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Hydrochemical characteristics of aquifers in Northern Gezira State, Central Sudan

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Abstract: This paper presents an assessment of the hydrochemical characteristics of groundwater in Northern Gezira State, Central Sudan. The approaches followed here include the chemical analyses for major ions chemistry and construction of hydrochemical maps of total dissolved solids (TDS), sodium (Na^+), bicarbonate (HCO_3^-), and chloride (Cl^-) ions. The hydrochemical characteristics of the groundwater in each aquifer and management consideration are discussed. Sources of major ions in groundwater are analyzed. The hydrochemical maps of important species are constructed. The relationship of groundwater to use is elaborated. High concentrations of the chemical and hydrochemical constituents and the occurrence of calcretes ($CaCO_3$) in upper zones suggest a long history of evaporation and increasing leachates.

Key words: total dissolved solids; hardness; aquifer; chemical constituents

Understanding the hydrochemical characteristics is crucial for groundwater investigation in the study area. The differences of dissolved ions concentration in groundwater are generally governed by lithology, velocity and quantity of groundwater flow, nature of geochemical reactions, solubility of salts and human activities[1]. Hence, groundwater quality could reveal important information on the geological history of the aquifers. The main objectives of this paper are to evaluate the present status of the water quality, and construct the hydrochemical maps of total dissolved solids, sodium, bicarbonate, and chloride ions, to assess the suitability of groundwater to different uses. The study area lies in the northern part of Gezira State between latitudes 14°40′ to 15°25′N and longitudes 32°20′ to 33°18′E and covers an area of about 5 800 km^2 (Fig.1). It 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 situated in the transitional zone between an arid and semi-arid climate. It is characterized by a hot dry summer (April to October), and cold dry winter (November to March). The mean annual precipitation varies from 310 to 175 mm, mainly from August to October.

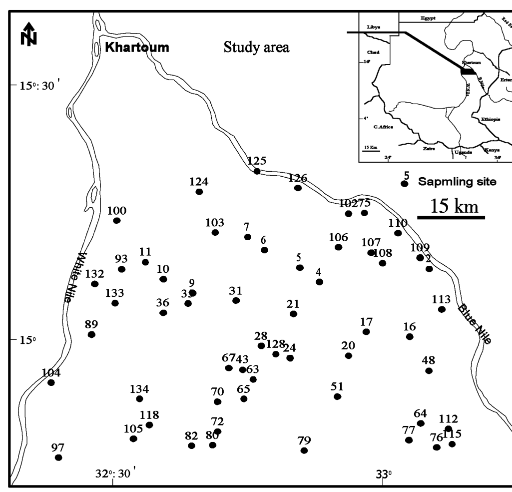

Fig.1 Locality map of the study area showing sampling sites

1 Geology and Hydrogeology

The study area is composed of Pre-Cambrian Basement complex, Cretaceous sedimentary formation and Quaternary Gezira formation. Basement complex consists of highly weathered grey gneisses and reddish granites. The Cretaceous sedimentary formation is composed of sandstone (calcareous, ferruginous and siliceous), mudstone, shale, and conglomerate. The maximum penetrated thickness of the Cretaceous sedimentary formation, is more than 400 m in the center and northeast part of the area[2]. Quaternary Gezira formation constitutes unconsolidated gravel, sand, silt and clay overlying the Cretaceous sedimentary formation. Calcretes ($CaCO_3$), basalt,

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evaporite deposits and salt rock patches are the characteristics features of the Gezira formation. Gezira and Cretaceous sedimentary formations encompass the main aquifer systems, namely: upper Gezira, lower Gezira and Cretaceous sedimentary aquifers in descending order. Groundwater occurs under confined and semi-confined conditions. Depth to groundwater varies from 15 to 50 m. Gezira and Cretaceous sedimentary aquifers are partially hydraulically interconnected[3]. The hydraulic gradient is estimated to be 10^{-3} from the Blue Nile westwards, and 7×10^{-4} from the White Nile eastwards. The Blue Nile, White Nile, seasonal streams, direct precipitation and irrigation canal of Gezira scheme represent the recharge source of the aquifer system.

2 Methodology

Fifty-five samples from shallow wells and deep boreholes in different sites and geological formations at depths ranges from 15 to 45 m below ground level were collected for hydrochemistry (Fig.1). They were analyzed for the major ion chemistry, using standard methods[4]. Parameters such as electric conductivity (EC) and hydrogen ion concentration (pH) were measured immediately at the field site, using portable Orion EC- and pH-meters. 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) and calcium (Ca^{2+}) were analyzed titrimetrically using the standard EDTA. Magnesium (Mg^{2+}) was calculated from TH and Ca^{2+}. Sodium (Na^+) was analyzed by flame photometry. Chloride (Cl^-) was estimated by titration with $AgNO_3$. 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%.

3 Results and Discussion

3.1 Hydrochemical characteristics

The pH of groundwater in Gezira and Cretaceous sedimentary aquifers are more or less similar and vary within small ranges elaborating a fresh and a slight trend of alkaline chemical reaction within the groundwater environment[5], see Tab.1. The mean values of EC are estimated to be 239.7, 80.3 and 46.3 mS/m in the upper Gezira, lower Gezira and Cretaceous sedimentary aquifer, respectively, which elucidate the decreasing of salinity with aquifer depth due to the dissolution of evaporites and salt rocks in upper Gezira formation (Tab.1). Similarly, the alkalinity, hardness and the alkaline earth elements (Ca^{2+}, Mg^{2+}) indicate the downward decreasing of chemical species responsible for these parameters and silicate weathering processes in the upper aquifer zones (Tab.1). The high content of Magnesium (Mg^{2+}) than relative to (Ca^{2+}) is due to the evaporations that result in the precipitation of Ca^{2+} as insoluble Kankar ($CaCO_3$) nodules. According to the classifications in Ref.[6], the Cretaceous sedimentary aquifer is characterized by moderately soft (50 to 100 mg/L) to hard water (> 200 mg/L), whereas that of the Gezira aquifers is moderately soft to very hard (> 300 mg/L). The hardness is attributed to the presence of calcretes, salt rocks and evaporite deposits, which are characteristic features of the upper part of Gezira formation.

Tab.1 Statistical overview of hydrochemical properties in Gezira and Cretaceous sedimentary aquifers

Parameter		pH	EC/ ($mS \cdot m^{-1}$)	ρ_{Na^+}/ ($mg \cdot L^{-1}$)	ρ_{Ca^+}/ ($mg \cdot L^{-1}$)	ρ_{Mg^+}/ ($mg \cdot L^{-1}$)	ρ_{Cl^-}/ ($mg \cdot L^{-1}$)	$\rho_{HCO_3^-}$/ ($mg \cdot L^{-1}$)	ρ_{TDS}/ ($mg \cdot L^{-1}$)	ρ_{TH}/ ($mg \cdot L^{-1}$)	$\rho_{T\ Alk.}$/ ($mg \cdot L^{-1}$)
Upper Gezira	Minimum	8.1	50	92	8	9	31.9	268.4	450	100	268.4
	Maximum	8.5	430	1 100	90	94	1 139.4	671	4 100	420	725
	Mean	8.3	239.8	479	55	62	324	458	1 610	259	490
Lower Gezira	Minimum	7.8	39	30	8	9	10	146	240	90	160
	Maximum	8.6	300	560	85	90	660	580	2810	400	230
	Mean	8.1	80.3	147	37	43	126	385	638	250	183
Cretaceous sedimentary	Minimum	7.5	25	10	10	13	5	122	200	30	100
	Maximum	8.3	106	230	95	96	350	354	680	250	290
	Mean	7.9	46.3	75	34	38	63	238	347	122	137

The total dissolved solids (TDS), a measure of salinity, indicate that most of the groundwater in the upper Gezira, belongs to the brackish type (TDS > 1 000mg/L) whereas that of lower Gezira and Cretaceous sedimentary aquifer is moderately fresh water (TDS < 1 000 mg/L)) confirmed the downward decreasing of salinity with increasing aquifer depths (Tab.1). The areal distribution of TDS in Gezira aquifers appears as irregular trough, east of the White Nile and isolated pockets in the northeast part close to the Blue Nile (Fig.2(a)). These salinity ambiguities are ascribed to the presence of evaporite deposits in the upper part of Gezira formation, low hydraulic gradient (7×10^{-4}) and increasing distance from the recharge sources as well as high evaporation and evapotranspiration rates in this arid area. Furthermore, the Cretaceous sedimentary aquifer is characterized by low salinity, although concentration of more than 500 mg/L appears in the form of a north-south trending trough (Fig.3(a)). This is endorsed to vertical seepage from the overlying Gezira aquifers elaborating partially hydraulic interconnection of the aquifer system.

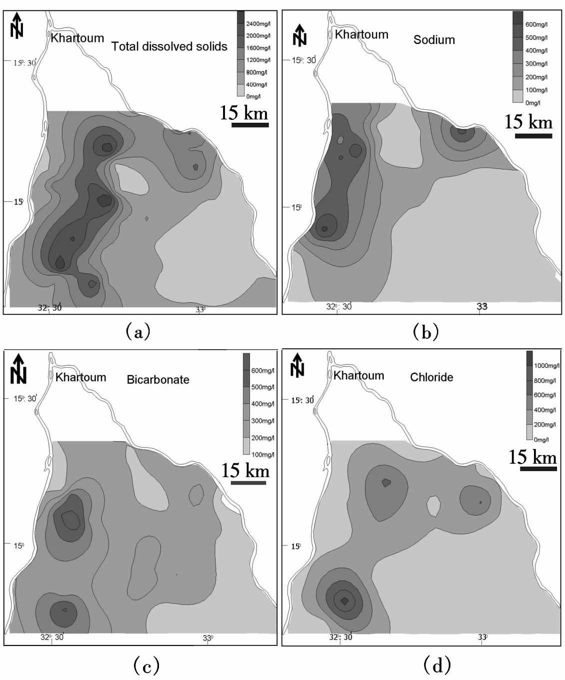

Fig.2 Areal distribution of hydrochemical characteristics of Gezira aquifer

Sodium ions concentration in the study area decreases downward from the upper Gezira, through the lower Gezira down to the Cretaceous sedimentary aquifer (Tab.1). The areal distribution of sodium ions reveals that, relatively high concentrations of sodium ions in the Gezira aquifers appear as an irregular trough zone east of White Nile and isolated pockets in the northeast part close to the Blue Nile (Fig.2(b)). However, the Cretaceous sedimentary aquifer is characterized by relatively low sodium concentration, evenly distributed throughout the area with few exceptions of relative high concentration spots at the center (Fig.3(b)). Significantly the increase of sodium in the upper zones suggests silicate weathering and/or dissolution of soil salts (Na_2SO_4) that characteristic of the upper part of Gezira formation.

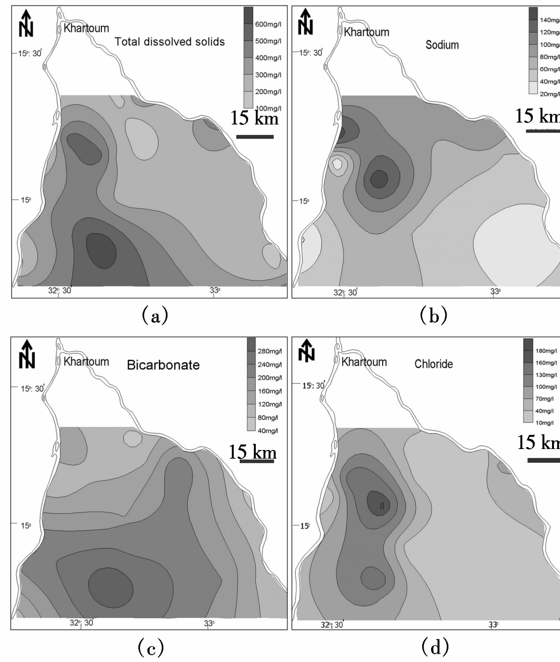

Fig.3 Areal distribution of hydrochemical characteristics of Cretaceous sedimentary aquifer

Bicarbonate concentration in the study area elaborates that the upper Gezira aquifer characterized by high bicarbonate concentrations compared to the other aquifers (Tab.1). The areal distribution of bicarbonate concentrations in Gezira aquifers shows the tendency of increasing towards the center of the study area concordant with the flow directions. High concentration pockets are encountered east of the White Nile, the center and northeast of the area (Fig.2(c)). The Cretaceous sedimentary aquifer is characterized by comparatively low concentration, although a tendency of increasing concentration towards the central-south part of the area exists (Fig.3(c)). High concentration of carbonate in upper aquifers is caused by the carbon dioxide (CO_2) present in the soil zone formed from the decay of organic matter and the root respiration and may also be derived from the dissolution of silicate and feldspars minerals and the weathering of parent materials (calcretes) due to consecutive dry and wet conditions, characteristic of the semi-arid climate of the area.

The chloride concentration decreases with increasing aquifer depth (Tab.1) similar to sodium, indicating a common source of these ions such as leaching of saline residues in the soil due to climatic conditions and anthropogenic activities. The areal distribution of the chloride ion in the aquifer systems is relatively irregular. Hence, most groundwater in Gezira aquifers is characterized by relatively medium chloride concentration. Relative high concentration appears as isolated pockets in the southwest, center, and east of the area (Fig.2(d)). Furthermore, Cretaceous sedimentary aquifer is characterized by low chloride concentration evenly distributed at most parts of the area, although considerable concentrations appear as north-south trough east of White Nile (Fig. 3(d)).

3.2 Relationship of groundwater to use

The main objective behind the hydrochemical study of groundwater is to determine its suitability to miscellaneous uses. Hence the suitability of water to agricultural uses depends on the concentration of the individual constituents, nature and composition of the soil and sub-soil, the position of water table, kind of crop grown, the amount of groundwater used, and the climate of the area[7]. Therefore, the sodium adsorption ratio (SAR) is used to classify the suitability of groundwater for different purposes according to the following equation:

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$$

where ion concentrations are expressed in equivalent per million (epm). Accordingly, the resultant water classes, for Gezira aquifers with few exceptions, ranges from fairly suitable to very hazardous to the soil texture and not suitable for most kinds of plants (Fig.4). Cretaceous sedimentary aquifer, consequently suitable for most kind of plants, except in high salinity areas at the center and northeast of the area, where special management of salinity control and certain kind of plants with good salt-tolerance should be considered. For domestic uses, water from the upper Gezira aquifer ranges from generally acceptable to poor. Whereas, water from lower Gezira aquifer is comparatively good although very saline and hazardous water is encountered at the center and northeast of the area. Moreover, water from the Cretaceous sedimentary aquifer is good for both drinking and household purposes.

4 Conclusions and Recommendations

High concentrations of chemical and hydrochemical constituents of groundwater in the upper and lower Gezira aquifers compared to the Cretaceous sedimentary aquifer could be accredited to the presence of kankar ($CaCO_3$) or calcretes and evaporite deposits, decayed organic material in the soil, ion exchange processes, low hydraulic gradient, evaporation and evapotranspiration in this semi-arid area. Water from the upper Gezira aquifer ranges from generally acceptable to poor for domestic uses and is very hazardous to the soil texture and not suitable for most kinds of plants, whereas, water from lower Gezira aquifer is relatively good to fairly suitable for domestic and irrigation purposes, although very saline and hazard our water is encountered. Water from the Cretaceous sedimentary aquifer is good for both drinking and household purposes and suitable for most types of plants. For water management consideration, the most frequent methods to decrease water quality fluctuation are the recharge techniques through spreading water on the land surface and allowing it to percolate to the water table and/or direct injection of water through wells with some consideration given to water chemistry. For agricultural development it is recommended to build small dams for surface water storage on seasonal streams and basins to be used during droughts as additional resources to avoid or to attenuate demographic imbalances and desertification risk in the study area. Moreover, special management of salinity control and certain kinds of plants with good salt-tolerance should be considered. It is also strongly recommended to extract potable groundwater from the lower Gezira aquifer and Cretaceous sedimentary aquifer through wells that should be grouted through the upper Gezira aquifer zone, using appropriate

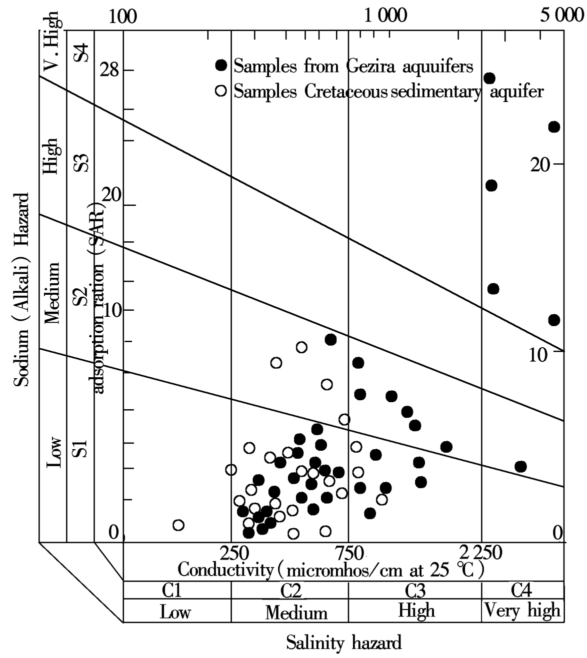

Fig.4 Classification groundwater for irrigation in the study area (After U.S., Dept. of Agr., Handbook 60, 1954)

techniques, to prevent mixing of poor water quality, that characterized the upper Gezira aquifer, with suitable water from the underlying aquifer zones.

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苏丹中部北杰济拉省含水层的水化学特征

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摘　要　对苏丹中部的北杰济拉(Gezira)省地下水的水化学特征进行了评价,评价方法包括地下水主要离子浓度的监测分析及矿化度、钠离子、重碳酸根离子和氯离子浓度等值线图的绘制.对每个含水层的的水化学特征及其地下水的管理问题进行了深入讨论,并对地下水的适用性进行了详细分析.在含水层上部存在的化学成分含量较高及碳酸钙的存在,是蒸发作用和渗入量增加的结果.

关键词　矿化度; 硬度; 含水层; 水化学成分
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