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Stable Oxygen and Hydrogen Isotopes for Groundwater Sources along River Nile, Dongola Basin, Northern State, Sudan

By

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Abstract

The purpose of this paper is to assess the interactions between surface and groundwater in Dongola basin area; Northern State, Sudan, the study area lies along the two banks of the River Nile. Using environmental and stable isotopes the results based on tritium concentration, therefore, groundwater is classified into groups; the first one is > 20 T.U., this water indicated mainly river water recharge more than 20 years ago; the second one is varying from 3 to 20 T.U., represents mixing with river water and the third group < 3 T.U. resulting paleo- water. According to stable isotopes (Oxygen-18 and Hydrogen-2) three groups are recognized; the recent evaporation the second is mixing water and the third is paleo- water, due to depletion in stable isotopes concentrations. The relation between Oxygen-18 and the Total Dissolved Solids (TDS) in some groundwater samples indicates the Total Dissolved Solids (TDS) increases with ∂ ^{18}O this means salinity due to recharge of surface water, while the other do not show any relation between them.

Keywords: *Dongola Basin, Groundwater, Hydrogen and Oxygen Isotopes, River Nile, Sudan.*

1.0 Introduction

Natural waters are complex chemical solutions. They always contain a number of dissolved species, suspended materials, and organic substances. Stable, radiogenic, and radioactive isotopes of elements or compounds present in the aqueous medium are outstanding sources of information on the processes occurring in the hydrosphere (David Saka, et al., 2013). The most widely used isotopes in hydro-geochemistry are the stable isotopes of oxygen, hydrogen, carbon, sulfur, nitrogen and the cosmogenic radioisotopes such as tritium and Carbon-14.

Environmental isotope studies of natural waters are concerned with the principle governing the distribution of the stable and radioactive isotopes in the hydrosphere. Such studies aimed to estimate the factors that determine these principles and to interpret hydro dynamical and hydro geochemical processes involved on the basis of the isotope composition of the various elements in the solution. Currently, environmental isotopes routinely contribute to such investigations, complementing geochemistry and hydrogeology. For instance, the stable isotopic composition of water is modified by meteoric process, and so the recharge waters in particular environment will acquire a characteristic isotope signature.

The isotopic composition of groundwater (expressed as abundance of oxygen-18 and deuterium) is determined by the isotopic composition of recharge. If most of the recharge is derived from direct infiltration of precipitation, the groundwater will reflect the isotopic composition of that precipitation. However, if most of the recharge is derived from surface water (rivers) instead of from precipitation, the groundwater will reflect the mean isotopic composition of the contributing river or lake. This isotopic composition is expected to be measurably different from that of local precipitation.

Groundwater in shallow aquifers typically has a residence time of decades to hundreds of years. In contrast, deeper and less permeable aquifers that extend for many kilometres can have through-flow times of thousands of years. If the flow

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regime is simple and mixing is minimal, such aquifers can serve as archives of information about environmental conditions at the time of recharge. The stable isotopes of hydrogen and oxygen in paleo-waters (groundwater recharged under climate conditions different than today) reflect the air temperature at land surface and the air mass circulation (origin of moisture) at the time of precipitation and infiltration. While paleo-temperatures derived from oxygen–deuterium analyses are useful, recently developed noble gas analytical methods provide greater certainty and precision in paleo-temperature determination.

The environmental isotopes represent one of the most useful tools in geochemistry to investigate groundwater quality, geochemical evolution, recharge process, rock-water interaction, and the origin of salinity and contaminant processes (Hsin-Fu Yeh and Jhe-Wei Lee, 2018).

This study used stable hydrogen and oxygen isotopes as natural tracers to investigate their isotopic composition in precipitation, and in shallow and deep groundwater in the Dongola Basin in the northern state. We aimed to understand the differences and relationships in isotope compositions within various water bodies and to evaluate the source of groundwater recharge. The hydrogen and oxygen isotopes compositions of sampled groundwater and River Nile water are mainly distributed along the meteoric water line in the Dongola Basin.

The isotopic composition of water sample (Stable Isotopes; Deuterium & Oxygen-18) is expressed in terms of per mille differences (δ‰) 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) **(Craig, H., (1961a).** δ ‰ = (R sample/ R 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 **(Craig, H., (1961b).** $\delta D = 8 * \delta\ ^{18}O + 10$ Global Meteoric Water Line (GMWL)

Precipitation in tropical region normally undergoes significant evaporation before joining the subsurface waters. This leads to isotopic enrichment in the percolating waters. Further isotopic enrichment takes place in the unsaturated zone and at shallow groundwater tables though vapour transport mechanisms (except transpiration) and capillary rise. In deeper aquifers the deuterium and oxygen-18 composition of water remains particularly unchanged unless exchange with the oxygen of water bearing formation under elevated temperature occurs, or unless mixing with other water of different isotopic composition take place. On the other hand, the deuterium isotopic exchange with the water-bearing material is quite negligible, even under very high temperatures, since its content in sedimentary rocks are extremely small (0.3%) compare to that of oxygen -18 (40%) **(Ferronski, V.I. and Brezgunov, V.S., 1989).**

The slope (8) of GMWL represents the separation of deuterium and oxygen-18 under liquid- vapour equilibrium conditions (Caraig, 1962a). This slope decreases significantly with the increase of evaporation, the slope 5 – 6 is typical for the precipitation in arid tropical regions where the evaporation rates are very high .The intercept 10 (deuterium excess δ) is related to kinetic separation effects over oceanic regions. **(Fontes, J.Ch., 1981).**

The importance of environmental isotopes studies in groundwater hydrology in arid and semi- arid zones need not to be emphasized. Isotopes techniques 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 is the most attractive environmental isotope for groundwater and surface water interactions. Its application was dramatically increased during and after the thermonuclear tests (1952 – 1962) when high concentrations of tritium were injected into the atmosphere and hence into ground. Before 1952 nuclear test, the majority of tritium in nature resulted from cosmic radiations and at natural concentrations varying from 0.1 – 10 TU (Doney, S.C., Glover, D.M. and Jenkins, W.J., 1992), it reached (in precipitation) thousands of TU, shortly after the powerful test of 1961 – 1962. The concentration of tritium in rainwater at Khartoum increased from 21.70 T.U in August 1963 to 50 TU in July 1975 and its concentration in the Nile water decreased from 146 TU to 20 TU in 1983 **(Lahmeyer International 2006).**

Tritium concentration in the River Nile measured at Karema the study area, dropped from 20 TU in 1985 to about 4.9 in the year 2000 (Khair) indicating that the Nile maintains the natural level before 1962 nuclear bomb explosion (**Groundwater and Wadis Directorate, 2000**).

Tritium concentrations in boreholes at Khartoum area vary from 3.8 to 103.3 T.U, and with the majority lies within 50 T.U **(**Ibrahim, M. E., 1985; German 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 aquiferous zones and that groundwater recharge from the local rainfalls is insignificant **(Groundwater and Wadis Directorate, 2000).**

1.1 The Study Area

The study area lies along River Nile in the Northern State. The area forms an elongated shape and generally bounded by longitudes (29°.80′ 00 – 31°.92′ 00 E and latitudes 17°. 19′ 00 - 20° .21′ 00 N (Fig. 1).

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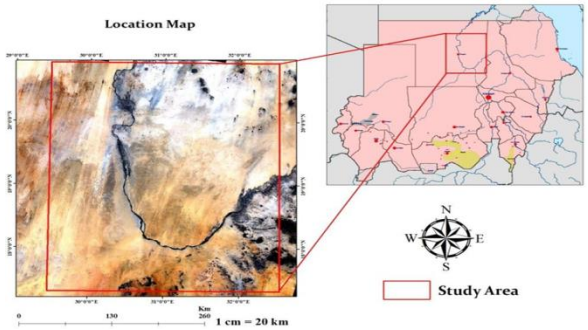

Fig. 1: Location of the study area

1.2 Climate and Vegetation Cover

The area lies in the arid desert region in which rainfall is very low (negligible). Winter season is distinctly pleasant, it stars 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 **(Salih, Lh. M., 1987).**

The wind blows from the north with a mean speed between 15 – 20 Km/h. Summer is long and very hot; it starts 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, 1986a).**

The mean annual rainfall is about 9.280 mm / annum (**Fig. 2**) (1989 – 2008), rainfall characterized by low variability 17.1223 as shown in Table 1.

Vegetation cover in the study area is restricted to the banks of the River Nile, the khors of the big seasonal gater resources such as Wadi El- Meill *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 (**Bonfica Geoexpert, 1986b**).

Table 1: Annual Rainfall Variability at Dongola

Lowest (mm)	Highest (mm)	Average Rainfall (mm)	Standard Deviation
0.0	74.2	9.280	17.1223

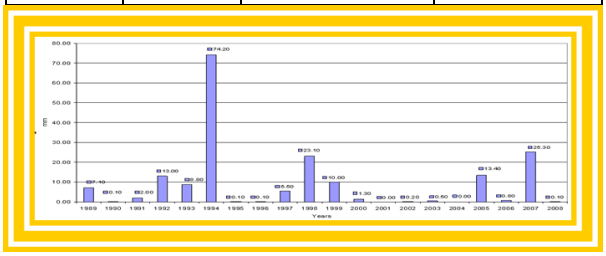

Fig. 2: Annual Average Rainfall in the study area (1989 - 2008).

1.3 The Statement of Problem

Quality of water becomes problematic in developing countries like Sudan. Many places contain saline water aquifers or subjected to mix or interaction by saline water**.**

1.4 Objectives

Deterioration of water quality has received considerable attention over the last few decades in response to the increasingly severe contamination of surface water and shallow groundwater by anthropogenic and agricultural chemicals contaminants and the objectives:

1. To detect Groundwater and Nile water interactions.
2. To determine flow direction of water (recharge and discharge) using environmental isotopes as a tool.

1.5 Geology of the Study Area

The Geology of the area consist mainly of Nubian Sandstone Rocks (Late Cretaceous- Paleogene) (**Fig. 3**) which is the most important water bearing formation in the Sudan (Siddig, M.E.; et al., 2022). This work reports an occurrence of brackish waters in the Dongola Basin sediments area. In view of this, the present paper is completely dedicated to the isotopes environment of groundwaters from the region of Dongola Basin. River Nile, main stream and little (scarce) rain water constitutes the main sources to the recharge of groundwaters (isotopes). Of the total amount of rain water received by the region, majority of it is lost as run off, a little part of it is lost by evaporation and an insignificant part of it is percolated down into soils (Elzien, S.M.; & Hamed, B.O., 2016; Siddig, M.E.; et.al., 2022, Siddig, M.E.; et.al., 2024). During the process of seepage of water into the soil and its migration downward to the zone of saturation, the meteoric water undergoes a number of physico-chemical change by various reaction with soil/rock material through which it passes, this finally leads to the changes in the chemistry of water, which will constitute till the water acquires a steady dissolved minerals/salts content (Siddig, 1992). The change in the chemistry of water are generally, governed by such factors as the climatic conditions, nature of vegetation cover, chemistry and mineralogy of the host rocks, topography, time and human activity, which usually have complex inter-relationships (Patil et. al, 1990). The changes in chemical equilibrium, many times, lead to the precipitation of certain salts that may eventually develop into a distinct litho-type (Siddig, 1992). Thus chemical characteristics of groundwater in various aquifers over space and time proved to be an important technique in solving many geochemical problems (Adams et al., 2001; Alberto et al., 2001; Atteia et al., 2006; Grassi and Cortecci, 2005; Lopez-Chicano et al., 2001; Zanini et al., 2000).

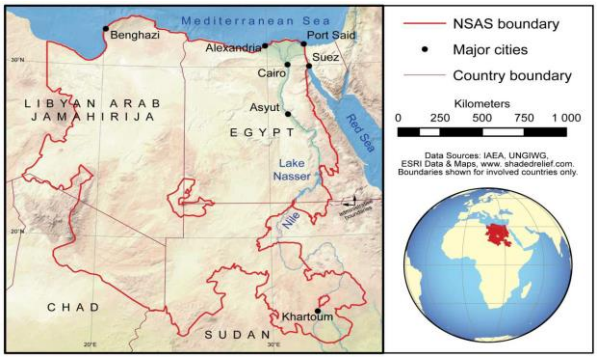

Fig .3: Map showing the location of the Nubian Aquifer.

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2.0 Material & Methods

2.1 Sampling and Analytical Procedure

Thirty-five water samples and sixty-seven water samples were taken from boreholes and the River Nile from both bank sides (**Fig. 4**), for radioactive and environmental isotopes (tritium, deuterium and oxygen-18). The result of concentrations of tritium deuterium and oxygen-18 and TDS were examined and analyzed using liquid scintillation counter analyzer and mass spectrophotometer. Results are shown in Tables 2 and 3.

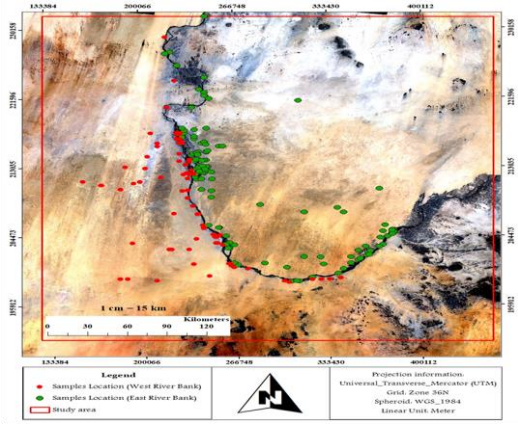

Fig. 4: Location of water samples in the study area.

3.0 Results

In Dongola Basin aquifer system (mainly Nubian Sandstone formation) interpretations of isotope data have been used not only confirm traditional hydrological studies but also to provide insight into groundwater flows and aquifer dynamics. In particular, isotopes have been used in these areas to define groundwater recharge sources and mechanisms to determine groundwater age and rate of movement, and to quantify the mixing of groundwater between aquifers. The result of the environmental isotopes components of the study area (Oxygen-18, Deuterium, and Tritium) and also TDS concentration are examined.

Table 2: Isotopes and TDS concentrations of the study area; East River Nile Bank

NO.	Locality	LONG	LAT.	Oxygen-18	Deuterium	Tritium	TDS
1	EL MIHILA (B)	3104	190053	-9.71	-73.81	0.50	246
2	NURI EL SAGAI	3151	1832	0.45	7.70	12.40	1032
3	MARAWI AIRPORT	3147	18321	-2.01	-12.60	0.20	504
5	EL MIHILA (A)	312827	184800	-5.04	-36.80	0.30	223
6	BIR MOHMD EL HADI	3034	19315	-1.76	-10.50	0.40	442
8	ABDALLA ALYAMANI	3121	1801	2.83	24.2	+1	534
9	ABDURAHMAN	30294	19235	-0.49	3.1	+1.2	373
10	ALKHANDAGAWI	30314	19251	0.66	3.5	0.9	651
11	FADLALLA HASSAN (ALLV	30402	18342	-0.85	-4.3	0.9	605
12	PUSHARA ABDULLA (ALL)	30301	19190	-0.67	2.3	+0.9	385
13	ABU RAIA	30370	19114	-2.31	-18.00	0.40	291
14	M.SAEED HASSAN	30330	19120	-1.08	0.00	10.3	431
15	KARIMA (ELECT. STATION)	31510	18303	-0.43	4.60	0.70	402
16	GUZ GURAVI	31413	18163	-1.78	-6.60	0.20	385
17	FAGIR UNKUTI	31183	18011	-1.96	-9.40	0.10	396
18	KARMAKOL	30590	18104	-0.71	3.30	0.20	189
19	HAMOUR	30463	18110	-0.95	-3.00	0.00	340

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20	ALKHANDAGAWI	30310	19241	0.66	3.50	0.90	651
21	M. ABDELRAHIM	30351	19252	-2.63	-20.30	0.70	231
22	AHMED IBRAHIM	30347	19193	-1.77	-17.50	1.20	692
23	M. ALKHAIR	30323	19195	0.50	0.50	0.80	1743
24	GABIR TAIIALLA	3032	19145	-1.77	-11.30	0.80	777
25	AHMED MUSALAM	3035	19152	-3.87	-26.60	0.90	390
26	AWAD ABDALLA	30311	190652	-1.83	-11.40	0.80	657
27	FADALLA HASSAN	30403	183429	-0.85	-4.30	0.90	605
28	ALSIR AL BAHI	30440	182040	-1.82	-5.90	0.90	672
29	AL TAHIR SAEED	3033	19070	-2.27	-12.90	0.70	76
30	ALI MAHMOUD	3037	19070	-1.35	-10.60	0.80	96
31	ABDALLA A. ALGALEL	3034	19133	-0.59	-9.50	0	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	
Min.				**-9.71**	**-73.81**	**0**	**76**
Max				**3.16**	**27.29**	**20.4**	**1743**
Avg.				**-1.07**	**-5.407**	**3.61**	**509.8**
Std.				**2.46**	**19.31**	**5.94**	**323.9**

Table 3: Isotopes and TDS concentrations of the Study Area; West River Nile Bank

No.	Locality	Long.	Lat.	Oxygen-18	Deuterium	Tritium	TDS
1	Wadi DEAB	304510	181000	-4.27	-29.00	0.47	175
2	DONGOLA AIRPORT	302540	191000	-0.70	2.00	7.60	154
3	KAREMA (NILE 1)	302430	193800	5.35	38.10	6.00	175
4	KULUMASID	302400	191900	0.18	3.50	0.30	162
5	DONGOLA UNIVERSITY	303000	191030	-0.49	4.00	0.40	171
6	EL SAIR	302800	192000	-0.28	4.70	-	221
7	WAD BAHI	301630	190800	-3.55	-23.9	0.4	296
8	UMM HILAL 1	300800	190500	-2.66	-16.7	0.1	420
9	UMM HILAL 2	300800	190500	0.94	-3.10	0.60	641
10	ESSWANI	300530	190400	-11.20	-85.50	0.50	260
11	BUDRAN	301100	192200	-4.13	-32.50	0.10	1372
12	HASSAH	301500	193100	-3.27	-23.20	0.30	545
13	MASHU	302300	193400	-0.49	4.00	-0.30	204
14	KULUMASSID	302400	191900	-0.18	3.50	0.30	175

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15	GARADA	302630	191640	-0.32	5.10	0.40	171
16	DONGULA HOS.LAND	302820	191020	-0.71	3.30	0.50	354
17	EL GURIBA	312530	180008	0.03	5.50	0.00	277
18	El GABAH NILE	304530	180900	5.48	38.80	5.70	158
19	DIAB	304510	181000	-0.95	0.20	0.30	296
20	Al GOLID BAHRI	303800	183000	-0.67	2.00	0.20	231
21	EL KHANDAC	303345	183610	-2.10	-6.70	0.30	210
22	LBLAB WEST 2	302730	185930	-1.11	2.90	0.00	385
23	AL TADAMOUN HOSP.	311826	175956	-4.44	-29.10	0.80	1176
24	MOHIEDEEN	304376	181031	-0.60	-2.10	1.00	247
25	AL BAKRI NORTH	303903	1824158	-1.53	-5.40	0.70	1295
26	KAREMA (NILE 1)	302430	193800	5.35	38.10	6.00	303
27	KULUMASID	302400	191900	0.18	3.50	0.30	347
28	DONGOLA UNIVERSITY	303000	191030	-0.49	4.00	0.40	898
29	EL SAIR	302800	192000	-0.28	4.70	0	184
30	WAD BAHI	301630	190800	-3.55	-23.9	0.4	791
41	El GABAHB (NILE)	304530	180900	5.48	38.80	5.70	534
49	MFAGIR YADY	303881	182816	-0.84	-4.20	1.00	506
50	HUSSEN YADY	303844	182815	-1.14	-5.10	0.80	268
51	ALI ABDALLA	303153	184335	-0.99	0.40	0.80	541
52	M.ALI SAAED	303130	184343	-1.51	-5.70	0.80	443
53	WAD NUMIRI	302514	185910	-0.54	-3.00	0.70	3052
54	AFRASSI	30104	191403	0.12	4.10	0.70	339
55	ABDALLA JALI		191460	-0.39	4.90	0.80	310
65	EL MULTAGA (3)		175633	-10.35	-78.30	0.24	334
Min.				**-11.2**	**-85.5**	**0.30**	**154**
Max				**5.48**	**38.8**	**7.60**	**3052**
Avg.				**-1.04**	**-4.15**	**1.16**	**477.46**
	Std.			**3.34**	**25.1**	**1.99**	**523.66**

4.0 Discussion

From the above results obtained the following discussions can be summarized as follows:

Radioactive Isotopes Tritium Concentration:

4.1 East River Bank

Based on tritium concentration results, two groundwater groups can be classified (Fig.5):

Group I

Tritium concentration < 3 T.U includes about 93% of water samples. This water is mainly River water recharge more than 20 years ago, when the river water contained high tritium concentrations than today.

Group II

With tritium concentration vary from 3 T.U to 20 T.U. This group includes two samples Nuri Al-Sagiia 12.4 T. U and Mohamed Saeed 10. 5T.U this group lay along the River Nile and represents river water infiltrated to recharge the adjacent aquiferous zones some 20 years ago.

4.2 West River Bank

According to tritium concentration results, there are also two groups (Fig.6).

Group I

99% of groundwater samples at the Western side of the River Nile have tritium concentration < 3 T.U.

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Group I, the water concentration < 3 T.U at the study area means no water younger than 20 years is present, that is more than 20 years are required for water to reach the sampling points from the recharge area. This case of the most confined aquifers.

Group I1

This group includes only one sample (Dongola Airport) 7.6 T.U. lay along the River Nile and represents river water infiltrated to recharge the adjacent aquiferous zones some 20 years ago.

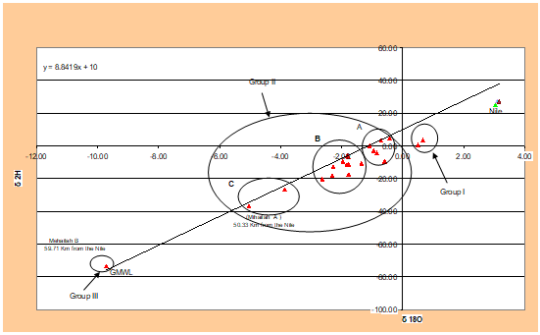

Fig. 5: Delta Oxygen-18 Vs Delta Deuterium in the Eastern River Nile bank of the study area

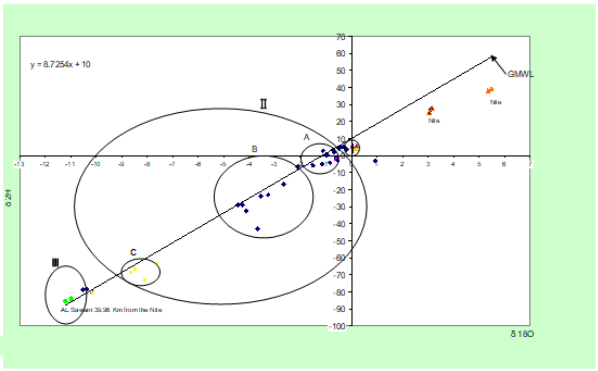

Fig. 6: Delta Oxygen-18 Vs Delta Deuterium in the Western River Nile bank of the study area
Delta Oxygen – 18 Vs Delta Hydrogen-2

4.3 Eastern side of the Study Area:

The relation between δ ^{18}O and δ ^{2}H for collected samples at the East River bank were plotted in Fig. 5 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.

4.4 Western side of the Study Area:

The west side samples were plotted in Fig. 6 According to this figure the water samples can be classified into the following groups:

Group I

This group represent recent water with evaporation, semi-similar to Nile water, includes three samples near the riverbed maximum value of δ ^{2}H 5.8‰ at Affarisi and minimum value 4.0‰ at Klumuseid and maximum 0.2‰ of oxygen –18 and minimum 0.03 at Guriba.

Group II

Mixing group (paleo water plus recent water), it includes the majority of samples; the rate varies from sample to another. Can be classified this group to three sub-groups according to the rate of mixing:

D- Recent mixing rate is greater than paleo rate.
E- Approximately recent mixing rate is equal paleo rate.
F- Paleo mixing rate is greater than recent mixing rate (two samples).

Group III

Al- Swani group this group represents paleo water (depleted in stable isotopes). The distance between AL- Sawani and the River Nile about 49.95 Km. so it represents paleo water that means there is no recharge at this distance from the Nile.

4.5 Delta Oxygen – 18 Vs TDS

4.5.1 East River Nile Bank

According to Fig. 7, the Eastern 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 δ^{18}O, which means salinity is due to recharge of surface water (high TDS due to irrigation water). The second shows that δ^{18}O do not increases with TDS.

4.5.2 West River Nile Bank

From **Fig. 8**, the West bank of the study area is divided into two groups; the first one shows that the TDS increases with δ^{18}O, it means salinity is due to recharge of surface water (high TDS due to irrigation water). The second shows that δ^{18}O do not increases with TDS.

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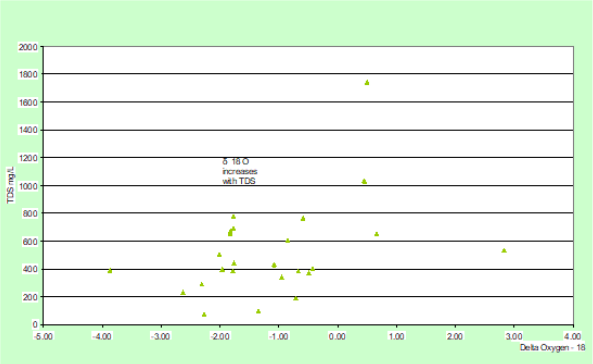

Fig. 7: Delta Oxygen-18 Vs TDS in the Eastern River bank of the study area

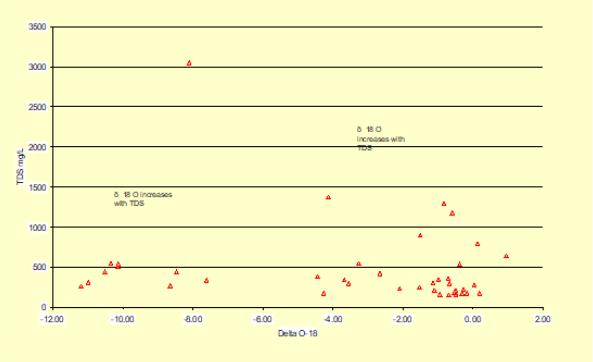

Fig. 8: Delta Oxygen-18 Vs TDS in the Western River bank of the study area.

5.0 Conclusions

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 (δ ^{18}O and δ ^{2}H) in the study area, the limits of recharge at the west and 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 δ ^{18}O of some water samples were proportional (δ ^{18}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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