Journal of Spatial Hydrology
Vol.4, No.2 Fall 2004

Hydrogeology of the Northern Gezira Area, Central Sudan

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Abstract: The aim of this study was to determine the hydraulic properties of the aquifers, evaluate the chemical characteristics of groundwater, and construct a water level and hyrochemical maps. Jacob's, and Theis's recovery methods were used to calculate the aquifer hydraulic properties. The chemical analyses of major constituents with aid of surfer software and Piper's diagram were used in evaluation of groundwater chemistry and construction of hydrochemical maps. The transmissivity and hydraulic conductivity of Gezira and Cretaceous sedimentary aquifers were calculated. Based on field and laboratory observations it was found that the groundwater in lower Gezira and Cretaceous sedimentary aquifers is suitable for domestic use whereas that of upper Gezira aquifer is extremely saline and considered to have been polluted by local lithological units. The hydrochemical composition of the groundwater in Gezira aquifers is $NaHCO_3$, Ca $(HCO_3)_2$, Ca SO_3, CaCl and $NaSO_4$ water types of alkaline character. The Cretaceous sedimentary aquifer is characterized by $NaHCO_3$, and NaCl water types.

Key words: aquifer, transmissivity, hydraulic conductivity, chemical analyses, hydrochemical composition.

Introduction:

Understanding the aquifer hydraulic properties and hydrochemical characteristics of water is crucial for groundwater planning and management in the study area. Generally, the motion of groundwater along its flow paths below the ground surface increases the concentration of the chemical species (Freeze & Cherry, 1979). Hence, the groundwater chemistry could reveal important information on the geological history of the aquifers and the suitability of groundwater for domestic, industrial and agricultural purposes. Moreover, pumping tests with the drilling results, are the most important information available for the groundwater investigations, as they are the only methods that provide information on the hydraulic behavior of wells and reservoir boundaries. The situation at the northern part of Gezira State represents a case study to evaluate the hydrogeologic and hydrochemical characteristics of the subsurface water, which should be abstracted from the aquifers on a sustainable basis, for dramatic increase of population and intensive agricultural and industrial development. The study area is located in the northern part of Gezira State, between latitudes 14^{o}: 40′ - 15^{o}: 25′N and longitudes 32^{o}: 20′ - 33^{o}: 18′ E (Figure 1). It is part of the Blue Nile Basin, covers an area of approximately 5800 Km^2. A feasible option might be to abstract more potable groundwater from Gezira and Cretaceous sedimentary aquifers to meet the drastic increase of water demand at the study area. Confined aquifers are the main characteristic of the groundwater system in the study area. The transmissivity (T) and hydraulic conductivity (K), can be determined by several pumping test methods summarized in Kruseman, and De Ridder (1990). Among them, Jacob method and Theis's recovery method are the most convenient methods for the available field data from the pumping test of the full penetrating wells of the study area to calculate the aquifer hydraulic characteristics. The chemical analyses of most common major constituents, with the aid of the Surfer software and Piper's diagram, were used to assess the general hydrochemical characteristics of groundwater and to evaluate its suitability for domestic purposes .

Geomorphology, Geology, and hydrogeology:

The study area is generally a flat plain covered by clays where the surface elevation ranges from 380 to 400 m above sea level (a.s.l). Seasonal basins are developed within the area by eolian and fluvial processes. The area is semi-arid (Saeed 1976, El Boushi& Abdel Salam 1982), characterized by hot dry summer (April-October) and cold dry winter (November-March). The mean annual rainfall varies from 310mm in the southern part, to 175mm in the most northern peripheries, mainly during August to October (Magboul, 1992).

The geologic setting is composed of Pre-Cambrian Basement complex, Cretaceous sedimentary rocks and Quaternary Gezira formations. Basement complex consists of highly weathered grey gneisses and reddish granites. Cretaceous sedimentary rocks, which are unconformably overlying the Basement complex (Wycisks et. al., 1990, see Figure 2a) are: sandstone (calcareous, ferruginous and siliceous), mudstone, shale, and basal conglomerate (Omer, 1983). With few exceptions, the Cretaceous sedimentary formation is either covered by Gezira formation or Recent superficial deposits (Magboul, 1992, see Figure 2b). This formation has a thickness of more than 400 m at the center of the area (Omer, 1983). Quaternary Gezira formation, is composed of unconsolidated gravel, sand, silt and clay and representing the upper most part of the geologic succession. Calcrete, basalt, evaporite deposits and salt rock patches are the characteristics features of the Gezira formation (William & Adamson, 1982; Salama, 1987).

Gezira and Cretaceous sedimentary formations encompass the main aquifer system in the study area. Groundwater occurs under confined conditions(Figure 2a&2b). The aquifers are partially hydraulically interconnected (El Boushi& Abdel Salam 1982, Magboul 1992). The main sources of recharge to the groundwater basin are the White Nile, Blue Nile, seasonal streams, direct rainfall and the irrigation return flows.The depth to groundwater level varies from few meters near the White and Blue Nile, to more than 55 m in the central part of the area. The saturated thickness varies from 5 to 80 m in Gezira aquifers and from 15 to 150 m in Cretaceous sedimentary aquifer.

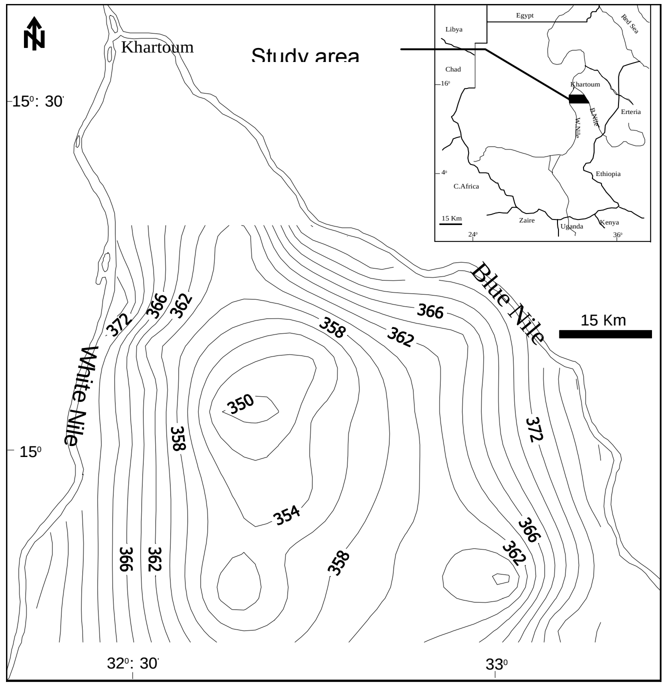

Figure 1: Piezometric surface contour map(in m. a.s.l.) of the Study Area

Methodology:

The hydraulic properties of Gezira and Cretaceous sedimentary aquifers were determined using pumping tests data. The time-drawdown data curves were plotted with respect to Jacob's, and Theis's recovery methods to calculate the aquifer hydraulic parameters (see Kruseman and De Ridder, 1990; Chae, 2000). Water heads in meters above sea level (a.s.l.); in each well that taps concurrently, Gezira and Cretaceous sedimentary aquifers were used to construct the piezometric surface contour map using the surfer software. MapInfo software was used to construct the lithologic cross-sections based on the well lithologic logs. Fifty-five samples from shallow wells and deep boreholes at depths ranges from 15 to 55 m below ground level were collected for hydrochemistry (Figure 3). They were analyzed for the major ion chemistry. Parameters such as electric conductivity (EC) and hydrogen ion concentration (pH) were measured immediately at the field site, using portable Orion EC- and pH-meter. Further analyses for major ions were performed in the Non-Nile Sudan Water Research Central Laboratories: total dissolved solids (TDS) were measured by sample evaporation techniques. Bicarbonate (HCO^-_3) and total alkalinity (T Alk.) were estimated by titration with HCl. Total hardness (TH) was analyzed titrimetrically. Sodium (Na^+) was analyzed by flame photometry. Chloride (Cl^-) was estimated by titration with $AgNO_3$. Piper's diagram was used to distinguish the groundwater types. The analytical precision for the measurements of cations-anions is indicated by ionic balance error, which is observed to be within the stipulated limit of ± 5%. All values were in milligram per liter (mg\l) or percent milliequavelt per liter (% meq/l) unless otherwise indicated.

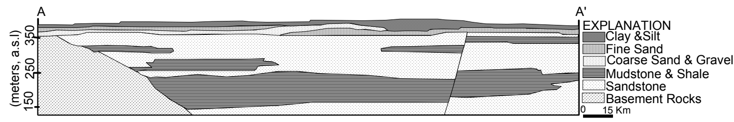

Figure 2a. Lithological cross-section

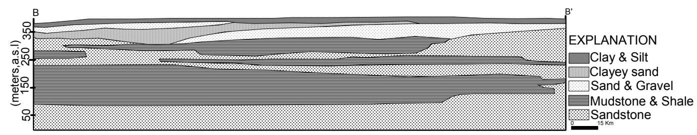

Figure 1b. Lithological cross-section

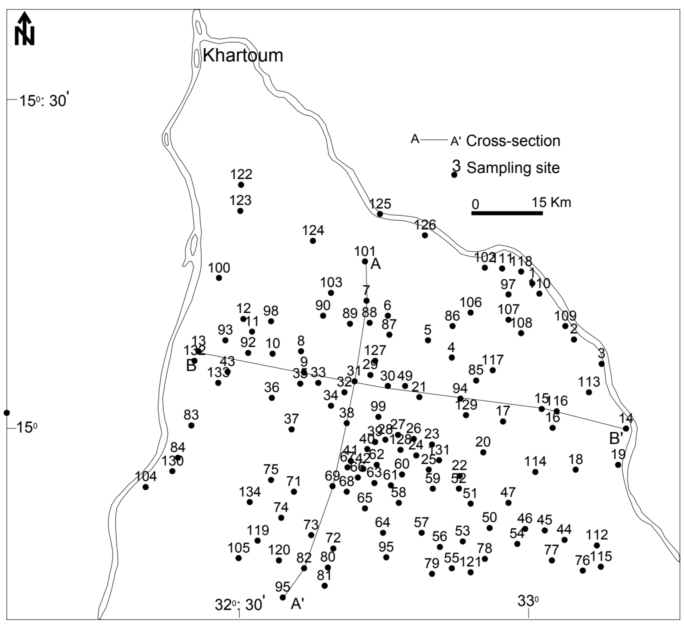

Figure 3. Sampling sites and cross-section trends

Table 1: Transmissivity and Hydraulic conductivity of Gezira aquifer

Type of Methods	Transmissivity (m^2/d)			Hydraulic Conductivity (m/d)		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean
Jacob's Method	28	824	368.7	0.411	91.55	34.03
Theis's Recovery Method	66.5	643.2	355.2	0.977	71.47	26.56

Table 2: Transmissivity and Hydraulic conductivity of Cretaceous sedimentary aquifer

Type of Methods	Transmissivity (m^2/d)			Hydraulic Conductivity (m/d)		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean
Jacob's Method	20.7	1098.7	291	0.155	156.96	41.98
Theis's Recovery Method	4.1	1129.8	407.2	0.031	161.4	43.17

Results and discussion:

1 Groundwater Dynamics:

1.1 Transmissivity:

The transmissivity concept can be used for all types of aquifers depending on the saturated thickness (Batu, 1998). According to aforementioned applied methods, the maximum, minimum and mean values of transmissivity in Gezira and Cretaceous sedimentary aquifers were recorded in table 1and 2 respectively. The wide range of the transmissivity values in Gezira aquifer are ascribed to the intercalation of fine sand and clay content of the Gezira formation whereas those of the Cretaceous sedimentary were attributed to mudstone and shale layers of the Cretaceous sedimentary formation. Hence the mean values of transmissivity of Gezira and Cretaceous sedimentary aquifers were found to be 368.7 and 407.2 m^2/d respectively.

1.2 Hydraulic Conductivity:

The hydraulic conductivity of the Gezira and the Cretaceous sedimentary aquifers were computed from the transmissivity values and the corresponding saturated thickness of aquifers at different sites according to the following equation:

$$K = \frac{T}{b}$$

where b is the aquifer-saturated thickness in meters. As a result, the hydraulic conductivity of Gezira and Cretaceous sedimentary aquifers were found to be 34.03 and 43.17 m/d respectively. Hence, the hydraulic conductivity of Gezira aquifer is comparatively lower than that of the Cretaceous sedimentary aquifer see table 1&2.

1.3 Piezometric surface contour map:

As a part of the hydrologic cycle, groundwater is always in motion from regions of natural and artificial replenishment to those of natural and artificial discharge (Bear, 1979). One of the main imperative approaches for the identification of groundwater flow directions is the water level contour map, which has been used as a basis for evaluating groundwater recharge. Hence, water level contour map of the study area was constructed, using surfer software, based on water heads in meters above sea level (a.s.l.); in each well that taps concurrently Gezira and Cretaceous sedimentary aquifers. It is obvious that, contour lines are more or less parallel to the Blue and White Nile rivers where groundwater levels decrease gradually towards the center of the basin (< 350 m a.s.l.), forming assign of cone of depression (Figure 1). The Hydraulic gradient is approximately 0.001 from the Blue Nile westwards, and 0.0007 from the White Nile eastwards. These phenomena confirmed that, Blue Nile and White Nile are the main sources of recharge to the aquifer systems.

2. Groundwater Quality:

The hydrochemical characteristics of groundwater in the study area were summarized as statistical overview in table 3.

Table 3: Statistical overview of Hydrochemical properties in Gezira and Cretaceous sedimentary aquifers (Data in mg\l unless otherwise indicated)

Parameter	Upper Gezira			Lower Gezira			Cretaceous sedimentary		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean
pH	8.1	8.5	8.3	7.8	8.6	8.1	7.5	8.3	7.9
EC(µS/cm)	500	4300	2398	390	3000	803	250	1060	463
Na^+	92	1100	479	30	560	147	10	230	75
Cl^-	31.9	1139.4	324	10	660	126	5	350	63
HCO^-_3	268.4	671	458	146	580	385	122	354	238
TDS	450	4100	1610	240	2810	638	200	680	347
TH	100	420	259	90	400	250	30	250	122
T.Alk.	268.4	725	490	160	230	183	100	290	137

2.1 Physicochemical characteristics:

The chemical composition of the groundwater varies over a wide range (Table 3) and this indicates that the groundwater in the study area is not uniform but differ considerably, both in salinity and ionic composition due to dissolution, precipitation, evaporation and cation exchange processes which are actively taking place within the groundwater system. Specifically, the pH values of groundwater in Gezira and Cretaceous sedimentary aquifers are more or less similar and vary within small ranges (Table 3). This elaborates a fresh and a slight trend of alkaline chemical reaction within the groundwater environment (Fetter, 1999). Electric conductivity (EC) elucidates the decreasing of salinity from upper Gezira, through lower Gezira down to the Cretaceous sedimentary aquifer and indicates the existing of fresh, marginal, and brackish water types (Table 3). Furthermore, the total alkalinity and hardness concentrations indicate the downwards decreasing of constituents responsible for alkalinity and hardness through the aquifer zones (Table 3). According to the classifications of Towert and others (1987), the water from the Cretaceous sedimentary aquifer ranges from moderately soft to hard, whereas that of the Gezira aquifers ranges from moderately soft to very hard, due to the presence of calcretes and evaporite deposits in Gezira formation.

2.2 Spatial distribution of hydrochemical species:

2.2.1 Total Dissolved Solids (TDS):

The total dissolved solids (TDS) enlighten downwards decreasing of salinity within the aquifer zones (Table 3) concordant with electric conductivity. The spatial distribution of TDS in Gezira aquifers elaborate an irregular north-south trending trough of salinity, east of White Nile and isolated pocket in the northeast part close to the Blue Nile (Figure 4a). The salinity is ascribed to the presence of evaporite deposits in the Gezira formation, low hydraulic gradient (0.001) and increasing distance from the recharge sources as well as high evaporation and evapotranspiration rates in this semi-arid area. Furthermore, Cretaceous sedimentary aquifer is characterized by low salinity, although concentration of more than 500 mg/l located in form of north-south trending trough east of the White Nile (Figure 5a). This is endorsed to vertical seepage from the overlying Gezira aquifer zones elaborating partially hydraulic

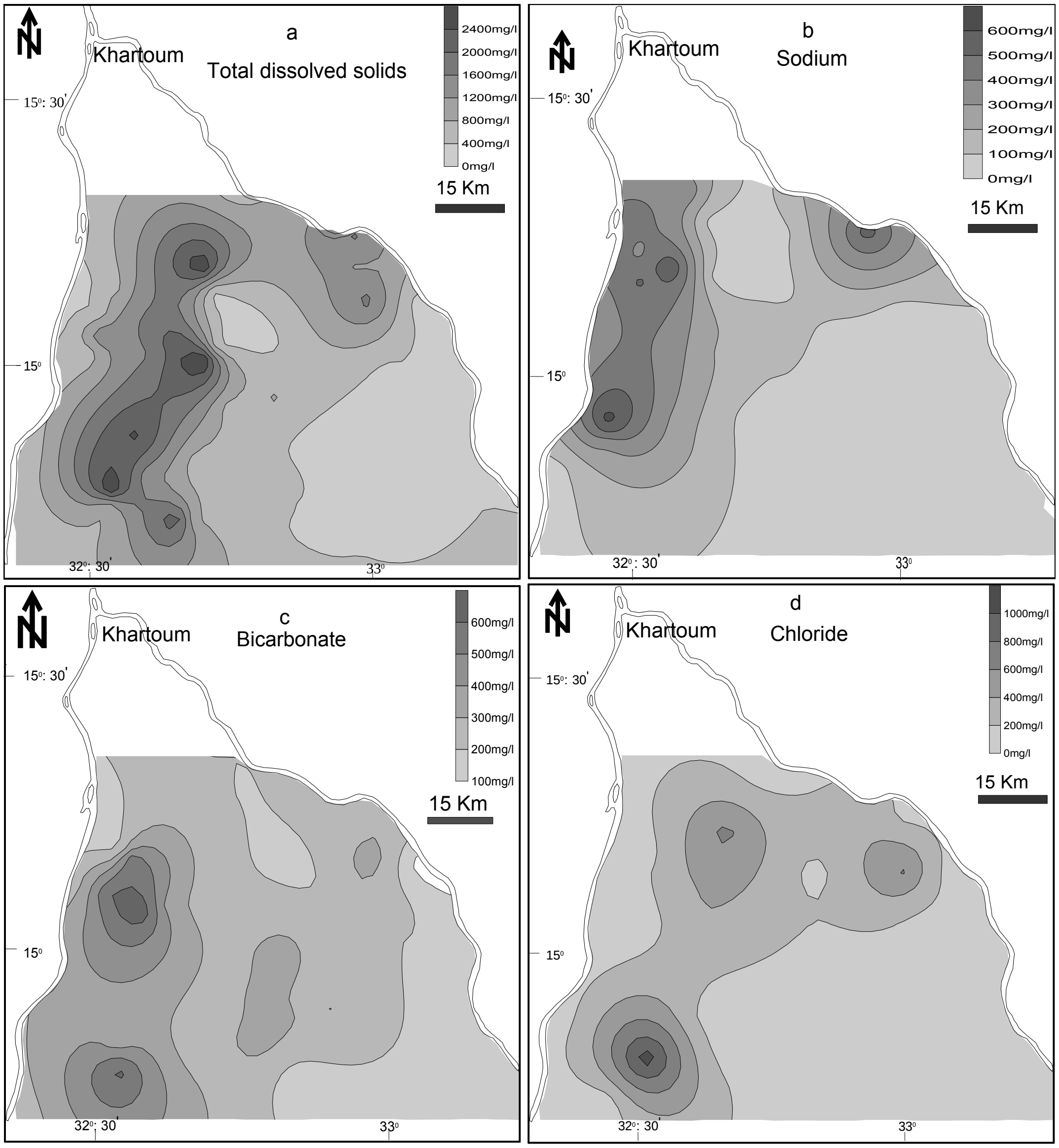

Figure 4. Spatial distribution of hydrochemical characteristics of Gezira aquifer

interconnection of the aquifers system.

2.2.2 Sodium:

The sodium concentration of the groundwater in the study area decreases downwards from the upper Gezira, through lower Gezira down to Cretaceous sedimentary aquifer (Table 3). The areal distribution is much similar to the total dissolved solids. Therefore, relatively high concentration of sodium in Gezira aquifers appears as irregular north-south extended trough east of White Nile and isolated pocket in the northeast part close to the Blue Nile (Figure 4b). Though, groundwater from the Cretaceous sedimentary aquifer, with few exceptions, is characterized by relatively low sodium concentration, evenly distributed throughout the area (Figure 5b).

2.2.3 Bicarbonate:

Upper Gezira aquifer characterized by high bicarbonate concentrations compared to the other aquifers (Table 3). The concentration in Gezira aquifers shows the tendency of increasing towards the center of the study area parallel to the flow directions. High concentration pockets are encountered in the east of the White Nile, the center and northeast of the area (Figure 4c). Bicarbonate concentration in the Cretaceous sedimentary aquifer is comparatively low, although a tendency of increasing concentration towards the central-south part of the area exists (Figure 5c).

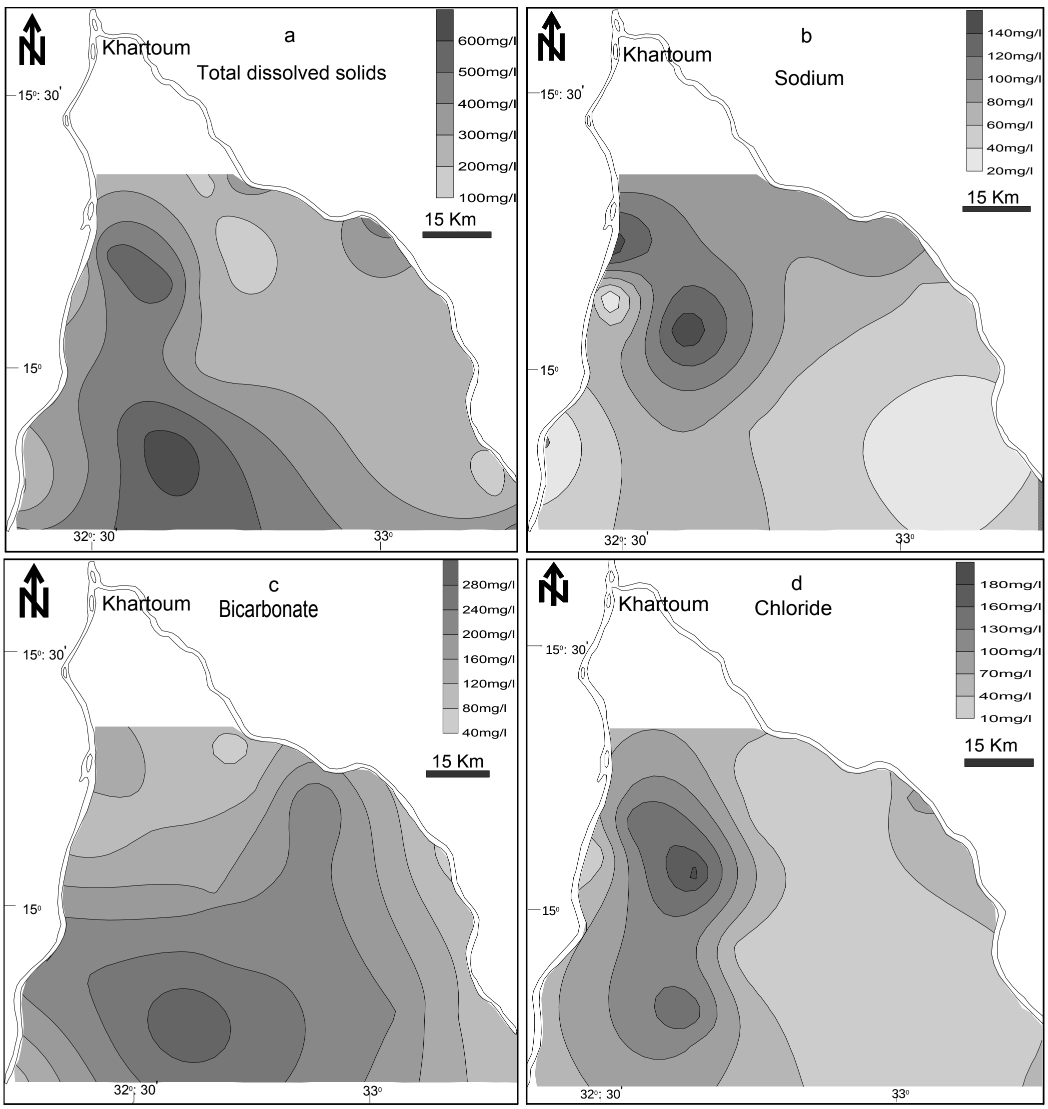

Figure 5. Spatial distribution of hydrochemical characteristics of Cretaceous sedimentary aquifer

2.2.4 Chloride:

The chloride concentration of the groundwater in the study area decreases downward through the aquifers (Table 3). The areal distribution of the chloride is relatively irregular. Hence, most groundwater in Gezira aquifers is characterized by relatively low chloride, although high chloride spots appears in the southwest, center and east of the area (Figure 4d). Furthermore, with few exceptions, Cretaceous sedimentary aquifer is characterized by very low chloride concentration evenly distributed through out the area (Figure 5d).

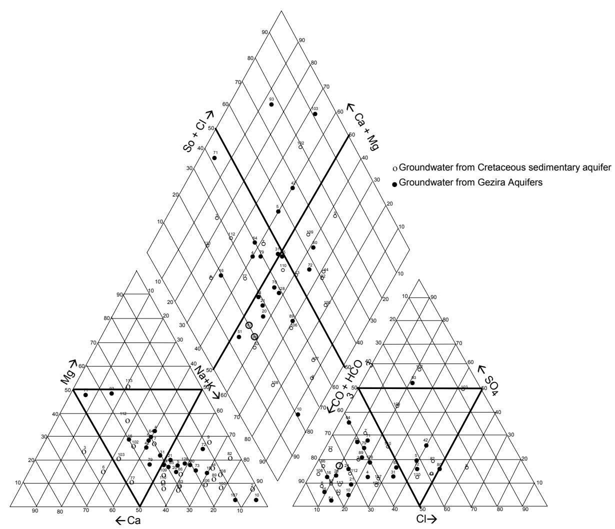

Figure 6. Piper diagram of the groundwaters of the study area

2. Groundwater types and suitability:

The chemical groundwater types of the study area were distinguished and grouped by their position on the Piper diagram where concentration is assigned in % meq/l (Figure6) (Piper 1944, Ophori & Toth, 1988; Kirchner, 1994). Based on the major cation and anion, various water types were found in the study area. Groundwater in Gezira aquifers is mainly NaHCO3, $Ca(HCO_3)_2$, $Ca SO_3$, CaCl and Na_2SO_4 water types, whereas that in Cretaceous sedientary aquifers are dominantly, $NaHCO_3$, and NaCl water type. The dominant anion of the groundwater changes from bicarbonate to sulphate to chloride with a corresponding increase in the TDS. This may be attributed to low hydraulic gradient and groundwater flowpaths. $Ca(HCO_3)_2$ type waters occur near recharge areas, are primarily a result of a dissolution of carbonate minerals during infiltration of water to the aquifers, and the NaCl type waters occur at the center of the study area. These various water types are generally a results of hydrogeochemical processes occur in the subsurface system.

The main objective following the hydrochemical study of groundwater is to determine its suitability to different uses. Hence, water from the upper Gezira aquifer ranges from generally acceptable to poor for domestic uses. Whereas, water from lower Gezira and Cretaceous sedimentary aquifers is fairly good for both drinking and household purposes(Table 3).

Conclusion:

The transmissivity and the hydraulic conductivity of Gezira and Cretaceous sedimentary aquifers were found to be 368.7 m^2/d, 34.03 m/d, and 407.2 m^2/d , 43.17 m/d respectively. Clay, silt and fine sand in Gezira formation reduced the hydraulic conductivity and transmissivity in Gezira aquifers. The Hydraulic gradient is approximately found to be 0.001 from the Blue Nile westwards, and 0.0007 from the White Nile eastwards, confirming that these rivers are the main sources of recharge to the aquifers. The processes of dissolution, precipitation, evaporation and cation exchange, primary control the formation of water types that evolves between the $Ca(HCO3)_2$ and NaCl water type. High concentrations of the physicochemical and chemical species in the upper and lower Gezira aquifers compared to the Cretaceous sedimentary aquifer could be accredited to the presence of carbonate and evaporite deposits, as well as pesticides of agricultural activities, decayed organic material in the root zone, cation exchange processes, high evaporation and low hydraulic gradient. The hydrochemical composition of the groundwater in the Gezira aquifers is dominantly $NaHCO_3$, Ca $(HCO_3)_2$, Ca SO_3, CaCl and Na_2SO_4 water types of alkaline character. Whereas, Cretaceous sedimentary aquifer is characterized by bicarbonate, chloride and sulphate water types. Water from the upper Gezira aquifer ranges from generally acceptable to poor for domestic uses (high salinity), whereas, water from lower Gezira and cretaceous sedimentary aquifers is relatively good for both drinking and household purposes although very saline and hazard water zones are encountered. As the result of this investigation, it is strongly recommended to abstract groundwater from a high potential and suitable fresh water lower Gezira and Cretaceous sedimentary aquifers through wells which should be grouted out through upper Gezira aquifer at high concentration zones, using appropriate techniques, to prevent downwards seepage of poor quality water.

Acknowledgment:

The authors are indebted to his Excellency Mr. Altayib Al Krail for providing financial support. Gratitude and thanks are extended to the members of Department of Geology, University of Khartoum, Sudan, for their vital assistant. Thanks also to Hohai University, College of water resources and environment, China, for collaboration.

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