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The Spacial Distribution and Time Variations in Physico-chemical Parameters of Groundwater at Khartoum Area- between two Niles–Sudan

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ABSTRACT

The study area occupied the Khartoum area at the confluence of the Blue and White Niles. The main groundwater-bearing formations in the study area are the Gezira and Sandstone sedimentary Formations. The main objective of the current investigation is to determine the correlation between physicochemical properties and their spatial distribution in different time intervals. The methods of investigations were based on the acquired hydro-chemical data and on their analytical results. The average of PH values in the two aquifers is in continuous changes from alkaline toward acidic water type. The dominant water samples were classified as hard and moderately hard. The average *TDS* value is about 394 mg/l for Gezira aquifer and about 373 mg/l for Sandstone aquifer. The anionic and cationic composition shows that the Bicarbonate (HCO_3^{-1}), Sodium (Na^{+1}), Sulphate (SO_4^{-2}) and Chloride (Cl^{-1}) ions are the highest concentrations in the two aquifers. The correlation matrix of 15 variables shows significant impact of period variations. (HCO_3^{-1}) - (Ca^{++}) and (HCO_3^{-1}) - (Na^{+}) are the dominant water facies. The majority of samples fall in rock dominance, the dissolution of carbonate and silicate minerals are the dominant controlling factors of the groundwater chemistry. The chlorine-alkali index (CAI), give an indication of the occurrence of exchange between Ca^{2+} and Mg^{2+} ions in water and Na^{+1} and K^{+1} ions in the host rocks. The Ammonia and Nitrate average values in both aquifers are increased with time as indicator of pollution, in which the Gezira aquifer is mostly affected.

Keywords: water chemistry, water quality, groundwater, Khartoum, Sudan.

INTRODUCTION

Recently water quality has become a very important issue due of the huge growth of population, urban expansion and development. Groundwater chemistry depends on the quality of recharge

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water and on geological as well as geographical residency in the area (Chandrasekar et al., 2014). Several factors such precipitation, groundwater flow patterns, rainfall patterns, infiltration rate, degree of chemical weathering of rocks in addition to water-rocks interaction affect groundwater chemistry (Okiongbo & Douglas, 2015).

Hydro geochemical processes like ion exchange, oxidation, reduction, desorption, precipitation and dissolution controls the hydro-geochemistry of groundwater (Gholam and Azam, 2012). The conventional techniques and statistical techniques are generally approved methods to determine the quality of water (Kumar et al. 2015).

Since the middle of the last century, drilling has been continuing in Khartoum city for various purposes and at different depths to cover the needs as a result of population growth/urbanization, agricultural and industrial expansion. Despite this, there are no enough wells to monitor the quality and quantity of groundwater.

Correlation is a mechanism used to identify the strength of relationships between features. It is a statistical method for determining how one parameter moves or changes with respect to another parameter. Positive correlation denotes that as one feature increases, the other tends to rise, while negative correlation indicates that as one feature increases, the other tends to decrease. At present time several studies using correlation matrix to study the relationship between diverse hydro-geochemical variables. Its aids in determine the relationship between groundwater chemical components (Ahamed & loganathan, 2017; Viswanath, et al., 2015).

Study Area

The study area occupied the Khartoum city at the confluent of the Blue and White Niles. It is confined between latitudes 15º 37/03//and 15º 23/ 20//N and longitudes 32º 27/ 26//and 32º 40/ 28//E with an area of about 324 Km^2, (Figure 1). The study area is generally flat to semi flat; it is covered with black clayey cotton soil and little silts. The area is characterized by an arid region (sub-Saharan region). According to the data between 1980 and 2020 the average annual rainfall is about 115 mm. Most of the rains fall during July and August. The daily average maximum temperature is about 38° C in summer (it exceeds ≥ 40˚C in May). The daily average minimum temperature is of about 20˚C in winter. The main water courses are Blue Nile and White Nile.

Geological and Hydrogeological Setting

Khartoum sub basin is situated at the northern edge of the Blue Nile rift basin (Salama, 1997). The Basement Complex partly bounds the sedimentary basin and forms its bottom limit at depth more than 500 m (Köhnke et al., 1993). The main rock units in the study area include Basement Complex (Pre- Cambrian), Nubian Sandstone Formations (Cretaceous), Volcanic Basalt (Tertiary), Gezira Formation (Quaternary) and superficial Deposits (Quaternary to Recent). The main water-bearing formations in the study area are the Gezira Formation and Cretaceous Sandstone Formations. Gezira formation represents the upper part of water-saturated zone. It rests unconformity over the Cretaceous sandstone formations. The Cretaceous Sandstone represents the most important and the main aquifer in the study area. Due to the existence of the impermeable layers intercalated the permeable ones more than one hydro-stratigraphic unit are existing.

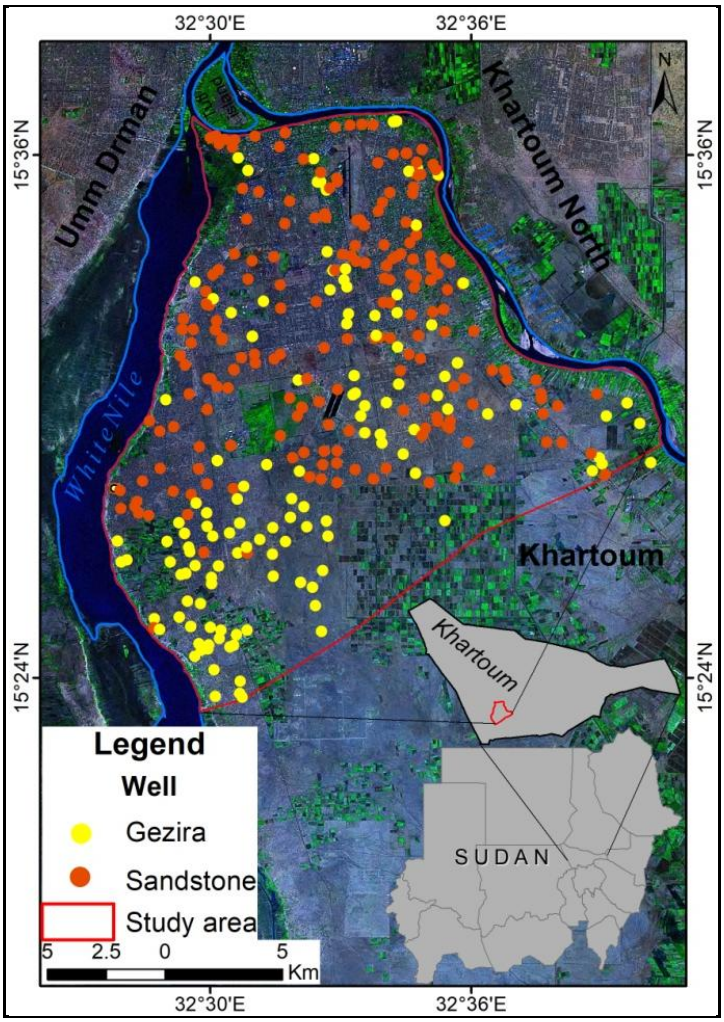


Figure 1: Location map of study area, showing wells distributions

Objectives

The main objective of the current investigation is to determine the correlation between physicochemical properties and their spatial distribution during different periods in Khartoum area. This includes the determination of the average values of physicochemical properties and to investigate the dominated hydro-chemical facies in addition to resolve of the mechanisms that controlling groundwater chemistry.

MATERIAL AND METHODS

To achieve the objectives of this investigation, large amount of collected data were distributed evenly throughout the study area (Figure.1). The data describing different parameter obtained from three water analysis laboratories *(Khartoum Water Corporation laboratory, Groundwater and Wadies General Directorate (GWWD) laboratory and Central Laboratory for Technical Services and Calibration (CLTSC))*.The first stage in data processing is the checking for its ionic balance. The data was categories into 4 periods (before 1990, 1991-2000, 2001-2010 and 2011-2020) for each aquifer. A correlation matrix calculated for different pairs of major ions, PH, TDS and EC. The relationships between the hydro-chemical parameters may help into identify the main processes contributing to groundwater salinity. Hence the physiochemical

properties variations were express in maps for each aquifer throughout the mentioned four periods.

RESULTS, ANALYSIS, AND DISCUSSION

PH Values

The average of PH values for Gezira and Sandstone aquifer are of closely values. It decreases gradually in both aquifers during four periods of investigation from alkaline toward acidic water type (figure 2).

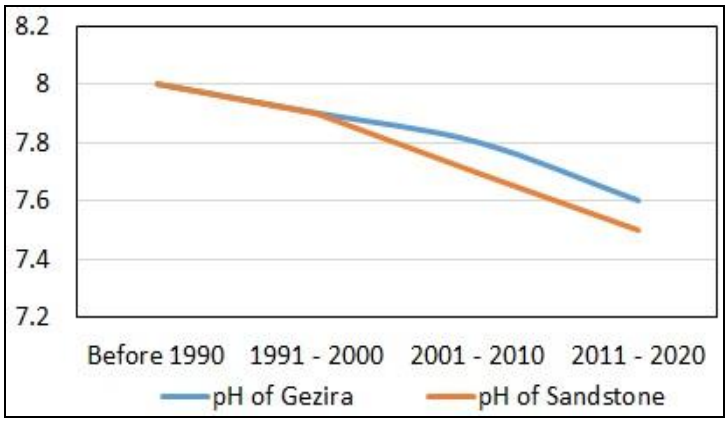


Figure (2): Shows the changes of average PH values versus time for Gezira and Sandstone aquifers.

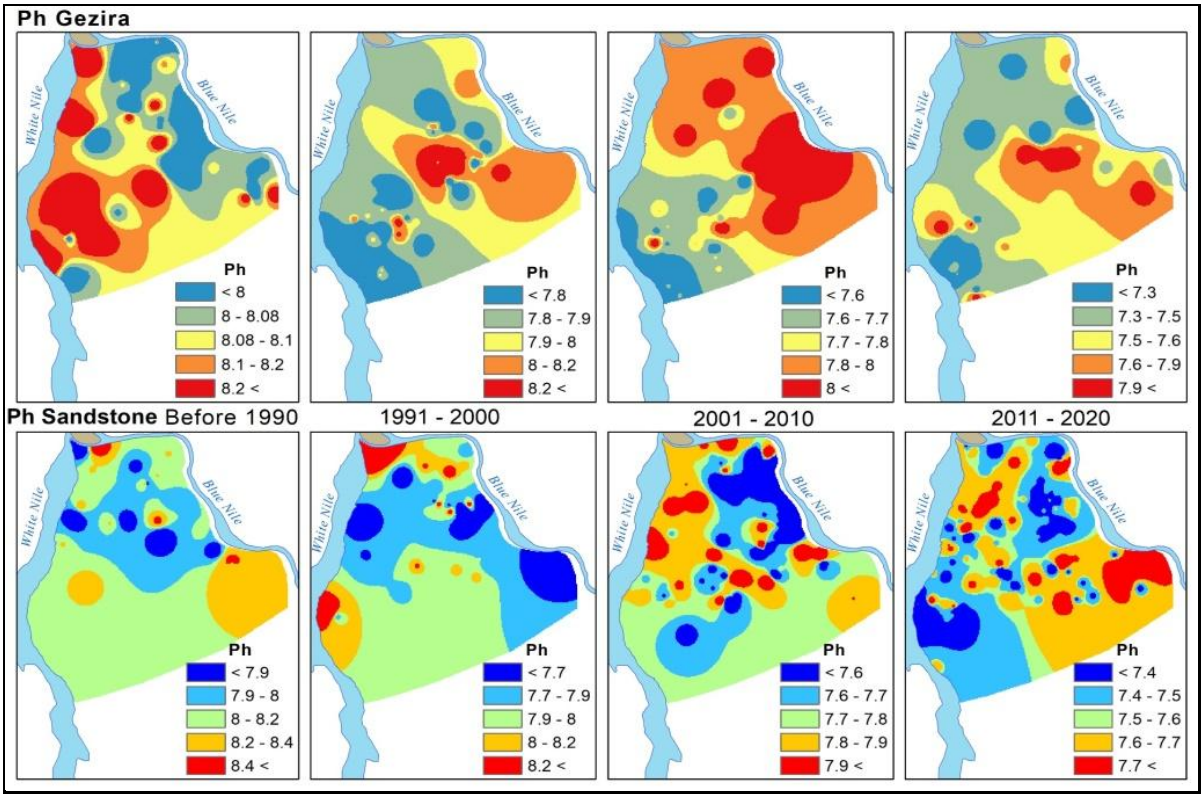


Figure 3: The spatial distribution of PH values for Gezira and Sandstone aquifers with respect to time borders.

The pH values in Gezira aquifer is relatively higher in area parallel to the White Nile in the period before 1990 and at the area parallel to Blue Nile in the period between 2001 – 2010. In general the spatial distributions of the PH values in Gezira formation aquifer is in continuous change with time, where in the sandstone aquifer the pH values were spatially varies in the last two decades (figure 3). The spatially distribution changes in PH values with time in two aquifers systems are attributed to the human activities such as waste disposal and to intensive pumping that leads water from nearby high water heads zones to move toward the lowest one.

Total Hardness (TH)

According to Sawyer and McCarty (1967) Classification of water types, 53% and 35% of samples in Gezira aquifer were classified as moderately hard and hard respectively. For Sandstone, aquifer 54% and 34% of samples were classified as hard and moderately hard respectively (figure 4).

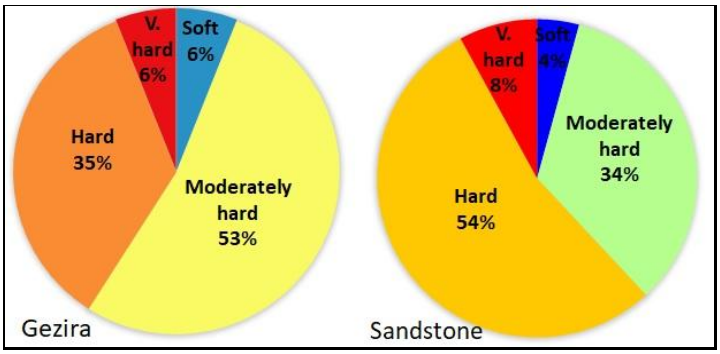


Figure 4: Shows the percentage of total Hardness for Gezira and Sandstone aquifers.

Generally, the spatial distribution of total hardness for Gezira shows high values at the north and at the south of the study area. For Sandstone aquifer the last two periods showed similar distribution of total hardness values where the high values extended from north to south and low values in area parallel to White and Blue Niles (Figure 5). The total hardness (TH) in water is generally refer to the soil and rocks chemistry in which the concentration of Na and S ions contents will influence on total hardness.

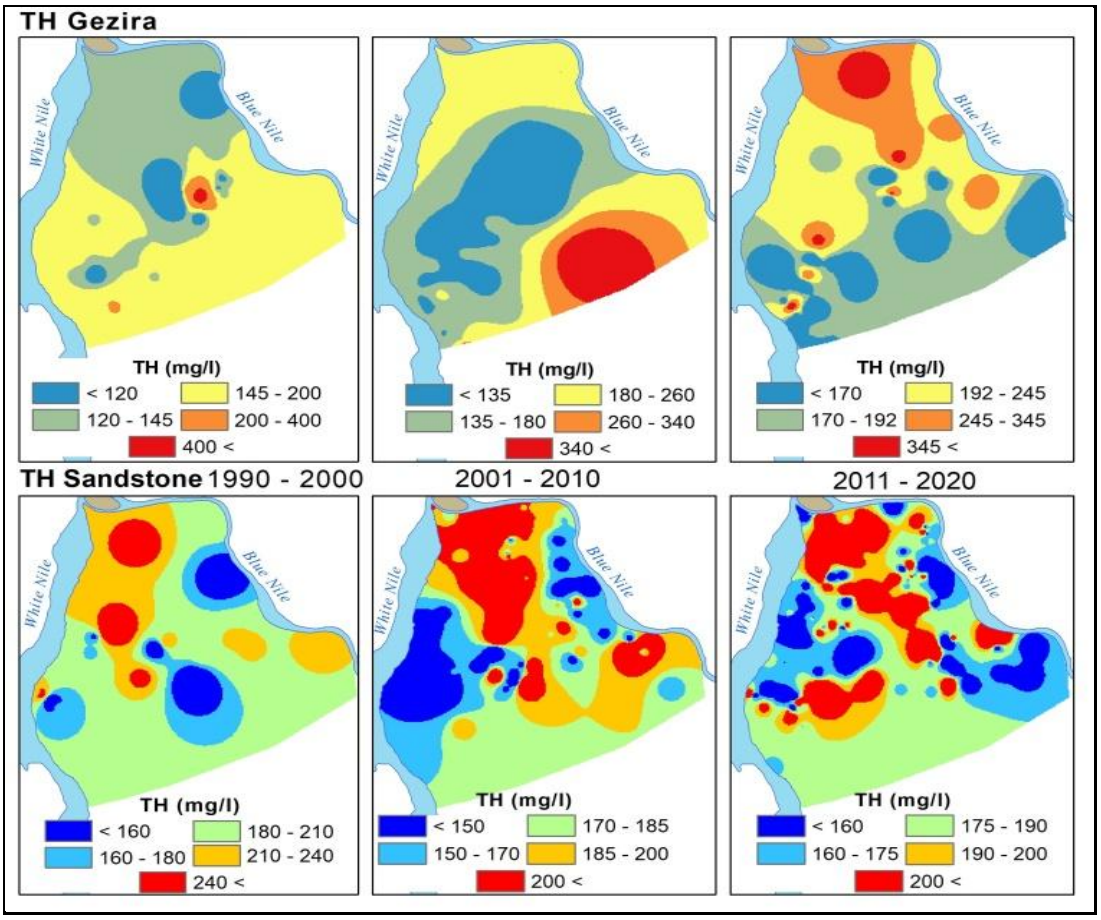


Figure 5: The spatial distribution of total hardness *(mg/l)* Vs time for Gezira and Sandstone aquifers

Electrical Conductivity (EC) and Total Dissolved Solids (TDS)

The average of EC values in Gezira aquifer is about 606 µs/cm and for Sandstone aquifer is about 617 µs/cm. The average *TDS* value is about 394 mg/l for Gezira aquifer and about 373 mg/l for Sandstone aquifer (table 1). That indicates Gezira aquifer is relatively more saline than the Sandstone aquifer due to the present of Kanker nodels and mud. Generally, *EC* and *TDS* for the two aquifers take the same increasing and decreasing patterns during the investigated periods (figure 6).

Table 1: Statistics summary of *pH, EC and TDS* for Gezira and Sandstone aquifers

	Gezira aquifer			Sandstone aquifer		
Parameter	**Min**	**Max**	**Average**	**Min**	**max**	**Average**
pH	6.7	9.3	7.9	6.2	9.6	7.7
T. Hardness (mg/l)	20	790	156	20	480	182
E.C (µs/cm)	180	4250	606	74	1815	617
T.D.S (mg/l)	120	2975	394	35	1012	373

Obvious increasing in *EC and TDS* values are recorded in Gezira aquifer with time which may be regards to the groundwater contamination due to waste disposal to the upper Gezira aquifer. In the Sandstone aquifer the spatial distribution is almost consistence during the time which is attributed to the depth of the aquifer where is being far from pollution risk. The lowest values of *EC and TDS* are recorded in area parallel to White and Blue Niles, while the high values are recorded at the centre of study area for both aquifers (figure 7& 8). This indicates the influence of the Niles as water recharge source which are lowest the *EC and TDS* values. In the central part the values are increases as the result of groundwater flow regime which concentrates the ions towards the flow direction.

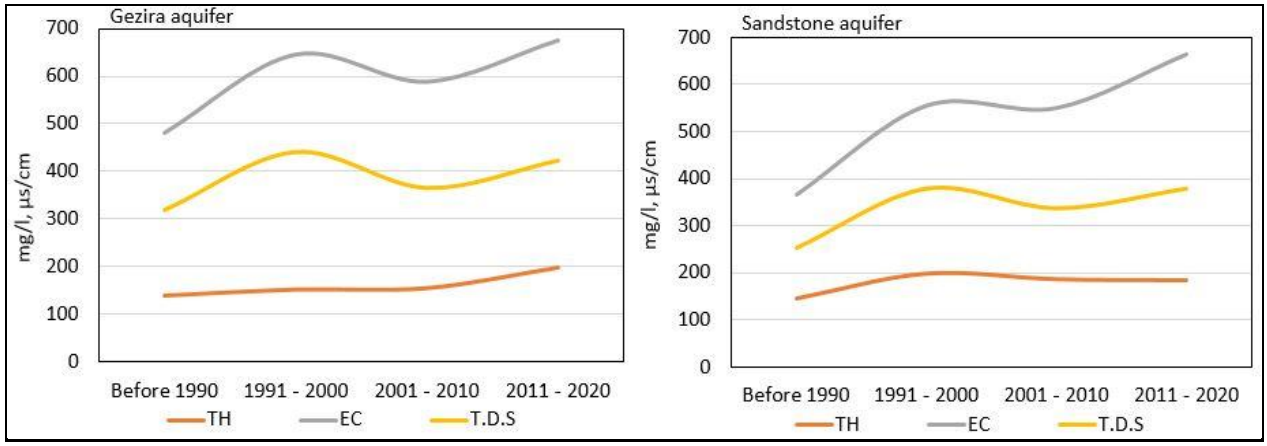


Figure 6: Shows the *TH, EC and TDS* patterns with time for Gezira and Sandstone aquifers.

The groundwater in the two aquifers is range from fresh to brackish water. According to Salinity Standards, classification adopted by Khartoum Laboratories 1982; 84% and 78% of the samples in Gezira and Sandstone aquifers respectively are classified as slightly saline water (figure 9).

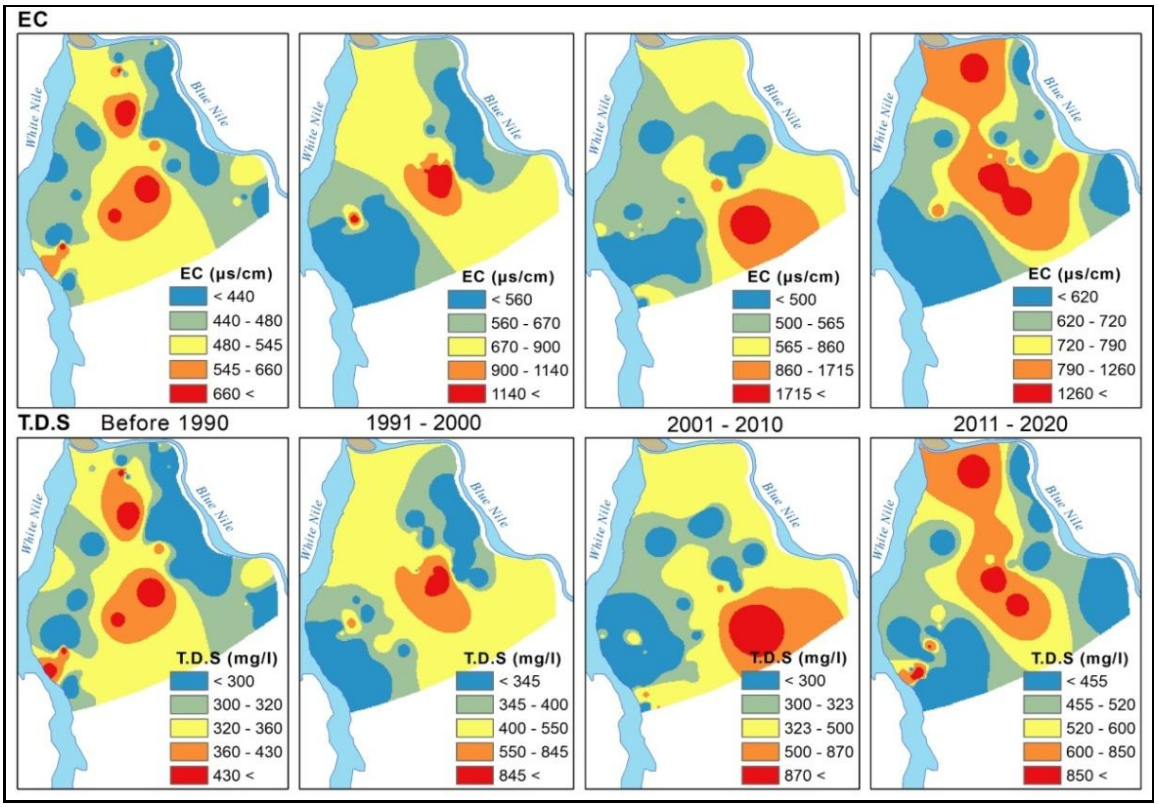


Figure 7: The spatial distribution of *EC µs/cm and TDS mg/l* for Gezira aquifer in 4 periods.

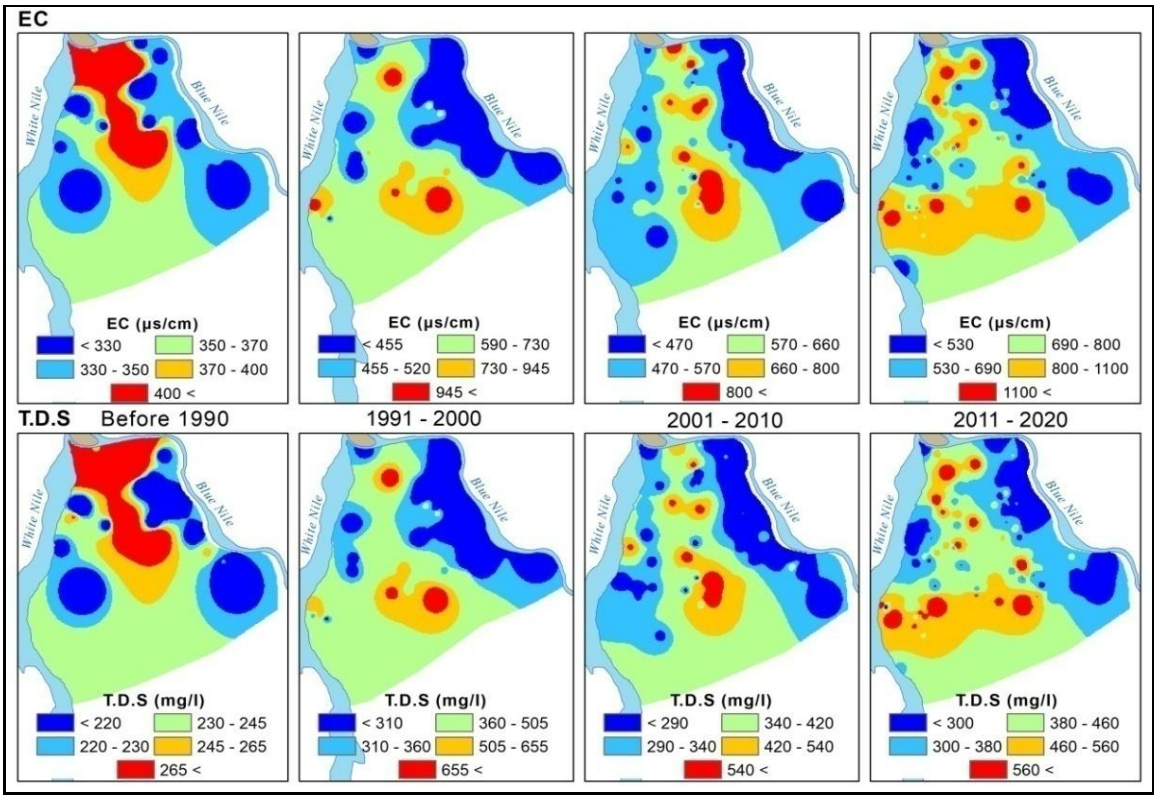


Figure 8: The spatial distribution of *EC (µs/cm) and TDS* (*mg/l)* for Sandstone aquifer in 4 periods.

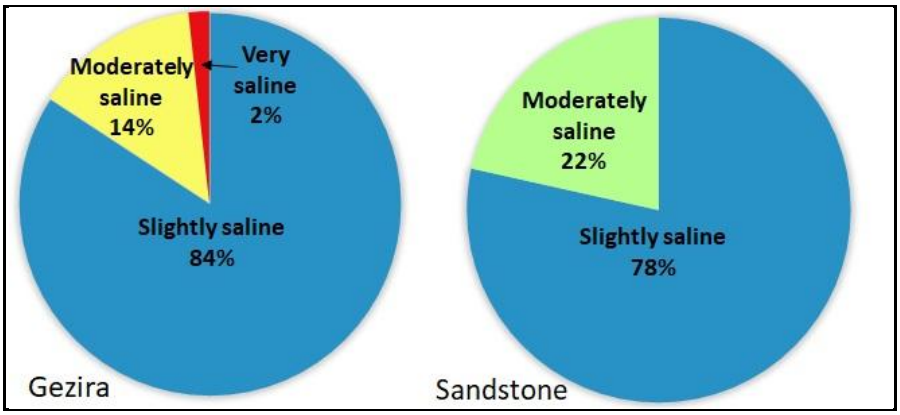


Figure 9: Shows the salinity ranges for Gezira and Sandstone aquifers.

Ionic Concentrations

During the four recorded periods, the total anionic and cationic values of the Gezira aquifer are higher than Sandstone aquifer. The anionic and cationic composition for the study area shows that the Bicarbonate, Sodium, Sulphate and Chloride are the highest concentrations in the two aquifers. The majority of the Cations that were monitored during the four mentioned periods are Na^+, Ca^{++}, Mg^+, and K^+. The Cations implement the same patterns of concentration per time in the two aquifers in which the Na^+ ions are the highest one where the K^+ ions represent the lowest values, (Figure 10).

HCO_3 is the most abundant Ionic in both aquifers. HCO_3 values in Gezira aquifer is higher than in Sandstone aquifer that refer to the direct recharge from the Niles Rivers (table 2). The HCO_3 values in two aquifers increased with time except in last period which it decreases in sandstone aquifer (figure 10). The average values of SO_4 ions in Gezira aquifer and CL ions in sandstone aquifer followed the same behavior in terms of increases and decreases during the four periods. CL and SO_4 ions in Gezira aquifer are similar spatially at the last three periods while they are similar spatially at the first three periods in sandstone. Nitrogen components such as NH_3 and NO_2^- are very important ions to determine water quality. The ammonia is indicator of bacterial, sewage and animal waste pollution. Generally, in both aquifers the area beside White Nile is more affected by ammonia specially Shagera area in which the water bearing formation is near surface which subjected to the pollution from waste disposal sources, (figure13 and 16). The Nitrate average values in both aquifers increased with time as indicator for pollution as a result of human expansion. Nitrate average values in Gezira aquifer are relatively higher than in sandstone aquifer, where the Gezira aquifer is rest as top layers near the pollution sources, (table 2). Table (2) shows the maximum, minimum and average major ions concentrations in each aquifer. The spatial distributions of major ions for each aquifer during four periods are shown in figures (11, 12, 13, 14, 15 and 16).

Table (2): Statistics summary of major ions in Gezira and Sandstone aquifers *(concentration in mg/l)*

	Gezira aquifer			Sandstone aquifer		
Major ions	**Min**	**Max**	**Average**	**Min**	**Max**	**Average**
Na^+	7	810	73	2	299	63
K^+	0.9	24	5	1	12	4

Ca^{++}	4	108	34	4	102	38
Mg^{++}	1	127	20	1	64	20
HCO_3	100	732	267	48	570	254
SO_4	0.04	748	46	0.3	522	45
CL	5	589	37	2	256	43
NH_3	0.01	5	0.4	0.01	6	0.6
NO_2	0.0001	1.2	0.1	0.001	1.5	0.4
NO_3	0.09	154	11	0.1	83	6

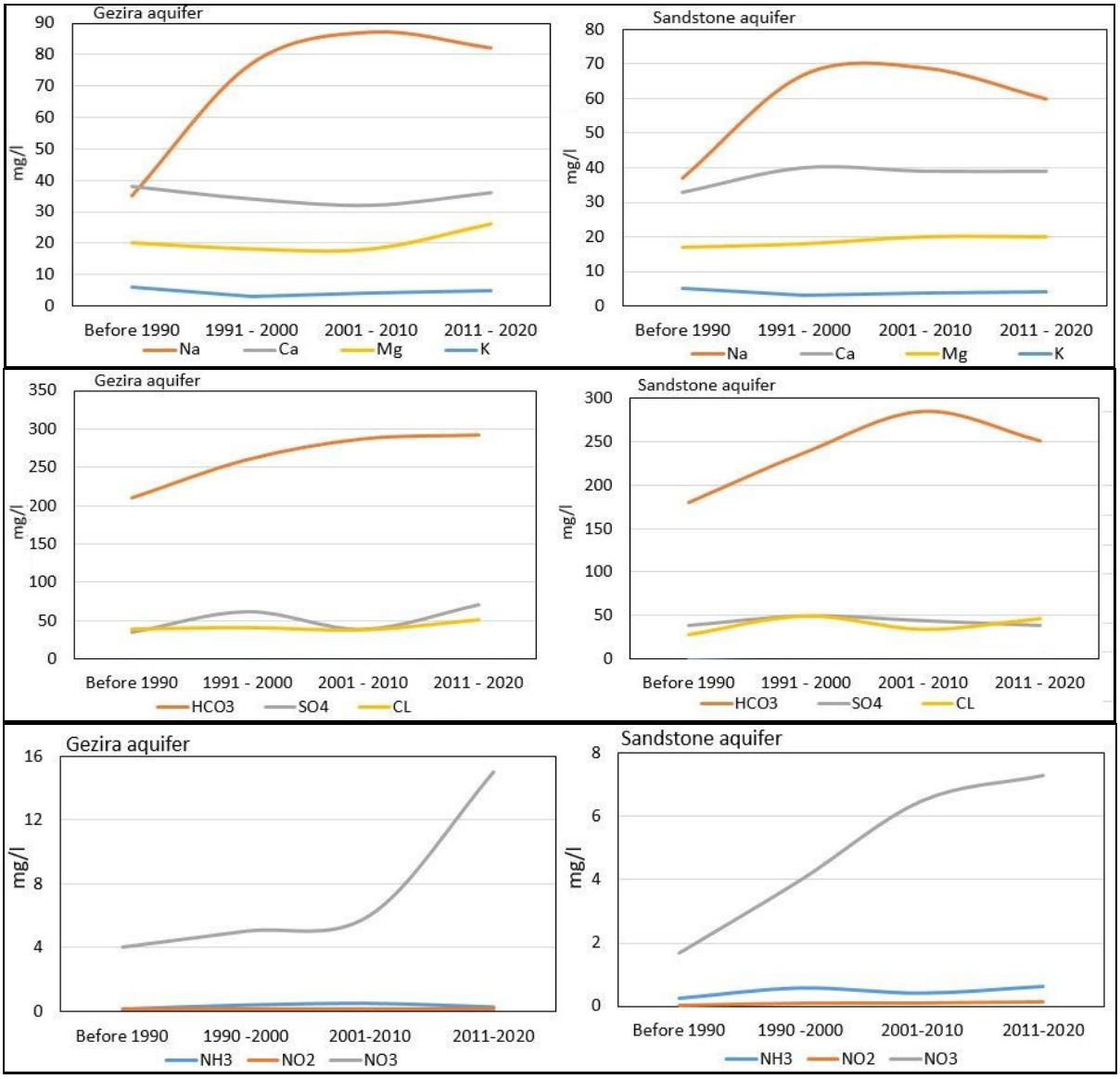


Figure 10: Shows the trend of major ions with time for Gezira and Sandstone aquifers

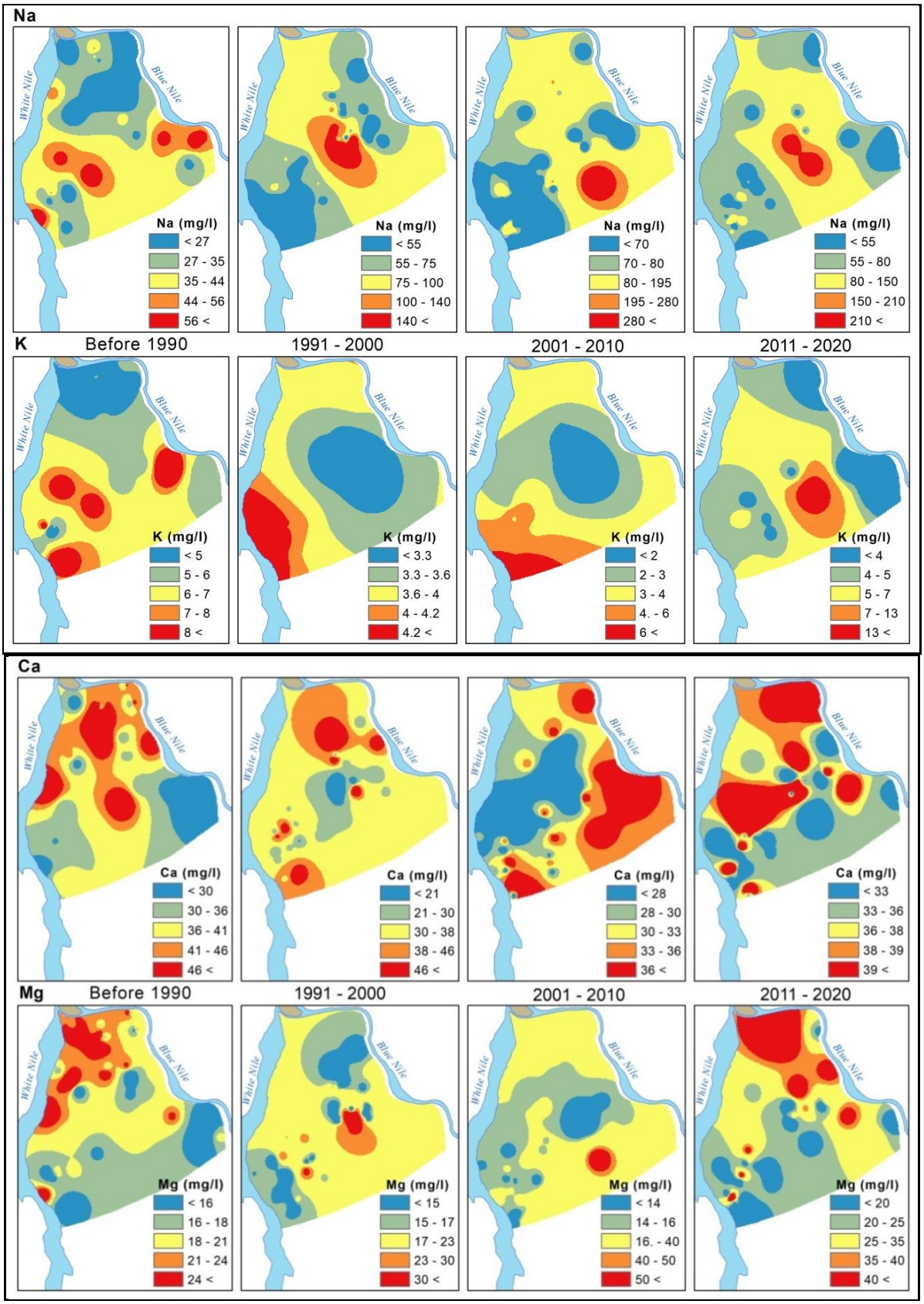


Figure 11: The spatial distribution of Na, K, Ca and Mg ions (*mg/l)* for Gezira aquifer

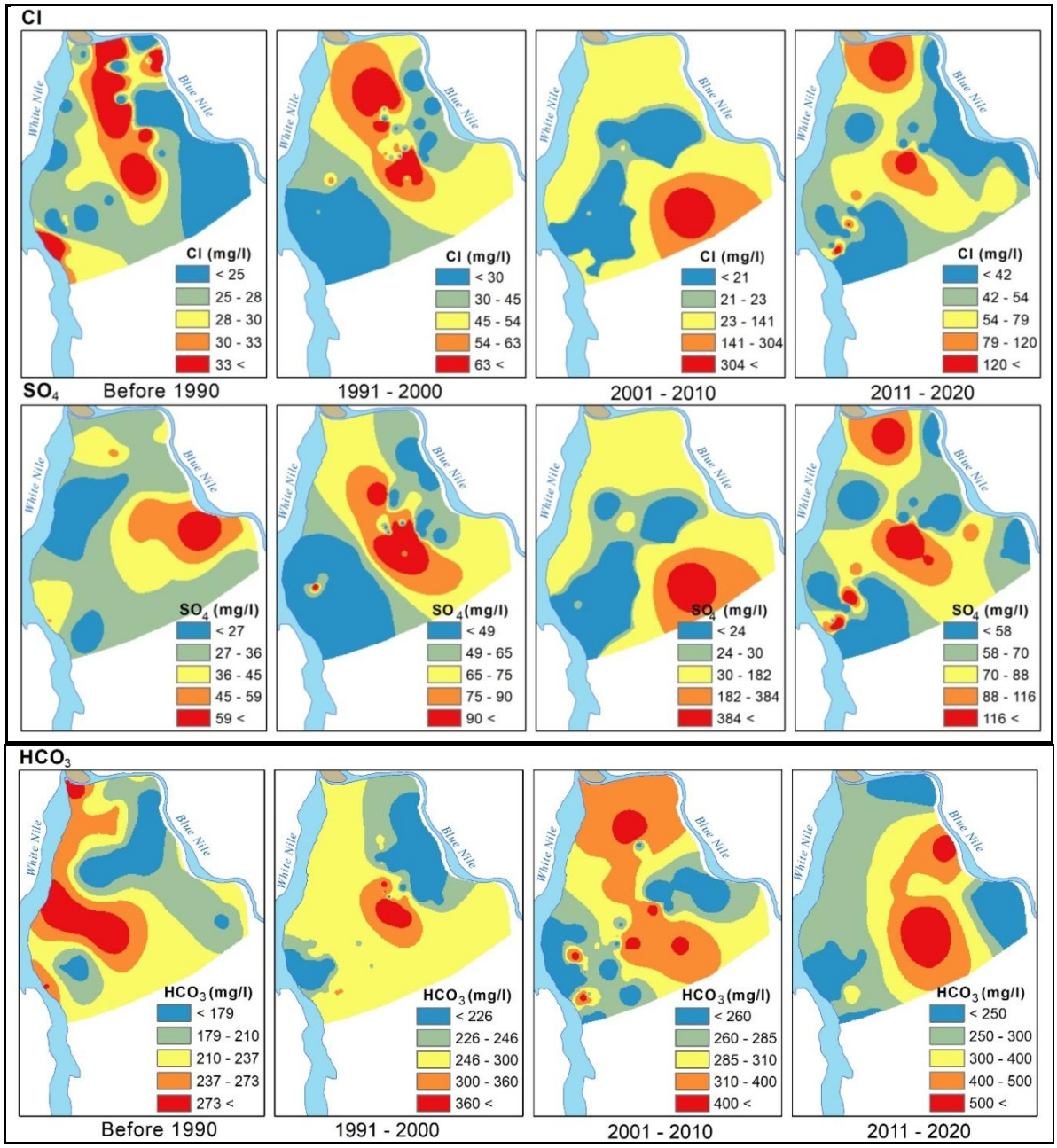


Figure 12: The spatial distribution of CL^-, SO_4^-, and HCO_3^- ions (*mg/l)* for Gezira aquifer

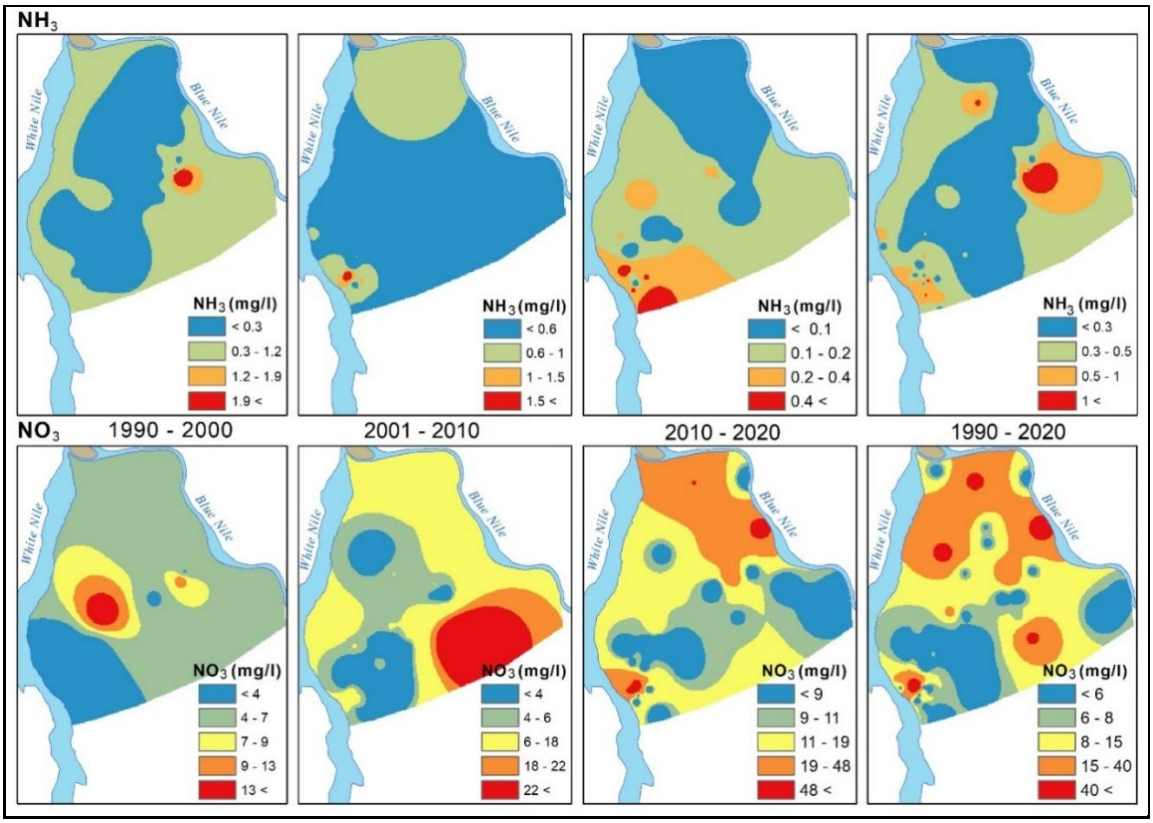
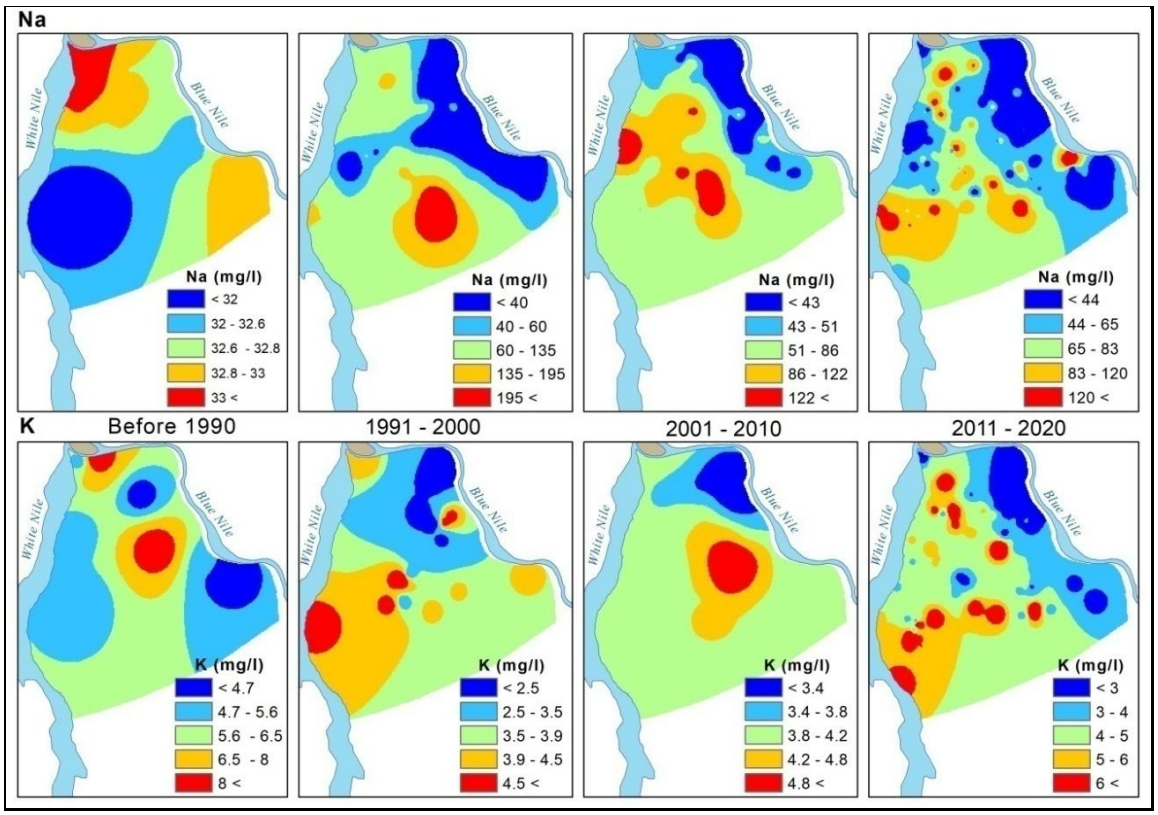


Figure 13: Spatial distribution of NH_3^- and NO_3^- ions for Gezira aquifers



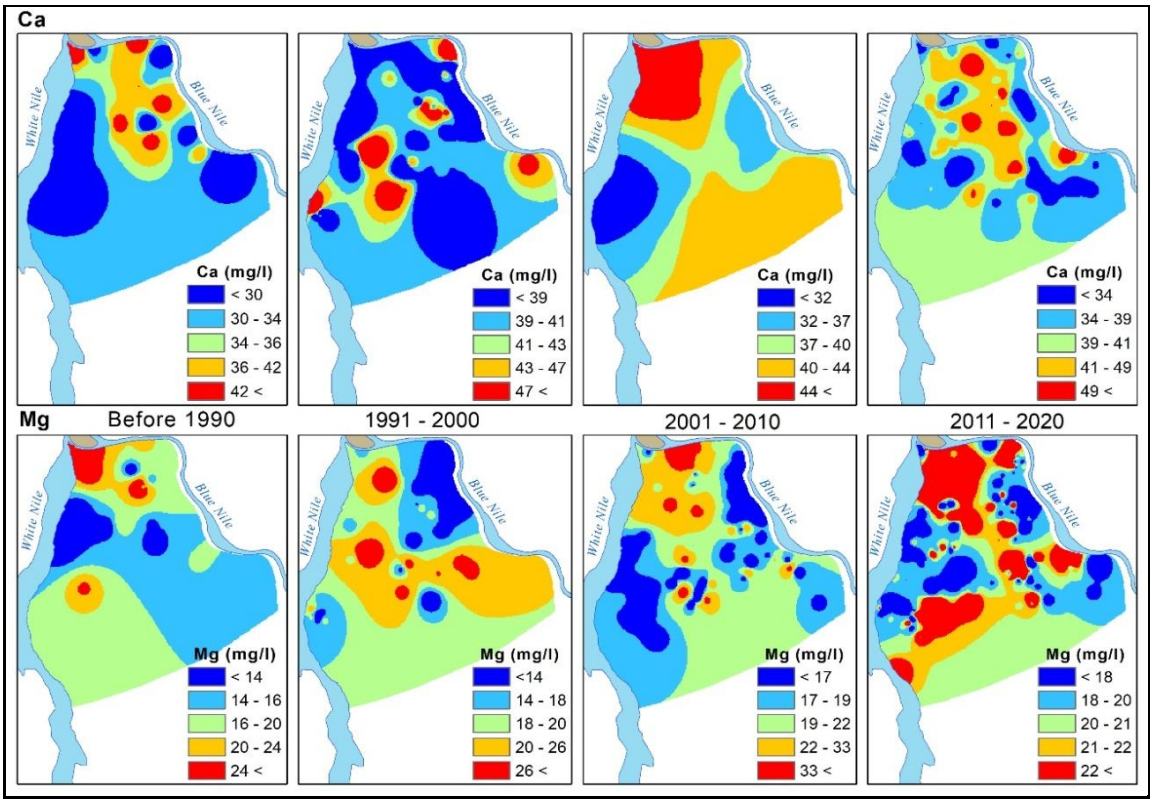
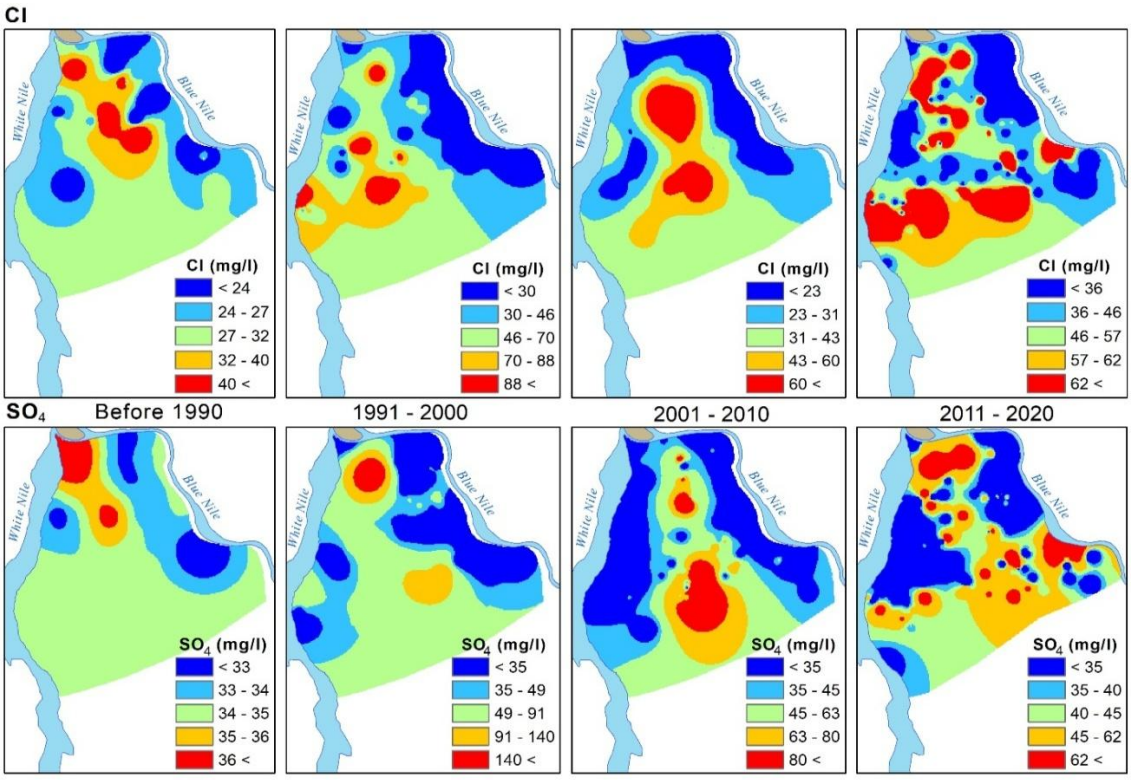


Figure 14: The spatial distribution of Na, K, Ca and Mg ions *(mg/l)* for Sandstone aquifer



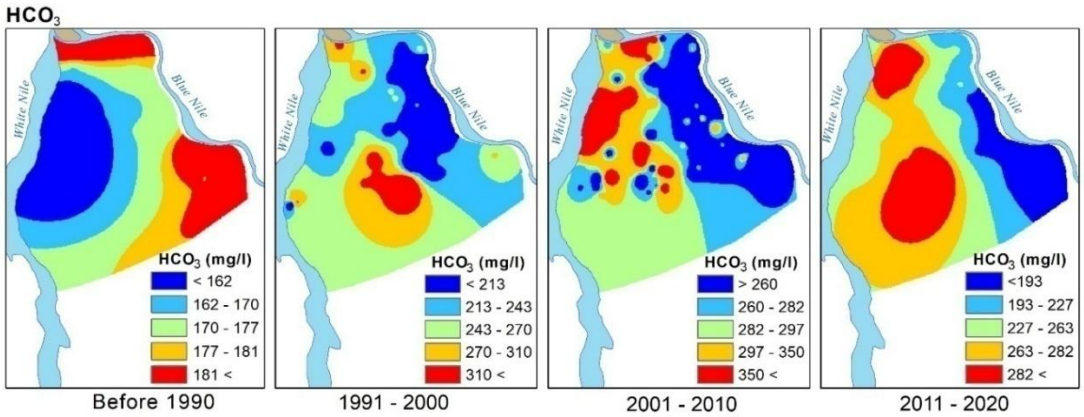


Figure 15: The spatial distribution of CL, $SO_4^-$and HCO_3^- ions *(mg/l)* for sandstone aquifer

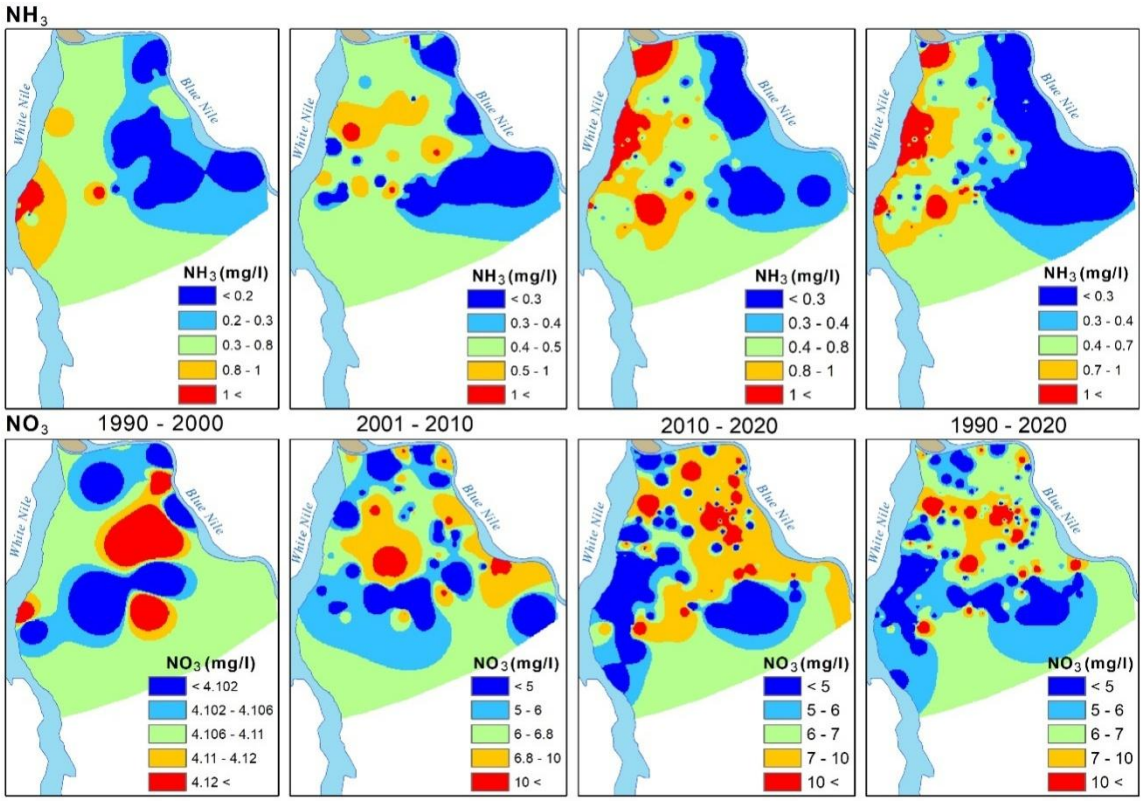


Figure 16: Spatial distribution of NH_3 and NO_3^- ions in sandstone aquifers

Correlation Analysis

The correlation matrix of 15 variables were prepare in four periods for each aquifer. It shows contentious relation and temporal relation for each aquifer in which significant impact of period variation in the study area was recorded. The strong correlations between EC and TDS in all periods for both aquifers are dominant. In Gezira aquifer a strong correlation was observed between EC &TDS with CL, SO_4 and Mg ions during the recorded periods. The presence of Na, Mg, Cl and SO_4 ions are greatly influence on the TDS and EC. Significant positive correlations between different physicochemical parameters such as TH with Ca, Mg, Ca & SO_4 ions are common in Gezira aquifer that regards to the formation components.

In Sandstone aquifer, the most correlations are moderate (between 0.6 and 0.5) and temporal. The strong and contentious correlation between TH – Ca during all period and TH - Mg during period from 1991 to 2020 was observed, in which a great dependence of hardness on magnesium and calcium ions. A strong correlation between TH with CL & Na and the HCO_3 with EC and TDS during period from 1991 to 2000 was observed. During the period from 1991 to 2020, the dominant correlation is moderate and temporal relation such as TDS with CL, SO_4, HCO_3& Na and the TH with CL & SO_4ions.

The NH_4, NO_2 and NO_3 ions did not show any significant correlation with any physiochemical parameters for the two aquifers during the four periods except NO_2 & NO_3 ions in Gezira aquifer during period from 2011 – 2020 which is attributed to the increasing rates of pollution from the waste disposal, as domestic waste through siphons system.

Types of Water

According to the Piper Trilinear diagram (1944), the most dominant type of groundwater facies for the two aquifers is Bicarbonate - Sodium, Calcium - Magnesium types (Figure 17). Bicarbonate - Sodium type represents 42 % and 48% of the samples for Gezira and Sandstone aquifers respectively. Bicarbonate - Calcium type represents 33% and 37% of the samples for Gezira and Sandstone aquifers respectively. While Bicarbonate - Magnesium type represents 17% and 12% of the samples for Gezira and Sandstone aquifers respectively.

Generally, the spatial distribution of water facies for both aquifers shows that the Bicarbonate - Calcium and Bicarbonate - Sodium are the dominant water facies. Where, Bicarbonate – Calcium type distributed in the area parallel to Blue Nile and Bicarbonate – Sodium type distributed at the middle of study area. The Ca – Na & Cl – SO4 facies shown at isolated zones at the middle of the study area (figure 18). These reflect the composition of Nile waters and the influence of the recharge.

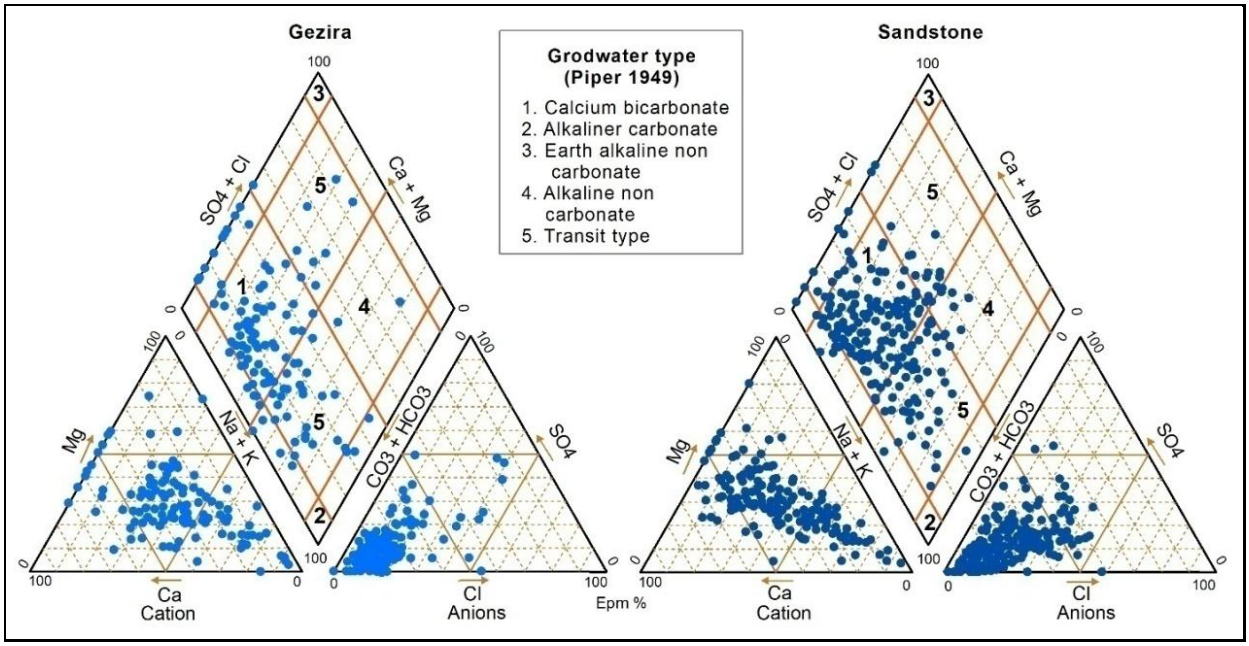


Figure 17: Classification of the groundwater facies for Gezira and Sandstone aquifers

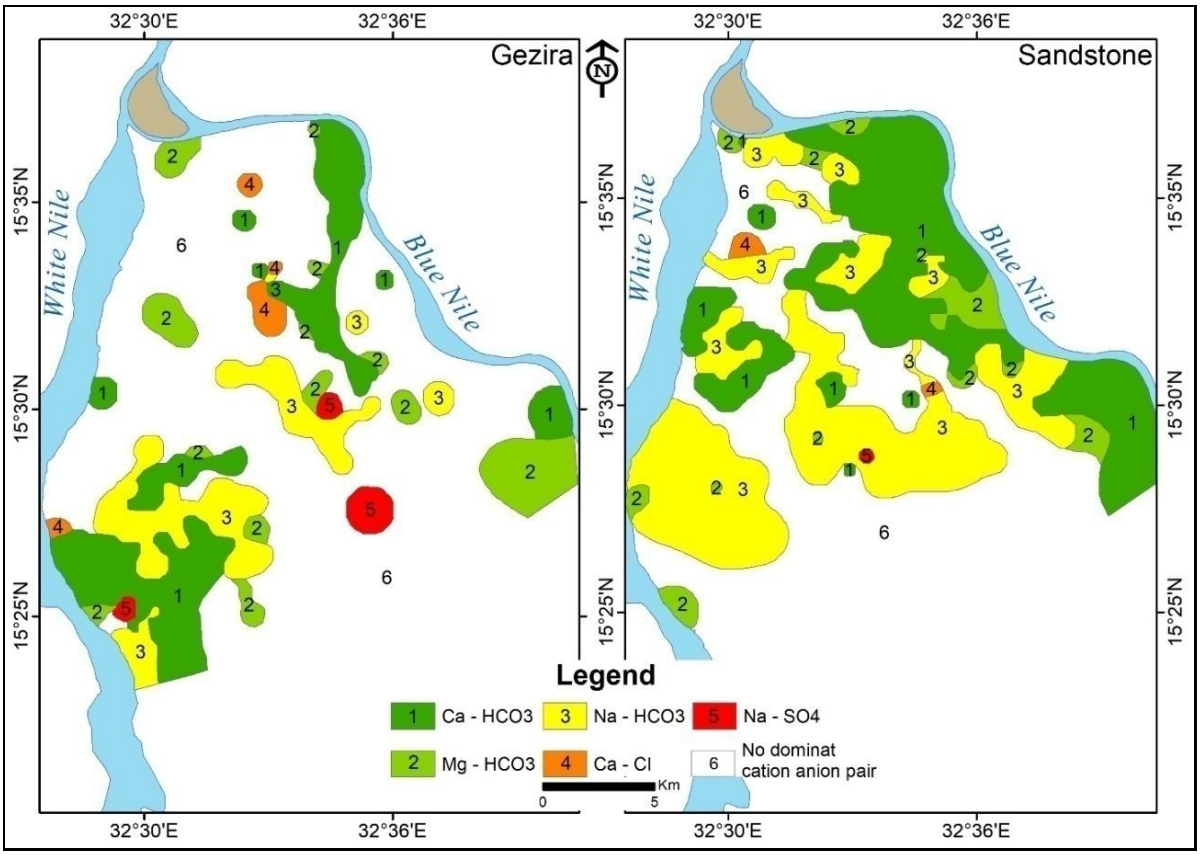


Figure 18: Spatial distribution of hydro-chemical facies for Gezira and Sandstone aquifers

Mechanisms Controlling Groundwater Chemistry

Gibbs diagram and water–rock interaction

According to Gibbs (1970) diagram in both aquifers, the majority of samples fall in rock dominance. Based on this diagram the dissolution of carbonate and silicate minerals are the dominant controlling factors of the groundwater chemistry in the study area. Next to rock dominance, in Gezira aquifer a few groundwater samples fall into evaporation dominance area (Figure 19).

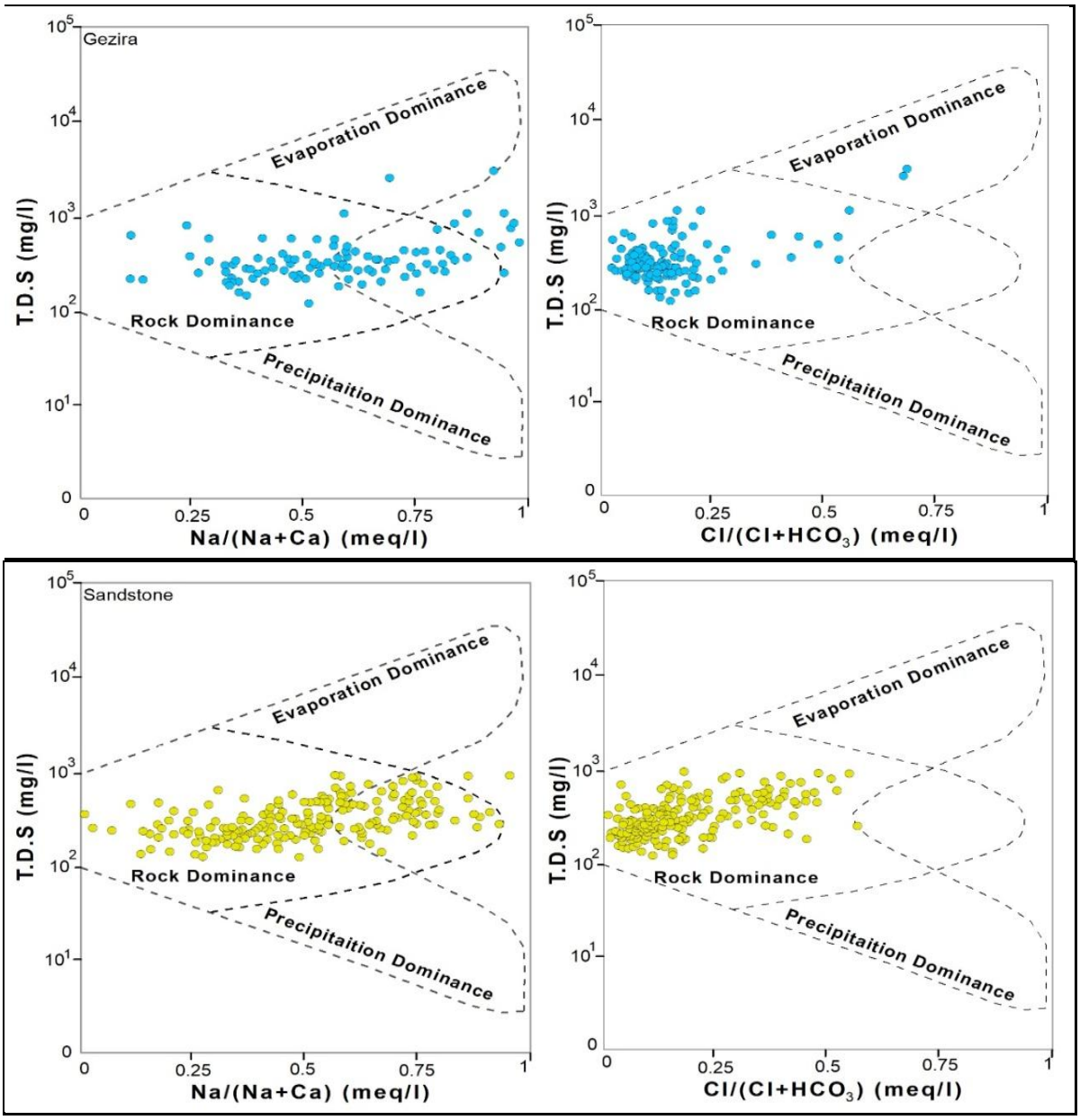


Figure 19: Gibbs diagram for anions and cations against TDS for Gezira and Sandstone aquifers

Silicate Weathering

The Na/Cl ratio is an important factor in determining the source of Na and Cl. If the Na/Cl ratio is around or above 1, it indicates that sodium is attributed from silicate weathering related to ion exchange processes (Tay, 2012; Kumar et al, 2006; Garcia, et al., 2001; Mayback, 1987) Most of the samples in both aquifers were located along and above the equiline. This indicted that Na^+ ions are not only derived from the dissolution, but also from other processes such as silicate weathering (figure 20). The Na-feldspars (Albite) is example of silicate weathering;

$$2Na\ Al\ Si2\ O3 + 2H2\ CO3 + 9H2O > Al2\ Si2\ O5\ (OH)4 + 2Na + 4H4\ SiO4 + 2HCO3$$

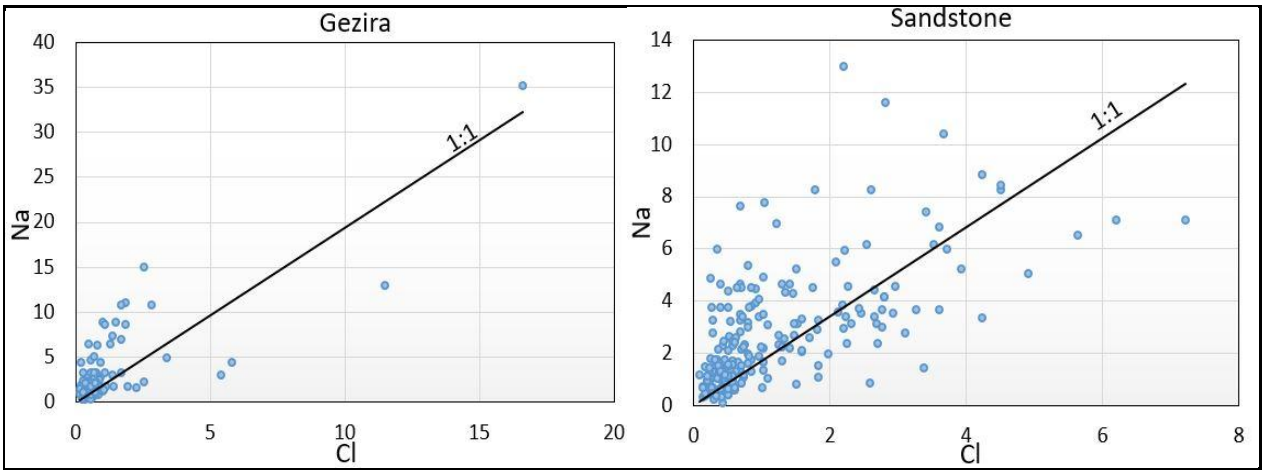


Figure 20: Plot of Na versus Cl ions for both Gezira and Sandstone aquifer

The HCO_3 versus Na ions scatter diagram shows that most of the samples cluster within the HCO_3 domains above the equity line, the excess of HCO_3 to Na ions is due to silicate weathering (fisher and Mullican, 1997), (figure 21).

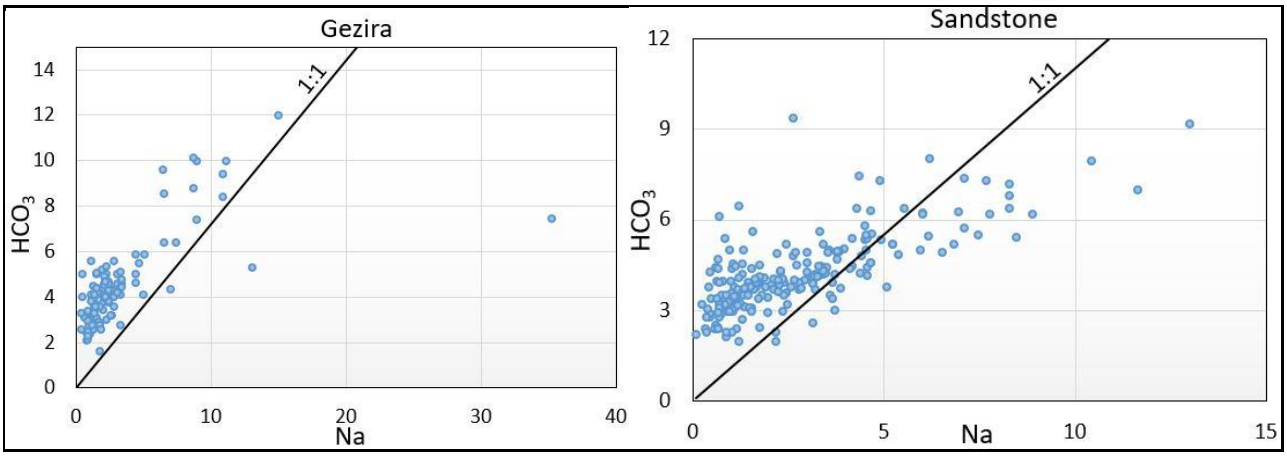


Figure 21: Plot of HCO_3 versus Na ions for both Gezira and Sandstone aquifers

Carbonate Dissolution

The dissolution of carbonate rocks is a significant source of calcium. The main minerals in carbonate rock are Ca-and Mg-carbonates which dissolve easily in groundwater and give the water its 'hard' character (Appelo, 2005). According to the following reaction, calcium can be released.

$$CaCO_3 \leftarrow Ca^{2+} + CO_3^{2-}$$
$$CaCO_3 + H_2O \leftarrow Ca^{2+} + HCO_3^- + HO^-$$

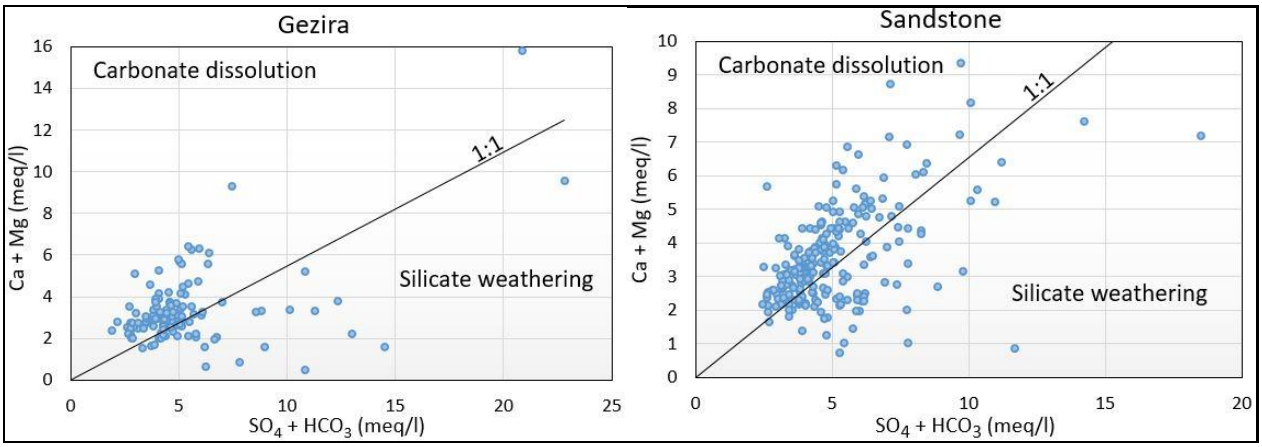


Figure 22: Plot of (Ca + Mg) versus (HCO_3 + SO_4) ions for both Gezira and Sandstone aquifers

The scatter diagram of (Ca + Mg) versus (HCO_3 + SO_4) ions for both aquifers was developed, (Figure 22). Most of samples distributed along and above the equity line. This indicates that carbonate dissolution is a major reaction-taking place.

If equivalent weight of Ca over Mg = 1 and Ca/Mg = 1-2 suggest dissolution of dolomite and calcite, respectively, whereas Ca/Mg > 2 (excess of Ca over Mg), indicates silicate weathering, according to Mayo and Loucks (1995) and Katz et al. (1998). The scatter diagram of Ca/Mg vs total cations for both aquifers (Figure 23) indicates that most of the samples fell along and below the line of Ca/Mg = 2 This evidence that dissolution of dolomite and calcite are a major reactions taking place.

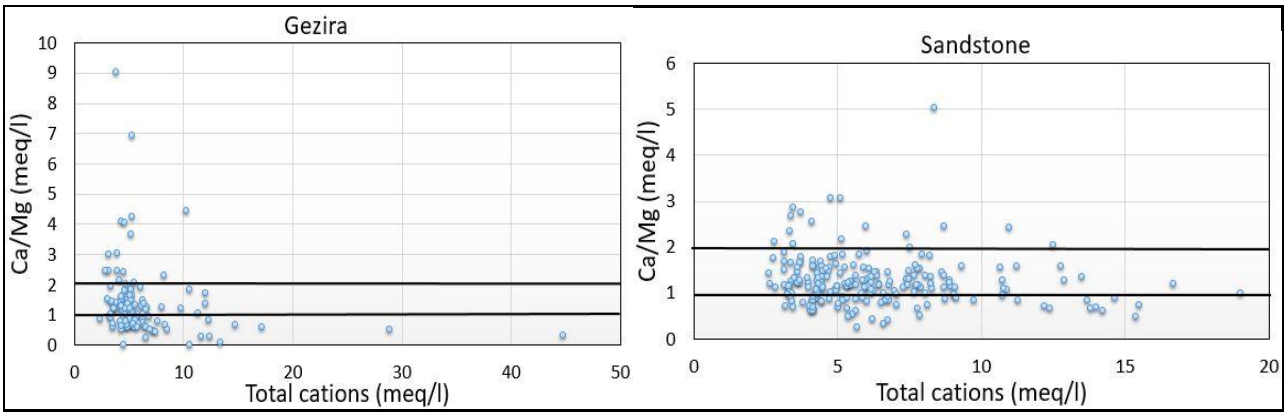


Figure 23: Plot of (Ca / Mg) versus total cations for both Gezira and Sandstone aquifers

Ion Exchange

Ion exchange is one of the most important geochemical processes and plays an important role in controlling changes in groundwater chemistry. It can be described by the chlor-alkali index (CAI), which was proposed by Schoeller (1977) to indicate the ion exchange between groundwater and its host environment. According to Schoeller, the CAI value is:

$$\mathrm{CAI-I} = \frac{[\mathrm{CL^-} - (\mathrm{Na^+} + \mathrm{K^+})]}{\mathrm{CL^-}}$$

The negative values of CAI mean the occurrence of sodium and potassium exchange with calcium and magnesium in the rocks by a Base Exchange type. Meanwhile, a positive value of CAI indicates the absence of Base-Exchange reactions and the existence of cation–anion exchange type of reactions (El Tahlawi, Et al., 2014).

In the study area 88% and 89% of the samples for Gezira and Sandstone aquifers respectively recorded negative CAI values that give an indication of the occurrence of exchange between Ca^{2+} and Mg^{2+} ions in water and Na^{+1} and K^{+1} ions in the host rocks.

The binary analysis plot of (Na−Cl) versus (Ca + Mg-SO_4- HCO_3) was used to evaluate the cation exchange process (Ettazarini, 2005; Rajmohan and Elango, 2004). If cation exchange is the dominant process between Ca^{2+}, Mg^{2+}, and Na^{+}, K^{+}, these two parameters should be linear with a slope of −1 (Fisher and Mullican, 1997), (Figure 24).

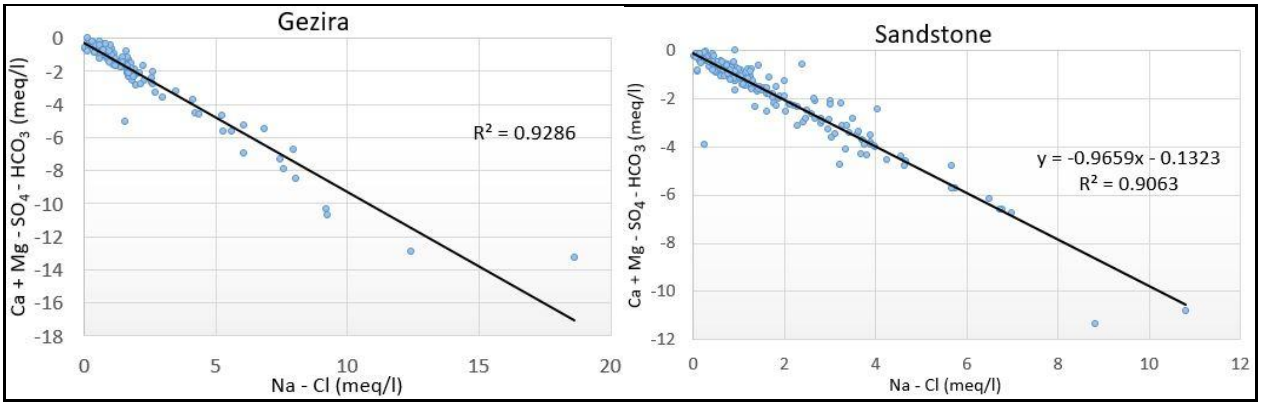


Figure 24: Plot of (Na−Cl) versus (Ca + Mg-SO4- HCO3) for both Gezira and Sandstone aquifers

Evaporation

The scatter diagram of Na versus Cl ions (Figure 20), shows that the sample points are on and above the 1:1 equiline suggesting the process of evaporation and halite dissolution respectively, (Jankowski and Acworth, 1977). The binary analysis plot of Na/Cl ratio versus EC (Figure 25) gives a horizontal line. This means that the Na/Cl ratio does not change during the increase of EC, suggesting an increase in Na and Cl ions concentrations by the process of evaporation or evapo-transpiration.

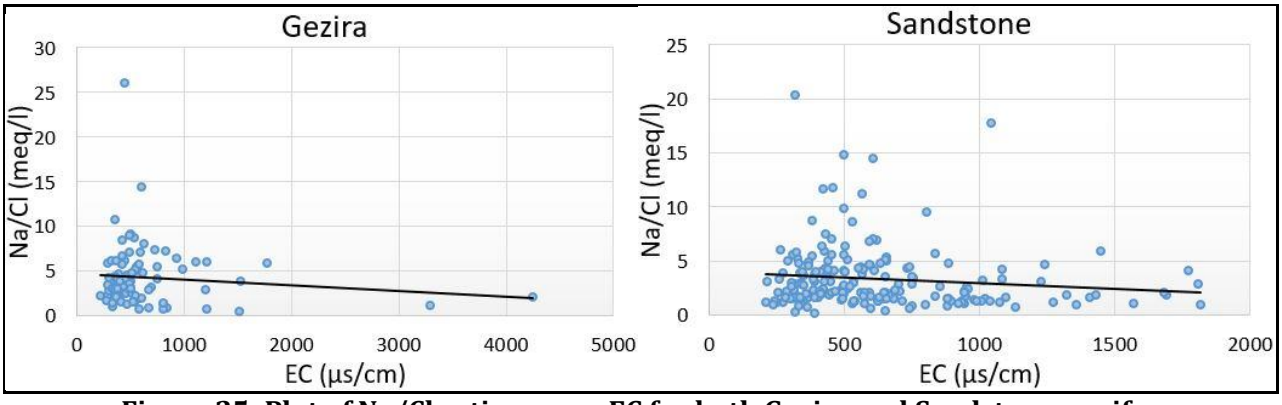


Figure 25: Plot of Na/Cl ratio versus EC for both Gezira and Sandstone aquifer

CONCLUSIONS

Groundwater chemistry depends on the quality of recharge water and on geological as well as geographical residency in the area. Several factors such precipitation/rainfall patterns, groundwater flow patterns, infiltration rate, disillusion of rocks, water-rocks interaction in addition to human activities affecting groundwater chemistry.

The study area occupied the Khartoum area at the confluent of the Blue and White Niles. The area is characterized by an arid region (sub-Saharan region), with average annual rainfall is about 115 mm. The main water-bearing formations in the study area are the Gezira Formation at the top and Cretaceous Sandstone Formations below.

The main objective of the current investigation is to determine the correlation between physicochemical properties and their spatial distribution during time intervals in Khartoum area. Large amount of collected data were distributed evenly throughout the study area. The data describing different parameter obtained from three water analysis laboratories. A correlation matrix calculated for different pairs of major ions, TDS, EC, PH. major anions and cations.

The average of PH values for Gezira and Sandstone aquifer are of closely values. It is change in both aquifers during four periods of investigation from alkaline toward acidic water type. Classification of water types, 53% and 35% of samples in Gezira aquifer were classified as moderately hard and hard respectively. For Sandstone, aquifer 54% and 34% of samples were classified as hard and moderately hard respectively.

The total hardness (TH) in water is generally refer to the soil / rocks chemistry in which the concentration of Na & S contents will influence on total hardness. The average *TDS* value is about 394 mg/l for Gezira aquifer and about 373 mg/l for Sandstone aquifer.

During the four recorded periods, the total anionic and cationic values of the Gezira aquifer are relatively higher than Sandstone aquifer. The anionic and cationic composition for the study area shows that the Bicarbonate, Sodium, Sulphate and Chloride ions are the highest concentrations in the two aquifers. The correlation matrix of 15 variables were prepare in four periods for each aquifer. It shows contentious relation and temporal relation for each aquifer in which significant impact of period variations in the study area was recorded.

Generally, the spatial distribution of water facies for both aquifers shows that the Bicarbonate - Calcium and Bicarbonate - Sodium are the dominant water facies. The majority of samples fall in rock dominance, the dissolution of carbonate and silicate minerals are the dominant controlling factors of the groundwater chemistry in the study area. Based on chlorine-alkali index (CAI), in the study area 88% and 89% of the samples for Gezira and Sandstone aquifers respectively recorded negative CAI values that give an indication of the occurrence of exchange between Ca^{2+} and Mg^{2+} ions in water and Na^{+1} & K^{+1} ions in the host rocks.

The Ammonia and Nitrate average values in both aquifers are increased with time as indicator for prolusion as a result of human expansion. The values in Gezira aquifer are relatively higher than in sandstone aquifer, where the Gezira aquifer is rest at top near the pollution sources.

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