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Full Length Research Paper

Structures controls on groundwater occurrence and flow in crystalline bedrocks: a case study of the El Obeid area, Western Sudan

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This study aims to evaluate geologic and structural influences on groundwater in El Obeid area as an essential resource in outcrop area, and to evaluating the structures of the site because of local field conditions within the site, such as rock type and complex structure. The geology of the area is range in age from Precambrian for the old rocks of granite, gneisses, schist and quartzite rocks, to recent age overlain by thick layers of superficial and alluvial deposits. The older rocks comprise the major hydrogeologic units of the deep groundwater system in the study area. The tectonics was important in establishing the distribution of the rocks that control the present flow patterns of groundwater. The study area is affected by tectonic that was caused faulting, folding, and fracturing. Four main types of structures that are investigated which including faults, fractures, folds and veins. These structures were influence of groundwater occurrence and flow. Two type of folds (anticline and syncline) act as accumulation and drainage channels of groundwater flow and also as aquifer in the area. The structures in the target area they are responsible for the dryness of wells in parts of the El Bangadeid, El Molbas, and Keryako hand dug wells. The relationships between surface and subsurface structural geology observed in the study of fractures in drill holes at the target area, the subsurface structures above about 100 m depth at boreholes are similar to surface structure, which have been helpful in assessing the surface structure. Surface structural geology fractures at the site consist of widely spaced, and the distribution of fractures relative to rock type at the surface; more fractures occur in brittle especially in schist rocks. The geological contacts between hydraulically different lithologies, they have virtually no primary porosity and they have secondary structures developed from the tectonic events. These include porosity, lithological boundaries, large faults, fracturing and weathering, which permits the flow and storage of groundwater. In the study area there are two main groundwater aquifers namely; Quaternary, and fractured basement. It's recharged directly from the rainfall and indirect from the basement rocks through fracture systems. Quaternary aquifer is restricted and recorded especially in the El Bangadeid, El Molbas, and Keryako hand dug wells, where the fractured basement aquifer is widely distribution.

Keywords: Basement, geological, structures, groundwater occurrence, El Obeid

INTRODUCTION

Water is the most important component of the development of any area. Human settlement depends to a large extent on the availability of water resources in close proximity to the settled localities. There has been a tremendous increase in human population in El Obeid area. Moreover, there has been a lot of industrial expansion and farming activities as livestock within the

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Figure 1. Showing the study area.

area. These factors have over water demands in the area.

The present research is important for understanding the factors influencing the distribution, flow, yield, and quality of groundwater. The study area is located in the north and east part of El Obeid town. The area ranges in elevation between 750 and 500 m above sea level. The area is bounded by latitudes 32° 25' 38" N and 32° 33' 21" N and longitudes 35° 45' 02" E and 35° 57' 20" E, which is about 340 km^2 (Figure 1).

Groundwater is simply water that occurs in the ground; in the pore spaces between mineral grains or in weathering, cracks and fractures in the rock mass. It's usually formed by rain water or snow melt water that seeps down through the soil and into the underlying rocks. Crystalline bedrocks in this paper we refer to igneous rocks as granite and metamorphic rocks, such as, gneisses, schist, and quartzite, where the intergranular pore spaces are negligible and where almost all groundwater flow takes place through weathering, cracks and fractures in the rocks. The formation of the study area was accompanied by tectonic movement as fractures, joints, faulting, folds, and veins.

Structures playing different roles in groundwater quantity and quality variations include the following: groundwater reservoirs occurring in igneous, sedimentary, and metamorphic rocks; voids between minerals and grains; and joints, fractures, and faults. The distribution and composition of rocks affect the availability and chemical constituents of groundwater. In general, a geological study should include a lithological phase covering mineral composition, grain size, sorting and packing; a stratigraphic phase describing the age, unconformities, and geometrical relationships between different lithologies; and a study of structural features. Collection of this information gives a rather clear picture of the subsurface geology, leading to a better understanding of various water bearing formation distributions.

Structures as hydrodynamic contacts impact on the groundwater flow pattern of an aquifer, as well as, the major structural features impacting on groundwater are fractures and folds. Fractures are subdivided into joints, fissures and faults, which are formed by brittle fracturing of rocks (Roberts, 1982). Folds are produced by ductile deformation, and the extent of this deformation reflects on the magnitude of the features formed i.e. synclines and anticlines. Fractures are not homogeneously distributed in the rock mass, and because the permeability of the fracture system is very sensitive to the fracture aperture and degree of fracture connectivity, it is very difficult to predict the yield of a well or borehole in crystalline bedrocks (David and Nick, 2002).

Aims and Objectives

Many geological type outcrops were visited to verify descriptions of lithological units and to assessment of joints, fractures, folds, and views different types of large faults. These structures are great influence on

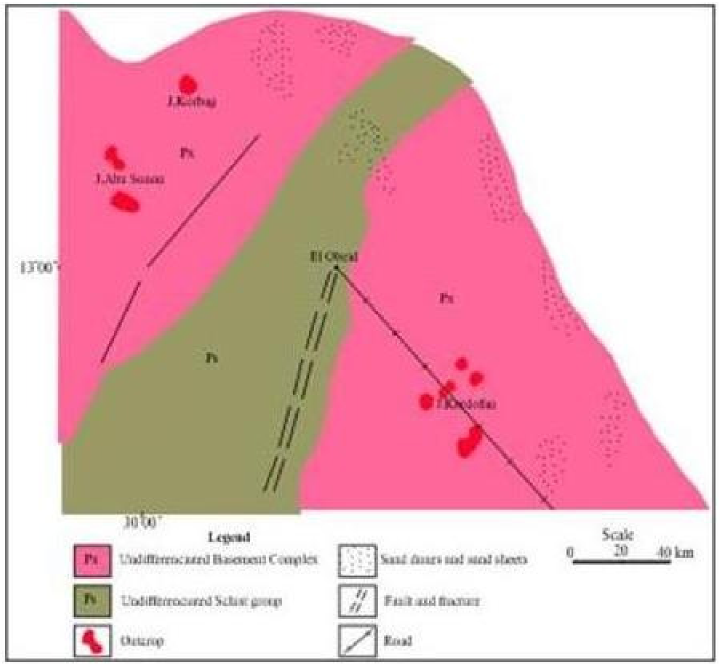

Figure 2. Geological map of the study area.

groundwater flow patterns in the aquifer of the study area.

The main objective is to create a clearer picture of flow in the aquifer. An improved understanding of structures, and how they affect flow at all levels of the aquifer, will be achieved. The main objectives of this study are:

- The identification, description and evaluation of structures.
- The interpretation of structures and their impact on groundwater flow.
- The relationships between structures and groundwater.

The outcome hoped for is a better understanding of the complexities of the geology and the effects it has on hydrogeological conditions by integrating all the data available into useful concepts of groundwater occurrence and flow.

Geological setting

In the study area the crystalline basement is exposed extensively in the mountains of the north and east of El Obeid area; there are outcrops of rocks belonging to the crystalline basement complex, which are composed of granites, gneisses, mica schists, and quartzites. The ages of these rocks in most localities are assigned to the Precambrian period. However, in many localities intrusive rocks are recorded, the rocks of the basement complex are gradually overlain by a series of mostly unfossiliferous formations composed of unconsolidated material of sands, and clays which are commonly termed the Superficial deposits or alluvial in recent age. Its vary in thickness from some few of meters in the southern regions to about tens of meters in the northern localities.

Detailed geological studied for rock samples and their field relationships representing these complexes were carried out to be compared and correlated with those complexes surrounding the study area.

The Basement complex in the study area is affected by tectonic activities, which resulted into widely distributed joints, faults, foliations and folds, which including meta-sedimentary rocks. The gneisses have a general foliation trend of east to west with a dip angle varying towards the northeast. In most localities, the gneisses are highly weathered. In hand, specimens the gneiss rocks are compact, fine to coarse grained, grayish brown to light in colour. The essential mineral consists of biotite, orthoclase and quartz. Previous of the mention minerals the garnet and tourmaline minerals also are present throughout the gneiss rocks of regional metamorphism, it's found to the estern part of J. Kordofan (Figure 2). The mica schist rocks in the eastern part of J.Kordofan, which had been refolded strongly in some places and symmetrical alternate (chevron) folds anticline and syncline pairs, which representing elastic deformation and brittle deformation also deduced in hand specimens essential mineral mica, and quartz. The quartzite rocks were cropped out in J.Abu Khureis, north of El Obeid, beside J.Ed Dago, Hemdela, and J.Abu Urog east of El Obeid (Figure 2). This quartzite composed essentially of quartz mineral in fine to medium grained in texture.

Table 1. Stratigraphic column for the area.

Group	Formation	Thickness (m)	Age
El Obeid	Basement complex	50	Recent to Pre-Cambrian
Tagat	Basement complex	60	Recent to Pre-Cambrian
J.Kordofan	Basement complex	35	Pre-Cambrian
J.Korbag	Basement complex	40	Pre-Cambrian

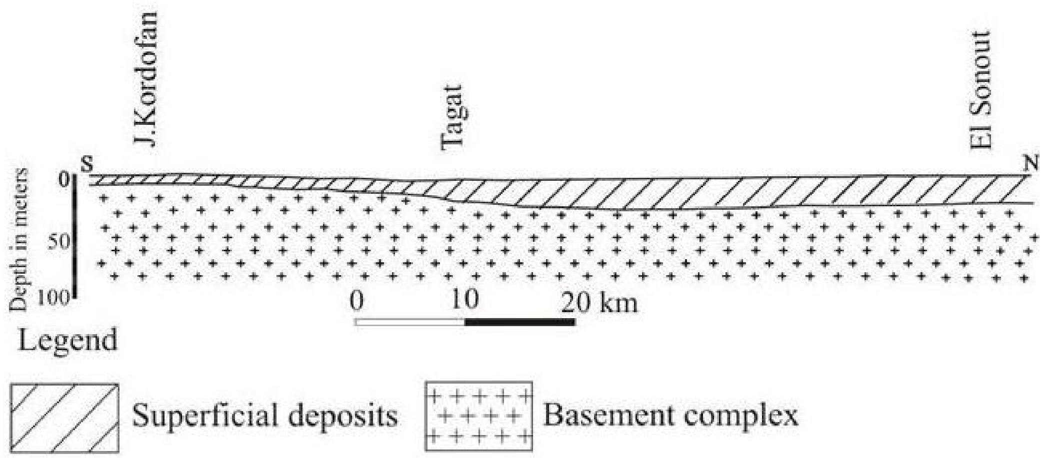

Figure 3. Lithological logs cross section along study area (modified after Elhag, 2009).

Stratigraphy

A detailed lithological description of the El Obeid stratigraphy was compiled by using outcrop data and extrapolations. Broad groupings showing the constituent units are shown in (Table 1). The cross section showing the geology of the area consist of the superficial deposits and alluvial for the overlying Basement Complex (Figure 3).

Structures evidence

The study of structures and their role in flow control has shown the importance of understanding the fundamental geological features of an area. The nature of the stratigraphic units and the composition of the lithological units, act as structural controls to flow. Structures in the study area show strong influence on the topography and also on the surface drainage patterns. There is evidence that the same applies to groundwater flow at the local level and is probably also the case for deep flow. The lines of evidence will be led in support of this assumption using a range of data.

The morphology of structural or residual hills is controlled by large-scale rock structures and lithology. Since the rocks in this unit are hard and compact, they act as run-off zones; limited infiltration can take place along the weak planes like joints faults, fractures, folds, dykes and veins. (Singhal, B.B. and Gupta, R.P. 1999) divided the residual hills into upper to lower as inselberg, pediment, buried pediment, valley fill respectively.

Discontinuity is a collective term used here to include joints, fractures, folds, veins, mineral cleavage, foliation, shear zones, faults and other contacts etc. In this discussion using a genetic approach, we group discontinuities into the following categories:

1- Foliation.
2- Fractures (joints).
3- Faults and shear zones.
4- Other geological discontinuities.

Structures can be defined for purposes of this study as two dimensional features that affect flow rates by reducing hydraulic conductivity across them or increasing it several folds, acting as barriers or conduits to flow. There are three main hydrogeologically significant structures in the study area that were considered. These can be classed as follows:

- Contacts (geological).
- Primary structures (bedding).
- Secondary structures (tectonic, fractures and folds).

Secondary structures are those resulting from the events producing the major folds, shear zones, fractures, veins and the large faults (Figure 4). These features are observed throughout the J. Kordofan area and thus have the greatest effect on flow. The different responses to deformation and the intensity of this deformation caused differing levels of fracturing of the brittle rock. The type

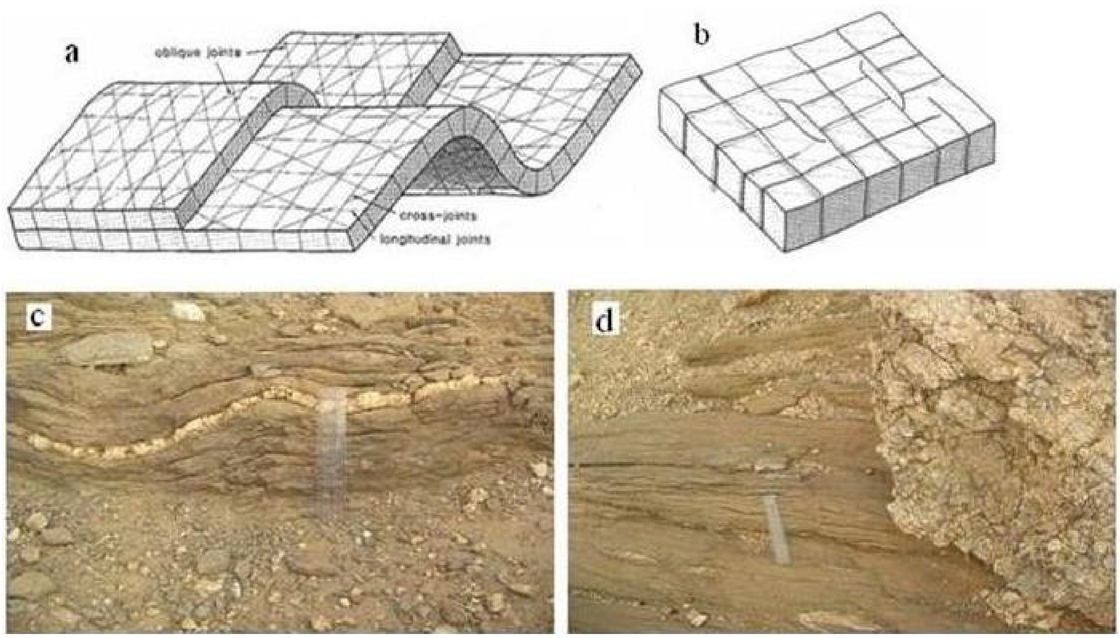

Figure (4 a, b, c, d). Field photograph showing Joint sets in fractured rocks (a, b). Examples of joint patterns in folded, showing strong bedding joints, from (Robers, 1982), (c) and (d) showing bed, long and cross joints at J Kordofan.

Figure 5. Faults benefit for groundwater recharge and wetland of Khor Tagat.

and intensity of fractures then imparted secondary permeability in the form of joints along beds and transverse to folds (Nakhwa, R.A., 2005). Joints occur as well-defined sets along the bedding planes at right angles to the bedding (longitudinal), cross-joints are normal to these, and oblique-joints cut at acute angles to the cross-joints (Figure 4.a,b). The longitudinal and cross-joints are formed by extension fractures, but near fold hinges longitudinal joints may form conjugate shear fractures (Roberts, 1982). High intensities of joints lead to increased permeability and connectivity, whilst bedding planes allow for preferential flow. From field evidence it appears that the bedding joints are the dominant master joints in the folded J. Kordofan (Figure 4.c, d).

The different structures influenced, and control on flow, by acting as low permeability zones (barriers) or high permeability zones (conduits). For example the fault is open or closed, the logic is that if the fault acts as a conduit it will direct flow in the path of the fault, and if it is closed or weakly permeable the flow will be along or parallel the side of the fault. In general, an open fracture will increase permeability. If flow is along faults then it would be observed in the north direction either side of the Khor Tagat, which assumes recharge from the J.Kordofan south along the faults to the north (Figure 5).

Generally the different structures in the study area

Figure 6. Slickensides on faults at eastern of J. Kordofan.

were discussed separately as follows:

Faults analysis

Faults act as conduit can make rocks excellent aquifers. On the other hand faults act as drains, lowering water table and thus affecting the distribution of groundwater (Mulwa et al., 2005). Further, faults act as barriers to the flow of groundwater if filled with impermeable material such as silts and clays. These factors have a strong influence on the aquifer yields through boreholes, static water levels, flow, and hence distribution of groundwater. Therefore the amount of water available in a faulted region would be influenced. Generally a comprehensive understanding of the influence of structures on groundwater is necessary for the selection of drill sites of productive boreholes in this area and in other areas of similar geological setting.

In the study area a number of different types of faults were identified in the field. One of these minor faults showing a localized thin shear zone is exposed at J. El Dago and J. Kordofan, the long and wide of shear zone are approximately thousands to tens meters respectively. This is high permeability in the shear zone. There would be both vertical and horizontal components of flow in this shear zone, and there are indications of possible conduit flow in this site.

There are numerous seasonal streams in the study area. Its are important as they indicate the recharge areas of the flow system. Most streams are lithologically controlled with issue points at contacts with the basement rocks. The position of the streams indicates lithological structure control on local flow, and there are a few others that seem to follow large fault traces. In the target area some parts from the wetlands found in the Khor Tagat, which is supporting the groundwater recharge. The pictures are of the same views looking north down the valley of the Khor Tagat and other Khors along the intersection of faults there is a small wetland, and there are remarkable faults in several localities; it is detected due to the valleys in the south against the Khor Tagat in the north direction (Figure 5). These examples are used to illustrate the possibility of fault flow feeding the formation or alternatively fault barriers creating elevated water levels which could then feed seeps at the surface. These may be cases to support the flow proposed for the study area but further work is still needed to substantiate the evidence.

The slickensides on faults planes indicate the direction of most recent fault movement. There are many groups of consistently oriented slickensides and occur on nearly sub-horizontal to sub-vertical direction at J. Kordofan, which is presence of re-crystallization process of quartz mineral (Figure 6).

Fractures and joints analysis

The relationship between the occurrence of groundwater and fracture traces for aquifers, particularly in lineaments underlain by zones of localized weathering, increased permeability, and porosity. The fracture morphology can be important factor of fracture porosity and permeability is the morphology of the fracture planes. This morphology consists of three basic types of natural fracture plane morphology as follows:-

1- Open fractures.
2- Mineral-filling fractures.
3- Deformed fractures (Slickenside fractures).

The structures within the study area are the extensively developed joint systems. These have been recognized for their importance in groundwater flow. Probably of greatest importance is the role of the joints, making up the predominant bedding planes and sets of interconnected joints. These have been shown to be distributing throughout the study area, and their cumulative effect on flow is considerable. Fractures in

Figure 7. Open and slickenside fractures in outcrop which is incompletely mineralized fracture in schist rocks.

Figure 8. Complex of chevron folds in Schist is asymmetrical including anticline and syncline pairs.

rocks may affect groundwater recharge, movement and particular importance as barriers or conduits for flow of groundwater. In this regard, both surface and subsurface fractures at the location can be characterized in two classes: open or closed. Open fractures can be simple apertures or permeable zones, some of which contain open cavities (Figure 7). Closed fractures can consist of simple fractures with hairline apertures or wider apertures sealed by secondary mineralization. In the study area the core and log analysis of the dug well has been used successfully to delineate fracture occurrence and distribution in the wellbore.

Folds analysis

Fold structures are important in their flow control on a large scale, which are restricting flow. For example the flow system separated was observed from the some parts of J. kordofan, where the folds become an impermeable boundary on all sides of the asymmetrical including anticline and syncline pairs except the weathered folds, as well as, the flow along the strike of the folds is also very significant (Figure 8).

In the study area Folds obvious in the northeastern parts of the J. Kordofan. The fold axes are of two trends; the first is NE-SW, and the other is ENE-WSW. Generally, they are plunging to the west, and the trend is formed due to compression. The structure of the cover rocks in the area within the eastern part of J. Kordofan domain are dominated by open synclines and parallel minor folds which may show steep dips in places. The main fold structures of the study area running from south to north consist of the syncline and Anticline pairs (Figure 8). The dip angles (Table 2) for the fold limbs (anticline and syncline) range from 7° to 50°, and are an important

Table 2. Show dip angles of the folds limbs at J.Kordofan.

Location	Dip of anticline	Dip of syncline
North	15 - 35°	8 - 50°
South	10 - 50°	7 - 40°

Figure 9. Weathered quartzite vein observed at J. Abu Gour.

control on the gradient of flow of groundwater within the aquifers, and especially for deep flow.

Veins analysis

The role of the intrusive rocks is little known not least because of their concealed position. Based on inferred width and depth, their role in flow control depends on their characteristics. Vein intrusions are looked at as hydraulic boundaries, contributing to compartment of the aquifers and creating specific site flow conditions. The veins not appearing else where is explained by the thick sequence of rocks forming an impenetrable barrier, causing the placed of the veins below surface. The veins may be linked by the same tectonic events which would explain similarities between fault orientations and fold directions (Nakhwa, R. A., 2005). Intrusive rocks occur in the study area and consist of quartzite veins. Here quartz veins were exposed at the J. Kordofan and there is a weathering. Quartzite veins observed in J. Abu Gour range on the surface from northwest to southeast direction, and their width measure several meters and about 20 kilometers in length (Figure 9).

The weathered veins have a higher permeability and conductivity than the country rock (Figure 9), but the compacted veins may be the opposite. However, the presence of highly fractured contact zones either side of the veins could provide preferred flow channels that may have higher permeability than the country rock.

Tectonic setting

In October 1966, Kordofan States were shaken by strong earthquakes recorded in J. Damber and El Dayer that have great attention to hydrology due to the formation of fractured zones among the rock of the Basement Complex and sedimentary basin. The geological structures are usually observed in limited and widely separated outcrops. Otherwise, the highly weathered schist and gneisses rocks reflected to tectonic events which would explain similarities between fault orientation and veins directions.

Tectonic movements usually generate sub-vertical fractures associated with folding which facilitate groundwater circulation and storage in Precambrian rocks. Brittle deformation has a positive effect on transmissivity and cataclastic deformation has a negative effect (Tamiru, A., 2006). The deformed metamorphic and intrusive rocks develop typical fractures called as type fractures (Figure 7). The jointing of as type is often shown prominently in areal photographs as well developed pattern of parallel lines, which are perpendicular to the fold axis or an intrusive flow structure, therefore local variations often occur in their direction. This type of tectonites is generally a poor aquifer because of weak interconnection between the joints. The main problem for the hydrogeologist undertaking groundwater exploration in basement areas is to find a fracture pattern with maximum storage capacity. It is well known that biotite schist, which constitute the internal bodies of the Lower complex

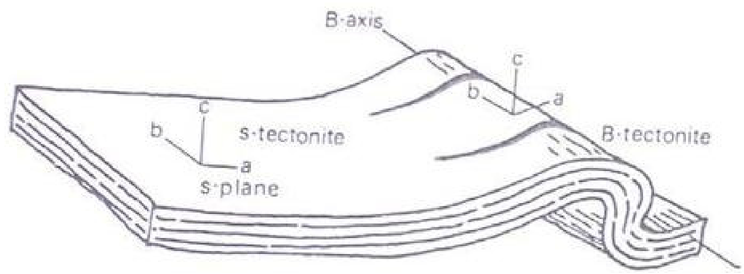

Figure 10. S and B tectonites in deformed rocks (after Larson, 1972).

frequently, form synclinal and anticlinal structures characterized by evident schistosity planes. These fold structures seem to be old relics of S-tectonites formed by compressive stresses along the deformation plane (a-b plane), cut by a wide pattern of tensile, and shear fractures. Tensile fractures generally have high storage capacity and they collect water from small fractures (Larson, 1972) (Figure 10).

Hydrogeology

Groundwater is the main source of water supplies in the study area. The occurrences, distributions, and quality of groundwater aquifers controlling by different factors such as structures, geomorphology, climate changes, type of rocks and minerals. In the study area there are two major aquifer systems presented in Khor Tagat alluvial aquifer, and the much larger secondary fractured rock aquifer of the area as follows:

Quaternary aquifer

In the study area quaternary aquifer fill the valleys and Wadis, and is composed mostly of sand, clayey sand, and alluvial that overlain weathered and fractured basement rocks respectively, although the composition of the quaternary aquifer makes them more permeable than under-lying rocks, but it's limited in extent. The aquifer recharged directly from rainfall and through structures systems. Most wells in quaternary aquifer presence in the study area are shallow wells with limited production reaching about 500 g/h. The hand dug wells tapping the deposits of quaternary aquifer namely; El Bangadeid, El Molbas wells in southern site of El Obeid town, and Keryako wells in western site of El Obeid market. In October 1966 and 1973, Kordofan State was shaken by strong earthquakes that have great attention to hydrology due to a few of groundwater wells in the aquifer are dry.

The alluvial aquifer covers an area of approximately 100 km^2 in the study area. It varies in width from 1 km to 5 km and has a variable thickness from a few meters to tens meters. Water levels are generally more than 20 m below surface. The aquifer supplies water for a few agricultural and domestic uses, with yields varying from 8-10 g/min. The main villages are totally dependant on this source and the proximity of the aquifers means continued exploitation as demand increases.

Fractured basement aquifer

Fractured basement rocks belonging to precambrian time are outcropped in the many sites, and composed of igneous and metamorphic rocks that are mentioned before. It's characterized by high density of fractures beside the permeability of aquifer is of secondary type that is formed due to the effect of regional and local structural events. Rainfall is the main source of aquifer recharge and other fracture systems, where the quantities of rainfall affect the rate of recharge of groundwater. In the study area numbers of wells restricted at El Obeid area were dry due to the lack of recharge (precipitation) and the presence of structures that act as barrier preventing the groundwater movement.

In hard rock areas, weathered and fractured zones form aquifers. Even in a small area, the nature and extent of weathering vary a lot and depend mostly on the present of fractures at depth and favourable morphological features at the surface. In fresh rocks, joints and fissures tend to close at a depth of about 70 meters and there will be practically no circulation of groundwater below this level. Pockets of weathered and fractured rocks may form isolated groundwater reservoirs (Verma R.K., et al, 1980). Fracturing and folding result in a high degree of inhomogeneity in the hydrogeological characteristics of different aquifers. This inhomogeneous character causes aquifer yields and groundwater flow direction to vary over a whole area (Mulwa et al., 2005).

The secondary weathered and fractures aquifer extends across the whole study area. It has variable thicknesses ranges from the 20 to 40 m. The lithological units compose the aquifers and aquitards. The basement aquitard is the clay formation forms the aquitard between the lower aquifer (weathering and fractures) and upper aquifer (quaternary).

Groundwater occurrence and flow

Hydrogeology of igneous and metamorphic rocks has become very important because hard rock terrain covers good part of the North Kordofan State. With the growing demand of water, groundwater exploitation in this terrain has become inevitable. More boreholes over these rocks being vats (dry) in arid and semi arid areas, their importance has become significant for development.

Structures in the study area show strong influence on the topography and also on the surface drainage patterns. There is an established north and south trend to these features as there are for the faults. There is evidence that the same applies to groundwater flow at the local level and is probably also the case for deep flow. The lines of evidence will be led in support of this assumption using a range of data (Figure 5). Mainly based on field evidence the indications of what the characteristics of structures are and the confidence of the assumptions are presented.

RESULTS AND DISCUSSION

To understand the geological and structural influence on groundwater due to combination of lithology, and tectonics is under-scored by the difficulties in interpreting its dynamics. A good understanding of its various components and their interrelationships were achieved by the integration in this study of geology, structure, topography, and hydrogeology.

The study identified the different types of structures, namely geological contacts, fold systems, faults and joints. It provided detailed descriptions of these features from field investigation, and went further to evaluate the effects and controls they have on groundwater flow in the study area.

CONCLUSIONS

The groundwater potential in the area is generally acceptable since the mean yield of all aquifers is about 500 g/h. Aquifers on fault zones have the highest water yield; and are very deep as depicted by the depths of boreholes tapping water from such aquifers. The depths of these boreholes signify that faults have drained groundwater to deeper levels. Generally, hard rock and dense compact rock units underlying aquifers often act as controls to the downward migration of groundwater. In the study area contributed to migration of groundwater to deeper levels, especially along the joints and faults. The faults in the area are excellent aquifers and excellent conduits to the flow of groundwater.

The recharge zone is due to an immediate by joints and faults or rainwater infiltrating into the subsurface. Aquifers with high water yield are located on the up thrown side on the faults system. The discharge region is located on the downthrown block of the main faults. The water yield from these aquifers is less than 2000 g/h and has an average of 500 g/h. The excessively high yield from aquifers tapped through boreholes is due to the influence of the numerous faults in this region. The structures as faults and folds act as barriers or semi-barriers to the groundwater flow, while joints trending facilitate the groundwater flow.

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