



Recharge Sources and Hydrogeochemical Evolution of the Groundwater in the Quaternary Aquifer El Gallaba Plain, Southwestern Desert, Egypt.



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Abstract

Groundwater has been regarded as the primary source of fresh water for agriculture and daily use purposes in El-Gallaba Plain, West Kom Ombo, Aswan. Recently, this plain has been considered as one of the most promising areas for government development projects. To develop a sustainable management plan for groundwater in the region, it is necessary to identify the main sources of recharge for this reservoir. Expect the extent to which the water level in the reservoir is related to the water level in River Nile, as well as Lake Nasser and the Nubian aquifer in the Western Desert. Due to the presence of more than one source, which may be single or combined, through which the Quaternary aquifer is recharged, the geochemical development of the groundwater is one of the most important means by which the main recharge source could be expected which is either Nile water or Nubian groundwater. Then, it will be clear to develop a permanent plan to exploit this reservoir based on determining its source of recharge. Three water types are detected along El-Gallaba Plain, using hydrochemical Facies Evolution Diagram: T1 (Ca-Mg-HCO₃), T2 (Ca-Mg-SO₄), (Ca-Mg-Cl) and T3 (Na-K-Cl), (Na-K-SO₄). In which, the salinity of groundwater varies between 843 and 4960 ppm. The mineralization of the aquifer groundwater is believed to be from fossilized meteoric water of Nubian aquifer. Under open system and reverse cation exchange, the Nubian water mixes with agricultural return water in the eastern part of the plain close to the Nile floodplain resulted in high TDS groundwater rich in Ca and Mg (T2 water type). The close system and cation exchange with sulphate reduction develop the Nubian groundwater water to high TDS groundwater rich in Na and Cl with subordinate SO₄ (T3 water type). It is clear that the main source of recharge for the Quaternary aquifer in El-Gallaba Plain area is the Nubian reservoir. Therefore, a plan must be developed for the optimal exploitation of the aquifer, based on the water needs required for future expansions and the ability of the aquifer to recover.

Keywords: El-Gallaba Plain, government development projects, Nubian aquifer, Lake Nasser, Quaternary, geochemical, hydrochemical Facies, and Evolution.

1. Introduction

1.1 Background

In recent years, Safeguarding food security and sustainable growth are the main concerns of the Egyptian government. Therefore, major programs have been undertaken in the last decades to release the overpopulation along the narrow Nile Valley, increase the agricultural land and creating job opportunities for people. Finding the suitable place for urban and agricultural development is crucial to achieve these goals. Therefore, developing the unexploited desert areas surrounding the Nile Delta and the valley has become necessary. In this context, ^[1] proposed a new development corridor aimed at

expanding development activities from the western side of the delta and valley to tens of kilometers west. This corridor is divided into 12 sectors. The study area is located in one of them, which is the Aswan sector.

Horizontal expansion in the desert fringes of the governorates is a strategic solution that the Egyptian government has been seeking for a long time, provided that suitable water sources are available to reclaim new lands without resorting to the Nile waters, since Egypt suffers from a severe shortage of surface water resources ^{[2], [3]}.

El Gallaba Plain with an area of about 5500 km² (≈550,000 Hectare) is one of the promising new lands

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targeted for reclamation. This plain is a desert area at the western fringes of the Nile Valley in Upper Egypt and lies to the Northwest of Aswan City and west of Kom Ombo town. The large area and distinguished location near Aswan, Daraw, Kom Ombo, and Idfu are the most important components of the El-Gallaba Plain to become part of the Egyptian government's sustainable development plan (Figure 1).

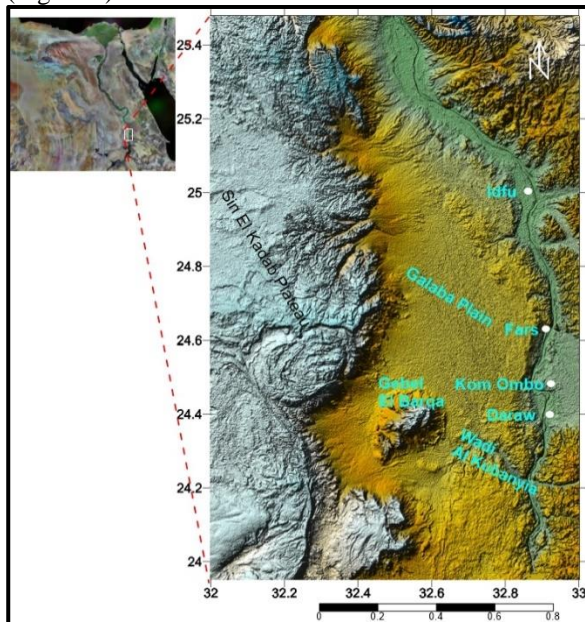


Figure 1: Location map of the study area

Due to the advantages of this area, it has attracted many investments in the field of agricultural reclamation during the last two decades, relying on groundwater as the sole source of irrigation water. Tens of wells have been drilled and land reclamation activities in the area are still ongoing. This acceleration in groundwater exploitation was accompanied by few studies to evaluate the geological and hydrogeological conditions of the aquifer in the area. Until 2011, the hydrological setting of the desert plain area located west of the Aswan city was not well understood, so that, its groundwater potential remains largely unknown [4]. Based on ground penetrating radar together with a new generation of satellite borne radar images, the fracture systems underneath El-Gallaba plain and its vicinity were identified. These structure elements seem to bring groundwater from the Nubian aquifer and possibly excess water from the River Nile or Lake Nasser into the study area [5]. El-Gallaba plain is a graben-like structure with a maximum depth to the basement of about 150 m and shallower depths toward the edges. Consequently, this structurally controlled basin could be a promising area for groundwater accumulation and exploration [6].

Integration of hydrogeophysical studies, hydrochemical analyses, and remote sensing were conducted to identify the recharge potential of the groundwater aquifers in El-Gallaba Plain [7]. This study revealed that El-Gallaba plain is a large graben-bound aquifer with a thickness of more than 220 m. The aquifer in the plain receives little recharge from the western fractured calcareous plateau with no indication for recent recharge from Lake Nasser. Transient Electromagnetic (TEM) data were acquired at 66 stations in El-Gallaba Plain [2]. The groundwater flow map derived from the TEM interpretation revealed that the flow is mainly toward the central part of the plain, with a perfect flow direction from south to north. The alluvial deposits aquifer is likely recharged from the Nubian Aquifer in the south. The Qualitative and geometrical features of the groundwater aquifer in El-Gallaba plain were investigated through 60 vertical electrical sounding and time-domain electromagnetic soundings [8]. The results showed that El-Gallaba plain has high groundwater potentiality of meteoric origin in two main Pleistocene aquifers: shallow fresh water and deep brackish water. Silicate weathering and evaporation processes occurring in the aquifer matrix increase the salinity of groundwater.

According to the climate changes and conditions that Egypt is exposed to now and expected to continue in the future regarding the increased demand for water sources, especially for agricultural purposes, plans must be developed for the sustainable management of any water resource. Although its importance, the overexploitation of groundwater in several regions of the world resulted in diminishing water levels, deterioration of water quality, and even resource depletion [9]; [10]. Based on these challenges, the United Nations has set a Sustainable Development Goal (SDG) on water, which includes a focus on sustainable groundwater management [11], [12]. The term "sustainable groundwater management" refers to the responsible and effective use of groundwater resources with the goal of maintaining these resources for future generations [13]. Sustainable groundwater management highlights groundwater connectivity with other water resources and the necessity for a comprehensive approach to management [14] and [15].

The rising water demand, along with the consequences of climate change, such as drought and variability in precipitation patterns (IPCC 2021), has raised the need for sustainable groundwater management. Changes in recharge, discharge, and water quality are projected to have a considerable influence on groundwater resources ([16]; [16]; [16]).

Determining the source of recharge for a specific groundwater reservoir, in addition to its relationship

with the surrounding water sources, is considered a cornerstone of developing a sustainable management plan for this reservoir. The geochemical evolution of the groundwater reservoir and the extent of its relationship to the geochemistry of the water sources surrounding it are important indicators in determining the source of recharge for this reservoir [17] and [18]. The aquifer in the study area is surrounded by many water sources, all or some of them may recharge this aquifer. They are represented by the Nubian aquifer (fossil water of last pluvial period) in the west, the Nile course in the east, Lake Nasser and the Toshka depression in the south (Figure 2).

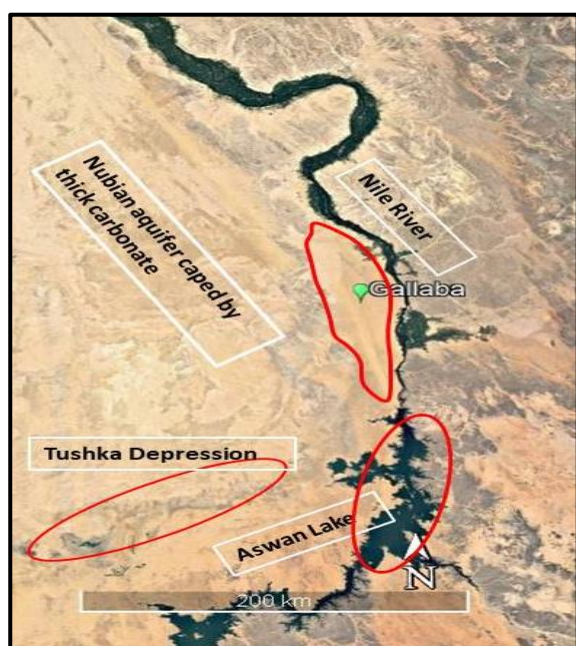


Figure 2: The Main water sources surrounding El Gallaba plain aquifer.

As far as I know, the previous studies have not precisely identified the main source/s of recharge for this reservoir so that a sustainable management plan for this underground reservoir can be developed. Therefore, this attempt was made to study the geochemical evolution of groundwater in the study area and its relationship with surrounding water sources to identify the main sources of recharge for this reservoir.

1.2 Objective of the study

This study focuses on determining the sustainability of the Quaternary aquifer through its relationship with the groundwater of the Nubian reservoir, the surface waters of the High Dam Lake (Lake Nasser), the Nile River, and the Toshka Depression. It is necessary to determine the expected source of

recharge to the aquifer in the study area. This point will be adopted by monitoring the geochemical development of groundwater within the aquifer and the extent to which this development is related to the geochemical diversity of water in the surrounding reservoirs. In addition, it includes some specific goals: a) Evaluate the quality of groundwater in the study area through hydrological and environmental measurements, including analysis of the physiochemical characteristics of the water, and b) Assess the geochemical processes controlling groundwater composition.

1.3 Materials and Methods

For hydro-chemical investigation, twenty-four groundwater samples were collected from productive wells representing the groundwater aquifer, in addition one sample from the Nubian aquifer plus 3 surface samples from the Nile River, High Dam Lake, and Toshka depression (Figure 3). The sample locations were determined using a handheld global positioning system (GPS) (GARMIN, Germany). The groundwater sampling was done following the USGS methods, [19]. Physicochemical parameters were determined during water sampling using calibrated portable instruments. Calibration of the field instruments was done at least once a day prior to sampling. A portable pH meter was used to measure the pH and Electrical conductivity (EC) was measured using an EC meter. High-density polypropylene (HDPP) bottles were used to store the sampled water.

Concentrated HNO_3 was added to the cation samples to maintain the pH below 2. The sample bottles were detailed labeled in the site and kept in ice box, then in the fridge. The samples were transported safely to the Desert Research Center laboratory and kept refrigerated at 4 °C.

Lab work, Chemicals, and double-distilled water were used to prepare solutions. The samples were analyzed for major ions using standard procedures [20]. Total Dissolved Solids (TDS) were measured by an evaporation method, Calcium (Ca) and magnesium (Mg) were determined titrimetrically using standard $\text{Na}_2\text{-EDTA}$; Chloride (Cl) by standard AgNO_3 titration; Carbonate (CO_3) and bicarbonate (HCO_3) by titration with H_2SO_4 ; Sodium (Na) and potassium (K) by flame photometry; sulfate (SO_4), was determined by the turbidity method using UV/Visible spectrophotometer, Unicam model UV4-200 (UK); wavelength 420 nm. The ionic charge balance error was less than 5 % in all measured samples.

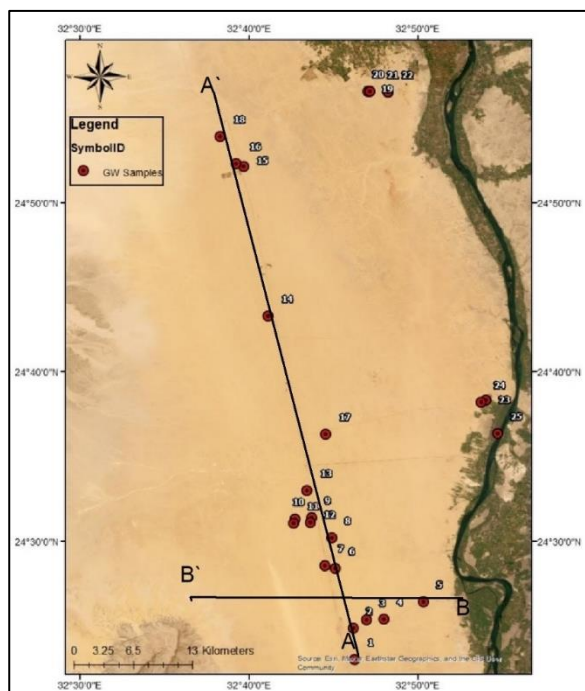


Figure 3: Locations of collected water samples.

1.4 Study Area

El-Gallaba Plain extends from the northwest Aswan district in the south to northwest Idfu City in the north. In contrast, it is geographically located between latitudes 24° 00' and 25° 3' 20" North and longitudes 32° 15' and 33°00' East (Figure 1). It is a vast plain covered by foreland sediments that range in age from upper cretaceous (Nubian Sediments) to Pleistocene (gravel and sand) [2]. El-Gallaba plain prolonged approximately 110 Km length and its width varies from 25 Km in the south to 50 Km on the center and north with a mean width of about 35 Km [7].

1.5 Climatic conditions

This area experiences hyper-arid conditions, with hot and lengthy summers, short and warm winters, the air temperature in this location ranges from a low of 16.5 °C (61.6 °F) in January to a high of 34.9 °C (94.8 °F) in August. The average temperature throughout the year is 18 degrees, with high evaporation rates, fast wind speeds, and very little rainfall, with an annual range of only 1-14 mm (Aswan Meteorological Station).

2. General Geology and Hydrogeology

2.1 Geological setting

The geologic setting in El Gallaba Plain and its surrounding area has been previously tackled by many authors such as [21], [22], [23], [24], [25], [26], [27] and [28]. The stratigraphic sequence of the area ranges in age from pre-Cambrian to Quaternary. The Pre-Cambrian rocks which consist mainly of igneous and

metamorphic rocks are not exposed in Gallaba plain but to the south of Aswan. According to the geologic maps of (CONOCO, 1987) and others (Figure 4), the exposed rock units in the area are summarized in the following from base to top.

Upper Cretaceous: The older Phanerozoic rocks exposed close to El Gallaba plain from the south. It represents the Nubian Sandstone and includes the following formations:

- **Abu Aggag Formation** (Nubian sandstone): it is mainly of coarse sandstone with mudstone intercalations.
- **Timsah Formation** (Nubian sandstone): it is made up of siltstone, sandstone, and shales with iron ore bed.
- **Um Barmil Formation** (Nubian sandstone): it is composed of medium sandstone with claystone intercalation.
- **Quseir Formation** consists of Varicolored shale, siltstone and sandstone.
- **Duwi Formation** made up of glauconitic sandstone with grey shale.
- **Keseiba Formation** consists of fine-grained sandstone with shale and silt intercalations.

Tertiary: the following formations are exposed as very thin layers at the west of El-Gallaba plain (Figure 4):

- **Dakhla Formation** (Paleocene- Eocene): it is made up of laminated shale.
- **Kurkur Formation** (Paleocene): it is mainly dolomitic and marly limestone.
- **Garra Formation** (Paleocene): it is built up of limestone, partly chalky and intercalations of marl and shale.
- **Thebes group** (Lower Eocene): it consists of earthy brown grading into greyish white limestone with chert. This limestone with a great thickness represents the main surface exposure along the vast extension of Sen ElKadab plateau which borders the Plain from the west (Figure 4).

Quaternary: it is the only sediments that cover the whole area of El-Gallaba plain (Figure 4).

It is the youngest deposit that covers the entire area of El Gallaba plain and is composed mainly of alluvial sediments (a mixture of gravels, sands, silts and mud).

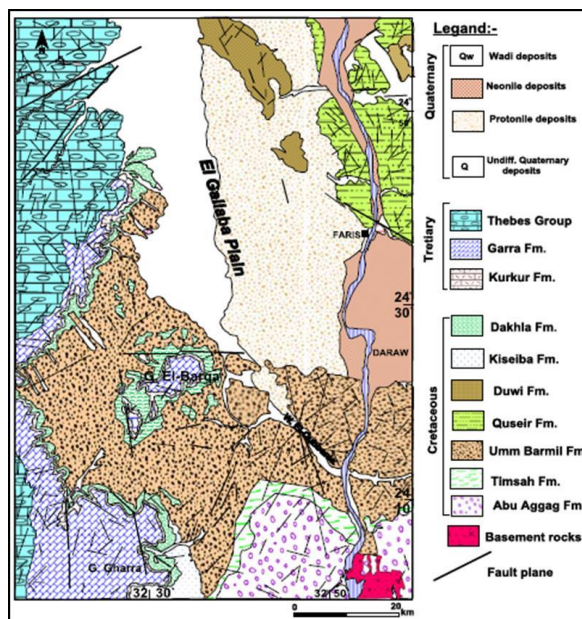


Figure 4: Geologic map of the area. Compiled after CONOCO 1987, [28], and [2].

Structurally, the study area is situated within the African Platform with its Pre-Cambrian folded basement, so the regional tectonic framework of the area is related to the Last African Orogenic belt ([21], [29]). Gallaba plain is a part of the Nile Valley in Egypt which is, mainly, controlled by wrench faults that are generally parallel either to the Gulf of Suez or the Gulf of Aqaba directions [30]. Thus, the study area has been affected by the same structural deformation processes that generated the Nile Valley and shaped the Kom Ombo basin located east of the Nile River [5].

2.2 Hydrogeological Setting.

The Quaternary aquifer's sediment types and extension were clarified by studying two hydrogeological cross-sections. These sections, constructed in SE-NW and E-W directions (Figure 5), demonstrate the lateral and vertical lithofacies changes of the aquifer sediments in those directions. Geoelectrical cross sections in E-W and N-S directions detected the vertical and horizontal variations in the parameters of the water-bearing layers in addition to the structural elements that affect the area in different directions (Figure 6) [2].

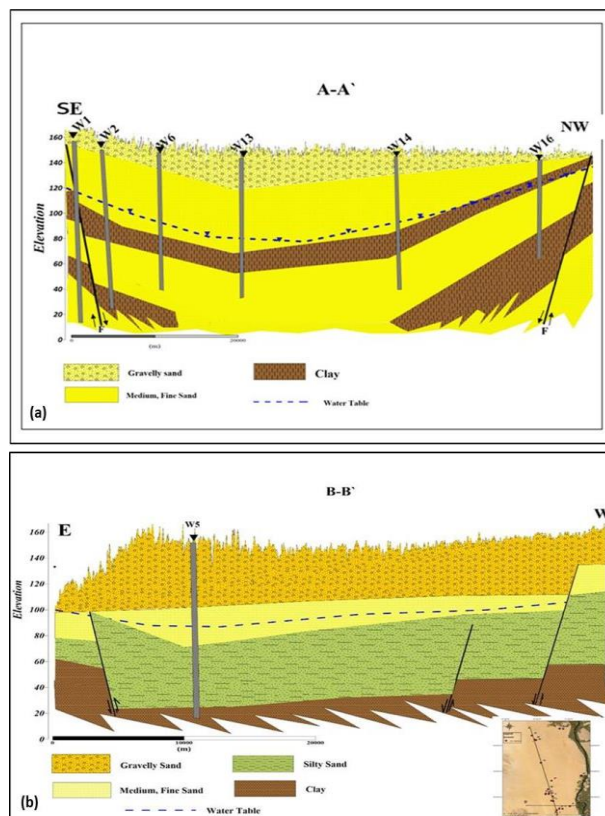


Figure 5: The Quaternary aquifer in El-Gallaba Plain: (a) NW-SE direction; (b) E-W direction.

The cross-sections show the horizontal and vertical variations of the existing water bearing layers. The vertical relative displacement of layers is due to faulting and the water table. The most important structural effect is represented by the uplifted of older aquitard layers which, may, correspond to Duwi Formation and the underlying formations facing the relatively younger Quaternary deposits.

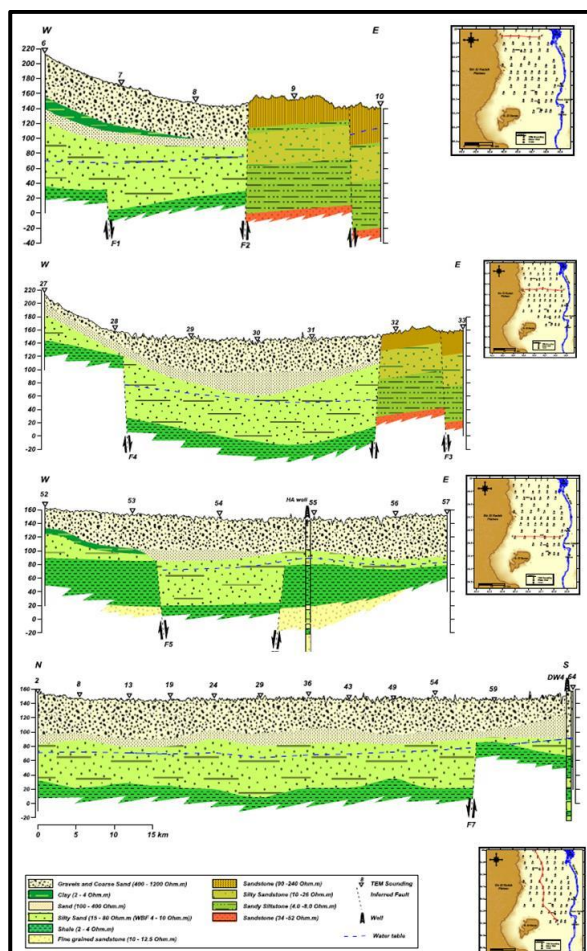


Figure 6: Geo-electromagnetic Cross-sections (Cross-sections A-A', B-B', C-C' and DD' in W-E direction Cross-section E-E' in N-S direction). [2].

The above cross sections indicate that the thickness of the groundwater bearing layers increase from south to north along El Gallaba plain. Going to the east toward the Nile floodplain and to the south the aquiclude layers expected at shallow depths that could be limited the hydrologic connection between the water bearing layers in El Gallaba plain and the Nile floodplain aquifer.

The aquifer in the area is primarily made up of sand with fine to coarse grain size texture and contains interbeds of clay and silt [7]. The sand sediments are dominant in some parts of the south, where most of the lithologic section is largely composed of clay sediments. The changes in the sediment types of the aquifer located in the plain are influenced by structural elements, such as faults, present in the study area. The Quaternary aquifer is considered semi-confined or confined due to the presence of capped clay beds and shale lenses.

The effective porosity of the Quaternary aquifer in El-Gallaba plain reaches about 19.06%. Hydraulic

conductivity values range from 0.48 m/day to 28 m/day. It increases from south to north; the transmissivity values range from 58 m²/day to 3400 m²/day as a result of pumping tests and logs analysis [31]. Groundwater levels range from 20 m in the south to 75 m in the Northwest and 80 m to the southeast direction and depths increase dramatically to the north and northwest (Figure 7).

Groundwater flow in the region moves in several directions, i.e., from south to north in the southern region, from east to west in the central region, and from west to east in the northern region. This variation in the groundwater flow direction in the plain could be related to the local variations in the abstraction rate.

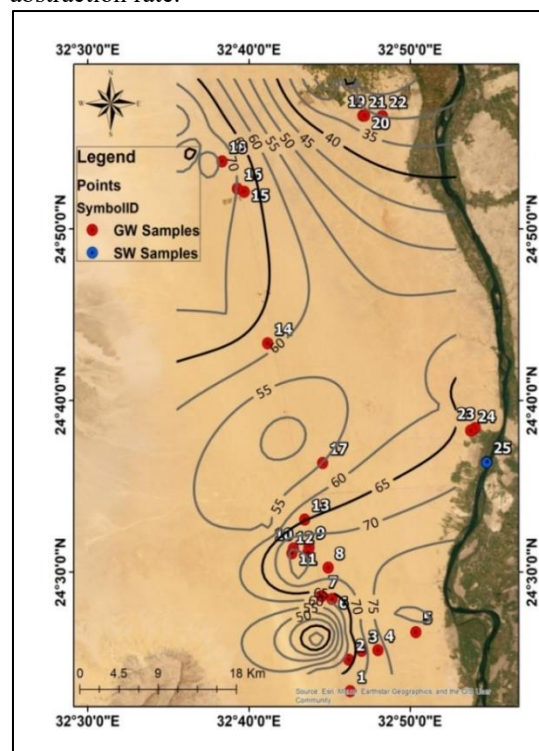


Figure 7: Groundwater level contour map of the Quaternary aquifer in El-Gallaba plain.

1. Results

1.1. Geochemical Water types

Chadha (1999) [32] developed a helpful genetic groundwater classification scheme to differentiate different types of water-rock interaction processes in aquifers. The classification involves plotting the difference in milliequivalent percentage between alkaline earth (calcium plus magnesium) and alkali metals (sodium plus potassium) on the X axis, and the difference in milliequivalent percentage between weak acidic anions (carbonate plus bicarbonate) and strong acidic anions (chloride plus sulphate) on the Y axis. This allows for a clear differentiation between

various water-rock interaction processes. The analysis of the chemical properties of ground waters reveals three distinct water types as shown in Figure 8a. To better understand how recharge evolved into groundwater and the relationship between surface water and groundwater, geochemical data from the River, Aswan High Dam Lake (AHDL), Toshka Khor, and Nubian water samples were added to the processed groundwater data. The geographical distribution of different groundwater types in the area is illustrated in Figure 9.

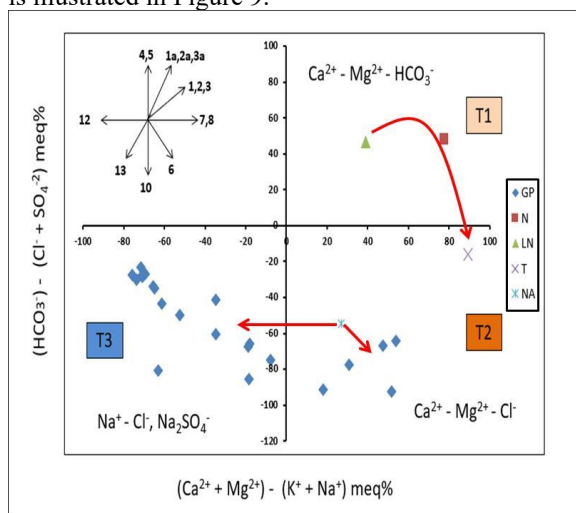


Figure 8: Geochemical classification of groundwaters; the groundwater type (T1) is Ca-Mg-HCO₃, (T2) is Ca-Mg-Cl with MgSO₄ and MgCl₂, and (T3) is T3 (Na-K-Cl), (Na-K-SO₄). The geographical locations of the groundwater types in the aquifer are shown in Figure 9. The red arrows refer to the proposed evolution trends of water types.

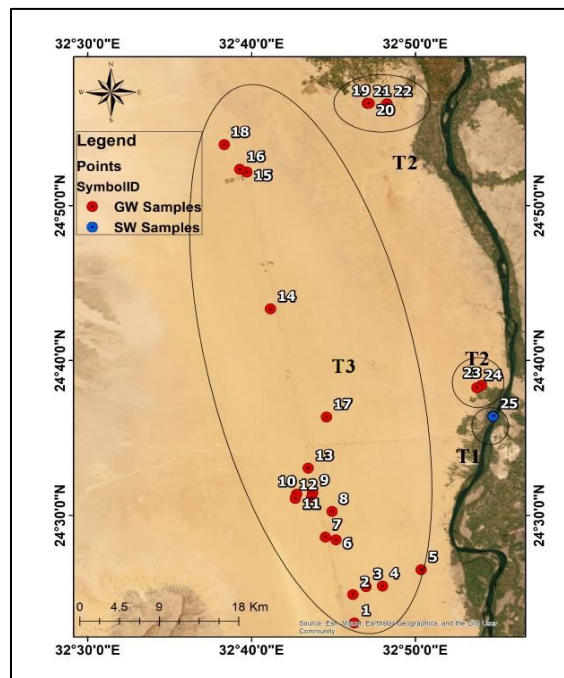


Figure 9: The geographical distribution of the groundwater types in the aquifer.

Table1: Chemical Analysis of Groundwater Samples

WT	data	K ⁺	Na ⁺	Mg ⁺⁺	Ca ⁺⁺	Cl ⁻	SO ₄ ⁻	HCO ³⁻	SI Dolomite	SI Calcite	SI Gypsum
T3	w1	0.263427	9.243149	3.4090371	4.3318962	6.854725	0.80762	8.03163	-1.91	0.44	-2.25
	w2	0.212276	32.45977	2.014431	3.4036327	27.967278	2.358942	4.736602	0.52	0.12	-2.13
	w3	0.163683	28.38191	4.028862	2.4753693	26.047955	0.974235	2.883149	1.48	0.37	-2.64
	w4	0.194373	28.54502	2.7892122	6.1884232	25.499577	0.245034	8.649448	0.93	0.37	-2.86
	w5	0.202046	23.16224	3.8739058	7.4261078	26.733427	0.189205	6.590055	1.05	0.41	-2.9
	w6	0.181586	26.31579	1.2396499	2.7847904	17.822285	0.505465	9.885083	1.35	0.59	-2.83
	w7	0.207161	27.72031	1.5495623	3.0942116	18.919041	0.338122	11.94448	1.48	0.62	-2.98
	w8	0.217391	26.31579	3.2540809	9.5920559	20.564175	4.11243	10.29696	1.85	0.9	-1.51
	w9	0.196931	23.37973	1.8594748	2.1659481	17.548096	0.235166	9.885083	1.54	0.53	-3.27
	w10	0.204604	21.9117	1.5495623	2.4753693	16.315938	0.213408	9.473205	1.46	0.56	-3.23
	w11	0.202046	21.20487	1.3946061	1.5471058	16.862623	0.466375	9.885083	1.02	0.26	-3
	w12	0.191816	23.21662	1.2396499	2.7847904	16.862623	0.445555	9.885083	1.43	0.62	-2.85
	w13	0.209719	22.89039	1.8594748	3.0942116	16.725529	0.44035	8.237569	1.84	0.76	-2.84
	w14	0.204604	24.52153	5.1135557	16.0899	20.564175	11.35374	4.530663	1.2	0.6	-0.19
	w15	0.171355	19.73684	4.4937307	9.2826347	20.289986	4.8934	5.148481	1.37	0.59	-1.42
	w16	0.168798	20.71553	4.3387745	9.901477	21.386742	3.102228	4.736602	1.33	0.59	-1.58
	w17	0.179028	27.51196	1.7045186	4.9507385	22.483498	0.107537	8.855387	1.48	0.7	-3.28
	w18	0.161125	21.36799	4.9585994	9.901477	21.660931	7.267333	2.265332	0.48	0.14	-1.24
w22	0.219949	33.92779	2.1693872	4.9507385	25.499577	0.290235	12.76823	1.37	0.61	-2.91	
T2	w19	0.769821	22.61853	16.115448	57.552335	59.361918	5.003748	2.471271	1.15	0.6	-0.95
	w20	0.506394	42.79034	15.960492	46.413174	38.934838	37.07641	3.500967	1.1	0.55	-0.24
	w21	0.255754	16.55937	10.227111	21.659481	20.838364	11.39746	4.118785	1.41	0.63	-0.86
	w23	0.232737	9.515007	5.5784244	21.659481	10.693371	10.25655	4.118785	1.09	0.6	-0.79
	w24	0.199488	7.079165	4.3387745	19.802954	10.96756	5.967937	3.706906	1.21	0.69	-1
	Toshka	0.2711	0.434972	4.5002057	8.0838323	2.3074753	3.22715	3.99882	2.1	0.86	-1.08
	Nubian	0.102302	4.523706	1.0530646	6.9860279	3.8363893	2.290235	1.802747	0.64	-0.15	-1.75
T1	Nile	0.140665	0.869943	1.2396499	6.8072655	1.096756	0.344909	4.118785	0.99	0.65	-2.38
	LN	0.127877	1.217921	1.0695187	1.6966068	0.3385049	0.811993	3.146612	0.37	0.02	-1.94

2.2.1 Groundwater type T1 Ca-Mg-HCO₃

This water type represents the surface water samples of the Nile River and High Dam Lake. It reflects the chemical composition of meteoric water located in the upper right quadrant of the Chadha's diagram (Figure 8). This water type is slightly alkaline (pH \geq 7.5, Table 1). Bicarbonate is the main anion, followed in concentration by Cl and SO₄ and in the Nile water sample while SO₄ > Cl concentration in the high dame lake. Calcium with subordinate Na and Mg are the main cations (Table 1). The concentration of HCO₃ and Ca and sometimes Na reflects the variation in TDS of both samples of this type. The Nile water is typically saturated with respect to calcite and dolomite but undersaturated with respect to gypsum, while the LN water is saturated with respect to dolomite but undersaturated with respect to calcite and gypsum.

2.1.2 Groundwater type T2 (Ca-Mg-Cl)

This water type is characterized by higher concentrations of strong acidic anions (Cl + SO₄) than weak acidic anions mainly HCO₃ and higher concentrations of alkali earth elements (Ca + Mg) than alkali metals (K + Na) (Table 1). Geographically, this water type includes the groundwater samples located close to the Nile floodplain plus the pure Nubian aquifer and Toshka groundwater samples (Figure 9 and Table 1). This water type is slightly alkaline, and the TDS is mainly controlled by the concentration of Cl, Ca and Mg ions. All groundwater samples of this water type are saturated with respect to calcite and dolomite except the Nubian water sample while all of them are undersaturated with respect to gypsum (Table 1).

There is no significant correlation between pH and HCO₃ concentration in type 2 waters (Fig10a). The relationships between dissolved concentrations of Ca, Mg and HCO₃ potentially will enable a distinction to be made between the principal carbonate mineral reactions involving in the geochemical formation of the groundwater^[33].

Calcium due to carbonate dissolution can be isolated from that due to the dissolution of anhydrite or gypsum by subtracting SO₄ from Ca (Edmunds et al., 1982). The molar plots of (Ca -SO₄) and Mg versus HCO₃ for T2 groundwater are shown in Figure 10b & c. (Ca -SO₄) and Mg are insignificantly correlated with HCO₃ which suggests initially that the dissolution of carbonate minerals have not much contributed to the geochemical evolution of the T2 groundwater.

Kimblin (1995)^[34] drew attention to the contribution of sulphate mineral dissolution to the concentration

of Ca in groundwater by studying the relation between the non-carbonate mineral derived Ca and Mg using [(Ca + Mg) - 0.5HCO₃] plotted versus SO₄. He also considered the possibility of cation exchange using the relationship between the molar excess of sodium over chloride (Na-Cl) and Mg with SO₄. It seems that dissolution of sulphate minerals seems to have affected nearly all the groundwater samples of T2 (Fig. 11b). Mg increased in T2 samples with the increase of SO₄ reflects the cation exchange between Ca and Mg (Figure 11c).

2.1.3 Groundwater type T3 (Na-Cl)

In this water type alkali metals exceed alkaline earths and strong acidic anions exceed weak acidic anions. The positions of data points in the proposed diagram represent Na⁺-Cl⁻-type, Na₂SO₄-type.

This type of groundwater can be considered regionally to be the main water type in the whole El Gallaba aquifer as it represents the chemical composition of most of the groundwater samples cover the whole area on El Gallaba plain (Figures 8 & 9). This water type is almost always alkaline (pH \geq 7.5, Table 1). Cl is the main anion in this water type, followed in concentration by HCO₃ and SO₄ (Table 1). Sodium with subordinate Ca and Mg are the main cations (Table 1).

The variation in the total dissolved solids (TDS) of this water type reflects the variations in the sum of the concentrations of the dominant anion and cations: Cl, Na, Ca and Mg (Table 1). The waters are typically saturated with respect to calcite and dolomite but undersaturated with respect to gypsum (Table 1).

There is a weak positive correlation between pH and HCO₃ concentration in T3 waters (Figure 10a). There is no clear increase in the carbonate calcium and magnesium with HCO₃ in T3 waters (Figures 10 b & c). The non-carbonate calcium and magnesium seem to be correlated with SO₄ in T3 waters (Figure 11 a & c, respectively) while the non-halite sodium does not correlate with SO₄ (Figure 11 b).

lower pH <7. Reaction 6 is the dissolution of sandstone sulphate mineral cement resulting in elevated Ca and SO₄. Reactions 7 to 9 and 13 involve clay-mediated cation exchange processes and only affect cation ratios. Reaction 10 is the process that leads to acid-mine drainage, and iron sulphide mineral oxidation. This results in elevated acidity and increased SO₄ concentration. Reaction 11 is the oxidation of reduced nitrogen species such as ammonia and also results in elevated acidity. Reaction 12 is the halite dissolution reaction results in elevated acidity.

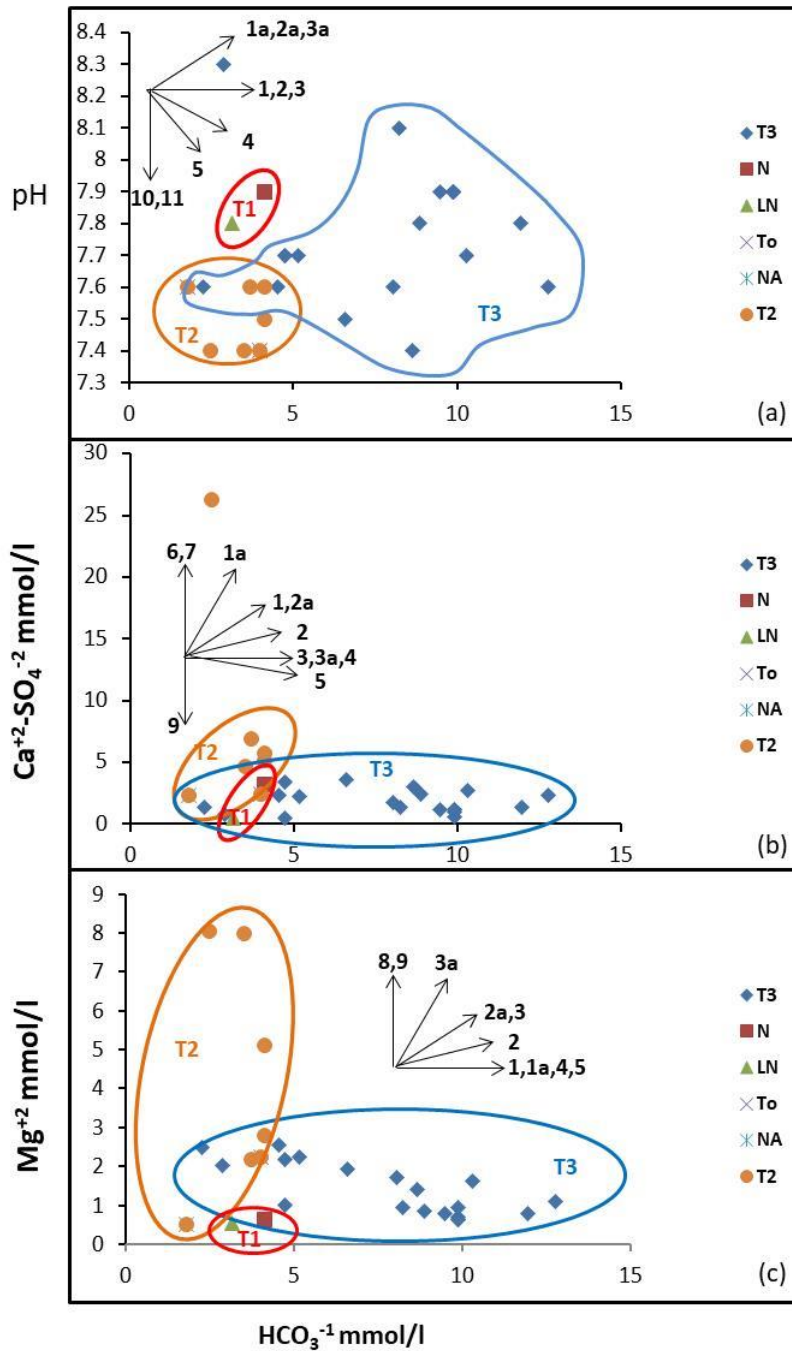


Figure 10: Geochemical cross-plots of groundwaters; (a) no significant correlation between pH and HCO_3^- in T1 and T2 while the pH increased with HCO_3^- in T3, (b) relationship between ($\text{Ca}^{2+} - \text{SO}_4$) and HCO_3^- ; the carbonate Ca slightly increased with HCO_3^- in T1 and T2 while no significant correlation between them in T3, and (c) Relationship between Mg^{2+} and HCO_3^- ; no significant correlation between Mg and HCO_3^- in T1 and T3 but they are significantly correlated in T2. Reaction vectors, listed in Table 2, indicate the general evolutionary geochemical trajectories of water if the indicated reaction occurs in the aquifer. Combination of reactions will lead to intermediate vectors. The vectors are not specific to any initial water type.

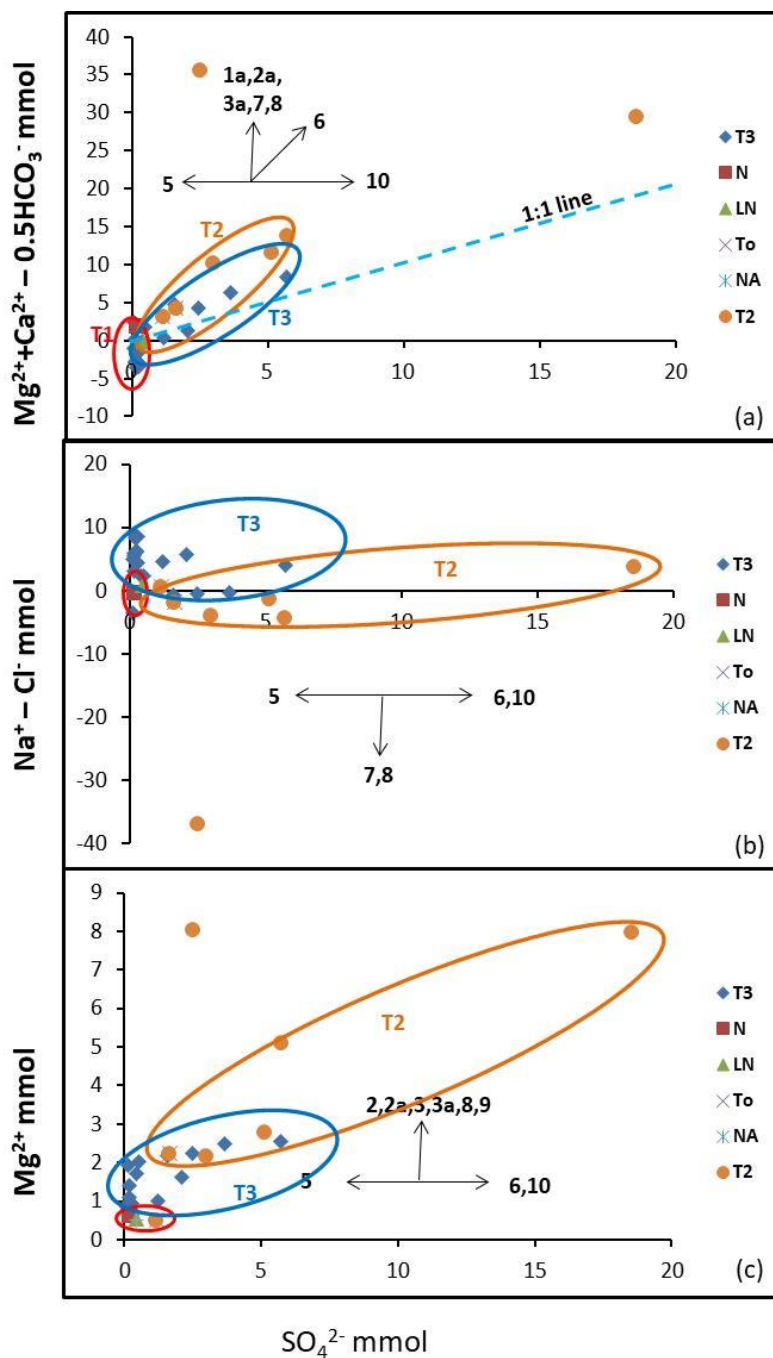


Figure 11: Geochemical cross-plots of groundwaters; (a) concentration of non-carbonate calcium and magnesium vs. sulphate for all samples; no significant correlation in T1 while they are slightly correlated in T2 and T3, (b) concentration of non-halite sodium with sulphate; no obvious correlation between them in three water types, and (c) Mg^{2+} vs. sulphate; no significant correlation between the both parameters in T1 but they are slightly correlated in T2 and T3. Reaction vectors, listed in Table 2, indicate the general evolutionary geochemical trajectories of water if the indicated reaction occurs in the aquifer. Combination of reactions will lead to intermediate vectors. The vectors are not specific to any initial water type.

3. Discussion

To assist with the interpretation of the processes that may have controlled the groundwater geochemistry in El Gallaba plain aquifer, reaction-specific vectors have been derived (for reactions 1 to 13, Table 2) specific to each of the bivariate geochemical plots. All geochemical reactions that could influence the X- and Y-axes have been plotted on each diagram. If a given reaction does not influence either the X or Y axis, then it is not plotted on the vector diagram. If a reaction only influences one or another axis, then the vector is parallel to that axis. If a reaction influences both X- and Y-axis parameters, then the vector has a gradient specific to the particular reaction. Thus Figures 9, 10 and 11 have summary vector diagrams to help reveal the dominant geochemical processes in the aquifer.

Reactions 1 and 2 are the complete dissolution of the common sandstone carbonate mineral cement, calcite, and dolomite. Reaction 3 is the partial, or incongruent, dissolution of dolomite resulting in remnant calcite (also known as dedolomitisation). Reactions 1a to 3a are also carbonate dissolution reactions but differ from 1 to 3 in that they require acidity and lead to different cation-to-anion ratios. Reaction 4 is the dissolution and dissociation of CO₂ from any source (atmospheric and biogenic, primarily). Reaction 5 is the bacterially-mediated reduction of SO₄ resulting in increased acidity and bicarbonate concentrations. Note that reaction 5 produced acidity not consumed acidity ($H^+ + 2CH_2O + SO_4^{2-} = H_2S + CO_2 + HCO_3^-$) because of the pH of the groundwater which is generally above 7. The consumed acidity sulphate reduction required a much lower pH <7. Reaction 6 is the dissolution of sandstone sulphate mineral cement resulting in elevated Ca and SO₄. Reactions 7 to 9 and 13 involve clay-mediated cation exchange processes and only affect cation ratios. Reaction 10 is the process that leads to acid-mine drainage, and iron sulphide mineral oxidation. This results in elevated acidity and increased SO₄ concentration. Reaction 11 is the oxidation of reduced nitrogen species such as ammonia and also results in elevated acidity.

Reaction 12 is the halite dissolution reaction that results in elevated acidity.

3.1. Carbonate chemistry

Lake Naser and River Nile waters are surface water that exists in an open system so a continuous supply of CO₂ from the atmosphere and biological processes is dominated. So, the congruent and incongruent dissolution of calcite and dolomite minerals with the continuous supply of atmospheric and biogenic CO₂ control the carbonate chemistry in T1 water type (Reactions 1,2,3&4, Table 2 and Figures 9,10a). Due to a small number of samples representing the T1 type, no clear indications about the role of cation exchange in the variation of Ca, and Mg concentration.

T2 groundwater is located in the area close to Nile River floodplain (Figure 9). This area has intense agricultural activity that depends on flood irrigation which results in a large amount of agricultural drainage with high salinity that seeps into the groundwater reservoir. This is reflected in the high TDS of aquifer waters in this area (Table 2 and Figure 9).

Shallow aquifer in El Gallaba plain is an unconfined aquifer that is open to atmospheric and biogenic inputs. During the infiltration of agricultural water return through overlying soil and the unsaturated part of the aquifer, a continuous influx of CO₂ has been maintained as a result of biochemical oxidation of organic matter and respiration of the plant roots [35], [36], [37], and [38]. This is in addition to the invasion of atmospheric CO₂ that might enhance dissolution processes of any carbonate minerals present in the aquifer. Like T1, carbonate mineral dissolution controls the carbonate chemistry in T2 waters ((Reactions 1,2,3&4, Table 2 and Figures 9,10a).

Table 2: Different geochemical reactions that could be operating in the aquifer.

Process	Geochemical reaction	Reaction
Congruent dissolution of calcite	$\text{CaCO}_3 + \text{H}_2\text{CO}_3 = \text{Ca}^{2+} + 2\text{HCO}_3^-$	1
	$\text{CaCO}_3 + \text{H}^+ = \text{Ca}^{2+} + \text{HCO}_3^-$	1a
Congruent dissolution of dolomite	$\text{CaMg}(\text{CO}_3)_2 + 2\text{H}_2\text{CO}_3 = \text{Ca}^{2+} + \text{Mg}^{2+} + 4\text{HCO}_3^-$	2
	$\text{CaMg}(\text{CO}_3)_2 + 2\text{H}^+ = \text{Ca}^{2+} + \text{Mg}^{2+} + 2\text{HCO}_3^-$	2a
Incongruent dissolution of dolomite	$\text{CaMg}(\text{CO}_3)_2 + 2\text{H}_2\text{CO}_3 = \text{CaCO}_3 + \text{Mg}^{2+} + 2\text{HCO}_3^-$	3
	$\text{CaMg}(\text{CO}_3)_2 + \text{H}^+ = \text{CaCO}_3 + \text{Mg}^{2+} + \text{HCO}_3^-$	3a
Biological processes and atmospheric gas	$\text{CO}_2 + \text{H}_2\text{O} = \text{H}_2\text{CO}_3 = \text{H}^+ + \text{HCO}_3^-$	4
Sulphate Reduction	$\text{CH}_2\text{O} + \frac{1}{2}\text{SO}_4^{2-} = \frac{1}{2}\text{HS}^- + \text{HCO}_3^- + \frac{1}{2}\text{H}^+$	5
Dissolution of gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O} = \text{Ca}_{(\text{aq})}^{2+} + \text{SO}_{4(\text{aq})}^{2-} + 2\text{H}_2\text{O}$	6
Na ⁺ exchange by Ca ²⁺	$(\text{Ca}) - \text{Ex} + 2\text{Na}_{(\text{aq})}^+ = \text{Ca}_{(\text{aq})}^{2+} + (2\text{Na}) - \text{Ex}$	7
Na ⁺ exchange by Mg ²⁺	$(\text{Mg}) - \text{Ex} + 2\text{Na}_{(\text{aq})}^+ = \text{Mg}_{(\text{aq})}^{2+} + (2\text{Na}) - \text{Ex}$	8
Mg ²⁺ exchange by Ca ²⁺	$\text{Mg} - \text{Ex} + \text{Ca}_{(\text{aq})}^{2+} = \text{Mg}_{(\text{aq})}^{2+} + \text{Ca} - \text{Ex}$	9
Iron sulphide oxidation	$\frac{15}{4}\text{O}_2 + \text{FeS}_2(\text{s}) + \frac{7}{2}\text{H}_2\text{O} = \text{Fe}(\text{OH})_3(\text{s}) + 2\text{SO}_4^{2-} + 4\text{H}^+$	10
Nitrification	$\text{O}_2 + \frac{1}{2}\text{NH}_4^+ = \frac{1}{2}\text{NO}_3^- + \text{H}^+ + \frac{1}{2}\text{H}_2\text{O}$	11
Halite dissolution	$\text{NaCl} = \text{Na}^+ + \text{Cl}^-$	12
Cation exchange	$2(\text{Na})-\text{X} + \text{Ca}^{2+} = \text{Ca}-\text{X} + 2\text{Na}^+$	13a
	$2(\text{Na})-\text{X} + \text{Mg}^{2+} = \text{Mg}-\text{X} + 2\text{Na}^+$	13b
	$2(\text{K})-\text{X} + \text{Ca}^{2+} = \text{Mg}-\text{X} + 2\text{K}^+$	13c
	$2(\text{K})-\text{X} + \text{Mg}^{2+} = \text{Mg}-\text{X} + 2\text{K}^+$	13d

Reaction sequence between groundwater and carbonate mineral phases can be characterized by variations in pH and the concentrations of dissolved Ca, Mg and HCO₃ (Table 1). Dissolution of

carbonate minerals seems to have affected the geochemical composition of groundwater type T2 since both HCO₃ and alkaline earth element concentrations increase (Figure 10b). Non-sulphate

sourced calcium (Ca-SO₄) and HCO₃ in this water type are slightly with the ratio of Ca to HCO₃ being approximately 1: 2. This suggests that reactions 1 and 2a the congruent dissolution of calcite and dolomite, respectively dominate the geochemical evolution of T2 water type (Reaction 1 and 2a, Figure 10b). This is further supported by a similar ratio between Mg and HCO₃ with a slope of 1:2 (Figure 10c). The dramatic increase in Mg concentration in T2 waters could be as a result of cation exchange between Na and Ca in water with Mg in the carbonate sediments (Table 2, Reactions 8 & 9, and Figure 10c). Although the TDS in the Nubian and Toshka groundwaters are much lower than the rest of the T2 type samples, they are all of the same type. This is due to the fact that the infiltrated agricultural drainage water does not affect the type of water, but only increases the concentrations of the ions.

T3 groundwater is the main water type represents the major area of El Gallaba plain aquifer (Figure 9). The alkalinity of this water type is slightly higher than the other two water types. The TDS of T3 is much higher than T1 but lower than the T2 (Table 9). This is due to the absence of agricultural wastewater leakage so the dissolved salts are a direct result of water-rock interaction processes as will be clarified later.

T3 samples reflect a significant correlation between pH and HCO₃ Shallow aquifer in El Gallaba plain is an unconfined aquifer that is open to atmospheric and biogenic inputs. The congruent and incongruent dissolution of carbonate minerals (Reactions 1,2&3, table 2) with the aid of atmospheric gas (Reaction 4) control the bicarbonate concentration in T3 waters (Figures 9,10a).

Reaction sequence between groundwater and carbonate mineral phases can be characterized by variations in pH and the concentrations of dissolved Ca, Mg and HCO₃ (Table 1). Dissolution of carbonate minerals should affect the geochemical composition of groundwater since both HCO₃ and alkaline earth elements concentrations increase. It is noted that the increase in bicarbonate is not accompanied by a clear increase in calcium and magnesium concentrations (Figure 10b,c). Therefore, it is clear that the increase in bicarbonate concentration in these waters does not depend primarily on the increase of carbonate minerals dissolution. This may be due to a reduction of sulphates (Reaction 5, Table 2, and Figure 10c).

The graben structure of El –Gallaba plain led to the Quaternary aquifer directly facing the Upper Cretaceous to Eocene deposits, which are rich in carbonates from the west, where the Nubian aquifer is trapped underneath. Therefore, recharging of El-

Gallaba reservoir from the Nubian aquifer passes through carbonate mineral phases. This increases the concentration of bicarbonate, calcium, and magnesium as well as TDS of T3 waters. Since the Quaternary aquifer in the area is characterized by the presence of aquiclude layers, which may result in reducing conditions in most of its area that triggers the reduction of sulphate by the anaerobic bacteria. Therefore, the source of this type of water is the Nubian reservoir with an increase in carbonate dissolution under reducing conditions, (closed system dissolution of carbonate [39], in most cases.

The dominant recharge of this aquifer is either directly from percolated naturally acidic rainfall or, more probably, via surface waters (i.e. soil water, streams, and rivers). The surface waters in this area tend to be neutral to slightly alkaline (pH of about 7.5; Fig. 3.4a, 3.6a). The lower TDS T1 groundwaters have a mean pH of about 7. The reduction in surface water pH at the preliminary stage of groundwater infiltration could be due to dissolution and dissociation of biogenic CO₂ (reaction 4); the oxidation of sulphide minerals (reaction 10); or nitrification of natural or anthropogenic ammonia (reaction 11). These reactions supply acidity to the system (vectors 4, 10 and 11, Fig. 3.4a). There is a hint in the spread of the data at lower bicarbonate concentrations that pH increases with increasing bicarbonate suggesting that pH-neutralising carbonate dissolution reactions (e.g. reactions 1a-3a) may have been effective to one degree or another, especially at the early stages of water-rock interaction (Table 3.6, Fig. 3.4a). This is besides the dissolution of silicate that may enhance the pH level.

In summary, the congruent and incongruent open system dissolution of calcite and dolomite minerals with the continuous supply of atmospheric and biogenic CO₂ control the carbonate chemistry in T1 (surface water and T2 (groundwater) types. The closed system dissolution of carbonate seems to control the carbonate chemistry of T3 groundwater type. Mixing between the Nubian groundwater with the agricultural return water dominates the T2 groundwater samples while T3 groundwater is Nubian origin with enhanced carbonate dissolution under reducing conditions.

3.2 Dissolution of sulphate minerals

Groundwaters with lower SO₄ concentrations of about 10-50 mg/l are likely to have acquired their SO₄ from rainwater (surface waters), possibly concentrated by evaporation during recharge (Kimblin, 1995). Surface water samples T1 water type has Sulphate concentrations < 50 mg/l while all

T2 and few samples of T3 groundwaters have concentrations > 50 mg/l (Table 1). To acquire aqueous SO_4 the waters must either induce sulphate mineral (e.g. gypsum or anhydrite) dissolution or undergo sulphide mineral oxidation (reactions 6 and 10; Table 2). The bulk of the data conforms to the vector for reaction 6 (i.e. non-carbonate sourced Ca increases commensurately with SO_4) which suggests that dissolution of calcium sulphate is the main source of the increased aqueous SO_4 (Figure 11a, b). Minerals in Quaternary and older deposits as well as anthropogenic influences such as fertilizer applications, agricultural and urban waste seepage and soil disturbance might be the main sources of SO_4 in this area.

In T2 and T3 waters, the molar concentration of non-carbonate Ca plus Mg and SO_4 are well correlated (Figure 11a). The stoichiometric dissolution of gypsum (reaction 6, Table 2) should give a slope of 1 to Figure 11a, for both water types. The best-fit lines on Figure 11a is slightly above 1 revealing that the concentrations of Ca and Mg in T2 and T3 water types are greater than would be expected from the dissolution of carbonate and sulphate minerals alone. Another process must have occurred. Likely, some degree of clay-mineral hosted cation exchange of Na by Ca (and possibly Mg; reactions 7 and 8 Table 2 and vectors 7 and 8, Figure 11) could have led to a slope >1 in Figure 11a. This implies a high sodium source should be expected in the aquifer (see section 3.3). This process is the reverse of the reaction normally expected where Ca displaces Na.

The high concentration of SO in T2 water samples supports the strong anthropogenic influence of fertilizer applications, agricultural and urban waste enhances the cation exchange of Na by Ca and Mg in T2 waters.

3.3 Ionic Ratios and Hydrogeochemical Evolution

Groundwater chemistry depends on geochemical reactions and processes within the groundwater system^[40]. Binary plots can explain the controlling mechanisms for the geochemical evolution of groundwater (Figure 12).

On the bivariate plot of total cations versus alkali earth metals (Figure 12a) shows that all samples of T1 (Lake Naser) and T2 (at the east of El Gallaba plain) are located between reference lines 1:1 and 2:1. This indicates that the presence of Ca and Mg ions play a significant role in the composition of the groundwater. The contribution of these ions may be due to carbonate and sulphate mineral dissolution^[36] or the weathering of calc-silicate and ferromagnesian minerals through leaching of River water to the granitic intrusions exposed in the area.

seepage on the area close to the Nile floodplain aquifer in the area. The elevated Na concentration in the drainage water mixed with the Nubian waters enhances the cation exchange of Na by Ca and Mg in T2 waters.

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Most of T3 samples plotted below 2:1 line in Figure 12a due to ion exchange process where the Na and K in the aquifer matrix have been replaced by Ca and Mg at favorable exchange sites (Reaction 13, Table 2). This phenomenon has accounted for the dominance of Na ion over Ca and Mg ions in T3 waters (Figure 12b). This support the closed system dissolution of carbonate which favoured by the reduction of sulphate (Reaction 5, Table 2 and

Vector 5, Figure 11c & e), that increases the concentration of Ca and Mg in Nubian water while recharging the Quaternary aquifer in El Gallaba

plain. Therefore cation exchange with Na and K on the clay minerals has been activated.

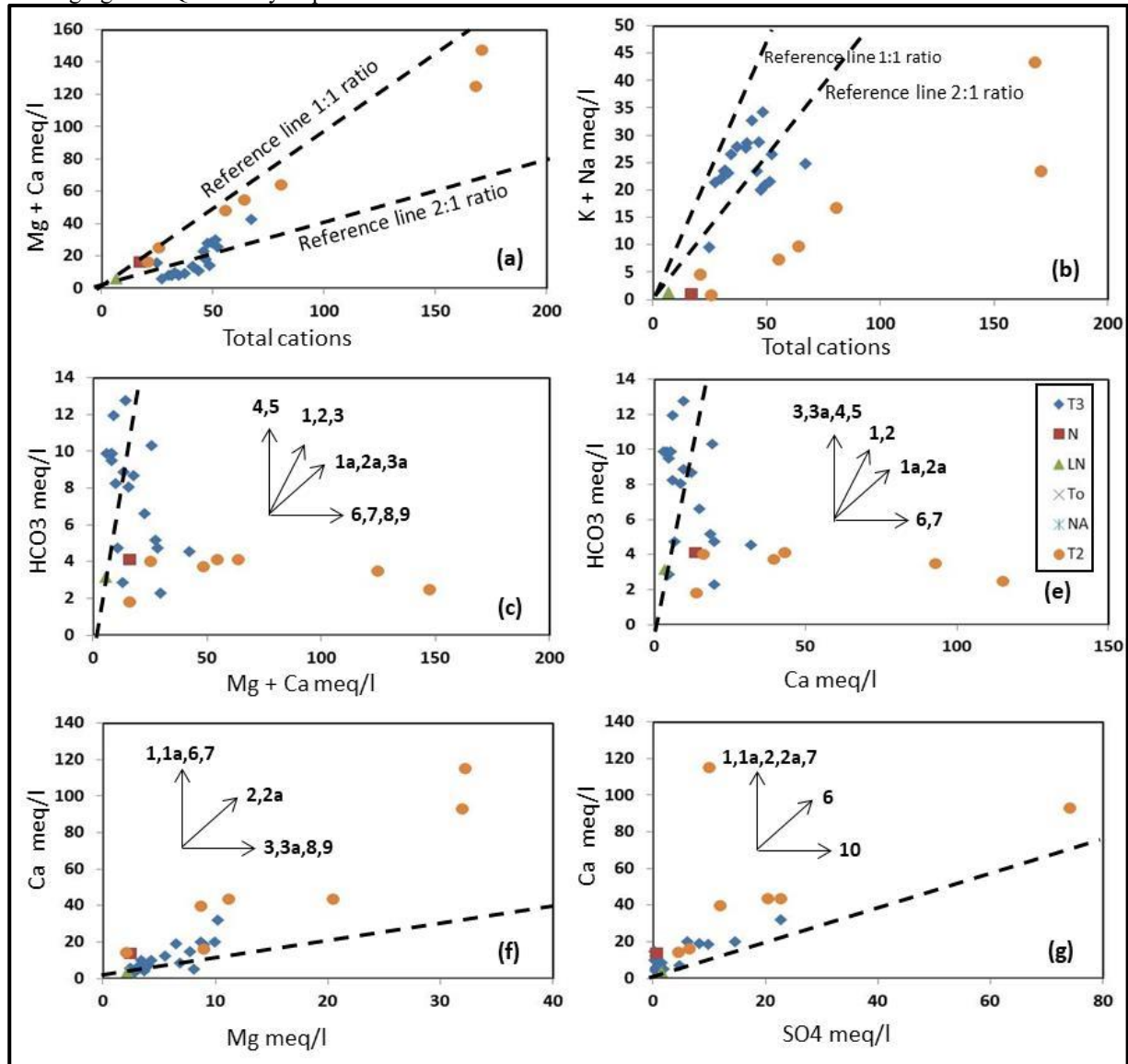


Figure 12: Fig.8. Bivariate plots of (a) $Ca^{2+} + Mg^{2+}$ vs. Total cation, (b) $Na^{+} + K^{+}$ vs. Total cation, (c) HCO_3^{-} vs. $Ca^{2+} + Mg^{2+}$, (d) HCO_3^{-} vs. Ca^{2+} , (e) Ca^{2+} vs. Mg^{2+} , (f) Ca^{2+} vs. SO_4^{2-} .

1.2. Geochemical evolution and recharge of groundwater aquifer in El-Gallaba Plain

The major hydrogeochemical processes that effectively control the geochemical evolution of the groundwater in El Gallaba plain under arid climatic conditions can be briefly discussed below (Figure 13).

1. The geochemistry of surface water in Lake Naser and River Nile stream (T1 water type) has

been mainly controlled by silicate weathering, dissolution of carbonate and sulphate minerals. The continuous supply of atmospheric and biogenic CO_2 controls the carbonate chemistry as the water type T1 is Ca-Mg- HCO_3 . The evaporation process increases the TDS from 224 mg/l in LN to 515 mg/l in Toshka where the water type developed to Ca-Mg-Cl. So, the main recharge of Toshka either surface or groundwater is the LN surface meteoric water under the effect of evaporation.

2. At the eastern margin of El Gallaba plain where intensive cultivation activity is dominated depends either on River Nile water or groundwater. The irrigation method adapted in this area is flood irrigation system which resulted in large volume of agricultural wastewater rich in chemical fertilizers, mainly Cl and SO₄ from anthropogenic source. The intensive evaporation process in the cultivated fields promotes the TDS in the wastewater. The high porosity and permeability of the shallow Quaternary aquifers permit deep percolation of the wastewater return. The high concentrations of atmospheric and biogenic CO₂ in this water accelerate the dissolution of carbonate mineral phased to increase the Ca, Mg. the deep percolated agricultural wastewater mixes with the Nubian groundwater recharged from west and southwest resulted in high TDS mixture (T2). Revers cation exchange process prevailed in this area of the aquifer to control the concentration of dissolved

cations mainly Na, Ca and Mg. This give rise a typical Ca-Mg-Cl water type developed by reverse cation exchange [32], [41], [34].

3. In the middle and western part of the aquifer, the dominant water type is Na-Cl with Na₂SO₄. Under semi-closed or closed system, reduction of sulphate enhances the dissolution of carbonate, where the cation exchange develops the Nubian groundwater into T3 water type. The produced water is higher in TDS, Cl, SO₄ than the proper fossilized Nubian groundwater.
4. The main recharge of El-Gallaba plain aquifer is mainly from deep seated, un-rechargeable old meteoric water trapped in Nubian sandstone aquifer since last pluvial period prevailed during Pleistocene.

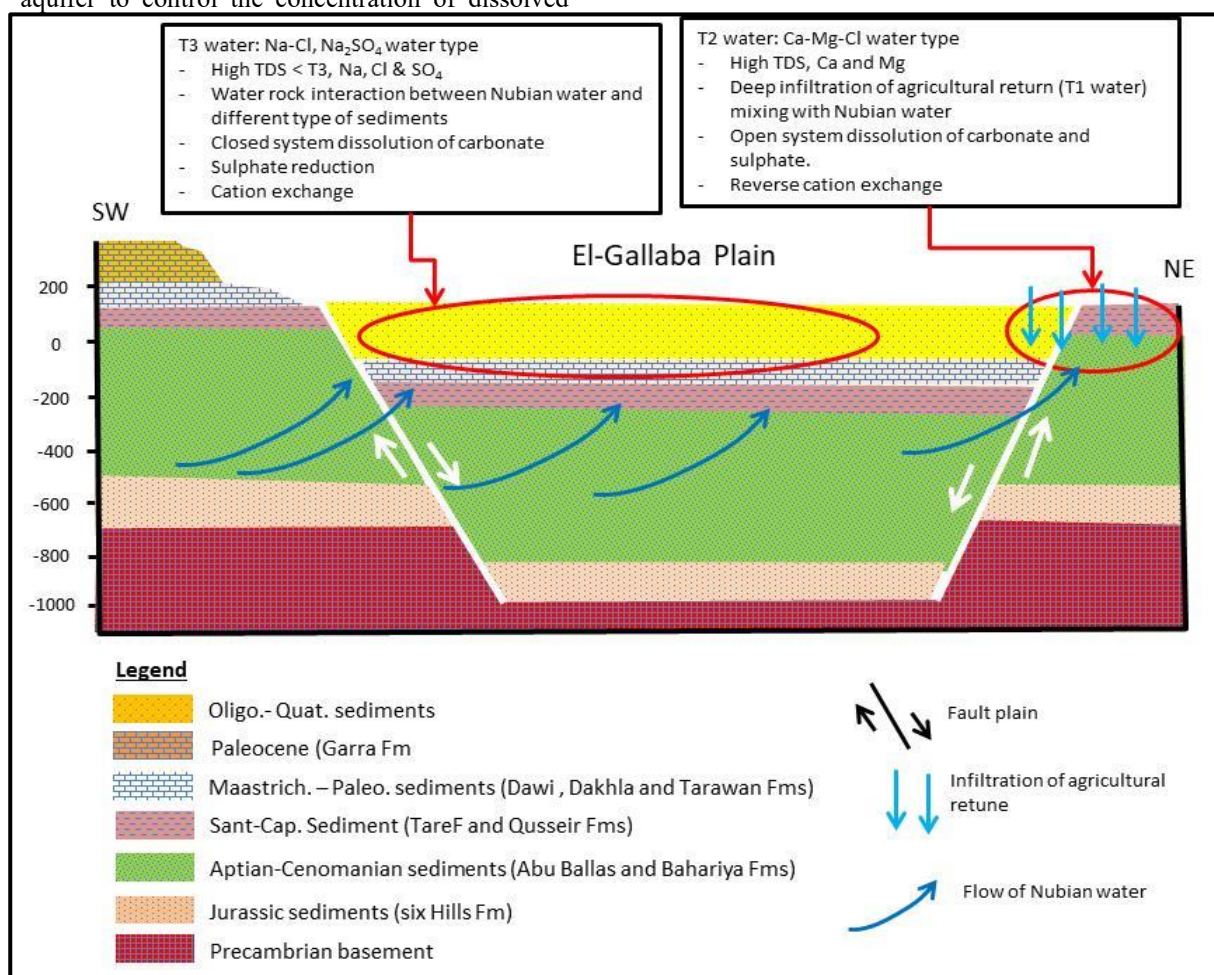


Figure 13: Schematic diagrams showing the hydrogeochemical evolution of groundwater and their controlling processes in the investigated area. Note the direction of groundwater flow from the water reservoirs in the vicinity of El Gallaba plain aquifer.

4. Conclusion

This study is an attempt to clarify the relationship between an underground reservoir in an arid area attractive for agricultural investment in southern Egypt (El-Gallaba Plain, Kom Ombo, Aswan) and neighboring water sources. The study focuses on the relationship between the groundwater of the Nubian aquifer, the surface waters of the High Dam Lake (Lake Nasser), the Nile River, and the Toshka Depression. It is necessary to determine the expected source of recharge to the aquifer in the study area. This point will be adopted by monitoring the geochemical development of groundwater within the aquifer and the extent to which this development is related to the geochemical diversity of water in the surrounding reservoirs. twenty-four groundwater samples were collected from productive wells representing the groundwater aquifer, in addition one sample from the Nubian aquifer plus 3 surface samples from the Nile River, High Dam Lake, and Toshka depression. The main water-bearing formation in the study area is the Quaternary aquifer, whose groundwater varies from fresh to brackish water types. The salinity of the groundwater ranges from 843 to 4960 ppm, with an average of 1882 ppm. The geochemical modeling of the collected water samples reveals the presence of three water types in the area. The first one is surface water represented in Nile, LN, and Toshka samples, T1 (Ca-Mg-HCO₃), Groundwater samples show two water types T2 (Ca-Mg-SO₄), (Ca-Mg-Cl) and T3 (Na-K-Cl), (Na-K-SO₄). The proper Nubian groundwater with low TDS has been mixed with deep percolation agricultural wastewater rich in anthropogenic pollutions and TDS at the eastern margin of the plain. The open system carbonate dissolution and evaporite mineral dissolution with intensive reverse cation exchange increase the TDS of T2 water much more than proper Nubian aquifer without drastic change in water type (T2, Ca-Mg-Cl). The regional water type prevailed the area of the aquifer is Na-Cl with subordinate Na₂SO₄ water, T3 water type. The Nubian water in the whole aquifer is under a reducing condition resulted in reduction of SO₄ and dissolution of carbonate. These processes go parallel with cation exchange to develop new type of water from Ca-Mg-Cl (T2) to Na-Cl with NaSO₄ (T3). Therefore, it is obvious that, the main recharge of the Quaternary aquifer in El Gallaba plain Nubian groundwater. Local hydrogeochemical processes resulted in specific evolution trends of the Nubian water. Also there is no indication about the possibility of recharge from the south (LN or Toshka depression). The only recharge from the Nile water is through the

percolation of agricultural wastewater at the eastern part of the plain.

5. Recommendations

In order to develop a sustainable plan for optimal exploitation of the underground reservoir in this important area, the following studies must be conducted, which is considered the next stage of this project.

- 1- Study of stable isotope concentrations, especially oxygen, deuterium, and tritium, in the groundwater of the Quaternary aquifer El-Gallaba plain.
- 2- The volume of agricultural drainage water that invades the groundwater reservoir to develop a plan to reduce its impact on the quality of the groundwater while expanding agricultural activity with time.
- 3- Make a mathematical model for the volume of water required for reclamation and the ability of the groundwater reservoir to compensate on the long-term level.
- 4- Develop a plan to monitor the change in the static groundwater level in the aquifer.
- 5- Develop an indicative plan for the areas that should be cultivated, based on the capacity of the underground reservoir.

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