



Hydro-chemical Characterization of Groundwater in Eastern Bank of the River Nile, Dongola Basin, Northern State, Sudan

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Abstract

Hydro-geochemical investigations are carried out in the eastern part of the River Nile, Dongola Basin; Northern State, Sudan in order to assess its suitability in relation to domestic and agricultural uses.

A total of 140 groundwater samples were collected and analyzed for various physicochemical parameters and major cations and anions, pH, EC, TDS salinity, Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , SO_4^{2-} , and HCO_3^- . The majority of water samples were moderately hard water, and temporary hard (carbonate and bicarbonate hardness). The water types of the studied area are 39% Na-HCO₃, 20%Ca-HCO₃, 14% Na-SO₄, 10% Mg-HCO₃, 8% Na-Cl, 0.7% Ca-SO₄ and the other rare type for Mg-SO₄ and Ca-Cl water types. Using environmental and stable isotopes (Oxygen-18 and Hydrogen-2), based on tritium concentration, groundwater is, classified into two groups; the first one is < 3 T.U. includes about 93% of water samples. Group II: with tritium concentration varies from 3 T.U to 20 T.U., therefore, the water recognized mainly as in filtered and discharged 20years ago from the River Nile. The Total Dissolved Solids (TDS) in some groundwater samples TDS increases with $\delta^{18}O$ this means salinity due to recharge of surface water.

Keywords: Groundwater Quality, Stable Isotopes, Dongola Basin, River Nile, Northern State, East Bank

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I. Introduction and Hydrological Setting

Water quality analysis is one of the most important aspects in groundwater studies. The Hydrochemical study reveals quality of water that is suitable for drinking, agriculture and industrial purposes. Further, it is possible to understand the change in quality due to rock- water interaction (Kelley, W.R., 1940; Wilcox, L.V., 1948; Siddig, M.E.; O.A.O. Al-Imam & Hussein, A. H., 2013 & Siddig, M.E. & Hamed, B. O., 2016, Siddig, M.E. et al., 2022) or any type of anthropogenic influence. Groundwater often consists of several chemical elements e.g. Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , HCO_3^- and SO_4^{2-} etc. The chemical parameters of groundwater play a significant role in classifying assessing water quality (Sadashiraiah, C., et al. 2008, Siddig, M.E. et al., 2022) considering the individual and paired ionic concentration, certain indices are proposed to find out the alkali hazards. Residual sodium carbonates (RSC) can be used as a criterion for finding the suitability of irrigation waters.

Hydrological Structure of the Dongola Basins is considered as one of the most important groundwater basins in Sudan in terms of groundwater availability, water quality and degree of utilization. The basin is considered as the northern extension of the Blue Nile– Khartoum rift basin. Groundwater occurs in the sandstone aquifers of the Wadi El Melek Formation and lesser extent in Wadi Howar Formation and the Sandy lenses of the River deposits. Depth to groundwater is controlled by topography, Basement configuration, proximity to the River Nile, as well as existing pumping regime (Ibrahim M.E., 1985; Lahmeyer International, 2006, Siddig, M.E. et al., 2022).

Groundwater in the basin occurs generally, under free water table conditions and depth varying from 2-5meters below ground surface along the Nile strip and the Qa'ab Depression, 10-25meters along Wadi El-

Mugaddam. In the study, groundwater occurs generally, under free table conditions, and may be some places are slightly confined resulting from the presence of sandstone or clayey lenses. The Lowest groundwater level is that around Al Selaim Canal (Mohamed, K. Omar, 1983 Siddig, M.E. et al., 2022).

The groundwater reflects the mineralogical composition of the rocks in the aquifer also can be used to localize recharge areas and to determine the origin of groundwater (meteoric, marine, fossil, or water) and of individual chemical components (e.g. carbonate, sulphate, nitrate and ammonium).

The water compositions can also give information about processes of water-rock interaction and microbial processes in the water chemical precipitation controlled by the solubility of a substance, and chemical alteration by e.g. oxydo-reduction and complexation processes. Cations in the water types derived mainly from the leaching of the rock, minerals and the soil whereas; the anions come mainly from lithological sources.

The purpose of this paper is to assess the interactions between surface and groundwater in Dongola basin area, using environmental and stable isotopes. The results based on tritium concentration, therefore, classified into three groundwater groups.

The study area lies along the eastern bank of the River Nile in the Northern State, Sudan. The area forms an elongated shape and generally (Dongola Basin) bounded by longitudes (29° 27' 52.13" – 31° 00' 00" E and latitudes 17° 19' 00" -20° 55' 59.42" N (**Fig. 1**), (Siddig, M.E. et al., 2022).

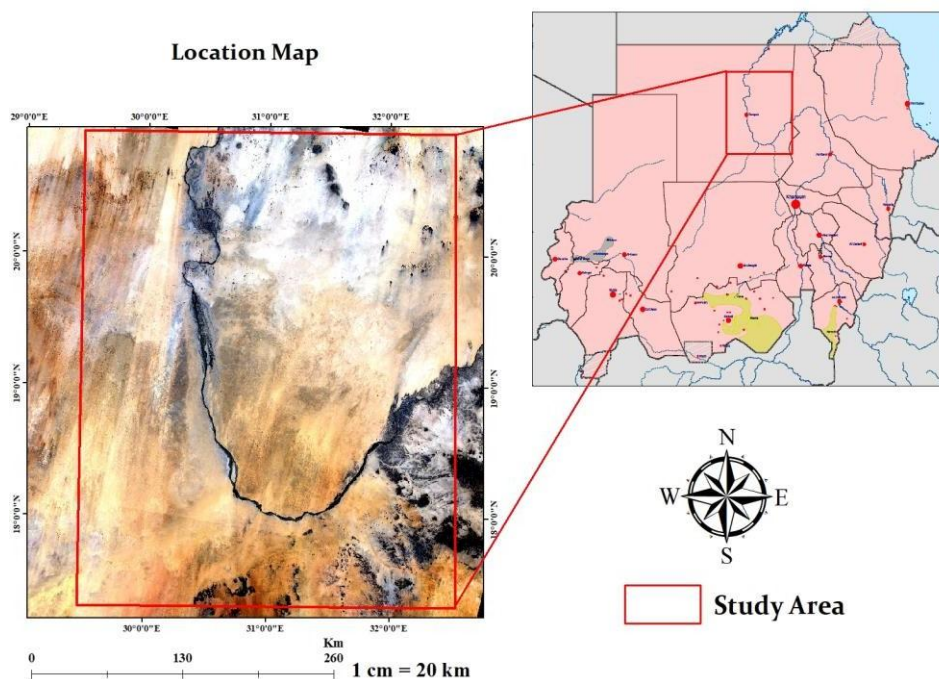


Fig. 1: Location of the Study Area

II. Physiographical Features

The River Nile is the most important source of water for irrigation and supply approximately about $800 \times 10^6 \text{ m}^3$ yearly. It is the only perennial surface water resource, available in this area. High water level occurs during high flood period (August – September) and the minimum water level during (December – June) the difference between the highest and lowest level is about 4.59 m at Dongola (Groundwater and Wadis Directorate & International Atomic Energy Agency, 2000, Siddig, M.E. et al., 2022).

The area lies in the arid desert climatic region, in which rainfall is very low /negligible. The winter season is distinctly pleasant; from October to mid-March, the mean daily temperature is below 20 °C, in the early morning, the temperature may fall to zero (0°C). The humidity is low, and there is very little cloud cover and no rain (Bonfica Geoexpert, 1986a).

The wind blows from the north with a mean speed between 15 – 20 Km/h. Summer is long and very hot; from the beginning of May until the end of September, the mean daily temperature reaches 40°C; humidity is high particularly in August, and the normal wind speed falls about 12Km/h; and blows from different directions (Bonfica Geoexpert, 1986b).

The mean annual rainfall is about 9.280 mm / annum (1989 – 2008), rainfall characterized by low variability 17.1223(Siddig, M.E. et al., 2022). Evapotranspiration is high ranging from 233 to 1677mm/annum. Vegetation in the study area is restricted to the banks of the River Nile and the floors of the big seasonal water resources such as Wadi El- Melek, Wadi Al-Mugaddam, Khor Abu Sunt and Khor Masur. In these stream beds,

coarse grasses and *Acacia tortilis*, *Acacia mellifera* and *Acacia Seyal* are found. Along both sides of the Nile Date Palms are intensively farmed. Some isolated trees of Sidr (*Ziziphus spina*), Haraz *Acacia Albida* and some green Nile grasses are also found. Herbs and fine grasses spring up after the very rare rain shower during the summer but they soon disappear (Salih Lh. M., 1987).

III. Objectives

The overall objectives of this work are to describe the hydrochemical composition of the groundwater underlying the study area and to assess its water quality with respect to domestic, agricultural, and industrial usage. The detailed objectives of the groundwater quality study are:

- Determination, description, and explanation of lateral and vertical variations of major ion concentrations in the occurring aquifers,
- Investigation of time-related changes of major ion concentrations,
- Calculation of saturation indices with respect to selected minerals for the assessment of corrosion and encrustation hazards,
- Determination of trace element concentrations and “fingerprints” in the different aquifers,
- Determination of detrimental effects of agriculture-related chemicals on the groundwater,
- Assessment of the water quality with regard to domestic, agricultural, and industrial usage.
- Using environmental and stable isotopes (Oxygen-18 and Deuterium), based on tritium concentration can yield valuable information for solving problems: determination of recharge source, rate and mechanism; residue time and interaction between different water bodies.

IV. Data used in this study

The groundwater quality study draws upon two datasets: data collected in the course of previous groundwater studies and new hydrochemical analysis of groundwater samples.

Numerous chemical datasets are given in previous groundwater studies. All existing chemical data was revised and incorporated into a database. From this database, those datasets were selected, that fulfilled the following criteria:

- The well was located in the selected study area,
- The dataset yields information about the relevant aquifers,
- The dataset contains all of the following parameters: total dissolved solids (TDS), calcium (Ca^{2+}), potassium (K^+), magnesium (Mg^{2+}), sodium (Na^+), chloride (Cl^-), sulphate (SO_4^{2-}), and bicarbonate (HCO_3^-).

The physico-chemical characteristics such as temperature, pH, and electrical conductivity (EC) available, this data was considered.

V. Methodology

5.1 Sampling and Field Analysis

Groundwater samples and measurements were collected from 140 boreholes and the River Nile in the East River Nile Bank. (Hager, M.A., 2010) (Fig.2), The GARMIN GPS was used to locate the exact coordinates of the sample collection to continue monitoring purposes. Samples were collected from operational or constantly operating production wells or in the course of the conducted pumping tests. In the case of the operational wells, the wells were purged before the samples were taken in order to minimize the risk of sampling stagnant water and to assure that the water sample is representative of the aquifer.

Field parameters like temperature, EC, and pH value were measured at the well head during sampling. The parameters were measured using universal pocket meters (EC meter). The meters have the following measuring ranges and accuracies (Table 1):

Table 1: EC and pH value measuring ranges and accuracies

Parameter	Measuring range	Precision
Temperature [°C]	-5.0...+105.0	± 0.1
EC [mS/cm]	0...500	± 1 %
pH value [-]	-2.00...+19.99	± 0.01

5.2 Laboratory Analysis

The major part of the chemical laboratory analyses were conducted by the Khartoum State Water Corporation (KSWC) lab. Some analyses were performed by Groundwater and Wadis Directorate (GWD) laboratory.

The following list gives an overview over the main methods that were applied in the course of the laboratory analyses:

- Atomic Adsorption Spectrometry (certain cations),
- Ion Chromatography (major ions, excluding bicarbonate),
- Inductively Coupled Plasma Mass Spectrometry (trace elements),
- Gas-Chromatography-Mass-Spectrometry (organic compounds),
- liquid scintillation counter analyzer,
- Mass Spectrophotometer

The equipment and instruments were tested and calibrated with calibration blanks and serious of calibration standards as per specifications outlined in standard methods of water (APHA, AWWA & WEP 1998). Total Hardness (TH) was calculated by the following equation (Raghunath, 1987), $TH = (Ca + Mg) \times 50$ where, TH is expressed in meq/L, and the concentration of the constituents are expressed in meq/L. The sodium absorption ratio (SAR) was calculated by the following equation given by Richards (1954).

Thirty three samples were taken from boreholes and three samples (**Fig. 2**) from the River Nile in the eastern bank to determine the radioactive and environmental isotopes (tritium, deuterium and oxygen-18).

5.3 Data Analysis

The chemical data were analyzed using the following techniques:

- Preparation of Box-Whisker-plots and tri-linear diagrams (Piper-plots),
- Preparation of maps showing the spatial TDS distribution,
- Preparation of maps displaying the spatial distribution of major cations and anions,
- Preparation of maps and diagrams for selected field parameters,
- Creation of diagrams illustrating vertical variations of concentrations of selected chemical constituents,
- Calculation of saturation indices for common minerals,
- Preparation of irrigation hazard diagrams,

For displaying the obtained data in maps, the Geographic Information System (GIS) software ArcGIS 10.5 by ESRI was used. The GIS was connected to either Excel tables or to an Access database containing all available reliable chemical data of the study area. The Box-Whisker-plots, tri-linear diagrams, and Wilcox-diagrams were prepared using the software AquaChem 10 by Waterloo Hydrogeologic. As the geochemical modeling software PHREEQC is integrated in this program, it has also been applied for the calculation of the saturation indices.

VI. Geology of the Study Area

The Northern State in general consists of two different zones, the extremely ancient rocks; crops out along the River Nile in the north of Karma and south of Kareima. These rocks are Precambrian-Cambrian in ages, and overlain by Nubian Sandstone Formation covered by superficial deposits ranging from Mesozoic to Quaternary (Andrew, G., 1948; Hager, M. A., 2010).

The Basement Complex extended along the River Nile between Karma and Kareima and extends southwards to lower Wadi El Mugaddam and Wadi El-Melek. The Basement Complex rocks are mainly composed of metavolcanics and metasediments and granitoid rocks (Kheralla, K. M., 1966).

The Nubian Formation unconformable overlies the Basement Complex. It is dominated by argillaceous and arenaceous beds with mudstone and siltstones. Calcareous and ferruginous beds are common (Kheralla, K. M., 1966). The formation is characterized by rapid facies changes in all lithologies. The Nubian Sandstone in Dongola area is referred to as Wadi El-Melek Formation which is divided into three units; pelitic sandstone at the top, followed by argillaceous sandstone of fine to medium intercalated with silts and clays with lateral and vertical facies changes. In general, this unit represents the major sandstone sequence, thickness ranges from 100-180m and conglomeratic sandstone lies unconformable over the Basement Complex and consists of medium to coarse sandstone, this unit appears at deep well (Kadruka Pilot Farm) in the northeast of this area and (Kheralla, K. M., 1966).

Wadi El-Melek Formation shows great vertical and lateral variability originated by cyclical deposition of fluvial-lacustrine environments of limited extension and under increasing subsidence within the indicated

graben structure (Klitzsch, E. & Squyres C. H., 1990). The lithological structure of Wadi El-Melek Formation is composed of three major lithological units (Ibrahim, M.E., 1985). These units covered by thick superficial deposit composed of sand, silt and clays of alluvial origin, varies in thickness between 2-20m. The Nile deposits are including fine alluvial deposits near the River Nile and the coarser alluvial deposits further away (Bonfica Geoexpert, 1986a). The sediments in the study area classified as Nubian Sandstone (Late Cretaceous-Paleocene) which is the most important water bearing formation in the Sudan.

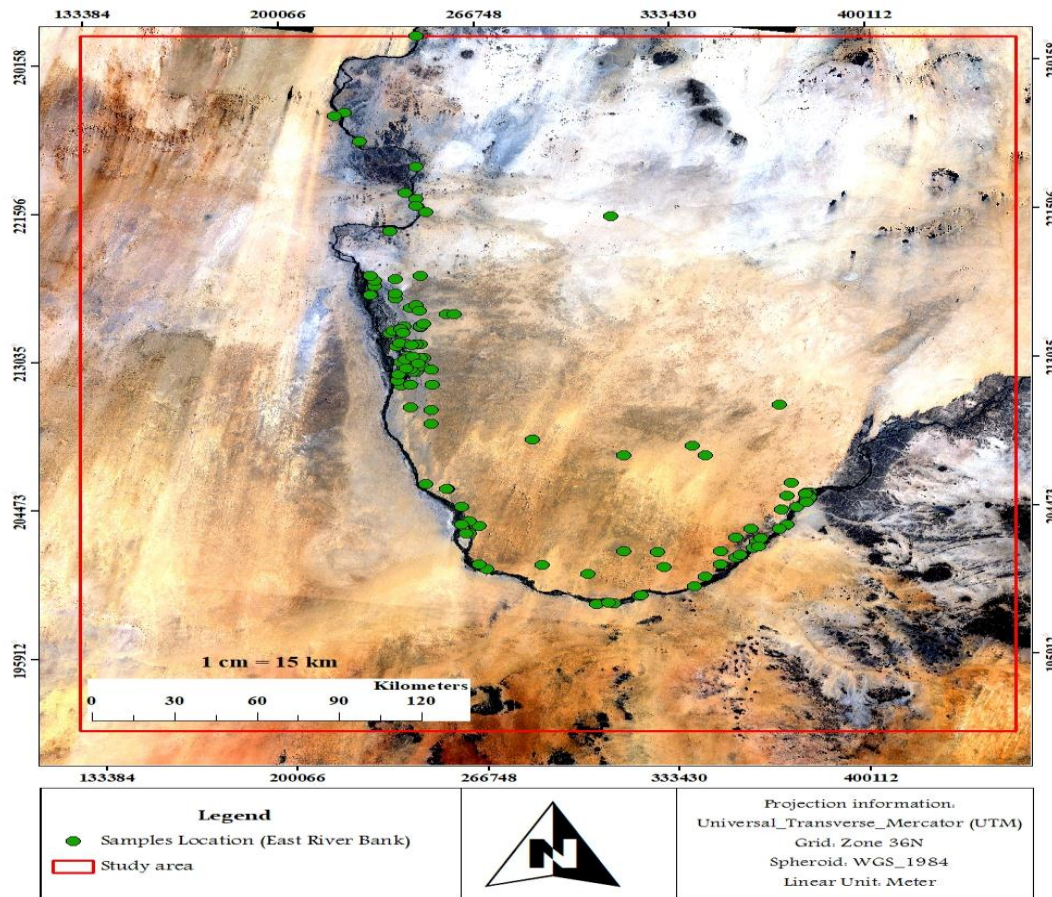


Fig. 2: Location of water samples from the Eastern bank of the River Nile, Dongola Basin.

VII. Results and Discussions

7.1 Geochemistry

Electrical conductivity is a parameter related to total dissolved solids (TDS). The importance of TDS and EC lies in their effect on the corrosivity of a water sample and their effect on the solubility of slightly soluble compounds such as CaCO_3 (Nas, B. & Bertay, A. 2010). Accordingly, to Langenegger (1990), the importance of electrical conductivity is an indirect measure of salinity in many areas, which generally, affects the taste and thus, has significance on the user acceptance of the water as potable. TDS values of the River Nile water samples varies from 163 ppm to 272 ppm. Groundwater samples TDS varies from 76 mg/l to 1748 mg/l indicates that 95.86% of existing groundwater sources at the East River bank. Most of them represent fresh water, according to classifications of water (Matthew, J.; Currel, Ian C.; Dean, C.; Bradley & Dongnei, Han, 2010), TDS range (0- 100 ppm). TDS - EC relationship (= geochemical coefficients) for the area East River Nile bank demonstrated Fig.3, the coefficients of 0.6826 (East Side) (becomes 0.7). About 4% of East River bank water samples represent brackish water (**Table 2**). The high a concentration of TDS in the open and a shallow well are due to evaporation and in the deep wells is due to leaching of rocks and concentration of chemical ions in the aquifer.

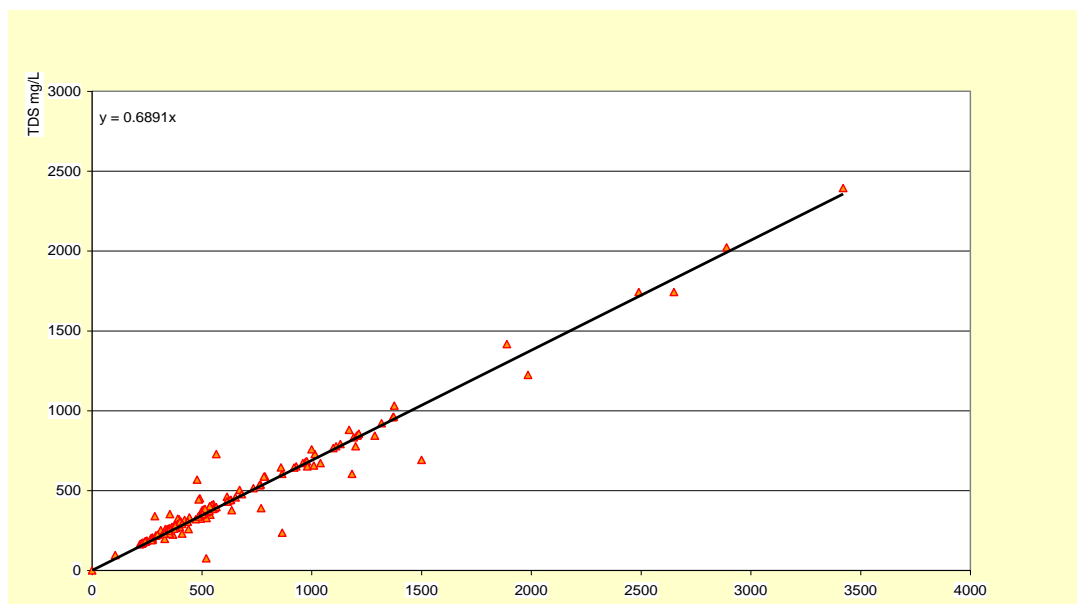


Fig.3: TDS vs. E.C. in the Study Area-East River Nile Bank

7.2 Suitability for Drinking

Table 2: The Drinking water problems of the study area-East River Nile bank

Parameters	Within the Range of WHO Standard		Greater than WHO Range		
	NO. of Wells	%	NO. of Wells	%	Remarks
pH	94	67.63	45	32.37	Many samples over the range.
TDS	135	97.83	3	2.17	Samples No.(75,81,102 and 122)
Total Hardness	136	98.55	2	1.45	Sample No. 44 and 102 ;122
Potassium	139	100	-	-	All samples within the WHO range
Sodium	133	95.68	6	4.32	Samples NO. 75,77,81,85,133 and 135
Calcium	135	97.12	4	2.88	Samples NO. 44,102,122 and 133
Magnesium	138	99.28	1	0.72	Sample NO. 44
Chloride	135	97.12	4	2.88	Samples (44,75,81 and 102)
Sulphate	129	92.81	10	7.19	Samples (27,44,77,81,93,102,121,122,133 and 138
Fluoride	138	99.28	1	0.72	Sample NO. 27; has 2 mg/l
Ammonia	139	100	0	0	All samples within the WHO range
Nitrite	139	100	0	0	All samples within the WHO range
Nitrate	139	100	0	0	All samples within the WHO range

There were some water samples at the East River Bank, unsuitable for human consumption, because there were one or more parameters greater than WHO and Sudanese Level Standard (Table 2). For example sample No 75 with high concentrations of sodium and chloride, this water resemble as the feature of sea water (NaCl). Sample No.44 recorded high calcium, magnesium chloride, and sulphate concentrations. We suggest there were $CaCl_2$ $MgCl_2$ - $CaSO_4$ - $MgSO_4$ rocks type in the locations, the majority of water samples was moderately hard water and temporary hard (carbonate and bicarbonate hardness) it is to be assumed that, groundwater having pH values above 8.4 are usually associated with sodium carbonate-bicarbonate water, moderately high pH (9.0) values are commonly associated with high bicarbonate concentrations, also we suggest the main rocks in the aquifer is calcium and magnesium carbonate and bicarbonates type (dolomite). The other type of hardness is permanent hardness (sulphate, chloride, salts).

Magnesium ion concentration- at East River bank varied from 0 mg/l to 167 mg/l. All samples were within the WHO range except for sample No 44 (167 mg/l). It is to be anticipated that the chemical composition of aquifer rocks is void of magnesium ion, or constituents of water may become modified by subsequent chemical reactions, such as cation exchange, absorption of dissolve ions and biological influences, also to my point of view; high magnesium concentration is related to high dolomite minerals if calcium ions are

found in the aquifer maximum concentration of calcium ions in the water samples at East banks in the study area is 120mg/l; basaltic composition maybe among the igneous rocks and in carbonate rocks (limestone, dolostone) among sedimentary rocks. Calcium is also a dominant cation in most river waters.

Sodium maximum ions concentration of groundwater samples taken in the study area was 524mg/l Na⁺ recorded at the East bank sample No. 81. While the minimum ions concentration about 0.996mg/l was measured for sample No. 1. The majority of samples were within the standard range (200mg/l); only six samples were of values greater than WHO and SLS.

The variations of sulphate ions concentrations in the study area are due to sedimentary rocks with evaporate comprising gypsum (CaSO₄.2H₂O) or anhydrite (CaSO₄). Ion concentrations in the study area varied from 0 mg/l to 2 mg/l (WHO 1.5mg/l).

Calcium concentrations at the Eastern bank varies from 4 mg/l to 120 mg/l, there were 88% of water samples over the standard ranges. Calcium ion is contributed by many dissolved minerals like dolomite, anhydrite and carbonate.

Four water samples at the East River bank were over the standard range (No. 44, 75, 81 and 102) their concentrations 334, 489, 550 and 383 mg/l respectively. The variation of chloride concentration ranged from 0 mg/l (sample No.39) to 550 mg/l (sample No. 81), it combined with sodium to form halite minerals.

The water samples from the Eastern River Nile bank recorded ten water samples greater than WHO and Sudanese Level Standard (SLS). The concentration of sulphate in association of calcium ion in the water to form anhydrite, calcium sulphate as one of the mineral dissolved in the aquifer.

According to the chemistry of water samples in the study area show dissolved minerals with different concentrations. The majority of water samples at the East bank lies between 1-25 mg/l of halite, the calcium carbonate concentration varies from 0-150 mg/l only one sample shows concentration greater than 150 mg/l, about 48.21 % of water samples shows dolomite concentration is 0 mg/l, but four samples at the East bank that have more than 150 mg/l. About 64% of the water samples lies between 50-200 mg/l of anhydrite; the majority of water samples lies from 0 – 10 mg/l of Sylvite (KCl); the fluorite concentration at the East River bank varies from 0 to 2 mg/l, there was only one sample over the standard range (sample No. 27). Ammonia (NH₃) concentrations of the samples from the study area varies from 0 mg/l (92.81%) to 1 mg/l (7.19%), all water samples were within the range of WHO and SLS, all water samples show nitrite (NO₂) within the standard ranges, nitrate shows the last stage of nitrogen cycle, the maximum value of nitrate at the East River bank was 26 mg/l (samples; 94 and 122) the concentration within the WHO and SLS standards range.

7.3 Suitability for Livestock

Table 3: The Guideline of California Control Board, (1963)

Quality Factor	Threshold Conc. mg/l	Limiting Conc. mg/l	Maximum Conc. in the Study Area
			East River Bank
TDS	2500	5000	2394 mg/L (NO. 81)
Ca ⁺⁺	500	1000	120 mg/L (NO.122)
Mg ⁺⁺	250	500	167 mg/L NO. 44)
Na ⁺	1000	2000	524 mg/L (NO.81)
HCO ₃ ⁻	500	500	469 mg/L (NO. 86)
Cl ⁻	1500	3000	550 mg/L (NO.81)
SO ₄ ⁻	500	1000	387 mg/L (NO.133)

According to Jack E. M. & Harold, W.W., (1963), (Table 3), all groundwater samples at the East side were suitable for livestock (because the quality factors of all of them are within the range of The Guideline of California Control Board, (1963).

7.3 Suitability for Irrigation

Table 4: Irrigation Problems in the Study Area, East River Bank

Irrigation Problems		No Problems		Increasing Problems		Severe Problems	
		No. of Wells	%	No. of Wells	%	No. of Wells	%
Salinity		100	71.94	37	26.62	2	1.44
Permeability	Adj. SAR	5	3.60	12	8.62	122	87.78
	Adj. SAR	5	3.60	12	8.62	122	87.78
Specific Ion Toxicity	Cl ⁻	125	89.93	11	7.91	3	2.16
	NO ₃ ⁻	88	63.31	49	35.25	2	1.44
Miscellaneous	HCO ₃ ⁻	5	3.60	133	96.68	1	0.72
	pH	0	0	0	0	139	100

Irrigation problems at the study area are described in details (Table 4) summarized as 71% water samples of East River bank were characterized by no salinity problems for irrigation, 100% of water samples at area of study were characterized by their severe problems of miscellaneous causes (pH) and 95.68% were characterized by increasing problems of miscellaneous (HCO_3^-).

Most of water samples in the study area indicated that so far there is no salinity problems, TDS values within the WHO and SLS (1500 mg/l, fresh water) also Electrical Conductivity (EC) measurements in mmhos/cm varied within the permissible range (<0.75). All water samples in the study area can be used for different types of irrigation according to the mentioned suitability classification for irrigation (Table 4) (Fig. 4).

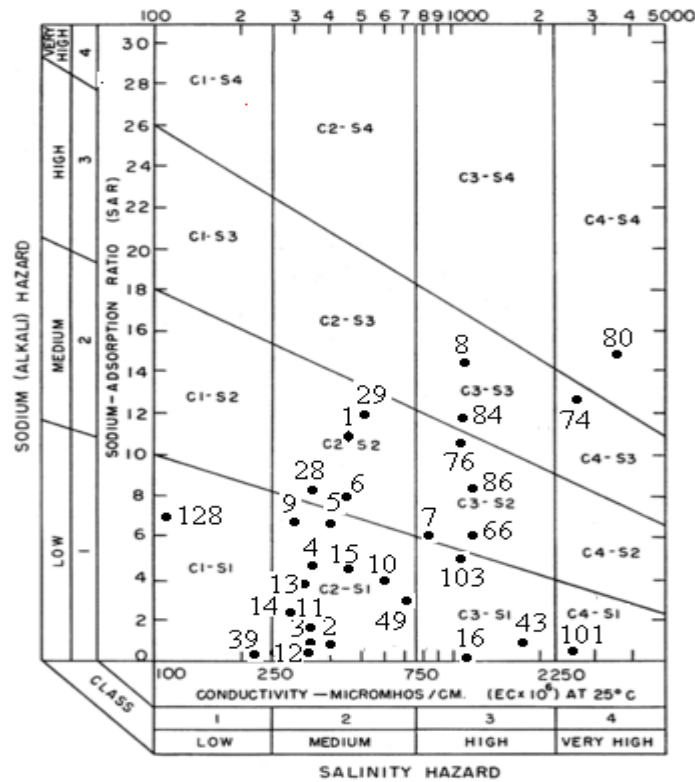


Fig. 4: Plots showing relationship between SAR & EC for Groundwaters from the East side of the River Nile (USSL 1954).

As the degree of mineralization varies widely, also the major ion concentrations show a broad data range **Fig. (5)**. Shows a Box-Whisker-plot displaying a statistical summary of selected chemical parameters that were measured. In a Box-Whisker-diagram, usually the median and certain percentiles are shown. In this study, the 5th, 25th, 75th, and 95th percentiles were chosen.

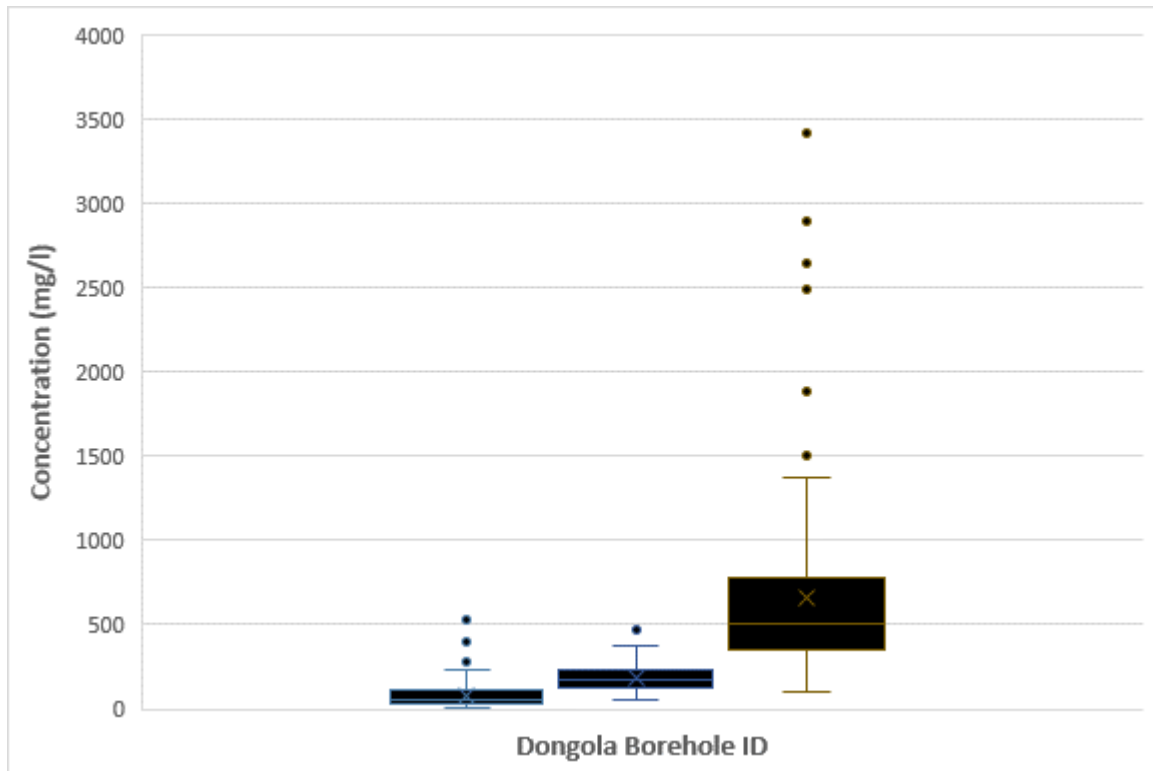


Fig. 5: Box-Whisker-plot for the main aquifer in the study area

In addition, a Durov and Piper-plot has been created in order to detect the dominating ions (Figs. 6 and 7). In this tri-linear diagram type, the proportions of the major ions are shown in meq. %. Neglecting the origin of the samples (outcrop/subcrop), it can be summarized that among the cations, sodium and calcium dominate and that, as far as the anions are concerned, chloride and sulphate are often the most important ions. Only a few samples are dominated by bicarbonate. Consequently, Ca-Na HCO₃, Na-Ca HCO₃, and Na Cl-HCO₃ are the dominant water types.

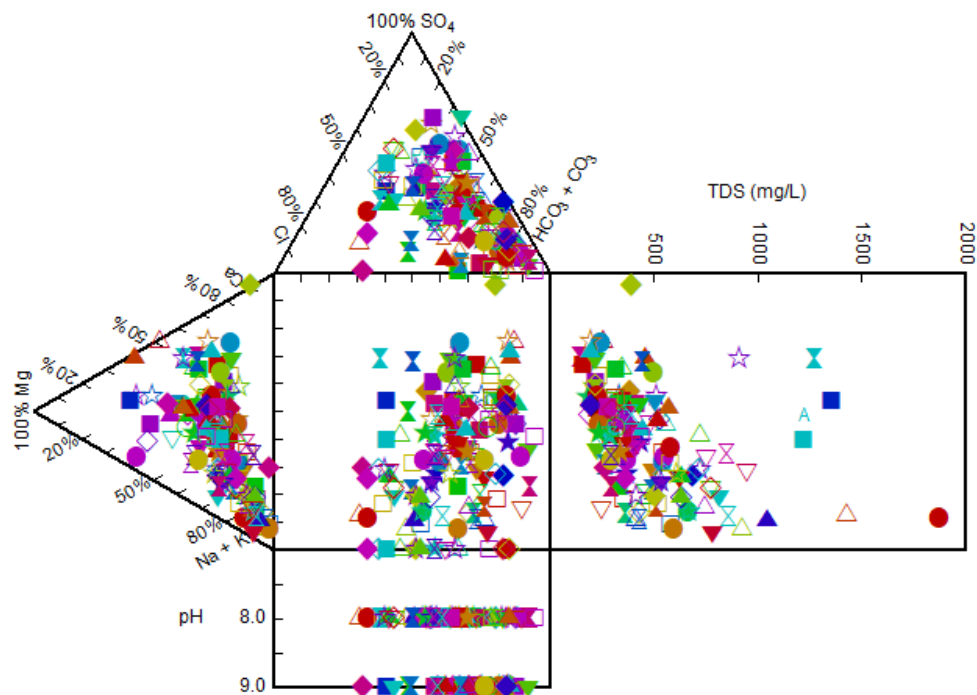


Fig. 6: Durov for the aquifer in the study area showing major ions in meq-%

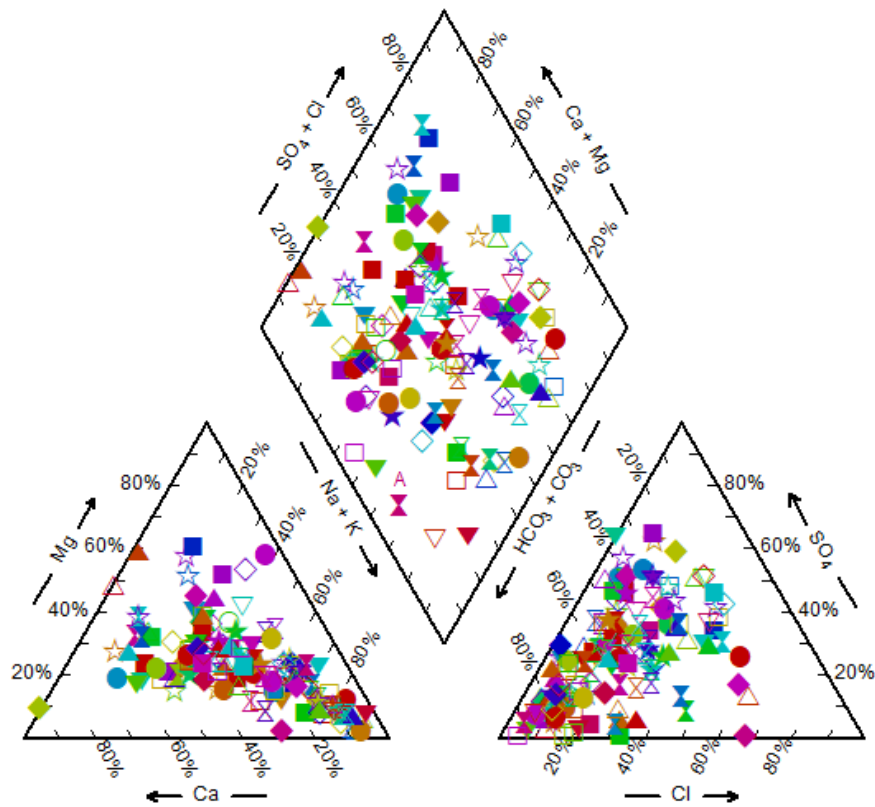


Fig. 7: Trilinear diagram showing hydrochemical facies of groundwaters from the Eastern side of the River Nile, Dongola Basin. (After Piper 1953)

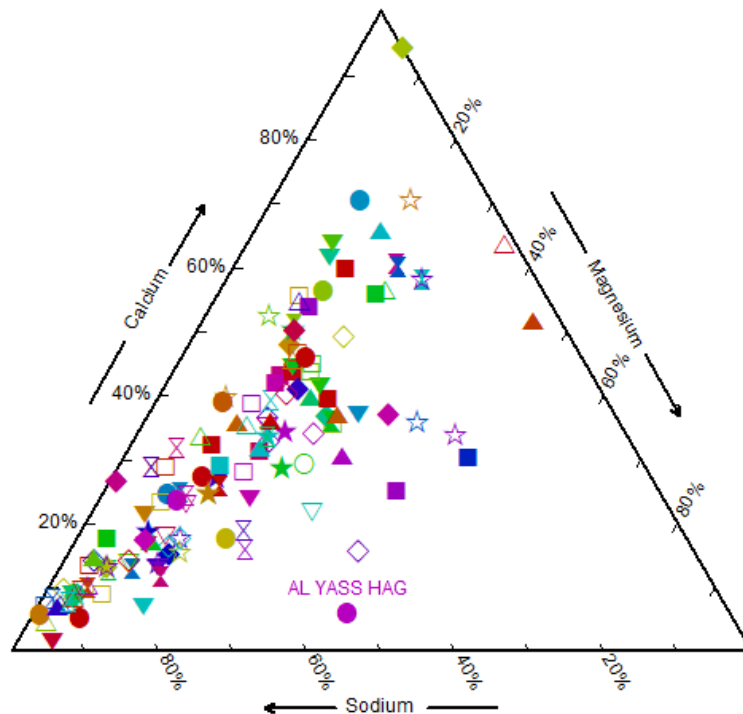


Fig.8: Ternary Diagram Dongola East

Figs. 7 & 8: Piper-plots for the main aquifer in the study area showing the proportions of the major ions in meq-%. Note the hydrochemical difference between the groundwaters from the outcrop area and the remaining waters.

The analytical results achieved from the samples when plotted on Piper’s plot, explained that the alkaline (Na⁺), appear considerably over the alkaline elements (Ca²⁺, Mg²⁺ & K⁺), and the weak acidic (HCO₃⁻) appear considerably over strong acidic anions (Cl⁻ & SO₄⁻²). According to the plotting from diagrams, most of the elements of water type are named within the NaHCO₃ zone.

The final result of the data analysis showed that the water types of the studied area are: 39% Na-HCO₃, 20% Ca-HCO₃, 14% Na-SO₄, 10% Mg-HCO₃, 8% Na-Cl, 0.7% Ca-SO₄, and the other rare type for Mg-SO₄ and Ca-Cl water types.

To interpreting chemical data and identifying the source of dissolved constituents and related hydrochemical problems, according to Piper (1964), the water from the East River bank dominant by three anions types as:

1. (HCO₃ + CO₃) type
2. (HCO₃ + CO₃) – (SO₄ – Cl) type
3. (SO₄ – Cl)type

The East bank dominated by

1. (HCO₃ + CO₃) type included the majority of samples, this water type divided into the following subgroups (**Figs. 6,7 & 8**) showing bicarbonate water type):
 - a. (Na +K)- (HCO₃ + CO₃)type
 - b. (Na +K)+ (Ca + Mg)-(HCO₃ + CO₃)type
 - c. (Ca + Mg)-(HCO₃ + CO₃)type
2. (HCO₃ + CO₃) – (SO₄ – Cl) type, this group represented 40% of water samples, this water was divided into the following subgroups:
 - d. (Na + K)-(HCO₃+CO₃) + (SO₄-Cl) type
 - e. (Na +K)+(Ca + Mg)-(HCO₃ + CO₃)+(SO₄-Cl)type
 - f. (Ca + Mg)-(HCO₃ + CO₃)+(SO₄-Cl)type
3. This group was dominated by (SO₄ – Cl) type; was divided into the following subgroups (**Figs. 6,7 & 8**):
 - g. (Na + K)- (SO₄-Cl) type
 - h. (Na +K)+(Ca + Mg)-(SO₄-Cl)type
 - i. (Ca + Mg)-(SO₄-Cl)type

Table 5: Hydrochemical datasets obtained in the course of this study. Figures displayed in red, represent violations of the respective WHO (2012) drinking-water guideline value.

Well Name	Na ⁺	K ⁺	Ca ⁺⁺	Mg ⁺⁺	HCO ₃ ⁻	CO ₃ ³⁻	Cl ⁻	SO ₄ ⁻	PH	EC	TDS
ABD EL RAOOF	167.7	0	13	2	146	0	66	185	8	486	316
ELARKE	26.174	0	38	49	305	0	12	83	8	399	260
BANGANARTE	41.44	0	45	34	286	0	13	86	9	368	239
MOL WAD B	81.144	0	13	4	195	0	14	44	8	350	228
OMAR		0	96	6	220	0	14	59	8	472	307
ELSAGAI	111.651	0	12	3	195	0	32	77	9	397	258
ABUFATMA	178.356	0	18	9	207	0	94	161	8	478	311
KIBERNARTI	91.62	0	9	4	171	0	23	63	8	866	563
ELSAGAY	275.706	0	12	8	268	0	173	191	8	1287	836

7.5 Saturation Indices

Saturation indices can be a useful tool to assess corrosion and encrustation hazards. The saturation index (SI) is defined as follows.

$$SI = \log (IAP/K) \tag{Eq.1}$$

In this equation, IAP represents the ion activity product and K is the solubility product (representing the equilibrium). Hence, a SI of 0 means that there is equilibrium between the mineral and the solution. A negative SI indicates sub-saturation and a positive SI indicates super saturation (**APPELO and POSTMA 2005**).

Before giving details about the calculation procedure and the obtained results, the most important aspects of corrosion and encrustation are presented in the following paragraphs.

The calculation of saturation indices focused on the carbonate minerals calcite (CaCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$), but also gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) was included in the assessment.

The saturation indices have been determined for all chemical datasets which include the parameters temperature, pH value, calcium, magnesium, sulphate, and bicarbonate. For the calculation the software AquaChem 10 by Waterloo Hydrogeologic, in which the multipurpose geochemical modeling program PHREEQC is integrated, was utilized. The results are presented in Table (6).

Table 6: Calculated Calcite, Dolomite, Gypsum Saturation Indices

Well Name	Aquifer	Well Use	SI Calcite [-]	SI Dolomite [-]	SI Gypsum [-]
ABD EL RAOOF	NS		2.34	3.99	-0.08
ELARKE	NS		3.08	6.44	-0.45
BANGANARTE	NS		3.71	7.56	-0.48
MOL WAD B	NS		2.56	4.76	-0.6
OMAR	NS		3.39	5.75	0.1
ELSAGAI	NS		3.09	5.81	-0.58
ABUFATMA	NS		2.53	4.89	0.08
KIBERNARTI	NS		2.34	4.48	-0.55
ELSAGAY	NS		2.35	4.65	-0.01
ABU DOOM	NS		2.34	4.55	-0.74
ABU EL RAO	NS		2.55	4.61	-0.03
HSSAN	NS		2.83	5.36	0.21
GANTE	NS		2.9	5.7	-0.53
LATEL-1	NS		3.54	7.32	-1.02
LATEL-	NS		3.53	7.06	-0.5
LATEL 4	NS		3.52	7.06	-0.36
LATEL 4	NS		3.75	7.72	-0.29
FAREG AMA	NS		2.92	5.43	0.43
FAREGELMO	NS		3.33	6.41	-0.28

The determined calcite saturation indices range between 0.7 and 3.08. 20 waters showed supersaturated ($\text{SI} > 0.7$). With respect to dolomite, the values varied between 0.0 and 6.26. Here, 2 groundwaters showed equilibrium (0 ± 0.1), and 18 waters were supersaturated ($\text{SI} > 0.1$). Thus, there are carbonate corrosive waters as well as waters that show a potential incrustation hazard. Nevertheless, it has to be kept in mind that the calculated values just reflect the overall chemistry of the sampled water and that microenvironments with differing physico-chemical conditions might develop. In these local environments, incrustation can occur although the general chemistry of the water suggests sub-saturation and vice versa.

As far as gypsum is concerned, only 3 samples showed equilibrium conditions ($\text{SI} = 0 \pm 0.1$). All other saturation indices, namely 6, were negative and the lowest value accounted for -0.42. Hence, the examined waters were mostly under saturated with respect to gypsum, which is ultimately attributable to its relatively good solubility of approximately 2.1 g/l (at 30°C, MATTHESS 1994).

Gibbs (1970) has pointed out that the chemistry of water is generally, controlled by the rate of evaporation, chemistry of rocks and rain water. To evaluate the sources of various ions, the chemical data of waters from the area of study (**Table7**) were plotted on Gibbs diagram (Siddig, M.E., et al., 2013). The plots of the total dissolved solids (TDS) versus $\text{Cl}/\text{Cl}+\text{HCO}_3$ (**Fig.9**) suggest that the ions are chiefly derived from the rocks dominants and their concentration in groundwaters is mostly due to evaporation. Similar results have been obtained when TDS plotted against $\text{Na}+\text{K}/\text{Na}+\text{K}+\text{Ca}$ (**Fig.9**). Precipitation, indicating contribution from the rain water, however, has not played any role in the concentration of ions in the waters from the area of study.

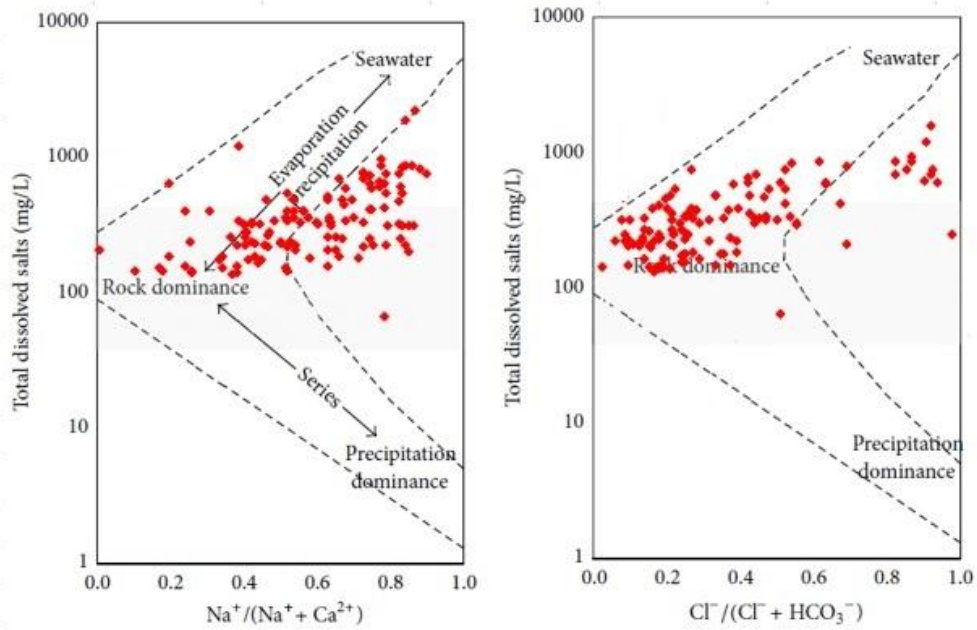


Fig.9: Gibbs diagrams for the ground water from the East bank of the River Nile, Dongola Basin

Table 7: Water Type of Groundwaters –Dongola East

Name	Long	Lat.	Water Type	Name	Long	Lat.	Water Type	Name	Long	Lat.	Water Type
M.ALKHAIR	303202	191952	Ca-Cl	KDWA KARM	303600	200100	Mg-HCO3	SAID AHMAD	314600	182800	Na-HCO3
OMAR	303300	193100	Ca-HCO3	KDWA KROM	303600	200100	Mg-HCO3	MOHAM ALI	314600	182800	Na-HCO3
GANTE	310940	175830	Ca-HCO3	LATE GSM	304430	182430	Mg-HCO3	MOH OSMAN	3144000	182200	Na-HCO3
FAREG NILE	302900	195500	Ca-HCO3	ARAB HAG	304310	182325	Mg-HCO3	MOH ALI M.	310800	180800	Na-HCO3
GALAT EL	313400	181100	Ca-HCO3	KAREMA ELE	315100	183030	Mg-HCO3	MOHD HASS	313100	180700	Na-HCO3
KSDKORMA S	303600	200100	Ca-HCO3	AL YASS HAG	311200	175900	Mg-HCO3	M.ABDULRA	303511	192533	Na-HCO3
AGTRE SURF	303400	201500	Ca-HCO3	ABDALLA AL	312136	180129	Mg-HCO3	EL MAHAD	302555	193930	Na-HCO3
AGTRE FRAH	303400	200500	Ca-HCO3	GOZ GURAVI	314130	181630	Mg-HCO3	AHMED MUS	303530	191528	Na-HCO3
MFRKA	303400	205600	Ca-HCO3	ELDOM H.P.	303030	191900	Mg-SO4	ALI MOHD	303715	190700	Na-HCO3
ELDOFOFA	302600	193755	Ca-HCO3	ELSAGAY	315100	183200	Na-Cl	ABDULLA JA	303246	191459	Na-HCO3
HEZAMA	314200	181900	Ca-HCO3	NURI EL SAG	315130	183200	Na-Cl	ALTAHIR	303300	190700	Na-HCO3
BANGARTE	304800	180930	Ca-HCO3	MARAWI AIR	314700	183215	Na-Cl	HILAT BALLA	313400	181500	Na-HCO3
ABO RANAT	314700	182320	Ca-HCO3	YOUSIF AT	311800	180100	Na-Cl	ABU FATIMA	302500	194100	Na-HCO3
KAREMA EL B	313700	181300	Ca-HCO3	ELAWAD MB	314100	181600	Na-Cl	M. SAEED H.	30330	191200	Na-HCO3
ELBARKAL S.	314900	182900	Ca-HCO3	ABD ALLA NA	313800	181400	Na-Cl	KAREMA ELE	315100	183030	Na-HCO3
ELSAGAE G.W	315135	183130	Ca-HCO3	ALFARISI A	303104	191403	Na-Cl	FAGIRI UNK	311830	180115	Na-HCO3
ELGRAF KAR	315130	183330	Ca-HCO3	ELARAK BAH	313700	181920	Na-Cl	HAMOUR	304630	181100	Na-HCO3
KAREMA ELE	315100	183330	Ca-HCO3	ABU RAI A	303700	191140	Na-Cl	M. ABDELRA	30351	192520	Na-HCO3
KAREMA WA	315118	183230	Ca-HCO3	AWAD ABD	30311	190652	Na-Cl	AHMED MUS	30351	191528	Na-HCO3
ELMATARAT	303000	194000	Ca-HCO3	PUSHARA AB	303012	191904	Na-HCO3	ALTAHIR SAE	303300	190700	Na-HCO3
ELMIHILA B	310434	190053	Ca-HCO3	MOL WAD B	303600	183600	Na-HCO3	ALI MOHMO	303715	190700	Na-HCO3
MUSTAFA M	303700	185900	Ca-HCO3	ELSAGAI	315100	183100	Na-HCO3	A3	303215	191215	Na-HCO3
ARAB ELSHE	312300	180100	Ca-HCO3	KIBERNARTI	302500	194100	Na-HCO3	A4	303330	191550	Na-HCO3
KADROKA	302900	192300	Ca-HCO3	ABU DOOM	314100	181800	Na-HCO3	A6	303315	191930	Na-HCO3
NAWA ALAT	304303	182856	Ca-HCO3	ABU EL RAO	304130	192900	Na-HCO3	A7	303130	192320	Na-HCO3
EL ELIEM GS	303230	191600	Ca-HCO3	HSSAN	303140	191240	Na-HCO3	A8	303530	192122	Na-HCO3
KARMAKOL	305900	181040	Ca-HCO3	LATEL-1	304603	182300	Na-HCO3	OMAR CAS	303447	192969	Na-HCO3

A1	303030	190815	Ca-HCO3	LATEL-	304630	182300	Na-HCO3	RAOOF	304000	192900	Na-SO4
A5	303050	192000	Ca-HCO3	LATEL 4	304630	182300	Na-HCO3	ABUFATMA	303500	194100	Na-SO4
FAREG AMA	302900	195500	Ca-SO4	ELGOLDAP U	311500	181500	Na-HCO3	FAREGELMO	302900	195500	Na-SO4
AGTREABD	303400	201500	Ca-SO4	PROTECTIO	303300	190000	Na-HCO3	OLGO NILE	303200	200700	Na-SO4
KEMTO NILE	302300	202300	Ca-SO4	PROTECT-9	303400	191100	Na-HCO3	LATE GSM-1	304430	182430	Na-SO4
ARO	302000	203200	Ca-SO4	PROTECT-13	303400	191100	Na-HCO3	ALI MOHAM ABDURAHM AN	312900	180400	Na-SO4
NILE	303900	210200	Ca-SO4	AHMED KAM	303500	192500	Na-HCO3	ALKHANDAG	302941	192358	Na-SO4
TLWA NILE	301800	203100	Ca-SO4	MOHAMED E	303400	193150	Na-HCO3	ALKHANDAG	303140	192519	Na-SO4
EL BOSHARE	303000	193530	Ca-SO4	KABARNATE	302500	194100	Na-HCO3	AHMED IBR	303456	191933	Na-SO4
ALKHANDAG	303100	192418	Ca-SO4	ARTGSHA EA	302500	193500	Na-HCO3	ALSIR ALBAH	304430	182040	Na-SO4
M.ALKHAIR	30323	191952	Ca-SO4	GANATI SAP	311300	175843	Na-HCO3	ABU RAI	303519	191247	Na-SO4
MSHDA-MAT	303400	200300	Mg-Cl	ELZOMA GA	314540	182200	Na-HCO3	IBRAHIM AH	303702	185448	Na-SO4
ARGE SURF	305700	180500	Mg-Cl	KAREMA MA	315118	183230	Na-HCO3	FADLALLA	304023	183428	Na-SO4
ELARKE	313100	184500	Mg-HCO3	KARIMA NILE	315045	183300	Na-HCO3	GABIR TAIL	303322	191458	Na-SO4
BANGANARTE	304800	180930	Mg-HCO3	ELMIHILA A	312827	184800	Na-HCO3	AHMED EBR	30347	191933	Na-SO4
LATEL 4	303000	193400	Mg-HCO3	BIR MOHAM	303300	191200	Na-HCO3	GABIR TAIL	30323	191458	Na-SO4
ELNAFAB	311500	184500	Mg-HCO3	BIR MOH HAD	303400	193150	Na-HCO3	FADLLA HAS	30403	183429	Na-SO4
KARMA-NR	311500	184500	Mg-HCO3	BASHEIR WA	314800	183630	Na-HCO3	ALSIR ALBAH	30440	182040	Na-SO4
PROTECT-12	303400	191100	Mg-HCO3	KALAF AL KA	311300	175935	Na-HCO3	A2	303040	191015	Na-SO4
								ABDALLA G	303434	191334	Na-SO4

VIII. Cluster Analysis

Multivariate statistical techniques, such as factor analysis or principal component analysis, provide more insight into the underlying structure of a data set, the use of these techniques might require further analysis to identify district groups. Cluster analysis (Davis, 1986), on the other hand, is a useful way of objectively organizing a large data set into groups on the basis of a given set of characteristics. This can ultimately assist in the recognition of potentially meaningful patterns (Swanson, et al. 2001).

To identify possible groups and relationship among the samples analysis based on major chemical compositions, ions species Ca^{2+} , Mg^{2+} , Na^+ , K^+ , SO_4^{2-} , HCO_3^- and NO_3^- (Figs.10&11) were considered as variables for application in Q-mode cluster analysis. The *clustering* procedure was performed by the ward's linkage method with the Euclidean distance as a measure of similarity of samples using the software's AQ/Qa used for water quality and Xisat for statistical analysis

In this study, the Spearman correlation method was chosen which is insensitive to outliers in the data, and the analysis, results are shown in Table 8. As shown in Table 8, the cations Na^+ , K^+ , Ca^{2+} , Mg^{2+} and anions Cl^- , SO_4^{2-} and bicarbonate, shows positive correlations with each other, which can be explained by the dissolution of chlorides and sulfate minerals, because they can release Ca^{2+} , Mg^{2+} , Cl^- and SO_4^{2-} into the water, also by water-rock interaction (Elzien, S. M & Hamed, B. O. 2016; Kai Chen, Sun LH, Tang, J., 2020, Siddig, M. E., et al. 2022).

The relationships among the water chemistry variables of the groundwater samples are shown by rank correlation matrix (Table 8). The factors were extracted from a correlation matrix of the variables by the principal component analysis. The terms, "strong" "moderate" and "weak" as applied to r values, refer to range of > 0.75 , $0.75-0.5$, and $0.5-0.3$, respectively (Liu et al., 2003). Strong correlation was observed between Na^+ and Cl^- , EC; SO_4^{2-} and EC there also Cl^- and EC. Moderate correlation was observed between Na^+ and $H_2CO_3^-$, SO_4^{2-} ; Mg^{2+} and Cl^- , SO_4^{2-} & EC; Ca^{2+} and Mg^{2+} & SO_4^{2-} ; $H_2CO_3^-$ and EC. There is also moderate correlation between SO_4^{2-} and Cl^- .

This may indicate cation exchange between these ions. For the rest of groundwater samples, there is weak correlation between K^+ and SO_4^{2-} , Cl^- and EC and between Bicarbonate both of Cl^- & SO_4^{2-} ; Na^+ and Mg^{2+} , K^+ , Ca^{2+} and K^+ , $H_2CO_3^-$, Cl^- , EC as well as Mg^{2+} and $H_2CO_3^-$, K^+ as shown at the correlation matrix (Table 8). Almost all analyzed metals showed strong correlation with TDS and electrical conductivity because the latter increases with dissolution of metals through ion exchange, dissolution/ precipitation and oxidation-reduction reactions in groundwater aquifer system (Subba Rao, 2002).

Table 8: Spearman Correlation of the major ions in groundwater, Dongola East

Variables	Ca	Mg	Na	K	HCO ₃ ⁻	SO ₄	Cl	EC	pH
Calcium	1								
Magnesium	0.549	1							
Sodium	-0.070	0.109	1						
Potassium	0.035	0.066	0.149	1					
Bicarbonate	0.255	0.404	0.450	-0.069	1				
Sulfate	0.487	0.444	0.625	0.133	0.268				
Chloride	0.319	0.425	0.734	0.231	0.350	0.634	1		
Conductivity	0.440	0.467	0.711	0.282	0.467	0.757	0.839	1	
pH	-0.198	0.012	-0.161	-0.156	0.019	-0.242	-0.126	-0.244	1

Values in bold are different from 0 with a significance level alpha=0.5

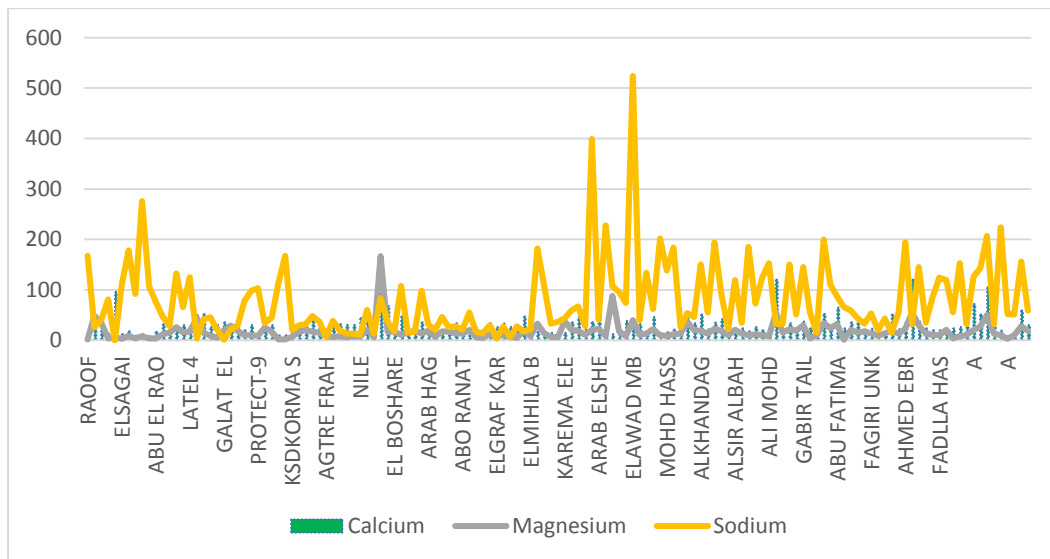


Fig.10: Relation between the alkaline cations (Ca²⁺, Mg²⁺ & K⁺) of the Watersamples -Dongola East

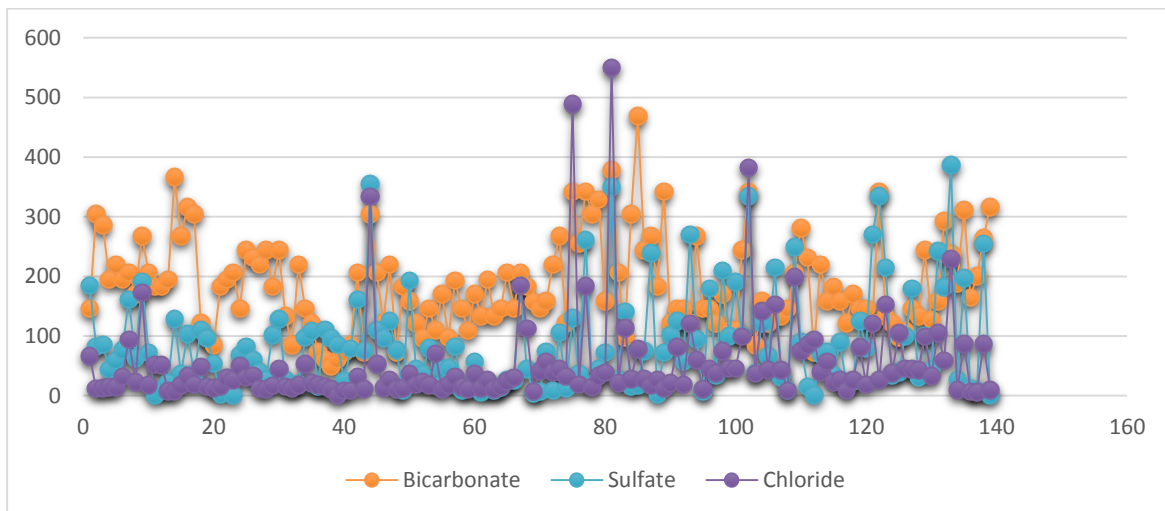


Fig. 11: Relation between the acidic anions (HCO₃, Cl⁻ & SO₄⁻² -Dongola East

IX. Environmental and Isotopes

The isotopic composition of water sample (Stable Isotopes; Deuterium & Oxygen-18) is expressed in terms of per mille differences ($\delta\%$) of its isotopic ratios $R = D/H$ and $R = {}^{18}O/{}^{16}O$ with respect to the isotopic ratios of a standard, the so-called Standard Mean Ocean Water (SMOW):

$$\delta \text{‰} = (R \text{ sample} / R \text{ SMOW} - 1) * 1000$$

The relation between deuterium and oxygen-18 in natural meteoric water, which have not undergone excessive evaporation, is described by the following linear correlation:

$$\delta D = 8 * \delta {}^{18}O + 10 \text{ Global Meteoric Water Line (GMWL)}$$

The importance of environmental isotopes studies in groundwater hydrology in arid and semi- arid zones need not to be emphasized. Isotopes techniques (Craig, 1961a&b) can yield valuable information for solving problems such as:

- ❖ Determination of recharge source, recharge rate, and recharge mechanism.
- ❖ Residence time
- ❖ Interaction between different water bodies.

Tritium concentration in the River Nile measured at Kareima in the study area, dropped from 20 TU in 1985 (to 4.9 in the year 2000) indicating that the Nile maintains the natural level before 1962 nuclear bomb explosion. Tritium concentrations, in boreholes at Khartoum, vary from 3.8 to 103.3 T. U., and with the majority lies within 50 T.U (Sudanese – German Exploration Project Technical Report, 1979), and tritium concentration drops from over 100 T.U near the Blue Nile to almost zero at a distance of 5 – 6 Km away from the Blue Nile River. This indicates that the River Nile is the main source of recharge to the adjacent aquifers zones and that groundwater recharge from the local rainfalls is insignificant (Table 9).

Table 9: Isotopic Components of the Study Area – East River Bank

NO.	Locality	LONGT.	LATIT.	LONGDEC.	LATDEC.	Oxygen -18	Deuterium	Tritium	TDS
1	EL MIHILA (B)	310434	190053	31.0761	19.0147	-9.71	-73.81	0.50	246
2	NURI EL SAGAI	315130	183200	31.8583	18.5333	0.45	7.70	12.40	1032
3	MARAWI AIRPORT	314700	183215	31.7833	18.5375	-2.01	-12.60	0.20	504
5	EL MIHILA (A)	312827	184800	31.4742	18.8000	-5.04	-36.80	0.30	223
6	BIR MOHMD EL HADI	303400	193150	30.5667	19.5306	-1.76	-10.50	0.40	442
8	ABDALLA ALYAMANI	312136	180129	31.3600	18.0247	2.83	24.2	+1	534
9	ABDURAHMAN	302941	192358	30.4947	19.3994	-0.49	3.1	+1.2	373
10	ALKHANDAGAWI	303140	192519	30.5278	19.4219	0.66	3.5	0.9	651
11	FADLALLA HASSAN (ALLV)	304023	183428	30.6731	18.5744	-0.85	-4.3	0.9	605
12	PUSHARA ABDULLA (ALL)	303012	191904	30.5033	19.3178	-0.67	2.3	+0.9	385
13	ABU RAIYA	303700	191140	30.6167	19.1944	-2.31	-18.00	0.40	291
14	M.SAEED HASSAN	303300	191200	30.5500	19.2000	-1.08	0.00	10.3	431
15	KARIMA (ELECT. STATION)	315100	183030	31.8500	18.5083	-0.43	4.60	0.70	402
16	GUZ GURAVI	314130	181630	31.6917	18.2750	-1.78	-6.60	0.20	385
17	FAGIR UNKUTI	311830	180115	31.3083	18.0208	-1.96	-9.40	0.10	396
18	KARMAKOL	305900	181040	30.9833	18.1778	-0.71	3.30	0.20	189
19	HAMOUR	304630	181100	30.7750	18.1833	-0.95	-3.00	0.00	340
20	ALKHANDAGAWI	30310	192418	30.5167	19.4047	0.66	3.50	0.90	651
21	M. ABDELRAHIM	30351	192520	30.5836	19.4219	-2.63	-20.30	0.70	231
22	AHMED IBRAHIM	30347	191933	30.5683	19.3258	-1.77	-17.50	1.20	692
23	M. ALKHAIR	30323	191952	30.5339	19.3311	0.50	0.50	0.80	1743
24	GABIR TAIALLA	30323	191458	30.5339	19.2494	-1.77	-11.30	0.80	777
25	AHMED MUSALAM	30351	191528	30.5833	19.2578	-3.87	-26.60	0.90	390
26	AWAD ABDALLA	30311	190652	30.5167	19.1144	-1.83	-11.40	0.80	657
27	FADALLA HASSAN	30403	183429	30.6675	18.5744	-0.85	-4.30	0.90	605

28	ALSIR AL BAH	30440	182040	30.7333	18.3444	-1.82	-5.90	0.90	672
29	AL TAHIR SAEED	303300	190700	30.5500	19.1167	-2.27	-12.90	0.70	76
30	ALI MAHMOUD	303715	190700	30.6208	19.1167	-1.35	-10.60	0.80	96
31	ABDALLA A. ALGALEL	303434	191334	30.5761	19.2261	-0.59	-9.50		766
33	NILE 1					3.04	25.22	17.7	
34	NILE 2					3.11	27.29	19.7	
35	NILE 3					3.16	27.08	20.4	

9.1 Delta Oxygen – 18 against Delta Hydrogen – 2

The relation between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ for collected samples at the East River bank were plotted in **Fig. 12** all samples plotted were below GMWL except one sample (Meheilah B). The samples were classified into three groups:

Group I

Group one represents recent water with evaporation, it includes two samples, (0.66, and 3.5) & (0.5, 0.5) the distance of these samples from the river are 1.92Km and 2.32 Km respectively. The samples are near the river so they are under recharge area.

Group II

Mixing group that means paleo water + recent water. This group includes the majority of water samples; the rates of mixing vary from sample to another. This group can be classified into three subgroups according to the rate of mixing:

- A- recent mixing rate is greater than paleo rate (more influence)
- B- Approximately recent mixing rate is equal paleo rate.
- C- Paleo mixing rate is greater than recent mixing rate.

This includes two samples, AL- Meheilah(A) with distance from the River Nile of about 50 Km. and Bir Ahmed Musalam 7.7 Km from the Nile.

Group III

This group includes only one sample, represent paleo water, because it is depleted in stable isotopes, also the tritium concentration is very low. The distance of sample from the River Nile is about 59.7 Km that means the recharge of the River Nile is less than that distance.

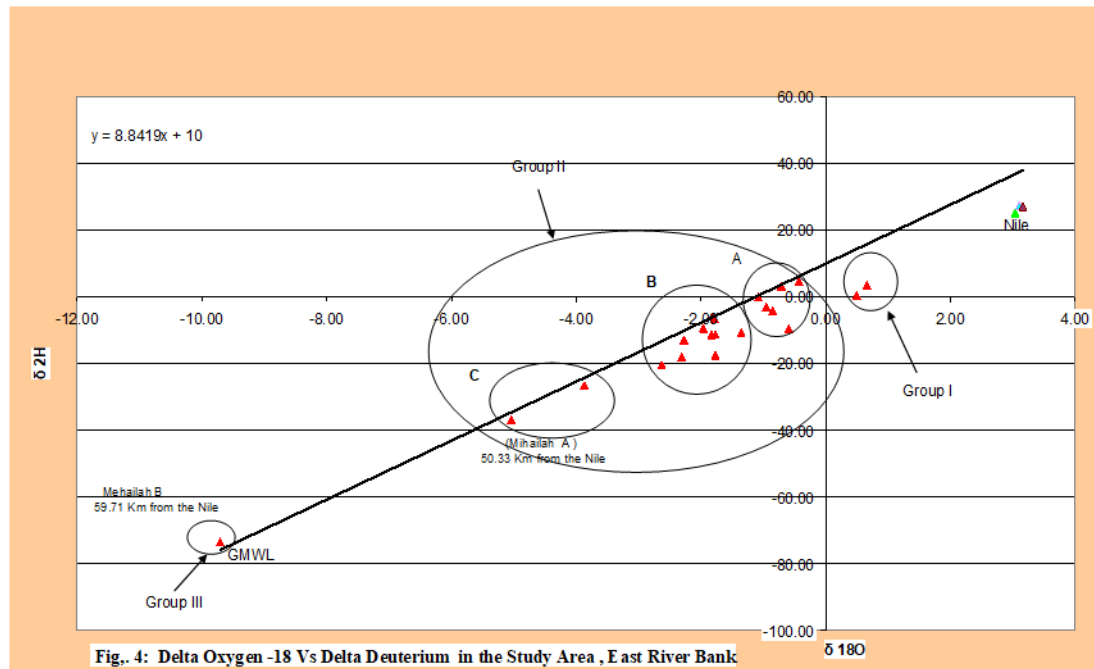


Fig. 4: Delta Oxygen -18 Vs Delta Deuterium in the Study Area , East River Bank

Fig.12: Delta Oxygen-18 vs. Delta Deuterium in the East Bank of the River Nile

9.2 Delta Oxygen – 18 against TDS

According to Fig. 13, the East bank of the study area is divided into two groups ; the first one represents most of the East water samples , shows that the TDS increases with $\delta^{18}\text{O}$, which means salinity is due to recharge of surface water (high TDS due to irrigation water). The second shows that $\delta^{18}\text{O}$ do not increases with TDS.

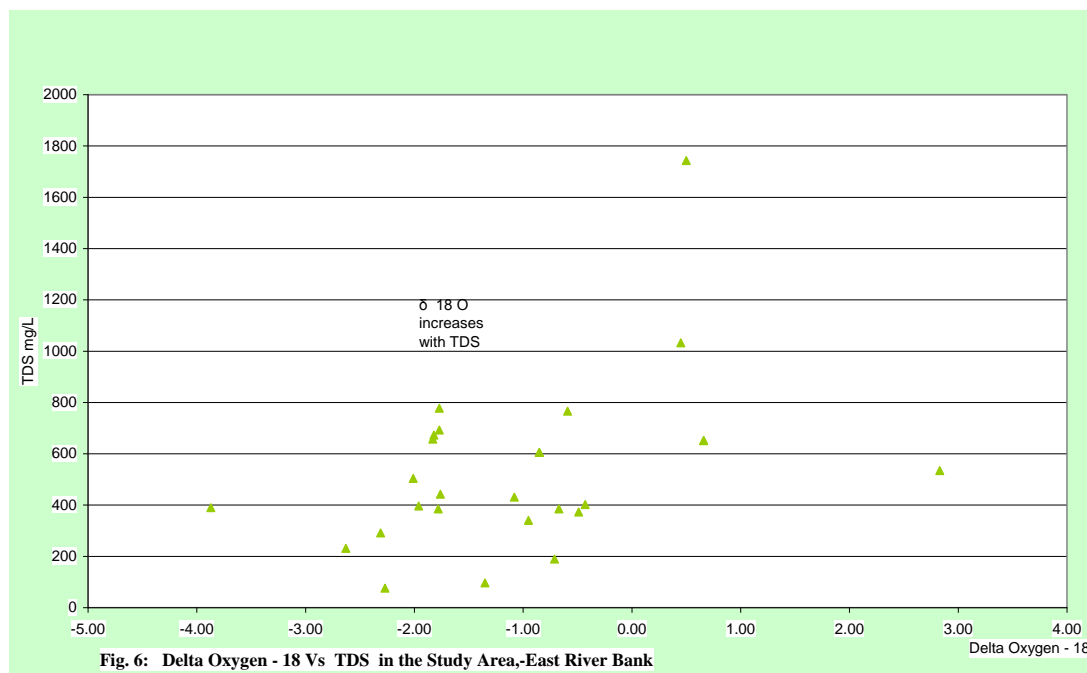


Fig.13: Delta Oxygen-18 vs. TDS in the East River Nile Bank

X. Discussion and Conclusion

The majority of water samples were moderately hard water, and temporary hard (carbonate and bicarbonate hardness). The water types of the studied area are 39% Na-HCO₃, 20% Ca-HCO₃, 14% Na-SO₄, 10% Mg-HCO₃, 8% Na-Cl, 0.7% Ca-SO₄ and the other rare type for Mg-SO₄ and Ca-Cl water types.

According to investigations of tritium concentration in the study area, the majority of groundwater samples lied under < 3 T.U; that meant that, no water younger than 20 years was present. More than 20 years are required for water to reach the sampling points from the recharge area. This is the case of the most confined aquifers. A few of water samples had tritium concentration that varied from 3 T.U to 20 T.U .This group included (Dongola Airport) 7.6 T.U, Nuri Al-Sagiia 12.4 T. U and Mohamed Saeed 10.5 T.U. This group lied along the River Nile and represented river water infiltrated to recharge the adjacent aquiferous zones some 20 years ago. Due to stable isotopes values ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) in the study area, the limits of recharge at the east river banks are 59.7 Km and 49.95 Km from the river Nile bed east and west bank respectively.

The relationship between TDS and $\delta^{18}\text{O}$ of some water samples were proportional ($\delta^{18}\text{O}$ increases with TDS) which means that salinity was due to recharge of surface water (high TDS due to irrigation water) while for other samples there was no relationship.

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