

## Exploring Surface- And Groundwater Interactions in East Delta Aquifer Using Conventional and Non-Conventional Techniques

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**Abstract:** Source of groundwater recharge to the Pleistocene aquifer in East Nile Delta, Egypt, is difficult to confirm, especially as the chemistry of groundwater is highly variable. To better define the recharge and hydraulic connection between the Pleistocene aquifer and surrounding water bodies, groundwater levels are measured for the available wells tapping the aquifer. In addition, sixteen groundwater and four surface water samples have been collected and analyzed for major ions, boron and strontium. Stable isotopic data was taken from already published works.

The Pleistocene aquifer is semi-confined and the groundwater is shallow and moves north-eastwards. The  $r(\text{Na}^+/\text{Cl}^-)$ ,  $r(\text{Ca}^{2+}/\text{Cl}^-)$ ,  $r(\text{Mg}^{2+}/\text{Ca}^{2+})$ ,  $r(\text{Na}^+/\text{K}^+)$ ,  $r(\text{Cl}^-/\text{HCO}_3^-)$  and  $r(\text{SO}_4^{2-}/\text{Cl}^-)$  ionic ratios and water isotopic ratios ( $\delta\text{D}$  and  $\delta^{18}\text{O}$ ) were used to define the interaction between the aquifer and surface water bodies. Four end members representing four poles (sources) of water were revealed. The first pole is the seepage from the River Nile and its canals (modern Nile water), the second pole is the surplus irrigation water which is better defined as agricultural return flow, the third pole is the leakage of wastewater as indicated from the content of heavy metals and the fourth pole is the old Nile water recharged before constructing the Egyptian Aswan High Dam. Each one of these sources is characterized by a distinguishable chemistry and well known isotopic ratios.

Water infiltration from the nearby canals in the unsaturated zone and its further movement to the groundwater table of the Pleistocene aquifer is of major importance for aquifer recharge concerning water quantity and quality. In this particular Ismailia canal acts as a loosing canal recharging the Pleistocene aquifer with considerable quantities of Nile water. The variation in salinity of groundwater of the aquifer ( $377 \text{ mg/l} < \text{TDS} < 8530 \text{ mg/l}$ ) and major ion compositions is primarily due to the mixing with recharged waters from different sources and dissolution of evaporite sediments in the aquifer.

**Keywords:** East Delta, Egypt, Pleistocene aquifer, potentiometric surface, ionic ratios, stable isotopes mixing phenomena

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### I. Introduction

#### 1.1. Aim of the Work

The present work aims at defining recharge and hydraulic connection between the Pleistocene aquifer and surrounding water bodies in East Nile Delta, Egypt.

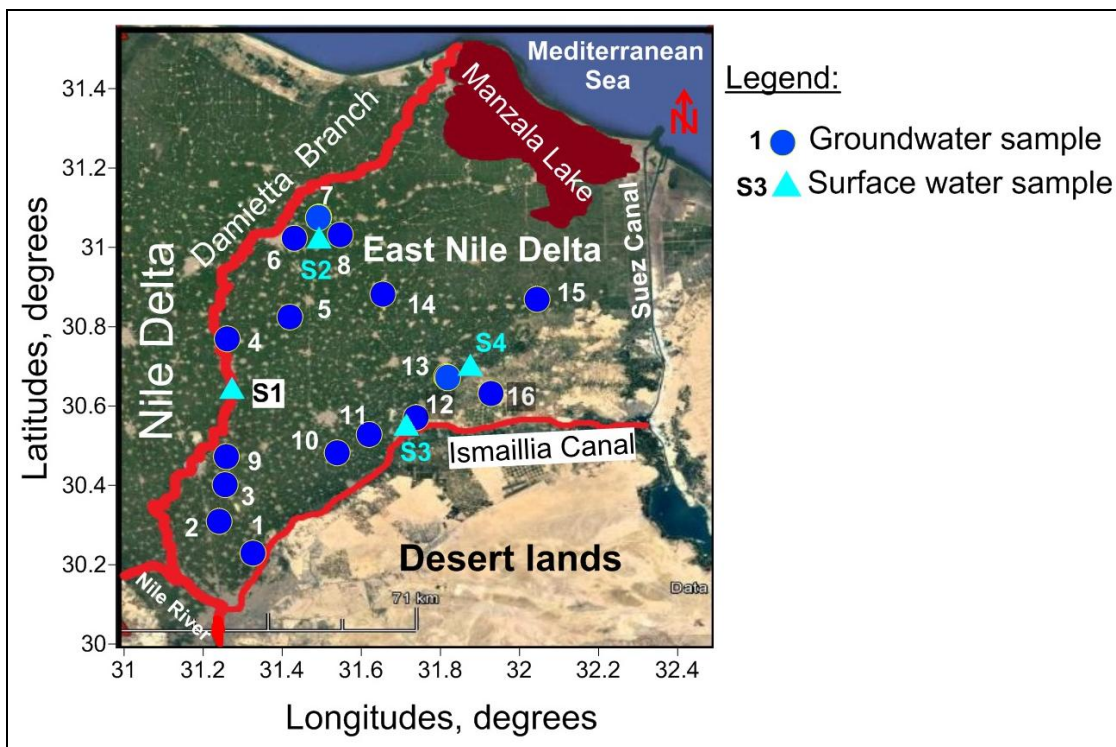
#### 1.2. Physiographic Setting

The study area, the Eastern Nile Delta, is part of the entire Egyptian Nile Delta situated in the northern part of Egypt. It has an area of about  $8500 \text{ km}^2$  and is bounded by Damietta Branch to the west, Mediterranean Sea and Al-Manzala Lake to the north, Suez Canal to the East and Ismailia canal to the south (Fig. 1). Agriculture, breeding cattle and poultry, small industries and urban development are the common human activities. Climatically, the area belongs to the arid belt of North Africa and South-West Asia. It is dominated by desert conditions (Deyab, 2006) and has cold winter and hot summer. Mean annual values of rainfall intensity and humidity increase northwards; they, respectively, range from 25 and 100 mm and between 60 and 70%. Annual means of daily minimum and maximum air temperature range from  $10 \text{ }^\circ\text{C}$  to  $25 \text{ }^\circ\text{C}$  and from  $20 \text{ }^\circ\text{C}$  to  $27.5 \text{ }^\circ\text{C}$ , respectively (EMA, 1996). The mean annual value of evaporation rate ranges from 5.6 mm/day to 6.4 mm/day (IWACO and RIGW, 1988).

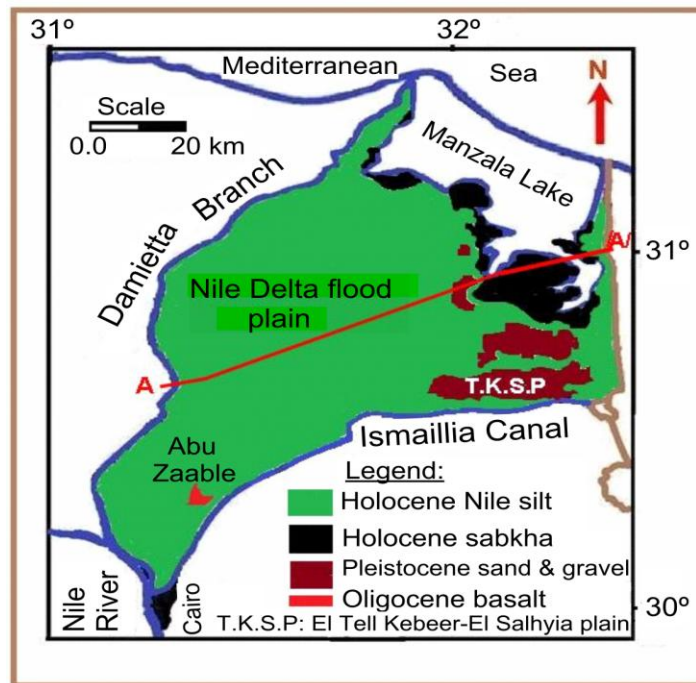
The eastern part of the Nile Delta represents a part of the Nile system morphologic depressions including the Nile valley and delta. Its landscape is formed of two main geomorphic units, the Nile Delta flood plain and El-Tell El Kebeer- El Salhyia plain (Fig.2). The area is occupied by a thick sedimentary succession (about 5000 m)

belongs to Cenozoic, resting on the basement rock (El Fayoumy, 1968), with local exposure of Oligocene basaltic flow at Abu Zaable area (Fig. 2). Of this succession, the Pleistocene deposits are considered by the present work, where they represent the most important water bearing formation in the area. Structurally, the area is located within the unstable shelf zone of Egypt (Said, 1962). It is part of the structural Nile Delta trough lying within the continental slop of the Mediterranean Sea and bounded from the north by a sub-latitudinal thrust fault and from the south (north Suez-Cairo road) by EW and NW-SE oriented normal faults. The subsurface area between these faults is dominated by a series of sub-parallel step faults (Sigaeiv, 1959 and RIGW, 1997), which may lead to an increase in the Quaternary deposits due north.

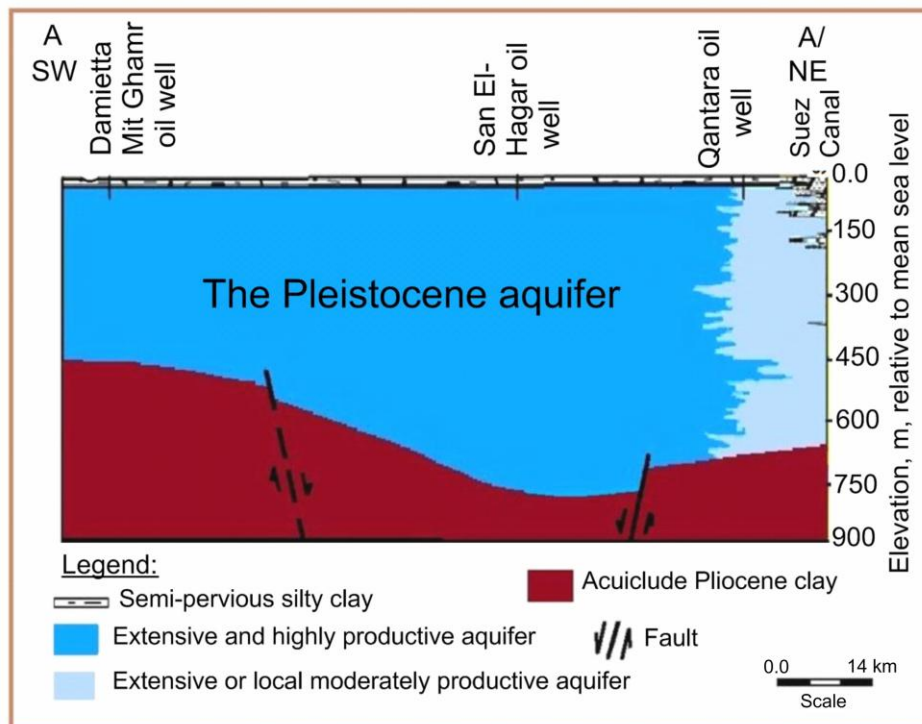
Important information dealing with the hydrogeologic conditions of the eastern Nile Delta is found in El Fayoumy (1968), Shata and El Fayoumy, 1970, El-Dairy, (1980), Hefny, (1980), Hefny et al. (1992) IWACO & RIGW (1983, 1988), RIGW (1992, 1997), Awad et al., (1999), Elewa (2010), Nofal et al. (2014). According to these studies, the Pleistocene aquifer is the main source of water for drinking, agriculture, domestic and industrial uses, where the fresh Nile water in canals decreases year by year. The aquifer is part of the great Nile Delta Basin consisting of alluvial deposits (unconsolidated sand and gravel with clay lenses and evaporate deposits). The aquifer thickness ranges between 100 m southwards and 800 m northwards. The Pleistocene aquifer represents the extensive and highly productive aquifer in the area. It is underlain by the Pliocene clay acting as an aquiclude and overlain by a semi-pervious silty clay layer (Fig. 3). Groundwater occurs under both semi-confined and unconfined conditions. The reported porosity values of the aquifer range from 25% to 40% and the effective porosity derived from the tracer tests varies between 23.25 to 37.35 %. The hydraulic conductivity values are in the range from 35 to 195 m/day and the transmissivity ranges from 5000 to 25000m<sup>2</sup>/day. The storativity varies from 0.000072 to 0.00023.



**Figure 1.** Location map of the study area with water points, East Nile Delta, Egypt.



**Figure 2.** Map showing the main surface geologic units, geomorphologic features and direction of hydrogeologic cross section A-A/, East Nile Delta area (after CONOCO, 1987 and RIGW1992).



**Figure 3.** Hydrogeologic cross section A-A/ cutting the area in an ENE-WSW direction (after RIGW, 1992), East Nile Delta, Egypt..

## II. Methodologies and Techniques

A total of twenty water samples were collected from the study area during November 2015, sixteen groundwater samples from wells tapping the Pleistocene aquifer and four surface water samples from main canals and drains. Water levels in these wells were measured by suitable water level meter; model kurt, MIGGGE, Gm.b. H, 69 Heidelberg 1. The in-situ measurements of pH, electrical conductivity and total dissolved solids were conducted using Manta 2, Water-Quality Multiprobe, Model Sub 3, USA. Coordinates and altitudes of water points were determined using the Global Positioning System device, eTrex, Personal Navigator. Chemical analysis was performed according to ASTM (2002) in Central Laboratory-Water and Soil Analysis Unit, Desert Research Center, Matariya Cairo. Major ions (except for sulfate, sodium and potassium) and heavy metals (strontium and boron) were analyzed using Inductively Coupled Argon Plasma, ICPA 6500 DUO, Thermo Scientific, England. Sulfate ions were determined using UV/Visible Spectrophotometer, Unicam UV 300, Thermo Spectronic, USA. Sodium and Potassium were determined using Flame Photometer, PFP7, Jenway, UK.

### III. Results and Discussions

Physical properties and chemical constituents of water points (groundwater and surface water) are shown in tables 1 and 2. Depths to groundwater water levels under the ground surface range from 1.9 m to 11 m. The potentiometric surface varies between 1.15 m (MSL) in the northern part of the study area and 12.5 m (MSL) in the southwestern parts. The groundwater and surface water in the area are alkaline ( $7 < \text{pH}$ ), however, great differences in their water quality are pronounced. The major ion composition, electrical conductivity and total dissolved solids of groundwater are higher than those of surface water (Table 2). The surface water is fresh ( $590 \text{ mg/l} > \text{TDS}$ ), while the groundwater varies between fresh and saline water ( $377 \text{ mg/l} < \text{TDS} < 8530 \text{ mg/l}$ ).

Salinity (as TDS) and concentrations of major ions and strontium generally increase northwestwards (Fig. 4), parallel to the groundwater flow (Figs. 5 and 6). Contrasting trend is observed for boron content that increases southwards. The variation in dissolved chemical constituents and salinity of the Pleistocene aquifer could be attributed to several factors. Of these factors is the mixing with different types of waters from different sources. Mixing criteria in the Pleistocene aquifer are discussed in the following paragraphs.

**Table 1.** The water point field data, East Nile Delta, Egypt

Site	Water Point	Latitude	Longitude	Well depth, m	Screen length, m	Depth to water, m (GS*)	Elevation, m (GS*)	Water Level, m (MSL)**
Kafr Hamza	1	30° 13.0' 05"	31° 19' 33"	27	3	6	18	12
Namool	2	30° 18' 3.44"	31° 10' 5.5"	70	40	5.5	18	12.5
Meet Kenana	3	30° 24' 06"	31° 15' 0.1"	100	50	4.53	14	9.47
Beshla	4	30° 46' 9.24"	31° 15' 0.54"	125	40	5.25	9	3.75
Senbela-waen	5	30° 49' 27.9"	31° 25' 9.18"	100	40	-	7	-
Meet Khyroon	6	31° 01' 3.10"	31° 25' 0.74"	40	10	3.3	6	2.7
Demna	7	31° 04' 5.22"	31° 29' 2.46"	33	3	3.85	5	1.15
Kafr Tanah	8	31° 01' 54"	31° 32' 8.24"	25	3	3.10	5	1.9
Shablanga	9	30° 28' 21"	31° 15' 1.56"	100	40	6.35	12	5.65
Belbies	10	30° 32' 42.7"	31° 42' 55.1"	38	5	6.22	14	7.78
Abu Hamad	11	30° 31' 42"	31° 37' 0.8"	90	40	11.08	16	4.92
Al-Qurain	12	30° 34' 14.7"	31° 44' 18.2"	24	3	7.56	13	5.44
Faqaos	13	30° 40' 26.5"	31° 48' 54.9"	24	3	7.4	10	2.6
Kafr Saqr	14	30° 52' 54.9"	31° 39' 5.8"	18	3	-	5	-
Bahr Al Baqar	15	30° 52' 08"	32° 02' 40"	10	3	1.90	4	2.10
Salhyia	16	30° 03' 53.9"	31° 55' 0.3"	80	30	26.5	31	4.5
Al Rayah	Al-Tawfeeky	S1	30° 38' 2.06"	31° 06' 19.4"	-	-	-	-
Bahr demna		S2	31° 04' 3.36"	31° 29' 6.98"	-	-	-	-
Ismailia canal		S3	30° 32' 42.7"	31° 42' 55.1"	-	-	-	9.80
Faqaos canal,		S4	30° 40' 27"	31° 48' 4.4"	-	-	-	-

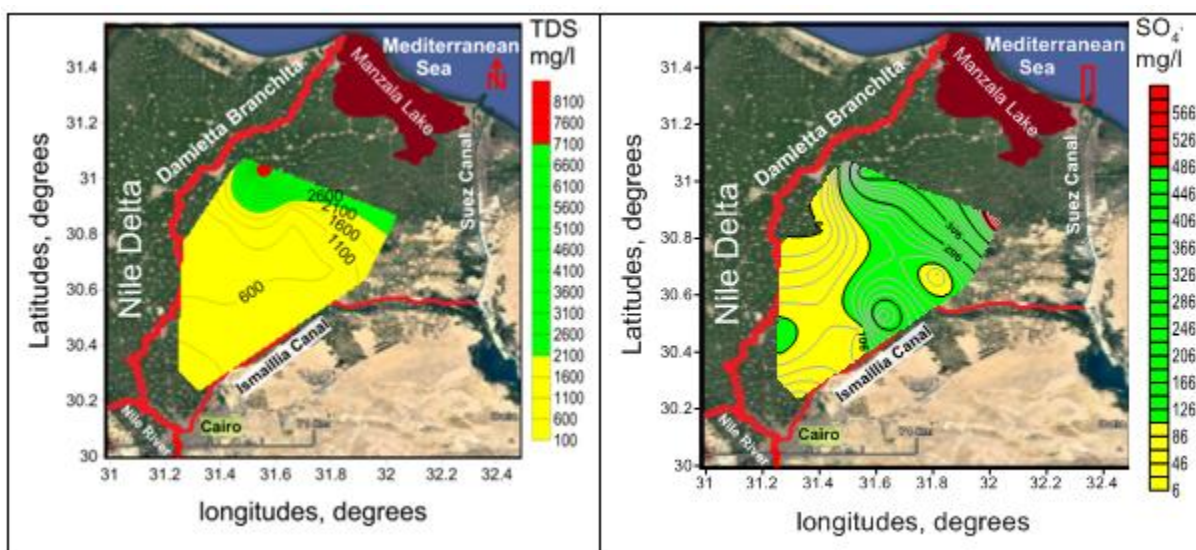
GS: ground surface MSL: mean sea level

**Table 2.** The results of chemical analysis of water points, East Nile Delta, Egypt

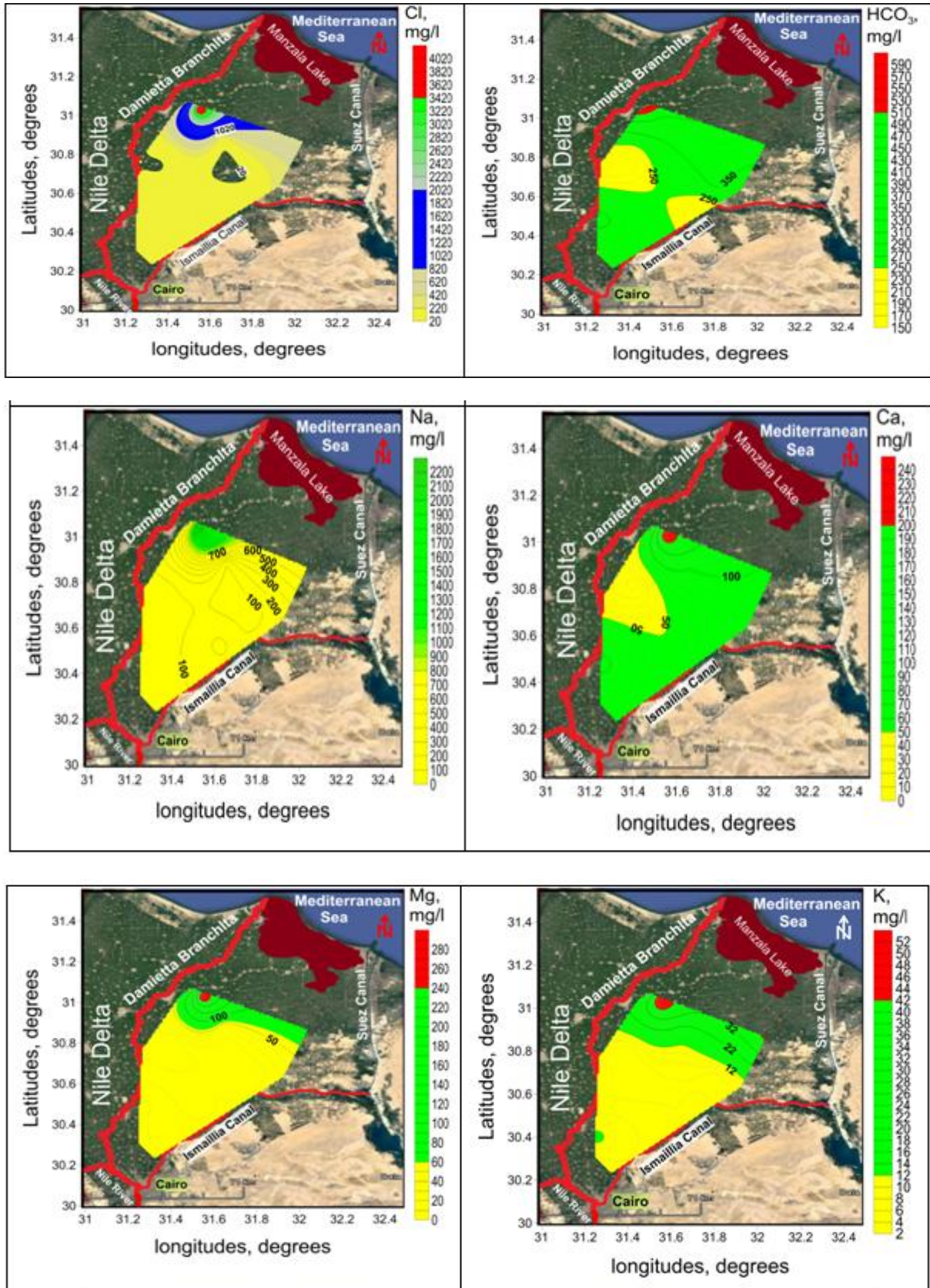
Water point	pH	E.C, $\mu\text{S/cm}$	TDS, mg/l	$\text{Ca}^{2+}$ , mg/l	$\text{Mg}^{2+}$ , mg/l	$\text{Na}^+$ , mg/l	$\text{K}^+$ , mg/l	$\text{CO}_3^{2-}$ , mg/l	$\text{HCO}_3^-$ , mg/l	$\text{SO}_4^{2-}$ , mg/l	$\text{Cl}^-$ , mg/l	Sr, mg/l	B, mg/l	$\delta^{18}\text{O}$ (‰)**	$\delta\text{D}$ (‰)	***d-excess (‰)
1	7.79	796.9	510.2	66	24	48	7	-	359.9	6.2	59.1	1.606	0.02	-	-	-
2	7.92	767.4	491	59	17	58	7	-	231.8	68.4	74.6	0.44	0.02	-	-	-
3	7.42	859.6	550.1	80	19	54	14	-	298.9	110	54	0.5185	0.02	1.59	20.1	7.38
4	7.98	433.8	377.7	29.59	9.67	32	4	-	176.9	15.3	21.9	0.3042	0.02	3.61	30.8	1.92
5	8.55	751.7	480.5	4.2	2.5	140	6	24	198.3	6.4	90	0.0421	0.02	1.97	21	5.24
6	8.25	2301	1472	43	53	400	26	36	518.5	29	462.8	0.5409	0.02	1.12	12.2	3.24
7	8.08	3032	1940	45.93	39.97	510	21	27	585.6	134.3	514.2	0.5296	0.1315	3.37	18.2	-8.76
8	7.53	13330	8529	236.5	289.4	2150	51	-	466.7	338.8	4113.5	3.458	0.4493	3.41	22.2	-5.08
9	7.74	1354	864.7	114.3	37.42	80	9	-	390.4	126	144	0.9327	0.02	4.23	36.3	2.46
10	7.67	1087	689	54.3	17.8	135	7	-	268.4	85.2	154.3	1.063	0.02	1.37	6.74	-4.22
11	7.59	1493	955.9	50.1	20.5	240	6	33	237.9	270	169.7	1.105	0.1957	0.05	8.6	8.2
12	7.71	1130	724.2	75.5	18.6	105	7	30	210.5	152.7	102.8	1.127	0.765	-	-	-
13	7.51	948.3	606.9	73.84	16.73	84	4	-	396.5	62.6	36	0.9425	0.02	1.89	20.9	5.78
14	7.43	1112	712.4	98	26.4	100	15	-	390.4	159.1	77.1	0.8977	0.02	0.2	7.5	5.9
15	7.79	4102	2624	94.2	78.2	610	45	45	405.7	600	707	1.402	0.4951	1.9	18.8	3.6
16	7.44	1976	1264	92.8	33.06	210	8	21	241	139.8	308.5	1.794	0.3224	2.91	24.5	1.22
S1	8.27	444.8	284.9	32.98	11.31	28	6	-	167.8	25.3	29.6	0.3316	0.02	-	-	-
S2	8.17	479.6	307.2	36.03	17.1	36	7	-	192.2	31.4	37.3	0.4519	0.02	-	-	-
S3	8.3	576.6	368.2	38.02	16.2	64	10	15	152.5	100	51.4	0.4715	0.02	2.01	18.08	2.0
S4	8.25	581.1	372.4	35.93	14.17	44	7	15	143.4	47.1	51.4	0.4512	0.02	-	-	-

\*: isotopic data is after Awad et al., (1999) and El-Sayed (2005). \*\*: per mil.

\*\*\*: d- excess is calculated based on the equation of Dansgaard (1964)







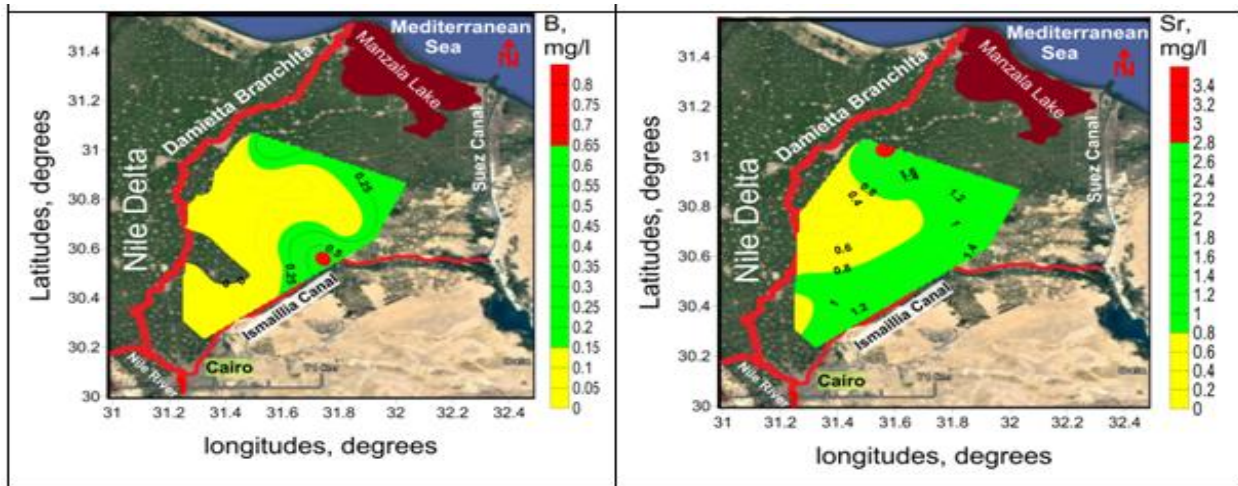


Fig. 4. Major ions and B and Sr metals distributions in the Pleistocene aquifer, East Nile Delta, Egypt.



### 3.1. Mixing criteria as indicated by conventional hydrology

Piezometric head map (Fig.5) constructed in 1992 (RIGW, 1992) is compared with that (Fig. 6) in 2015 originated from the present study. The comparison process reveals that contours of equal heads, i.e. equipotential lines, have become closer reflecting a much steeper hydraulic gradient as well as considerable shift in contour locations (Fig. 6). A further inspection of the same figure reveals a discharge area closer to Ismailia canal. The circular shape of contour lines of the foregoing discharge area reveals an over pumping or drafting that exceeds the aquifer safe yield as indicated by the steepness of contour lines ranging in head from 9 m to 6 m above mean sea level. It is obvious from the anomalous area that Ismailia canal is acting in this particular location as loosing canal recharging the Pleistocene aquifer with considerable quantities of Nile water (Fig. 6).

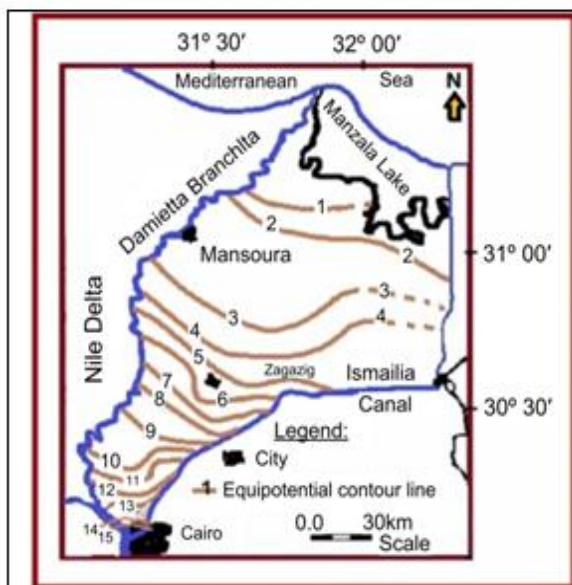


Figure 5. Equipotential contour lines in the study area for the year 1992 (RIGW, 1992).

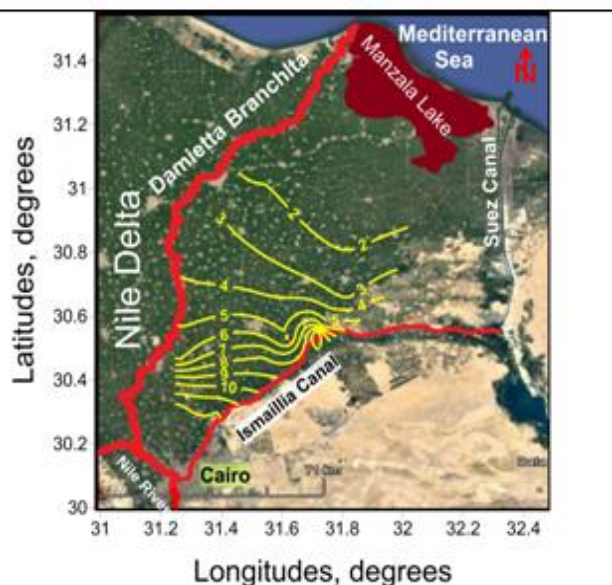


Figure 6. Equipotential contour lines in the study area for the year 2015 (the present work).

### 3.2. Mixing criteria as indicated by ionic ratios

Among the most important ionic ratios, the following are used in the present study:  $r(\text{Na}^+ / \text{Cl}^-)$ ,  $r(\text{Ca}^{2+} / \text{Cl}^-)$ ,  $r(\text{Mg}^{2+} / \text{Ca}^{2+})$ ,  $r(\text{Na}^+ / \text{K}^+)$ ,  $r(\text{SO}_4^{2-} / \text{Cl}^-)$  and  $r(\text{Cl}^- / \text{HCO}_3^-)$  (Table 3). The following speculations about the interpretation of each ratio can be made:

#### 3.2.1. $r(\text{Na}^+ / \text{Cl}^-)$

This ratio is always above unity in the Pleistocene aquifer reflecting water of a meteoric origin which has undertaken ionic exchange. However, only two water points (numbers 8 and 9) show values less than unity and amount to 0.81 and 0.86, respectively, which indicates a strong possibility of mixing with the more saline surface water such as drains and Al-Manzala Lake.

#### 3.2.2. $r(\text{Ca}^{2+} / \text{Cl}^-)$

The majority of water samples related to the Pleistocene aquifer show  $r(\text{Ca}^{2+} / \text{Cl}^-)$  values that are less than unity (water points 5, 6, 7, 8, 10, 11, 15 and 16). This reflects the cationic exchange process which has resulted in depletion of calcium content (Gustafsson et al., 2000). On the other hand, dissolution processes of halite minerals from the already existing evaporate may cause the measured increase in chloride content (Plummer et al., 1976). However, the groundwater samples showing  $r(\text{Ca}^{2+} / \text{Cl}^-)$  values above unity (water points 1, 2, 3, 4, 9, 12, 13 and 14) are closer to surface water bodies like Damietta Branch or Ismailia Canal and consequently receiving a considerable proportion of fresh water that reduces ion exchange from one hand and dilute the higher concentration of chloride ions on the other hand.



### 3.2.3. $r(\text{Mg}^{2+}/\text{Ca}^{2+})$

The majority of groundwater points as well as all surface water points show  $r(\text{Mg}^{2+}/\text{Ca}^{2+})$  ionic ratios below unity. The low Mg/Ca associated with high Na/Cl indicates dissolution of carbonates (Plummer et al., 1976). The water points that show ionic ratio above unity (water points 5, 6, 7, 8 and 15) and ranges from 1 to 2 are still far below the value of 5 which is a direct indication of mixing with sea water. However, the exceptional water points that show ionic ratio above unity may reflect a major contribution from the water of Al-Manzala Lake northwards.

### 3.2.4. $r(\text{Na}^+ / \text{K}^+)$

This ratio  $r(\text{Na}^+ / \text{K}^+)$  ranges from 6.53 to 71.91 for all water points related to the Pleistocene aquifer and from 8.13 to 10.69 for surface water samples. The present ratios reflect that the majority of the groundwater of the aquifer is contributed by Nile water. However, the present fact can not explain the ratio which is much more higher than 10, as per higher values of  $r(\text{Na}^+/\text{K}^+)$  are thought to be due to the adsorption of potassium on clay lenses .

### 3.2.5. $r(\text{Cl}^- / \text{HCO}_3^-)$

The  $r(\text{Cl}^- / \text{HCO}_3^-)$  ratio is always below unity for the Pleistocene aquifer and of course for all surface water points, reflecting that the water of the Pleistocene aquifer is dominated by bicarbonate ion and in turns reflects that the majority of the groundwater of the aquifer is contributed by fresh Nile water. Exceptionally high ionic ratios are observed in water point numbers 6, 7, 8, 11, 15 and 16 a fact which reflects the recharge by seepage from surface drains that usually have water with high chloride content.

### 3.2.6. $r(\text{SO}_4^{2-} / \text{Cl}^-)$

The majority of groundwater from Pleistocene aquifer show  $r(\text{SO}_4^{2-} / \text{Cl}^-)$  ratios less than unity. This confirms that the chloride ion is still the most prevailing anion due to either the recharge from the drains or due to the dissolution of halite mineral. Ionic ratios above unity are indicated by groundwater points 3, 11, 12, 13, 14 and surface water of S3 reflecting that the foregoing groundwater points are contributed by the surface water body (S3) of Ismailia Canal in a particular sector which is intensively polluted with domestic sewage that has abnormally increased sulphate ions.

**Table 3.** Ionic ratios calculated for water points, East Nile Delta, Egypt

Water point	Na/Cl	Ca/Cl	SO <sub>4</sub> /Cl	Cl/HCO <sub>3</sub>	Mg/Ca	Na/K	B/Cl
1	1.26	1.99	0.08	0.28	0.60	11.61	0.01
2	1.20	1.40	0.68	0.55	0.47	14.00	0.01
3	1.55	2.63	1.51	0.31	0.39	6.53	0.01
4	2.24	2.39	0.52	0.21	0.54	13.90	0.03
5	2.40	0.08	0.05	0.78	1.00	40.60	0.01
6	1.33	0.16	0.05	1.53	2.03	26.35	0.00
7	1.53	0.16	0.19	1.51	1.43	41.06	0.01
8	0.81	0.10	0.06	15.15	2.01	71.91	0.00
9	0.86	1.41	0.65	0.63	0.54	15.13	0.00
10	1.35	0.63	0.41	0.99	0.54	32.61	0.00
11	2.18	0.53	1.18	1.23	0.67	69.53	0.04
12	1.58	1.30	1.10	0.84	0.40	25.39	0.26
13	3.61	3.65	1.29	0.16	0.37	36.50	0.02
14	2.00	2.26	1.53	0.34	0.44	11.45	0.01
15	1.33	0.24	0.63	3.00	1.37	23.06	0.02
16	1.05	0.53	0.33	2.20	0.59	45.65	0.04
S1	1.47	1.99	0.64	0.30	0.56	8.13	0.02
S2	1.50	1.71	0.62	0.33	0.78	8.72	0.02
S3	1.92	1.31	1.43	0.58	0.70	10.69	0.01
S4	1.32	1.24	0.68	0.62	0.65	10.61	0.01

### 3.3. Mixing criteria as indicated by seepage of wastewater

Improper treatment and disposal of domestic wastewater could be one of the major sources of salinization in the East Delta Pleistocene aquifer. The chemical signature of water polluted with urban wastewater or from the reuse of treated wastewater is very distinguishable. Sewage effluent has a relatively high  $r(\text{SO}_4/\text{Cl})$  ratios that are greater than unity in particular for water points 3, 11, 12, 13, 14 and S3, as well as high  $r(\text{Na}/\text{Cl})$  above unity in most of water samples except for water point 8 and 9. These ratios are attributed to applications of NaCl salts and boron-enriched detergent and are typical of domestic wastewater in Egypt (Vengosh et al., 1999).

### **3.4. Mixing criteria as indicated by agricultural return flow**

Intensive agricultural activities consume about two-thirds of the water resources in the East Delta region. It is estimated that 25-30 percent of this water returns to the groundwater and is expected to be one of the major salinization sources to the aquifer (Metcalf and Eddy, 2000). Return flows from agriculture have a distinctive chemical composition relative to other salinization sources. This water is characterized by high  $r(\text{SO}_4/\text{Cl})$  ranging from 0.05 to 1.5 and high  $r(\text{B}/\text{Cl})$  ratios ranging from 0.005 to 0.20 (Vengosh et al., 2002). The high  $r(\text{B}/\text{Cl})$  (water point 12) and  $r(\text{SO}_4/\text{Cl})$  ratios (water points 3, 12, 13, 14, and S3) are attributed to the application of gypsum fertilizers enriched in boron and sulphate (Vengosh et al., 2002).

### **3.5. Mixing criteria as indicated by environmental isotopes**

The stable isotopic compositions of The Pleistocene's groundwater and the modern Nile water of Ismailia Canal (After the construction of the Egyptian Aswan High Dam) (Table 2) are plotted on the conventional  $\delta^{18}\text{O}$  and  $\delta\text{D}$  diagram (Fig. 7). For isotopic comparison, also, included are the isotopic compositions of the old Nile water (before the construction of the Aswan High Dam) (Awad et al., 1993) and the irrigation return flow (Salem, 1996). The diagram shows that all water samples are located below the world meteoric water line in the upper right quadrant (Fig. 7) suggesting the meteoric origin of the water. The isotopic compositions of groundwater samples vary widely, ranging from 0.05 ‰ to 4.23 ‰ for  $\delta^{18}\text{O}$  and from 7.5 ‰ to 36.3 ‰ for  $\delta^{18}\text{O}$   $\delta\text{D}$  (Table 2). The variation in the isotopic compositions of groundwater refers to the presence of multiple sources recharging the aquifer.

On the  $\delta^{18}\text{O}$  and  $\delta\text{D}$  diagram, the groundwater samples scatter between the old Nile water and irrigation return flow samples; meanwhile the groundwater samples 5, 10, 13, and 15 represent a cluster around the surface water sample of Ismailia Canal. Accordingly, the groundwater of the Pleistocene aquifer is a mixture of the modern and old Nile water as well as the surplus water of irrigation, and this may explain the variation in the  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values of the aquifer.

The deuterium excess values (d-excess) (Table 2) calculated for the groundwater samples vary considerably (Table 2). Inspection in this table reveals that the higher  $\delta^{18}\text{O}$  values are associated with the lower d-excess ones. This is in general accord with the accepted theory that reduced deuterium excess is associated with extensive evaporation before infiltration (Gat et al., 1970). The deuterium excess that ranges from 1 and 8 is a typical of arid zone, the conditions dominating the study area. It seems from the variation in d-excess value that the groundwater of the Pleistocene aquifer is affected by evaporation and/or mixing with water that has been subjected to evaporation. This is clearly imparted on the groundwater points 4, 7, 8, 9, and 16 having  $\delta^{18}\text{O}$  and d-excess values ranging from +2.91 ‰ to +4.23 ‰ and from -8.76 ‰ to +2.46 ‰, respectively.

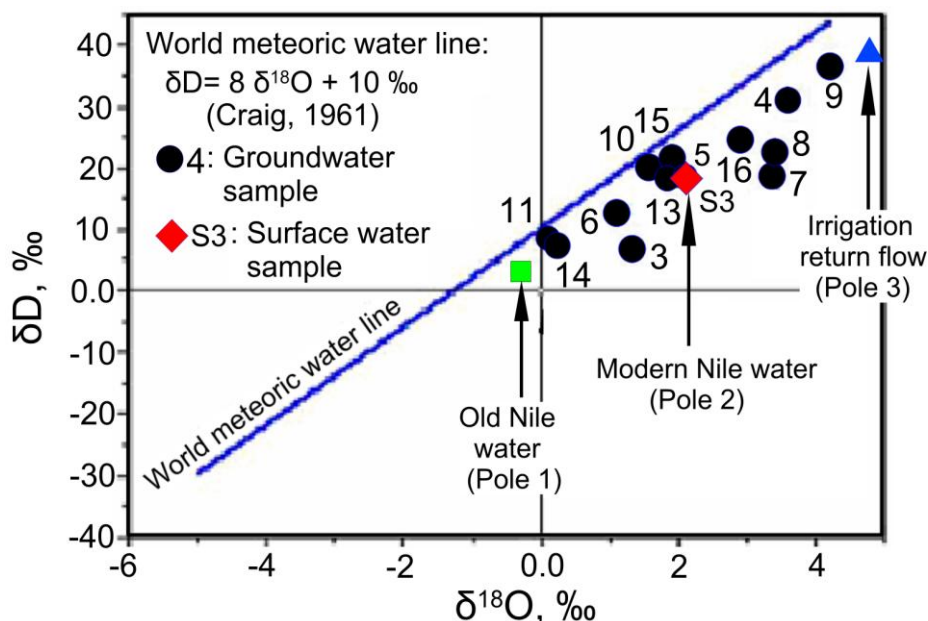


Figure 7. The  $\delta^{18}\text{O}$ - $\delta\text{D}$  relationship of groundwater and surface water samples, East Nile Delta, Egypt.

#### IV. Conclusion

The Pleistocene aquifer in East Nile Delta, Egypt is considered the second resource of water supply after the Nile water. The interconnection between the aquifer and surface water bodies was investigated using conventional and non-conventional techniques. The hydrogeologic investigations revealed that the Pleistocene aquifer is semi-confined and has piezometric heads ranging from 1.15 m (MSL) in the north to 12.5 m (MSL) in the south. Groundwater flows towards the northeast direction. Ismailia canal found in the southern part of the eastern Nile Delta is acting as loosing canal recharging the Pleistocene aquifer with considerable quantities of Nile water. The groundwater is alkaline ( $7 < \text{pH}$ ) and has different salinities ranging from fresh and saline water ( $377 \text{ mg/l} < \text{TDS} < 8530 \text{ mg/l}$ ).

Mixing from four poles of waters is thought to explain the most prevailing mechanisms recharging the Pleistocene aquifer, viz.; leaking from Nile water, surplus irrigation water from the surroundings agricultural activities as well as recharge from waste water and old Nile water recharged before the construction of Aswan High Dam. The mixing and dissolution processes were possible to establish through several evidences from hydrochemical and environmental point of view.

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