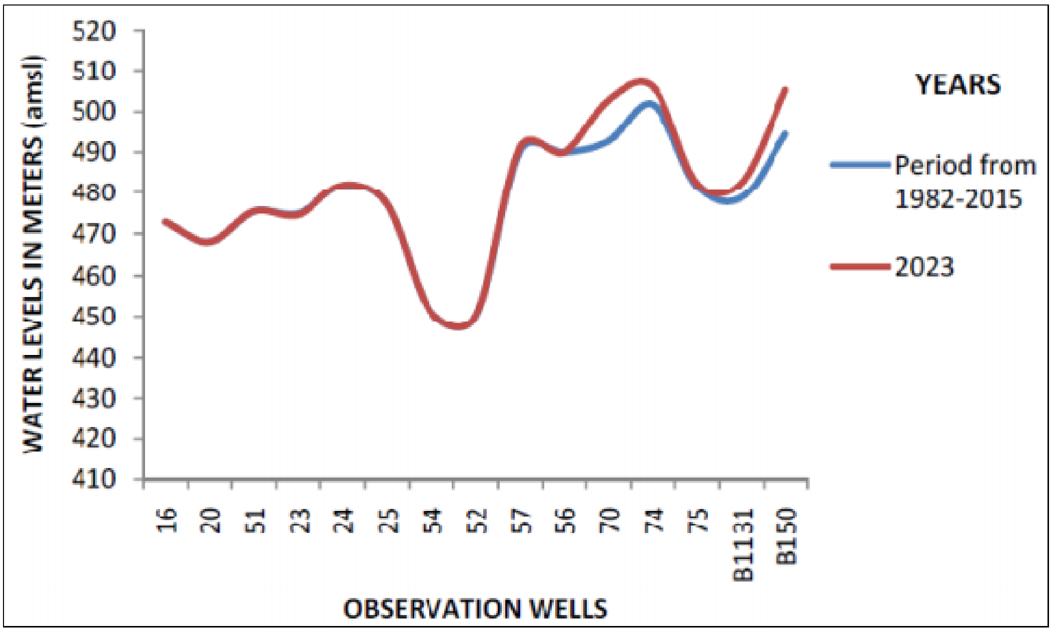


Figure 8: Groundwater levels fluctuations- wet season (October) along the study area (N-S profile)

3.2.4. The flow regime in the study area

The elevations differences between the upstream and downstream parts are controlled the flow regime in the study area. The groundwater movement defined as the flow of groundwater in response to a hydraulic gradient. Generally the hydraulic head, hydraulic conductivity and effective porosity are the controlling agent of the flow of groundwater, which is flows to the direction of the steepest hydraulic gradient, (Rogers et al., 1981).

From the generated groundwater flow map (Fig. 9), the groundwater flow direction is always in the same direction to the surface water flow of the River Atbara/Setit and their tributaries; the general flow is toward the northwest direction. The water level contour map confirmed that the River Atbara/Setit and their tributaries are the main recharge sources of the aquifer on the two sides of the rivers. The hydraulic gradient (I) is calculated as 0.005 in average through the groundwater flow regime.

The flow map (fig. 9) revealed two sedimentary depressions; the first one at the Southeastern part (Wald Elhelow basin) at the dam area which is of directs connection with the dam lake. The second one is an isolated basin from the river system at the western part (Gedaref basin). While the shallow basin flow regime are observed at the middle and northern parts of the area.

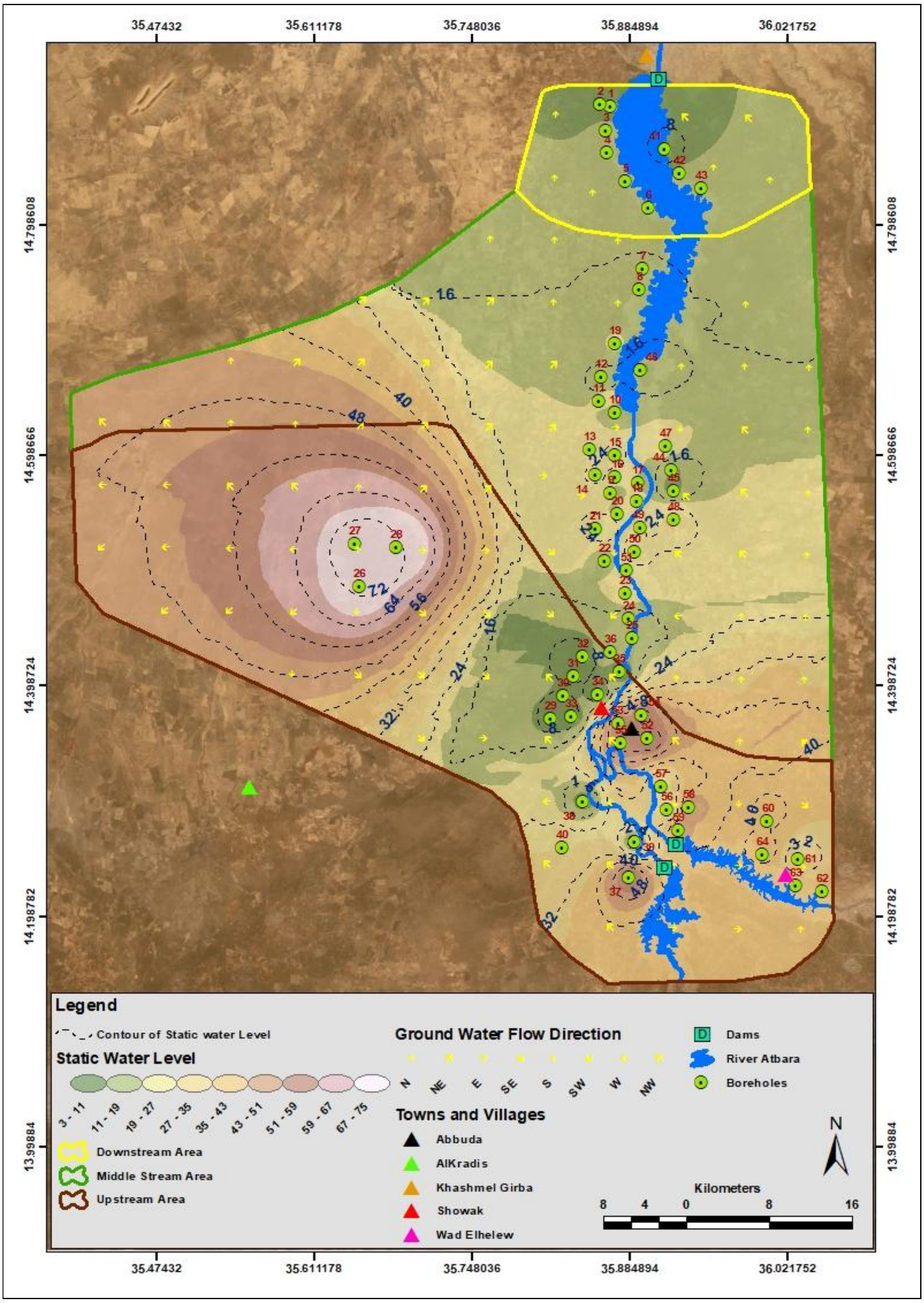


Figure 9: General groundwater flow map of the study area (Levels in meters from ground surface).

4. Conclusions

The study area is located in arid and semi-arid climatic zones; the climate is characterized by long hot summer with short cold winter with average rainfalls is of about 400mm annually during the summer period. The construction of the new dam was started in 2010 and completed in 2017, the planned total water storage capacity of the dam equal to about 3.7 Billion cubic meters.

The assessment of the effects of the newly established dam on groundwater storage is the main issue for the current investigations. The methods of the study included the collection and analysis of previous data, enhancement of remotely sensed data and field survey for to check the geological setting and for Hydrogeological elements measurements.

The main geological units in the River Atbara watershed include the old Precambrian basement complex, Jurassic to Cretaceous Sandstone, Tertiary basalt and Pleistocene to Recent alluvial sediments. Hydro-geologically the groundwater in the upstream area is closely related to the surface water in the River Atbara/Setit and storage Dam Lake. The dam is directly constructed on the permeable layer of alluvial sediments and the sandstone layers reveal direct relation with groundwater basins.

The monitoring data regards the measurements of water levels direct after the rainy season (October) and in dry season (June), reflect a clear continuous rising in water levels after the construction of the Dam which reflect the direct recharge related to the Dam Lake in which the groundwater levels in the upstream near the lake is increasing by about 10-15 meters during the last years after the construction of the dam. This reflects strong influence of the dam lake on groundwater system at the up-stream area. While at the middle and downstream areas the link between surface water storage at the Dam Lake and groundwater is insignificant due to the existence of less permeable layers.

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