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REVIEW ARTICLE

Impact of iron concentration as a result of groundwater exploitation on the Nubian sandstone aquifer in El Kharga Oasis, western desert, Egypt

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Iron concentration;
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Abstract The over exploitation represents the main problem of sustainable development of the groundwater aquifer in the study area, large drop in groundwater heads was recorded, it reached from 70 to 80 m, the main trend of water flow was also disturbed and many depleted closed areas were appeared. Groundwater quality shows relatively high salinity contents of some groundwater samples and abnormal concentration of iron element which was ranging from 2 to 10 mg/l produces rust-colored deposits and a brown slime that builds up on well screens, pipes, and plumbing fixtures. The dominant water type is sodium bicarbonate followed by sodium sulfate and sodium chloride. For proper development and optimal utilization of such non-renewable resources, daily groundwater exploitation should be decreased; the minimum spacing between wells should not be less than 2 km and total depth of wells should be between 600 and 700 m. Moreover, the present flood irrigation system should be replaced by more developed drip, sprinkle irrigation methods and less water consume crops should be recommended.

Contents

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1. Introduction

The area under investigation represents the northern part of El-Kharga Oasis. It lies between the latitudes 25° 00′ and 26° 00′ north and longitudes 30° 00′ and 31° 00′ east (Fig. 1). The area under investigation covers about 33,000 km^2. The study area is a part of Dakhla depression which is oriented north–south and extends southward from the escarpment of Abu Tartur Plateau to the granite hills of Abu Bayan. The north end of El Kharga Oasis is confined by Abu Tartur Plateau and Gebel Abu Tartur. To the southwest El Kharga is bounded by the west Kharga plain and to the east the Tebes Plateau. Elevations on the floor of the depression range from near 0 mean sea level (msl) to 120 m above msl. To the west, surface elevations rise gently from the depression to over 400 m above msl in the Kharga plain. Sixty five groundwater samples representing shallow and deep productive water wells were collected and analyzed (Fig. 2).

Over-exploitation concept describes the situation where the rate of groundwater extraction exceeds the average rate of aquifer recharge (Foster and Loucks, 2006). Over-exploitation of groundwater can cause a series of irreversible environmental–hydrological problems such as lowering of groundwater heads, change of recharge/discharge condition, shortage of water resources, deterioration of groundwater quality, and reduction of single well yield, which seriously affect the implementation of sustainable development strategy of regional economy, Furthermore, the over-pumping may

Figure 1 Key map of the study area.

considerably increase the thickness of the mixing zone, which can lead to the disastrous of the aquifer. Such resulting environmental problems limit development of any area.

During the last decade, the continuous development of human society as well as the side effects of land reclamation projects left negative impacts on water resources in Nubian sandstone aquifer western desert of Egypt where El-Kharga, Dakhla, Farafra, Bahariya and Siwa Oasis occur. Such negative impacts are pronounced in continuous groundwater deterioration and water pollution. El-Kharga area is located in the southern part of the western desert.

2. Geology and hydrogeology

The sedimentary succession ranges from Cretaceous, Tertiary and Quaternary, and it underlines by Pre-Cambrian basement rocks (Fig. 3).

From subsurface point of view information from drilled wells in the study area (162 production wells and 29 observation wells), indicates that the Nubian sandstone essentially of Cretaceous age constitutes the main rock unit in the subsurface in the study area. The Nubia facies are composed of sandstone, siltstone and interbedded with shale and occasional conglomerates. It rests nonconformably on the Precambrian at different depths due to the effect of structural elements. Abu Bayan uplifts are exposed on the surface at some places which affects the distribution of sedimentary succession both in thickness and facies (Fig. 4).

Two hydrogeological cross sections were constructed (Figs. 5 and 6). These sections show that the Nubian sandstone aquifer is divided into four layers (A, B, C & D layers). Layer (A) is considered the main water resource for shallow wells which ranges from 70 to 130 m. Layer (B) is considered the main bearing productive zone for deep wells which ranges in depth from 250 to 500 m in the study area. It has high potentiality due do its large thickness, high sand percent and high transmissivity. Layer (C) also considered water bearing formation for deep wells, especially in the wells located in the north of the study area. Layer (D) is the lowest layer in the Nubian sandstone formation.

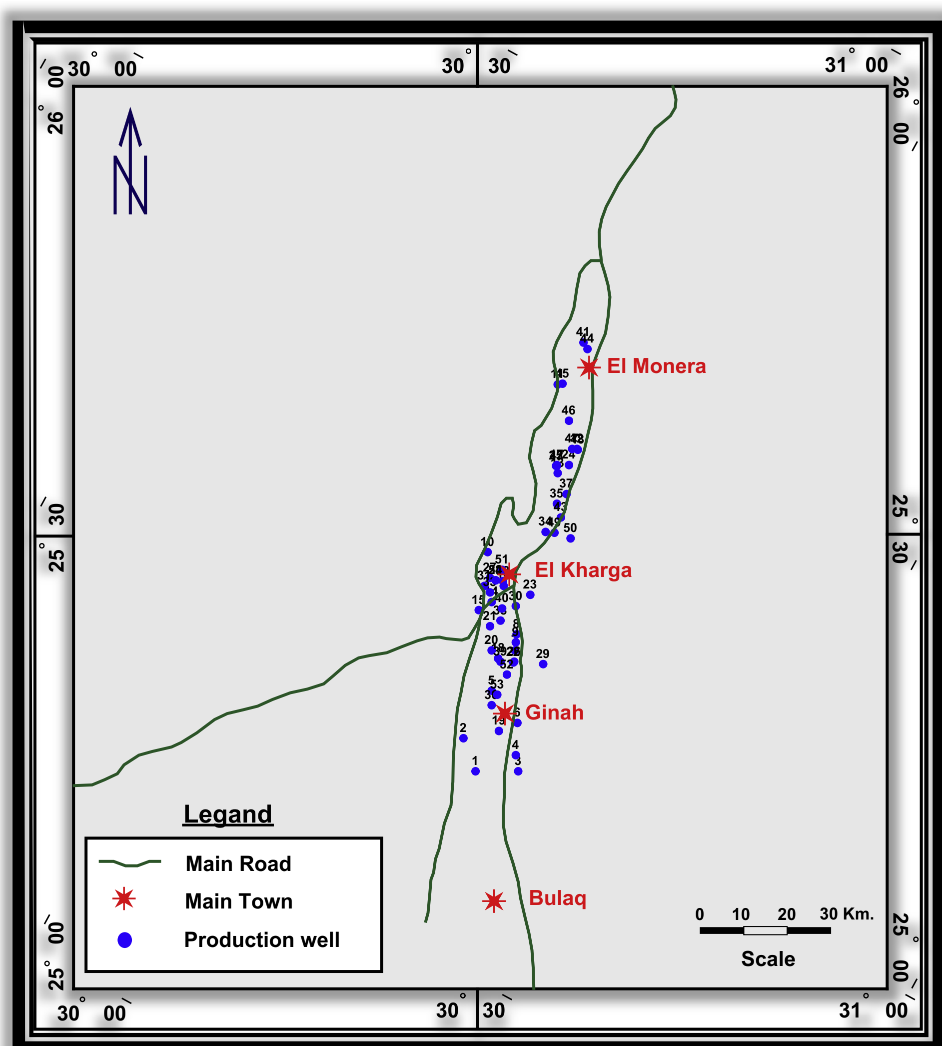

Figure 2 Samples location map.

The potentiality of aquifers is measured by determination of the main hydraulic parameters which include the coefficient of transmissivity (T), storativity (S) and hydraulic conductivity (K). Transmissivity values (T) of El-Kharga oasis range from 85.2 to 226.35 m^2/day. Hydraulic conductivity ranges from 0.47 to 1.1 m/day. It can be concluded that the Nubian aquifer is classified as low to moderate potential aquifer. The obtained result indicates that formation loss ranges between $2.75^* 10^{-3}$ and $2.2^* 10^{-2}$ day/m^{-2} indicate moderate to high formation loss reflect large amount of fine impermeable material of silt and clay in aquifer materials. The well loss varies from $8.21^* 10^{-8}$ day^2/m^{-5} to $3.13^* 10^{-6} day^2/m^{-5}$. The values of well loss for most wells are very close to zero indicating a laminar flow throughout the system and good wells design.

Groundwater exits under confined conditions where water bearing formation is covered by large thick shale and clay layers. Depth to water was measured of the present observation wells and depth to water map was constructed (Fig. 7), and it displays different values ranging from 30 m at Bulaq and ginah areas to 75 m at El-Kharga and El-Monira areas, large depths recorded at some localities are due to over exploitation and large drawdown.

Piezometric heads of the present observation wells were calculated and piezometric heads contour map was constructed. This map shows that groundwater heads range from +35 m to −25 m (amsl) (Fig. 8), large decrease in groundwater heads recorded at some areas reflects the effect of overpumping and rapid drawdown. The main trend of water flow was disturbed

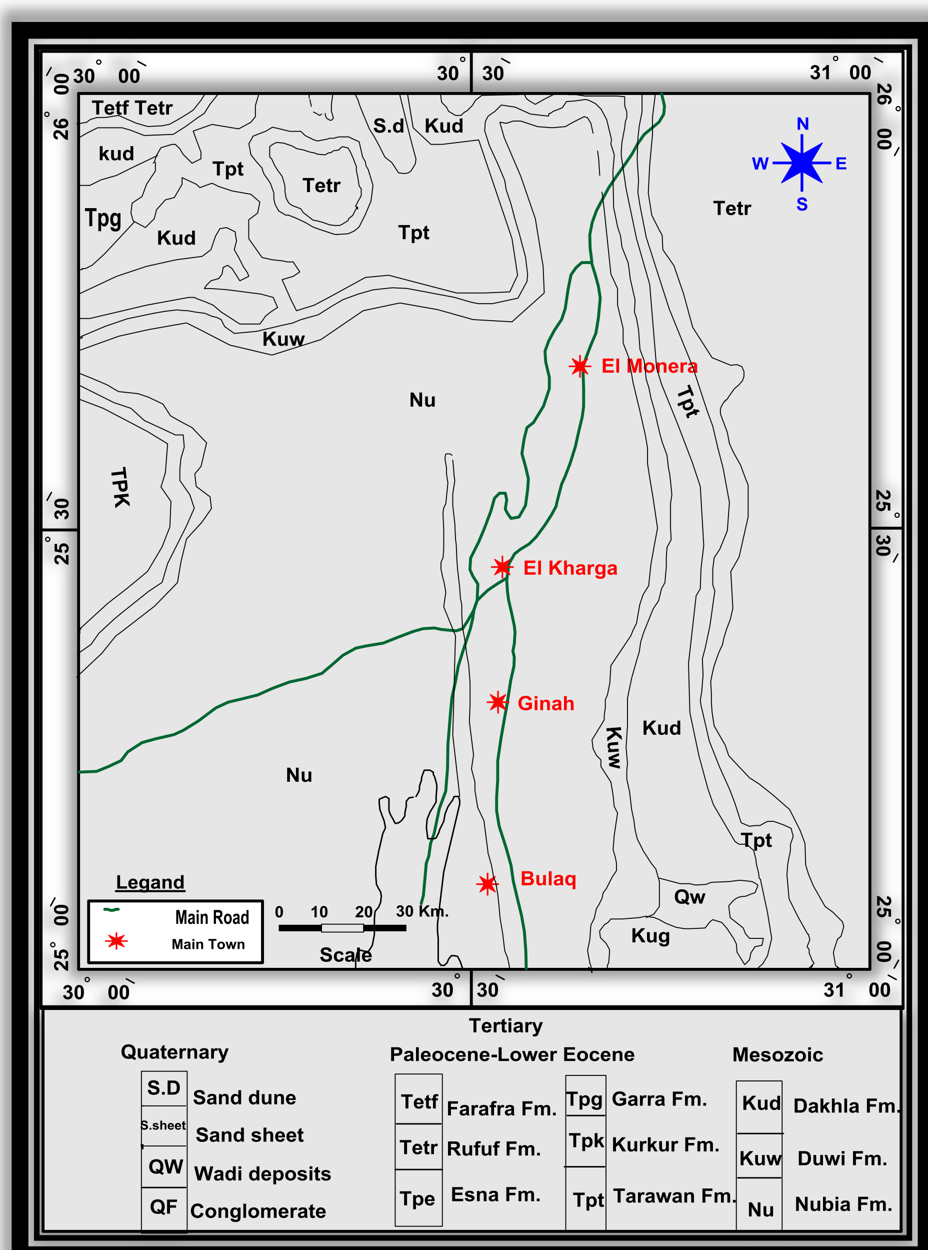

Figure 3 Geological map of the study area (after CONOCO, 1987).

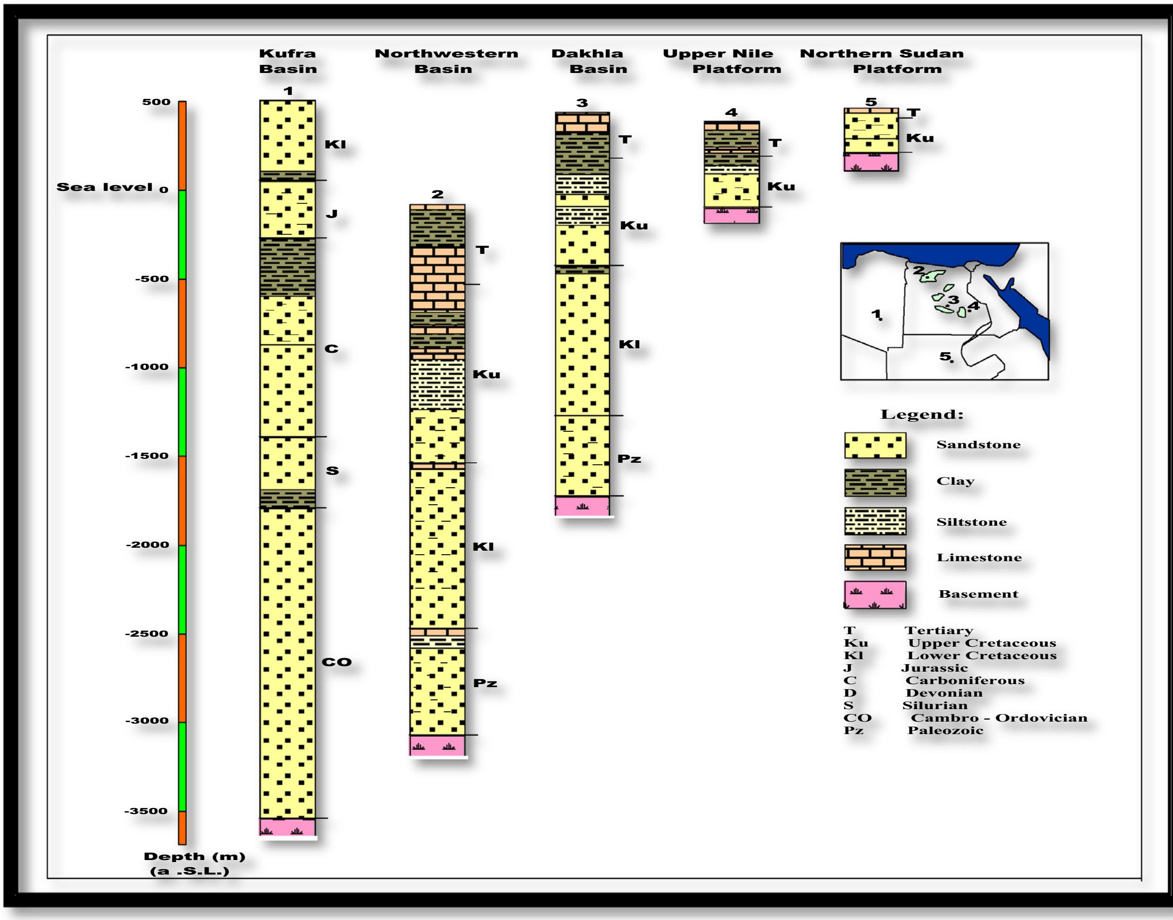

Figure 4 Generalized section of the units of the Nubian system (after Heinl and Thorweihe, 1993).

and more than one direction was appeared, moreover many depleted closed areas were appeared in the study area.

3. Impact of overpumping on piezometric heads

During the last decade, the continuous development of human society and land reclamation projects left negative impacts on water resources in Nubian sandstone aquifer in El-Kharga area. The over exploitation leads to rapid decrease in piezometric heads and large drawdowns, and five hydrographs were constructed to illustrate groundwater head decrease with time in the study area (Figs. 9–13). These hydrographs reflect the strong rapid drop in groundwater heads; it starts after the year 1975 at El-Kharga city and its vicinities, with annual rate ranging from 2.2 to 1.2 m/year (Fig. 10). While it starts after the year 1985 and 1990 at Bulaq area and its vicinities. At El monira and Umm El Qusur in the north of the study area, the annual rate of drawdown reached 1.6 to 0.93 m/year. The hydrograph in Fig. 12 represents head-time relationship of Malab El kheil well that located at the extreme west of the study area. Shows slow drop in the groundwater heads with time; it reached 0.48 m/year. This area lies outside the effect of over exploitation.

From the previous mentioned discussion of piezometric heads fluctuation and drawdown rates of the groundwater aquifer under the investigated area indicate deterioration of groundwater aquifer. More detailed, the area under investigation is classified into strongly hazard area which include El-Kharga city with total drawdown reached to 60 m and 70 m. Moderately hazard area which include El-Sherka area and its vicinities as well as Ginah and Bulaq areas with total drawdown reached to 50 m and 40 m and slightly hazard area which include El-Monira, Umm El-Qusur and their vicinities with total drawdown reached to 20 m and 30 m (Fig. 14). Finally the present groundwater extraction under such localities will change the recharge and discharge conditions, shortage of groundwater resources and deterioration of groundwater aquifer in study area.

4. Hydrogeochemistry

4.1. Salinity contents

Groundwater in the investigated area belongs to freshwater type with salinity contents ranging from 200 to 400 mg/l (Figs. 15 and 16). Some samples have salinity contents ranging from 400 to 600 mg/l. Relatively high salinity reflects leaching and dissolution of shale intercalated in aquifer materials.

The dominant cation in water samples is sodium followed by calcium and magnesium ions (Fig. 17), sodium ranges from

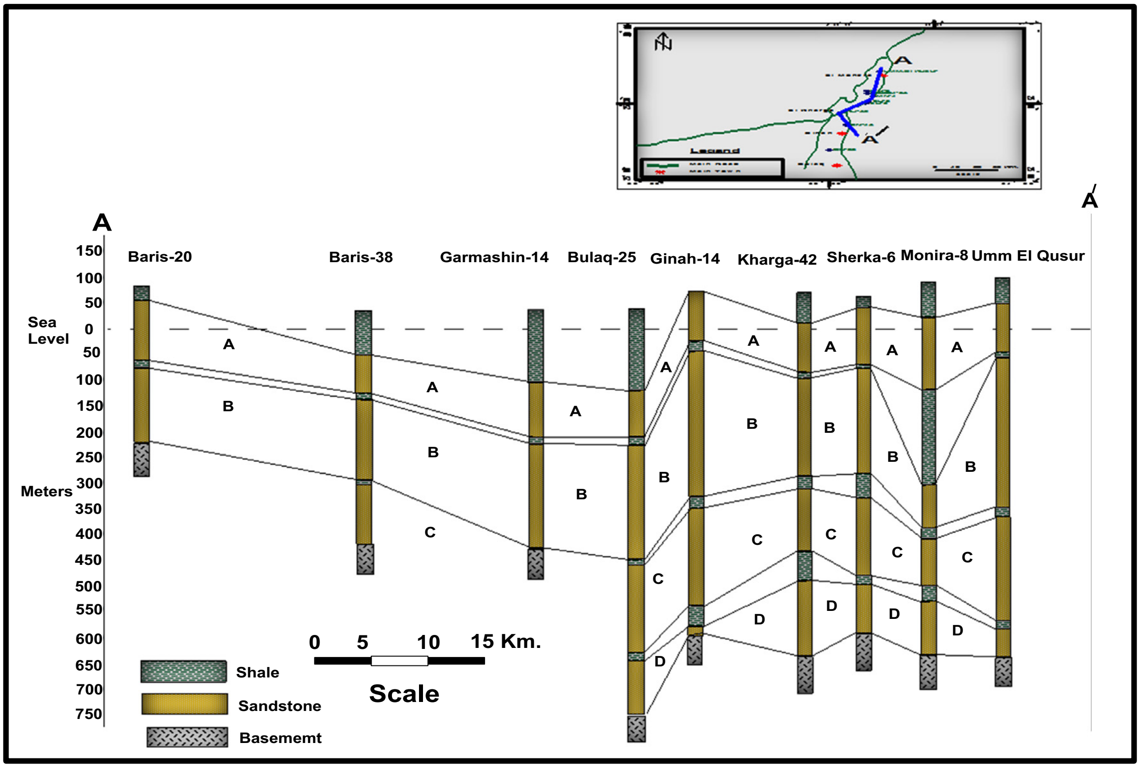

Figure 5 Hydrogeological cross section A–A′.

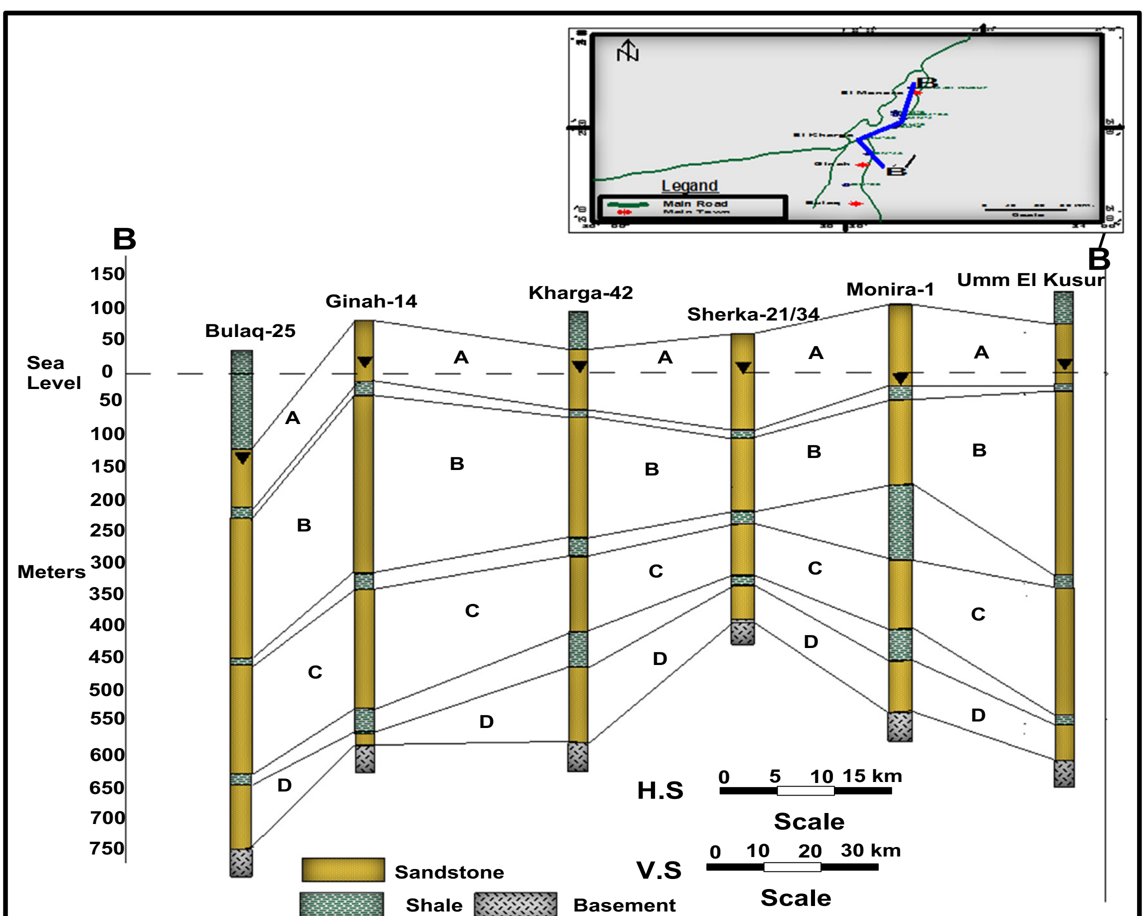

Figure 6 Hydrogeological cross section B–B′.

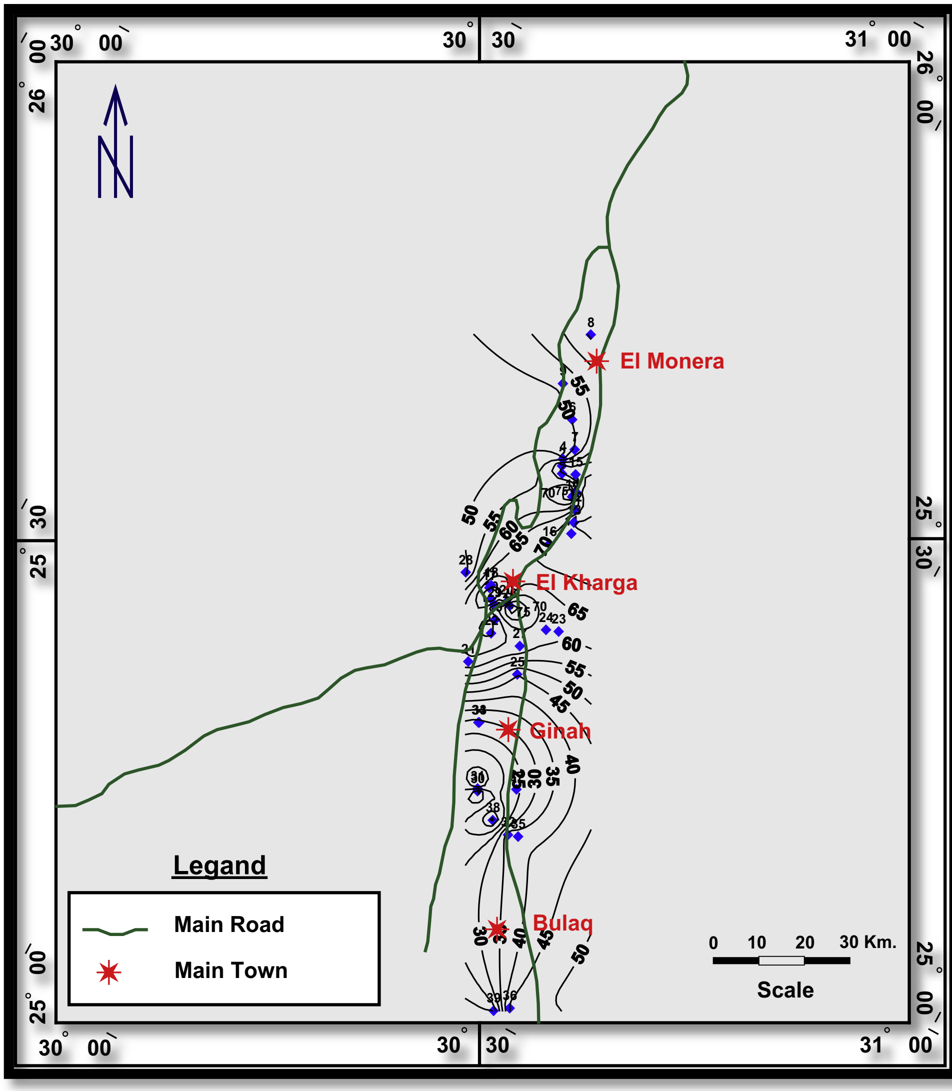

Figure 7 Depth to water head map (2012).

30 to 145 mg/l, calcium ranges from 7 to 31 mg/l and magnesium ion ranges from 7 to 23 mg/l. The dominant anion is bicarbonate followed by sulfate and chloride ions ranging from 20 to 380, 6 to 164, 15 to 115 mg/l respectively. The major elements in groundwater samples have also suitable values which not affect the groundwater quality. The values of minor elements (F, Cu, Mn, Zn, Cd and Pb) are also in the recommended limits with exception to iron element, which is characterized by abnormal high concentration ranging from 2 mg/l to 10 mg/l, iron concentration distribution shows gradual increases toward the southwestern portions of the study area (Fig. 17). High concentration of iron reflects dissolution of iron bearing deposits rich in aquifer materials.

According to Schoeller's semi logarithmic graphs (1962), ion sequences ordering of groundwater samples are presented in (Table 1) and (Figs. 18–20). The majority of water samples have ion sequence ordering $(Na^{+} > Ca^{++} > Mg^{++})/(HCO_3^{-} > Cl^{-} > SO_4^{--})$, and $(Na^{+} > Mg^{++} > Ca^{++})/(Cl^{-} > HCO_3^{-} > SO_4^{--})$, and $(Na^{+} > Mg^{++} > Ca^{++})/(SO_4^{--} > Cl^{-} > HCO_3^{-})$. Sodium is the dominant cation followed by calcium and magnesium as cations and bicarbonate over sulfate and chloride as anions in the majority of samples reflect the predominance of sodium bicarbonate flowed by sodium sulfate and sodium chloride water types. This reflects active leaching and dissolution of carbonate, sulfate and chloride minerals bearing in aquifer materials.

Piper's trilinear diagram groundwater wells consequently show that (Fig. 21), the projection of chemical composition of groundwater on the diamond field revealed that most of water chemical compositions are plotted in subarea 8 (40 wells), and in subarea 7 (21 wells) where subarea 8 reflects freshwater and that reflects Na–HCO_3 water type, while subarea 7 reflects sodium sulfate and sodium chloride water type. The prevailing sodium bicarbonate water type followed by sodium sulfate and sodium chloride reflects active leaching and dissolution of carbonate, sulfate and chloride minerals bearing in aquifer materials. The presence of sodium bicarbonate with high percent reflects effect of dissolution of carbonate rocks in aquifer.

The hydrochemical coefficient gave good indication of geochemical processes occurring in groundwater solution and groundwater origin. The hydrochemical coefficients (rK/rCl),

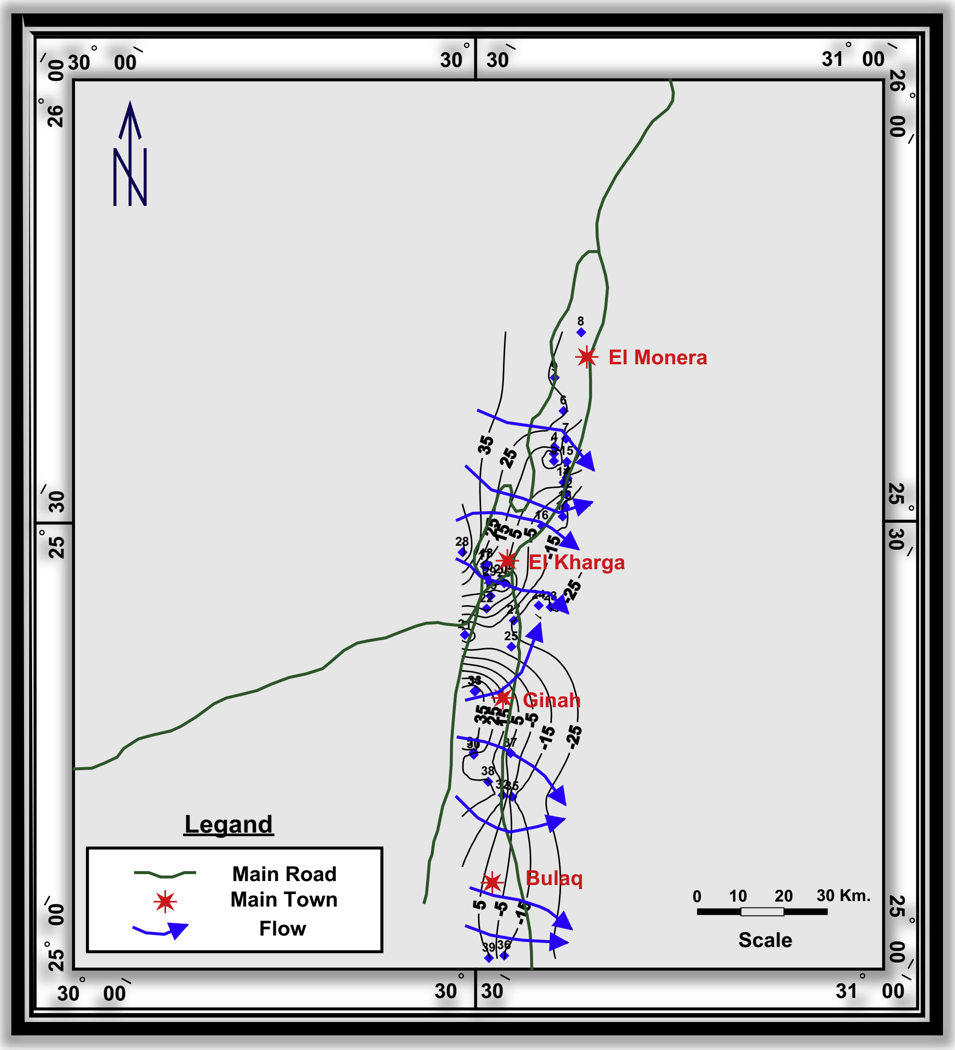

Figure 8 Potentiometric surface contour map and flow net (2012).

(rNa/rCl), (rMg/rCl), (rCa/rCl), (rSO_4/rCl), (rCl/$rHCO_3$ + rCO_3), ($rHCO_3$/rCl) and (rNa/rK) were calculated, which reflect meteoric water origin.

Regarding hypothetical salt combinations of the Nubian sandstone aquifer in the study area, groundwater samples have the following assemblage:

Assemblage I: KCL, NaCl, Na_2SO_4, Na HCO_3, Mg $(HCO_3)_2$, Ca $(HCO_3)_2$
(60.32% of the total groundwater samples)
Assemblage II: KCL, NaCl, Na_2SO_4, $MgSO_4$, Mg $(HCO_3)_2$, Ca $(HCO_3)_2$
(23.82% of the total groundwater samples)
Assemblage III: KCL, NaCl, Na_2SO_4, $MgSO_4$, $CaSO_4$, Ca $(HCO_3)_2$
(15.87% of the total groundwater samples)

Most groundwater samples of the Nubian sandstone aquifer in the study area are characterized by the assemblages of salt combination (Assemblage I, Assemblage II and Assemblage III). Assemblage I (60.32% of the total groundwater samples) represents an earlier stage of chemical development than that of assemblage III. Assemblages I (three bicarbonate salts) and assemblage II (two bicarbonate salts) reflect the effect of pure rain water on groundwater and also reflect recent recharge. Assemblage III (three sulfate salts) reflects the effects of leaching and dissolution of evaporates' deposits and represents intermediate stages of chemical development. Assemblage III is advanced stage of chemical development, and this salt assemblage reflects the effect of marine salt pollution (marine facies groundwater type) with possible contribution of cation exchange phenomena resulting from the presence of the clay intercalated with the Nubian sandstone aquifer in the study area.

4.2. Effect of high iron concentration

When high concentrations of iron are absorbed, for example by hemochromatose patients, iron is stored in the pancreas, the liver, the spleen and the heart. This may damage these vital organs. Healthy people are generally not affected by iron overdose, which is also generally rare. It may occur when one

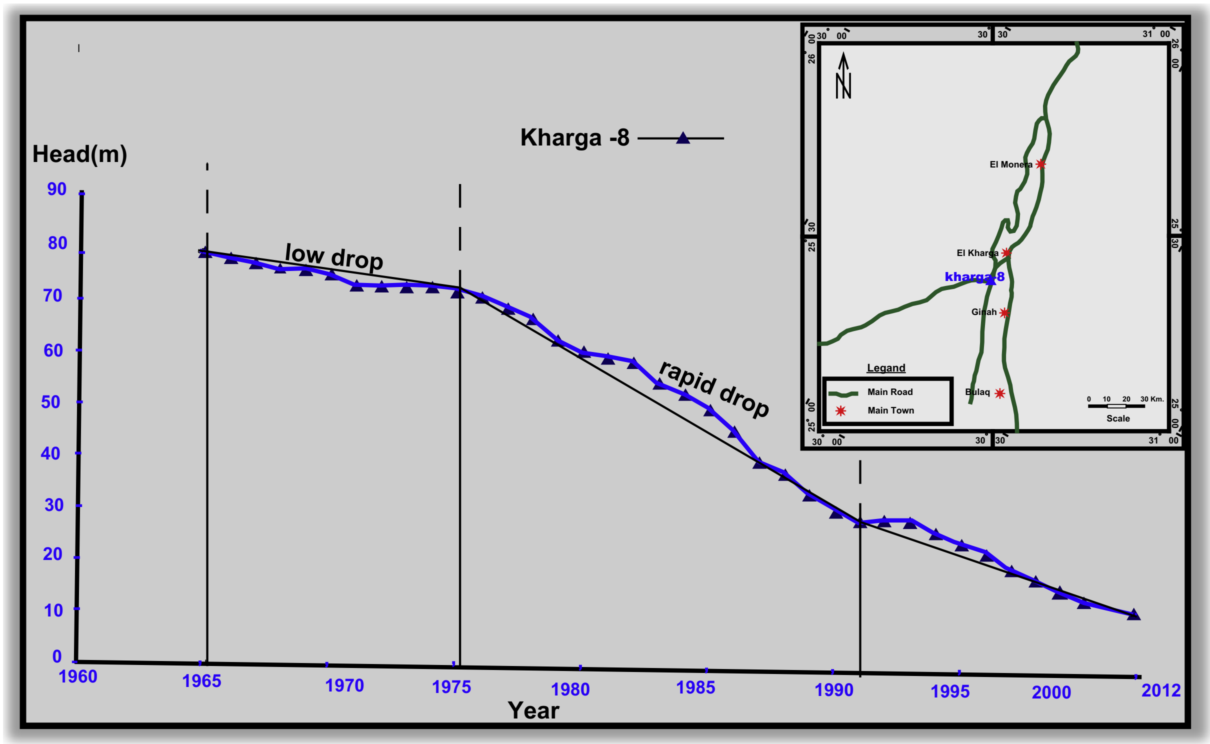

Figure 9 Hydrograph shows lowering in groundwater heads in El kharga-8 well from 1960 to 2012.

drinks water with iron concentrations above 0.3 ppm. Iron compounds may have a more serious effect upon health than the relatively harmless element itself. Water soluble binary iron compounds such as $FeCl_2$ and $FeSO_4$ may cause toxic effects upon concentrations exceeding 200 mg, and are lethal for adults upon doses of 10–50 g. A number of iron chelates may be toxic, and the nerve toxin iron pentacarbonyl is known for its strong toxic mechanism. Iron dust may cause lung disease.

Like animals and people, plants need a certain amount of iron to survive. Iron helps them create chlorophyll and aids in several other chemical processes that plants perform. However, too much iron can have a toxic effect on the plant, weakening and eventually killing it. It should be noted if plants only

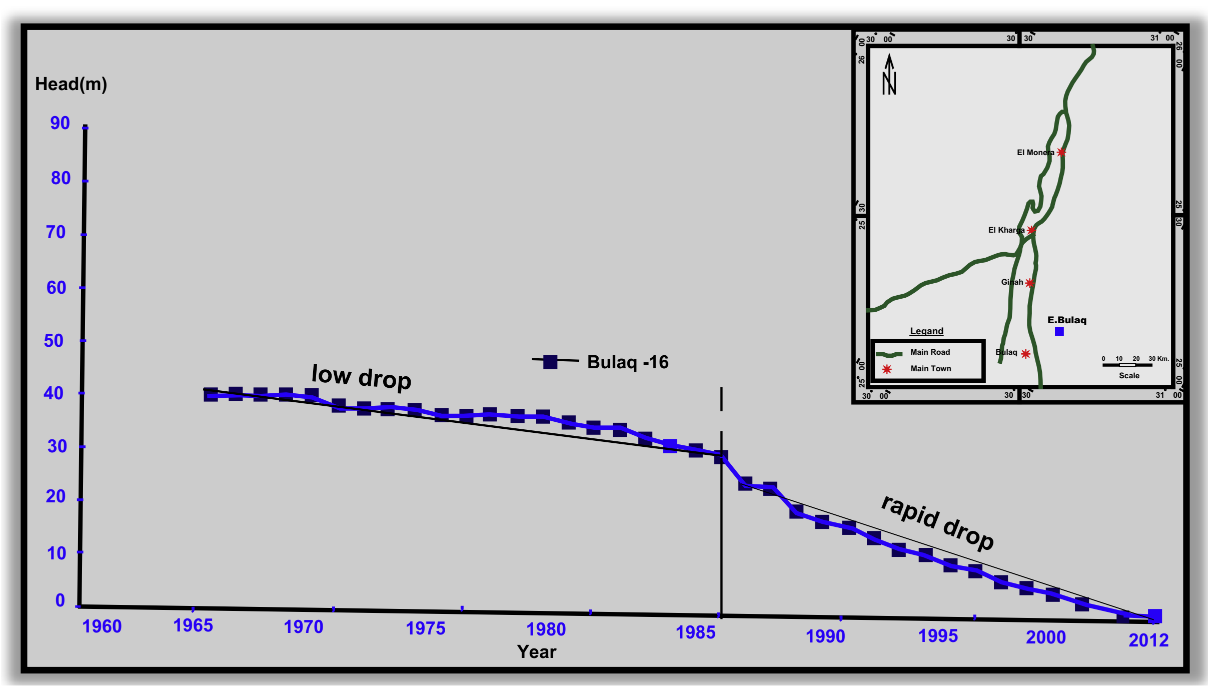

Figure 10 Hydrograph shows lowering in groundwater heads in Bulaq-16 well from 1960 to 2012.

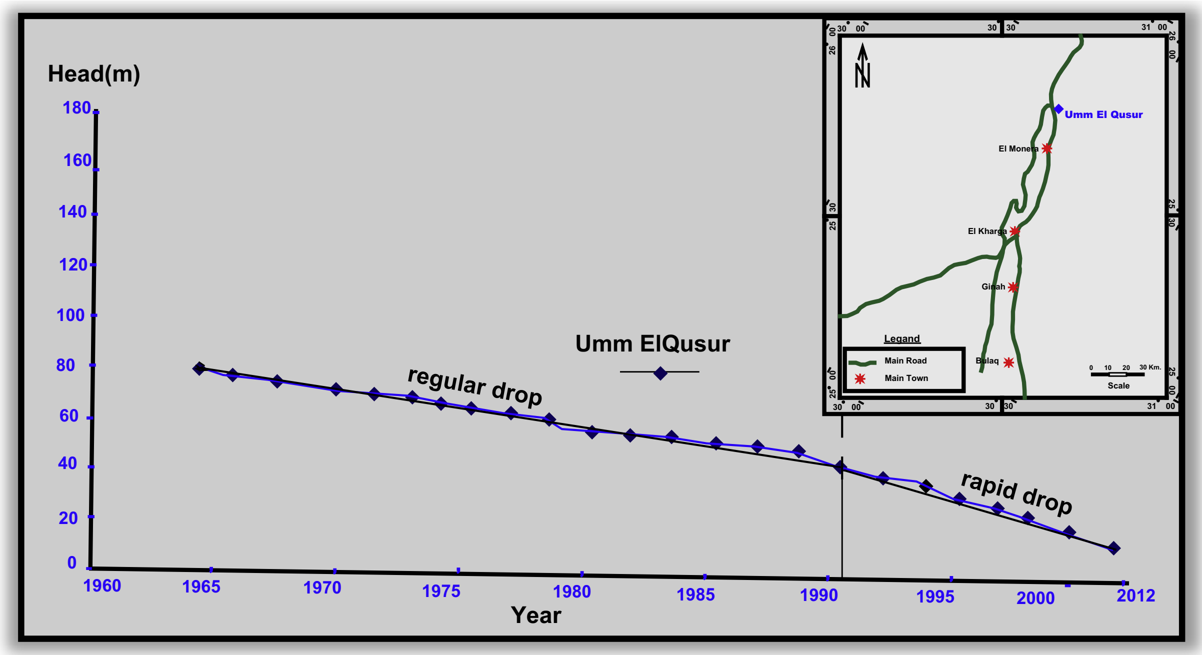

Figure 11 Hydrograph shows lowering in groundwater heads at Umm El-Qusur district from 1960 to 2012.

absorb ferrous iron particles from the soil, and that other types of iron particles will not affect plants. If the soil has too much iron, then plants will absorb it and eventually suffer from the continuing effects. According to scientific studies conducted by K. Kampfenkel, M. Van Montagu and D. Inze in Belgium (2005), soils become dangerous because of high iron content at levels of 100 mg or more.

At these levels, plants will be affected within 12–24 h. Lower rates of iron content can also be dangerous, but it can take longer for the effects to become noticeable. As plants take in too much iron, their chlorophyll fluorescence begins to change. Small amounts of iron are necessary for chlorophyll production, but too much iron can affect the chlorophyll itself, causing it to change and inhibiting the plant's ability to properly absorb energy from sunlight. Plants synthesize both chlorophyll and many of their own nutrients on a cellular level, including necessary proteins. Too much iron interferes with these processes, making it difficult for plants to perform the necessary chemical reactions. Not only does this make creating chlorophyll (already rendered more ineffective) difficult, but starves the plant of important sugars that it needs to survive and store for harsher seasons.

As iron levels continue to rise, the plant's ability to draw in nutrients from the soil will be hindered. This means that the

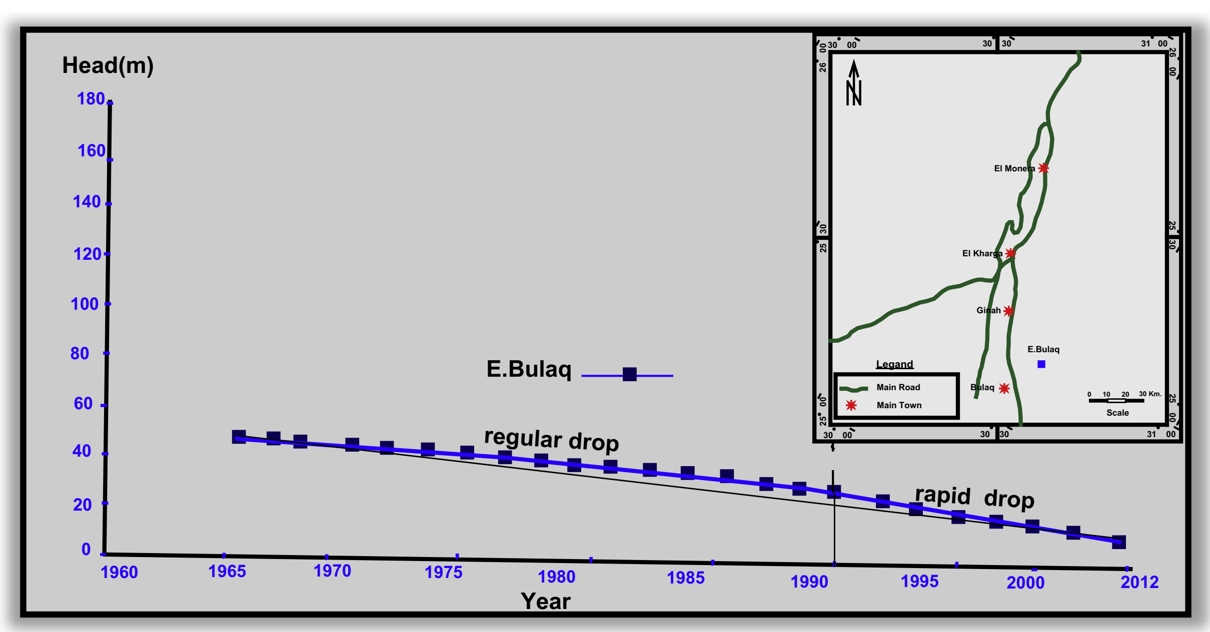

Figure 12 Hydrograph shows lowering in groundwater heads in East Bulaq district from 1960 to 2012.

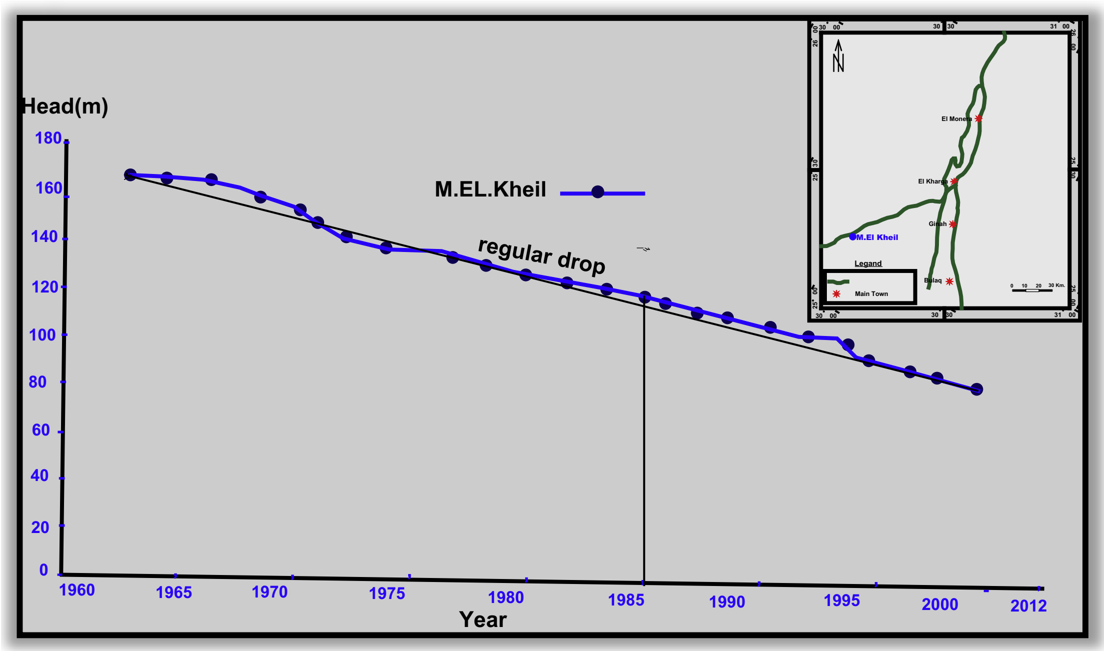

Figure 13 Hydrograph shows lowering in groundwater heads in Malab El kheil well from 1975 to 2012.

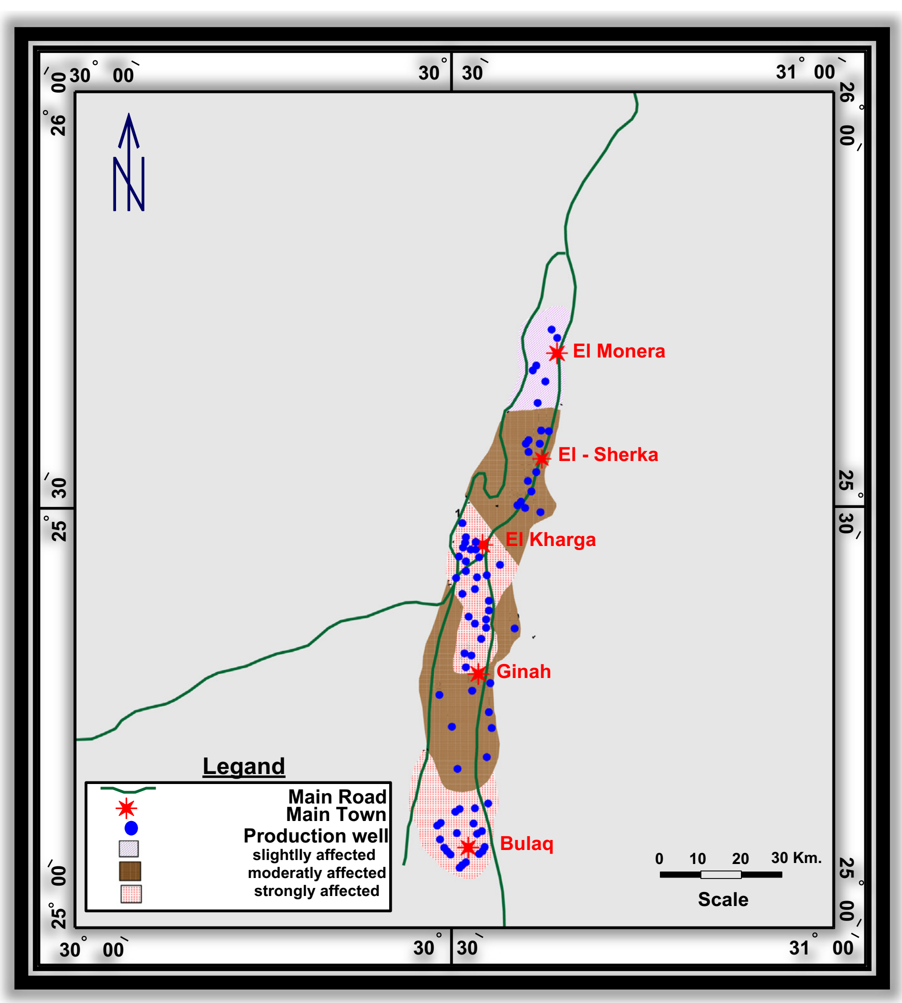

Figure 14 Hazard areas and deterioration of groundwater aquifer in the study (2012).

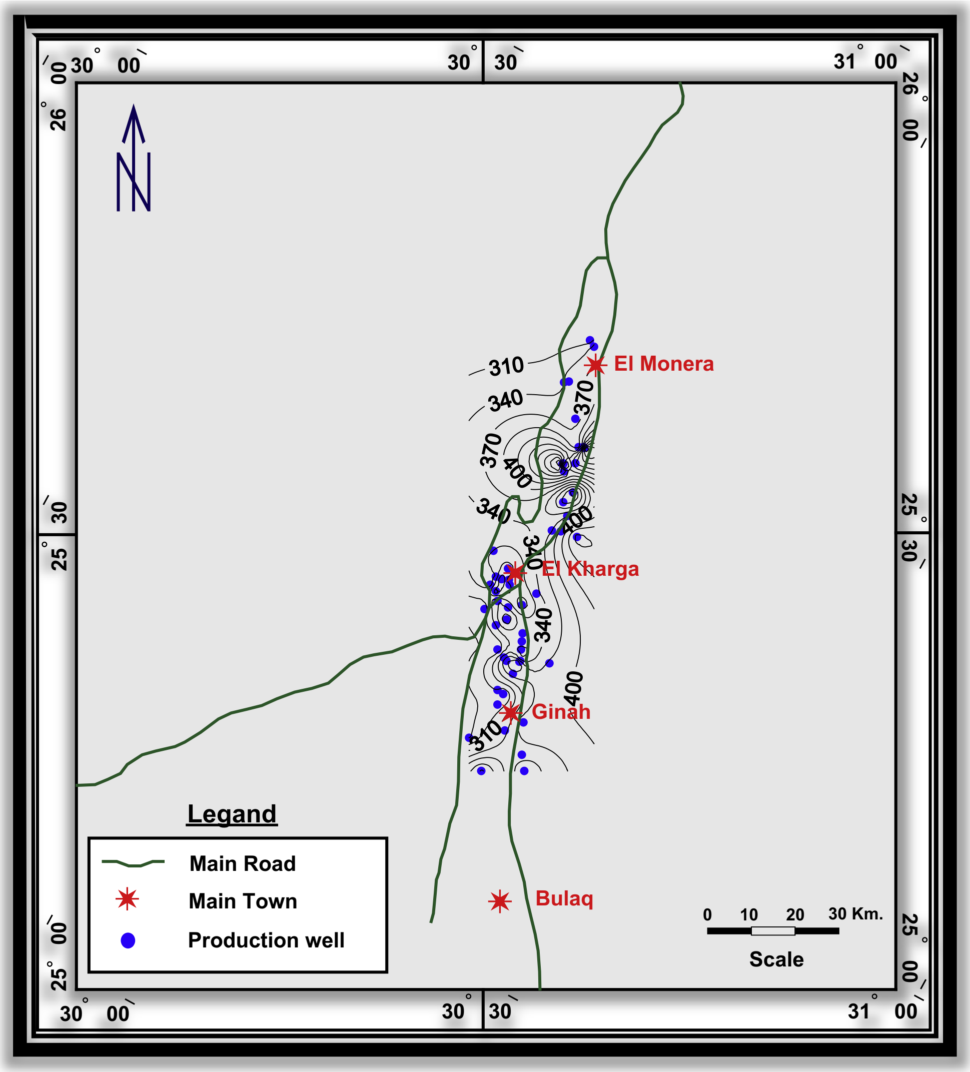

Figure 15 Salinity distribution contour map (2012).

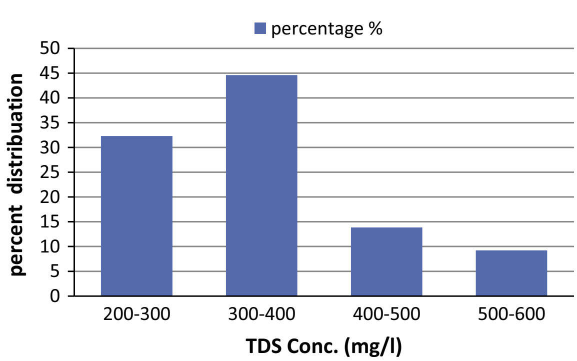

Figure 16 Frequency distribution of salinity concentration (mg/l).

plant can no longer draw in essential substances such as phosphate or nitrogen, which it needs to function but cannot produce on its own. Weakened on all fronts, the systems of the plant fail from within, causing severe decay of vital tissues in the stem and leaves, which inevitably leads to the plant's death.

While plants are not well-equipped to deal with too much iron in their soil, they do have delicate mechanisms that control how much iron they absorb, especially if there is too little iron present. Many plants are able to produce an enzyme called a chelate reductase enzyme to make iron easier to absorb, which is useful when there is not enough iron nearby. Plants can also lower the production of this enzyme if iron levels are sufficient or too high. Certain plants are deft at controlling this mechanism and can change very rapidly, but others have a much slower reaction time.

4.2.1. The relationship between pH-value and iron concentration

The pH value of water is very important because it can determine solubility and biological availability of iron (Worldwide Drilling Resource Marianne Metzger January 2005). The relationship between pH and iron values was constructed (Fig. 22), and it displays that the iron concentration increases with decreasing pH values. Lower pH value below 6.5 tends to keep iron deposits in solutions and will typically cause corrosion problems. Scaling and encrustation usually occur when the pH is above 8.5 keep in mind, if other ions like calcium or

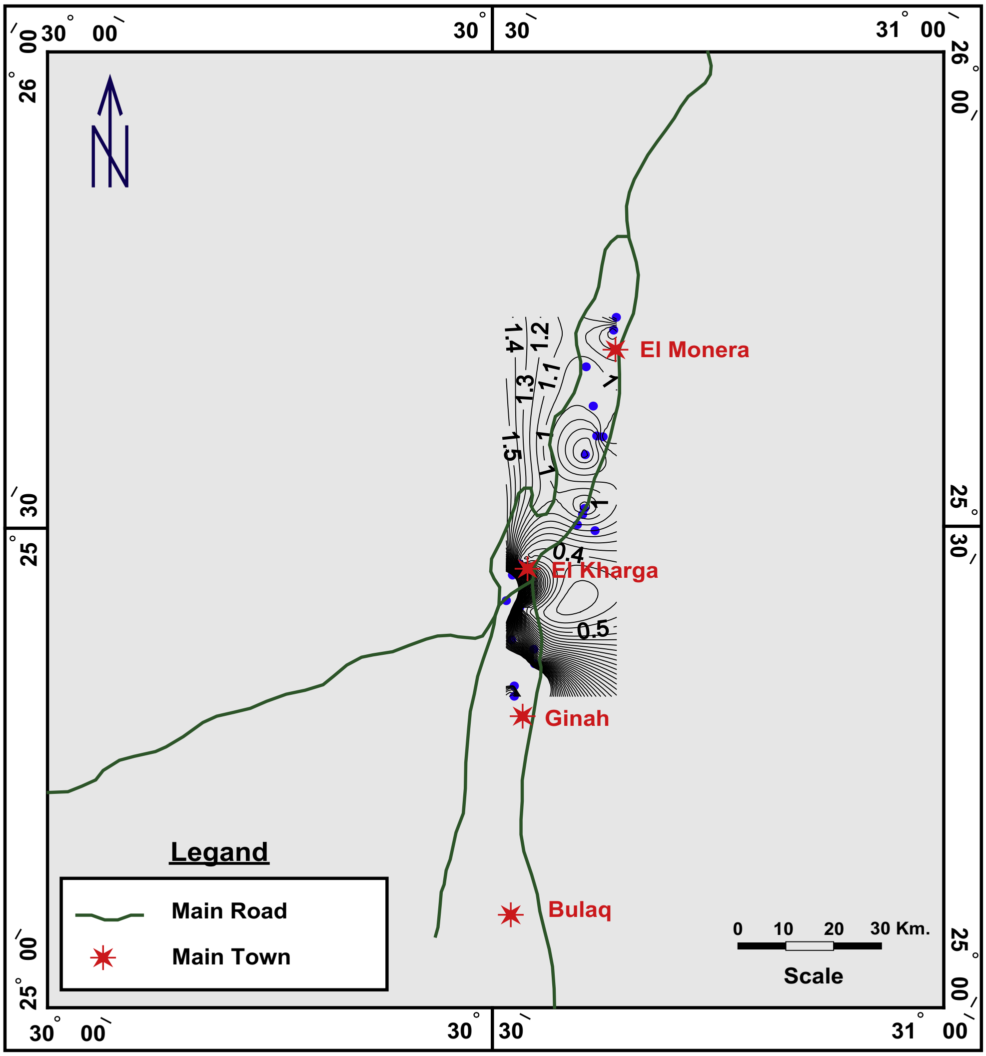

Figure 17 Iron distribution map of production wells in the study area.

Table 1 Ion sequence of groundwater samples of the Nubian sandstone aquifer in the study area.

Wells No.	Ion sequence	Chemical type	Percentage (%)
1-2-3-5-6-8-9-10-11-12-13-14-15-16-17-25-43-44-45-46-47-48-49-50-51-52-53-54-56-58-59-61-64	$Na^{+} > Mg^{++} > Ca^{++}$ $HCO_3^{-} > Cl^{-} > SO_4^{--}$	Na^{+}–HCO_3^{-}	54.01
1-4-7-18-19-23-24	$Na^{+} > Ca^{++} > Mg^{++}$ $HCO_3^{-} > Cl^{-} > SO_4^{--}$	Na^{+}–HCO_3^{-}	11.47
21-26-27-28-29-30-31-32-33-34-38-39-41-42	$Na^{+} > Mg^{++} > Ca^{++} >$ $SO_4^{--} > Cl^{-} > HCO_3^{-}$	Na^{+}–SO_4^{--}	23
20-55-57-22-35-37-40	$Na^{+} > Mg^{++} > Ca^{++}$ $Cl^{-} > HCO_3^{-} > SO_4^{--}$	Na^{+}–Cl^{-}	11.5

carbonate are present, they make a variety of precipitates that mix in with the iron hydroxide precipitates produce a crusty, gnarled coating that can be difficult to remove.

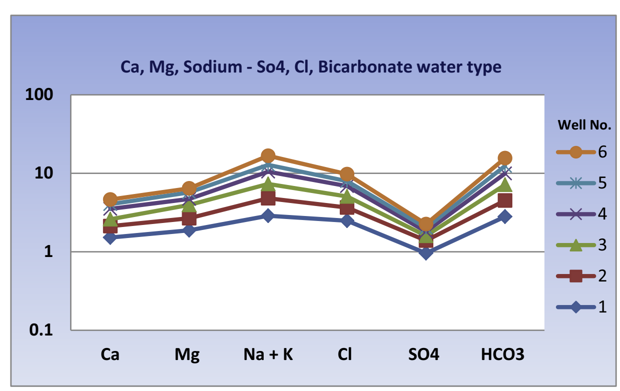

Figure 18 Sodium bicarbonate facies.

The pH values ranges from 6.5 to 7.54 are suitable for growing iron bacteria, which can be introduced into a well or water system during drilling, repair, or service. Elimination of iron bacteria once a well is heavily infested can be extremely difficult.

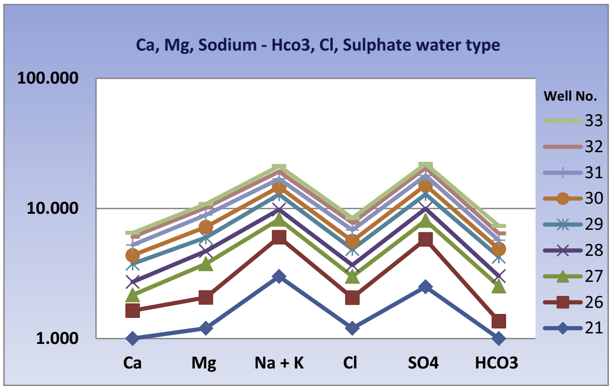

Figure 19 Sodium sulfate facies.

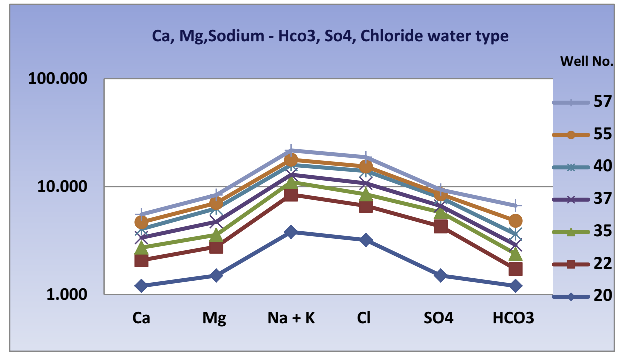

Figure 20 Sodium chloride facies.

Bacteria oxidize soluble ferrous iron to insoluble ferric iron which considered the main source for well and screen clogging, formation of ochre and bacterial slimes, these can clog intake screens of wells, and the filters, laterals and emitters of a drip irrigation system. Iron bacteria are a natural part of the environment in most parts of the world. These microorganisms combine dissolved iron or manganese with oxygen and use it to form rust-colored deposits. In the process, the bacteria produce a brown slime that builds up on well screens, pipes, and plumbing fixtures. Bacteria known to feed on iron are

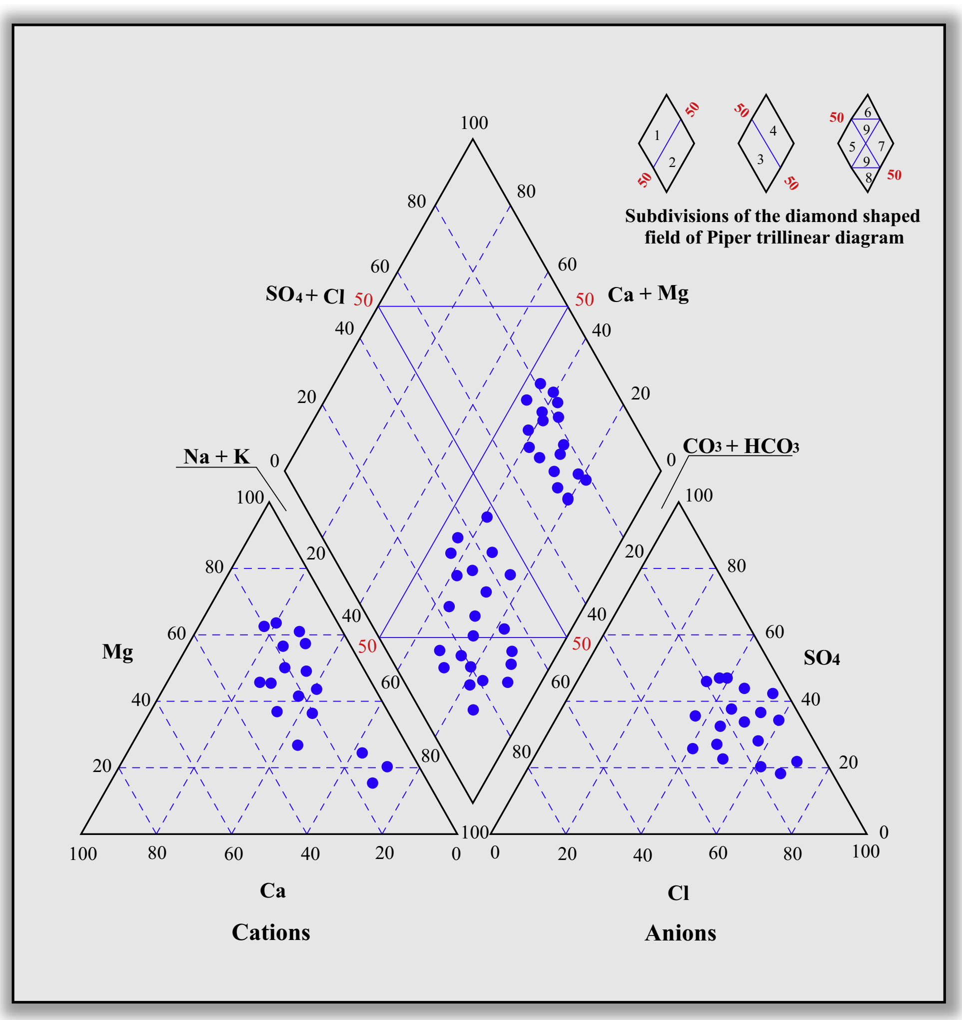

Figure 21 Trilinear diagram for the groundwater samples in the Nubian sandstone aquifer in the study area (Piper, 1945).

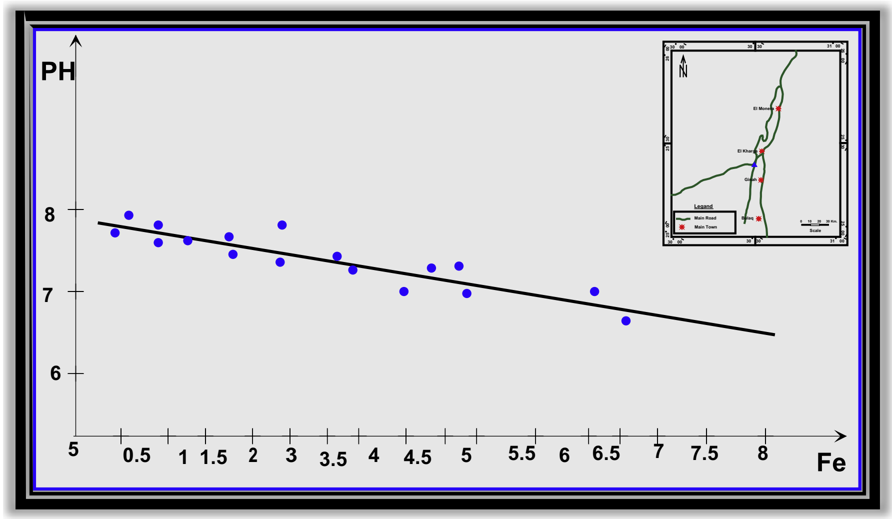

Figure 22 The relationship between pH and iron.

Thiobacillus, ferrooxidans and Leptospirillum ferrooxidans. When the de-oxygenated water reaches a source of oxygen, iron bacteria use that oxygen to convert the soluble ferrous iron back into an insoluble reddish precipitate of ferric iron:

$$2Fe(OH)_2 + O_2 \rightarrow H_2O + Fe_2O_3$$

(Iron [II] hydroxide) + (oxygen)
→ (water) + (Iron [III] oxide)

The dramatic effects of iron bacteria are seen in surface waters as brown slimy masses on stream bottoms and lakeshores or as an oily sheen upon the water. More serious problems occur when bacteria build up in well systems. Iron bacteria in wells do not cause health problems, but they can reduce well yields by clogging screens and pipes (Fig. 23).

5. Conclusions and recommendations

The development activities in the western desert depend on the groundwater resources in the Nubian sandstone aquifer. Groundwater exploitation should be directed to the development of the new proposed area, west of the study area, e.g. Malab El kheil area and its vicinities but this direction must be performed under conditions. Limitation of the groundwater exploitation in the production wells in the study area as the amount of groundwater withdrawn by pumping is much larger than that recharged to the aquifer. Prevent any new drilling wells at El-Kharga city and its vicinities and also Bulaq and Ginah areas. Changing the way of flood irrigation and exchanging it by more developed drip and sprinkle irrigation methods which save water will reduce the costs and efforts, and increase benefits. Furthermore, good management of irrigation by growing crops that takes small amounts of water e.g. growing of wheat, to minimize the effect of irrigation return flow in the reclaimed areas. The corrosion effect of groundwater on the well casing can be minimized by applying physical and chemical treatment methods for iron removal should be carried out in the study area. The wells should continue to discharge naturally over time. The minimum spacing between wells should not be less than 2 km. The wells should be constructed to extract water from the deeper horizons (B, C) of the Nubian sandstone aquifer, and this would avoid over-exploitation of the shallow horizon from which the existing springs and native wells derive their water for irrigation. More pumping tests must be carried out to obtain more information about aquifer hydraulic parameters.

Figure 23 Clogging screens and pipes at El-qulaa drinking water station.

Appendix A

The result of chemical analysis of major elements of the Nubian sandstone groundwater samples in the study area.

Sample	Well name	EC at 25 °C (mmohs/cm)	TDS (ppm)	pH	Unit	Cations					Anions					
						K^+	Na^+	Mg^{++}	Ca^{++}	Sum	NO_3^{--}	CL^-	SO_4^{--}	HCO_3^-	CO_3^{--}	Sum
1	Naser well 2	695	437	6.39	ppm	19.00	55.00	22.84	30.40		0.00	88.40	46.21	170.80	0.00	
					epm	0.49	2.39	1.88	1.52	6.28	0.00	2.49	0.96	2.80	0.00	6.25
					e %	7.76	38.10	29.92	24.22		0.00	39.82	15.40	44.78	0.00	
2	Genah 4 Elshark	389	245	7.1	ppm	16.59	34.55	9.72	12.00		0.00	41.80	20.77	103.70	0.00	
					epm	0.43	1.50	0.80	0.60	3.33	0.00	1.18	0.43	1.70	0.00	3.31
					e %	12.79	45.15	24.03	18.03		0.00	35.57	13.07	51.36	0.00	
3	Bolak 18	493	310	6.86	ppm	16.20	48.14	15.40	9.60		0.00	49.40	10.00	161.04	0.00	
					epm	0.42	2.09	1.27	0.48	4.25	0.00	1.39	0.21	2.64	0.00	4.24
					e %	9.76	49.19	29.76	11.28		0.00	32.82	4.91	62.27	0.00	
4	Genah 7	565.07	356	7.2	ppm	24.00	58.80	9.20	18.40		0.00	64.60	10.00	170.80	0.00	
					epm	0.62	2.56	0.76	0.92	4.85	0.00	1.82	0.21	2.80	0.00	4.83
					e %	12.69	52.73	15.60	18.97		0.00	37.69	4.32	57.99	0.00	
5	Genah 6	448	282	7.32	ppm	17.58	42.58	12.00	10.40		0.00	38.00	10.00	151.28	0.00	
					epm	0.45	1.85	0.99	0.52	3.81	0.00	1.07	0.21	2.48	0.00	3.76
					e %	11.83	48.60	25.91	13.65		0.00	28.10	5.47	65.11	0.00	
6	Umam Aly Ismail	623.22	392	6.8	ppm	25.88	74.88	8.74	12.00		0.00	64.10	11.00	194.80	0.00	
					epm	0.66	3.26	0.72	0.60	5.24	0.00	1.81	0.23	3.19	0.00	5.23
					e %	12.67	62.15	13.72	11.45		0.00	34.54	4.38	61.08	0.00	
7	El Kharga 48	470	295	6.9	ppm	17.50	44.22	8.20	15.20		0.00	30.24	14.00	161.20	0.00	
					epm	0.45	1.92	0.67	0.76	3.81	0.00	0.85	0.29	2.64	0.00	3.79
					e %	11.79	50.52	17.72	19.97		0.00	22.50	7.70	69.80	0.00	
8	El Kharga 51	500	315	6.91	ppm	16.83	44.82	13.12	12.80		0.00	38.22	10.00	170.00	0.00	
					epm	0.43	1.95	1.08	0.64	4.10	0.00	1.08	0.21	2.79	0.00	4.07
					e %	10.53	47.54	26.32	15.61		0.00	26.44	5.12	68.44	0.00	
9	El Kharga 7	530	333	7.1	ppm	17.72	58.00	11.60	8.00		0.00	37.05	17.30	178.12	0.00	
					epm	0.45	2.52	0.95	0.40	4.33	0.00	1.04	0.36	2.92	0.00	4.32
					e %	10.49	58.24	22.03	9.24		0.00	24.14	8.34	67.53	0.00	
10	EI Kharga 5	495	310	7.2	ppm	15.00	49.12	13.12	9.60		0.00	36.10	12.00	170.80	0.00	
					epm	0.38	2.14	1.08	0.48	4.08	0.00	1.02	0.25	2.80	0.00	4.07
					e %	9.43	52.35	26.45	11.77		0.00	25.00	6.15	68.85	0.00	
11	Bir Tolaib	532	334	6.81	ppm	18.00	60.00	9.20	8.80		0.00	33.25	12.01	186.65	0.00	
					epm	0.46	2.61	0.76	0.44	4.27	0.00	0.94	0.25	3.06	0.00	4.25
					e %	10.82	61.14	17.73	10.31		0.00	21.95	5.86	71.71	0.00	

(*continued on next page*)

Appendix A (*continued*)

Sample	Well name	EC at 25 °C	TDS	pH	Unit	Cations					Anions					
		(mmohs/cm)	(ppm)			K^{+}	Na^{+}	Mg^{++}	Ca^{++}	Sum	NO_3^{--}	CL^{-}	SO_4^{--}	HCO_3^{-}	CO_3^{--}	Sum
12	El Monira	755	475	7.5	ppm	25.50	95.29	13.12	8.00		0.00	70.00	10.00	245.11	0.00	
					epm	0.65	4.14	1.08	0.40	6.28	0.00	1.97	0.21	4.02	0.00	6.20
					e %	10.42	66.02	17.19	6.37		0.00	31.81	3.36	64.83	0.00	
13	El Monira 5	818	515	6.9	ppm	27.72	98.07	15.00	9.60		0.00	59.85	14.90	285.00	0.00	
					epm	0.71	4.26	1.23	0.48	6.69	0.00	1.69	0.31	4.67	0.00	6.67
					e %	10.63	63.75	18.44	7.18		0.00	25.28	4.65	70.06	0.00	
14	El Bostan	550	345	7.7	ppm	17.00	44.00	19.52	14.40		0.00	50.00	15.00	178.33	0.00	
					epm	0.44	1.91	1.61	0.72	4.67	0.00	1.41	0.31	2.92	0.00	4.64
					e %	9.33	40.93	34.34	15.40		0.00	30.33	6.73	62.95	0.00	
15	Bir El Mantaqa El Sinaiya	416	262	7.2	ppm	15.00	39.57	11.60	8.00		0.00	32.30	10.00	140.30	0.00	
					epm	0.38	1.72	0.95	0.40	3.46	0.00	0.91	0.21	2.30	0.00	3.42
					e %	11.12	49.74	27.58	11.56		0.00	26.62	6.09	67.29	0.00	
16	El Kharga 42	445	280	6.66	ppm	16.30	34.66	18.00	7.20		0.00	28.50	33.00	136.40	0.00	
					epm	0.42	1.51	1.48	0.36	3.77	0.00	0.80	0.69	2.24	0.00	3.73
					e %	11.10	40.02	39.31	9.56		0.00	21.54	18.45	60.01	0.00	
17	Kattara El Sherka 36 El monira	750	472	6.8	ppm	26.55	91.34	14.80	8.00		0.00	72.20	10.00	243.15	0.00	
					epm	0.68	3.97	1.22	0.40	6.27	0.00	2.03	0.21	3.99	0.00	6.23
					e %	10.86	63.35	19.41	6.38		0.00	32.44	3.32	63.58	0.00	
18	El Agoza 29	580	362	7.2	ppm	20.36	52.36	8.40	28.00		0.00	52.25	47.22	146.40	0.00	
					epm	0.52	2.28	0.69	1.40	4.89	0.00	1.47	0.98	2.40	0.00	4.86
					e %	10.68	46.56	14.13	28.63		0.00	30.31	20.26	49.43	0.00	
19	Genah 1 Estaoad	528	332	7.1	ppm	17.83	58.99	8.20	12.00		0.00	33.25	29.00	167.14	0.00	
					epm	0.46	2.56	0.67	0.60	4.30	0.00	0.94	0.60	2.74	0.00	4.28
					e %	10.64	59.70	15.70	13.97		0.00	21.88	14.11	64.01	0.00	
20	El Bydat 41	397	250	6.8	ppm	17.54	44.00	8.74	8.00		0.00	62.11	6.00	97.60	0.00	
					epm	0.45	1.91	0.72	0.40	3.48	0.00	1.75	0.13	1.60	0.00	3.47
					e %	12.92	54.95	20.64	11.49		0.00	50.35	3.60	46.05	0.00	
21	El Kharga 28	490	308	7.32	ppm	14.00	54.11	12.00	16.00		0.00	60.00	91.34	55.00	0.00	
					epm	0.36	2.35	0.99	0.80	4.50	0.00	1.69	1.90	0.90	0.00	4.49
					e %	7.98	52.30	21.94	17.78		0.00	37.60	42.34	20.06	0.00	
22	El Genah 12	710	445	7.6	ppm	28.00	90.00	15.40	17.60		0.00	122.00	133.00	32.00	0.00	
					epm	0.72	3.91	1.27	0.88	6.78	0.00	3.44	2.77	0.52	0.00	6.73
					e %	10.59	57.74	18.69	12.98		0.00	51.05	41.16	7.79	0.00	
23	El Kharga 10	530	333	6.77	ppm	16.83	56.22	8.00	16.80		0.00	40.85	18.00	170.80	0.00	
					epm	0.43	2.44	0.66	0.84	4.37	0.00	1.15	0.38	2.80	0.00	4.33
					e %	9.87	55.89	15.04	19.21		0.00	26.31	8.57	64.02	0.00	

24	El Sherka El Monira 36	831	523	6.5	ppm	26.66	94.11	12.86	19.20		0.00	53.20	32.69	280.00	0.00	
					epm	0.68	4.09	1.06	0.96	6.79	0.00	1.50	0.68	4.59	0.00	6.77
					e %	10.06	60.24	15.57	14.13		0.00	22.14	10.06	67.80	0.00	
25	El Monira 2 B	953	600	7.11	ppm	26.80	96.88	22.00	20.00		0.00	54.15	10.00	363.10	0.00	
					epm	0.69	4.21	1.81	1.00	7.71	0.00	1.53	0.21	5.95	0.00	7.69
					e %	8.91	54.64	23.47	12.97		0.00	19.85	2.71	77.44	0.00	
26	El Kharga 20	505	317	7.8	ppm	24.00	54.99	10.60	12.80		0.00	30.40	158.01	21.96	0.00	
					epm	0.62	2.39	0.87	0.64	4.52	0.00	0.86	3.29	0.36	0.00	4.51
					e %	13.62	52.92	19.29	14.17		0.00	19.00	73.02	7.99	0.00	
27	El Kharga 1S	493	310	6.88	ppm	16.22	41.55	20.40	10.40		0.00	33.25	110.00	71.57	0.00	
					epm	0.42	1.81	1.68	0.52	4.42	0.00	0.94	2.29	1.17	0.00	4.40
					e %	9.41	40.87	37.96	11.76		0.00	21.28	52.06	26.66	0.00	
28	El Zohor El Amiq	335	211	8.1	ppm	7.24	31.44	11.60	11.20		0.00	23.75	90.00	30.00	0.00	
					epm	0.19	1.37	0.95	0.56	3.07	0.00	0.67	1.88	0.49	0.00	3.04
					e %	6.05	44.58	31.11	18.26		0.00	22.04	61.76	16.20	0.00	
29	El Nasem 31 El Kharga	597	375	7.4	ppm	17.83	58.99	15.40	20.80		0.00	42.75	138.10	75.14	0.00	
					epm	0.46	2.56	1.27	1.04	5.33	0.00	1.20	2.88	1.23	0.00	5.31
					e %	8.58	48.13	23.77	19.52		0.00	22.60	54.00	23.12	0.00	
30	El Kharga 36	408.93	257	6.2	ppm	15.63	33.20	15.00	12.00		0.00	26.60	110.00	38.20	0.00	
					epm	0.40	1.44	1.23	0.60	3.68	0.00	0.75	2.29	0.63	0.00	3.67
					e %	10.90	39.25	33.54	16.31		0.00	20.43	62.49	17.08	0.00	
31	El Zohor El Kharga	521	328	6.11	ppm	16.20	41.57	20.80	17.60		0.00	42.75	132.58	50.00	0.00	
					epm	0.42	1.81	1.71	0.88	4.81	0.00	1.20	2.76	0.82	0.00	4.79
					e %	8.63	37.55	35.54	18.28		0.00	25.16	57.71	17.13	0.00	
32	El Kharga 6	477	300	6.2	ppm	16.23	43.50	15.00	16.00		0.00	33.25	126.11	44.00	0.00	
					epm	0.42	1.89	1.23	0.80	4.34	0.00	0.94	2.63	0.72	0.00	4.29
					e %	9.58	43.57	28.42	18.43		0.00	21.86	61.31	16.83	0.00	
33	El Amal 350m	356	224	7.1	ppm	15.00	36.24	8.26	8.80		0.00	23.75	70.88	55.24	0.00	
					epm	0.38	1.58	0.68	0.44	3.08	0.00	0.67	1.48	0.91	0.00	3.05
					e %	12.49	51.17	22.06	14.29		0.00	21.93	48.40	29.68	0.00	
34	Bir El Gamaa	583	367	6.8	ppm	17.51	66.17	10.60	20.80		0.00	38.00	164.01	44.66	0.00	
					epm	0.45	2.88	0.87	1.04	5.24	0.00	1.07	3.42	0.73	0.00	5.22
					e %	8.57	54.93	16.64	19.86		0.00	20.51	65.46	14.03	0.00	
35	El Sherka 5	433	272	7.8	ppm	17.72	49.11	9.72	12.80		0.00	65.00	72.59	40.40	0.00	
					epm	0.45	2.14	0.80	0.64	4.03	0.00	1.83	1.51	0.66	0.00	4.01
					e %	11.28	53.00	19.84	15.89		0.00	45.45	37.54	16.44	0.00	
36	Ahali Bor said	2162	1362	7.2	ppm	60.00	110.20	90.80	206.40		0.00	782.14	67.78	40.44	0.00	
					epm	1.54	4.79	7.47	10.32	24.12	0.00	22.03	1.41	0.66	0.00	24.11
					e %	6.38	19.87	30.96	42.79		0.00	91.39	5.86	2.75	0.00	

(*continued on next page*)

Appendix A (*continued*)

Sample	Well name	EC at 25 °C	TDS	pH	Unit	Cations					Anions					
		(mmohs/cm)	(ppm)			K^+	Na^+	Mg^{++}	Ca^{++}	Sum	NO_3^{--}	CL^-	SO_4^{--}	HCO_3^-	CO_3^{--}	Sum
37	El Sherka 7	370	232	7.2	ppm	15.11	34.00	14.00	12.80		0.00	80.00	40.00	30.50	0.00	
					epm	0.39	1.48	1.15	0.64	3.66	0.00	2.25	0.83	0.50	0.00	3.59
					e %	10.59	40.42	31.48	17.50		0.00	62.83	23.23	13.94	0.00	
38	El Qalaa	636	400	7.5	ppm	23.65	64.11	12.60	24.00		0.00	48.57	149.50	68.25	0.00	
					epm	0.61	2.79	1.04	1.20	5.63	0.00	1.37	3.11	1.12	0.00	5.60
					e %	10.77	49.51	18.40	21.31		0.00	24.42	55.60	19.97	0.00	
39	El Kharga 20	630	396	7.7	ppm	26.44	74.35	7.20	20.80		0.00	45.68	149.03	66.87	0.00	
					epm	0.68	3.23	0.59	1.04	5.54	0.00	1.29	3.10	1.10	0.00	5.49
					e %	12.23	58.32	10.68	18.76		0.00	23.45	56.58	19.98	0.00	
40	El Siet	535	336	6.8	ppm	17.83	58.99	18.94	13.60		0.00	114.00	61.55	45.25	0.00	
					epm	0.46	2.56	1.56	0.68	5.26	0.00	3.21	1.28	0.74	0.00	5.24
					e %	8.69	48.76	29.61	12.93		0.00	61.34	24.49	14.17	0.00	
41	Um El Kosor	463	291		ppm	16.83	44.82	15.00	12.80		0.00	33.25	140.19	23.10	0.00	
				6.2	epm	0.43	1.95	1.23	0.64	4.25	0.00	0.94	2.92	0.38	0.00	4.24
					e %	10.14	45.81	29.00	15.05		0.00	22.02	68.66	8.90	0.00	
42	El Monira 12	480	302	6.8	ppm	16.70	54.88	14.00	9.00		0.00	50.22	112.01	40.64	0.00	
					epm	0.43	2.39	1.15	0.45	4.42	0.00	1.41	2.33	0.67	0.00	4.41
					e %	9.70	54.04	26.07	10.19		0.00	32.05	52.86	15.09	0.00	
43	El Sherka 1	580	369	6.76	ppm	24.73	58.02	12.15	15.20		0.00	53.20	28.28	170.80	0.00	
					epm	0.63	2.52	1.00	0.76	4.92	0.00	1.50	0.59	2.80	0.00	4.89
					e %	12.90	51.32	20.33	15.46		0.00	30.66	12.05	57.29	0.00	
44	El Sherka 5	550	355	6.90	ppm	13.17	57.42	12.64	15.20		0.00	48.45	40.00	146.40	0.00	
					epm	0.34	2.50	1.04	0.76	4.63	0.00	1.36	0.83	2.40	0.00	4.60
					e %	7.29	53.88	22.43	16.40		0.00	29.68	18.12	52.20	0.00	
45	Privat well (tolaib)	560	355	7.25	ppm	17.84	66.20	12.64	7.20		0.00	38.00	40.00	170.80	0.00	
					epm	0.46	2.88	1.04	0.36	4.73	0.00	1.07	0.83	2.80	0.00	4.70
					e %	9.66	60.79	21.95	7.60		0.00	22.76	17.72	59.53	0.00	
46	Tolaib	566	358	6.89	ppm	17.83	59.00	14.58	12.00		0.00	44.65	34.88	170.80	0.00	
					epm	0.46	2.57	1.20	0.60	4.82	0.00	1.26	0.73	2.80	0.00	4.78
					e %	9.48	53.20	24.87	12.44		0.00	26.29	15.19	58.52	0.00	
47	Elaisawia	564	350	7.25	ppm	10.83	61.60	15.06	11.20		0.00	45.60	28.24	173.24	0.00	
					epm	0.28	2.68	1.24	0.56	4.75	0.00	1.28	0.59	2.84	0.00	4.71
					e %	5.84	56.33	26.05	11.78		0.00	27.02	12.37	59.73	0.00	
48	El monira Elbalad	600	375	7.20	ppm	21.44	59.41	15.55	12.00		0.00	57.95	8.00	195.20	0.00	
					epm	0.55	2.58	1.28	0.60	5.01	0.00	1.63	0.17	3.20	0.00	5.00
					e %	10.97	51.54	25.52	11.97		0.00	32.65	3.33	64.01	0.00	

49	Station water El Monira Elbalad	1005	631	7.10	ppm	15.30	146.60	14.58	16.80		0.00	114.00	84.02	234.24	0.00	
					epm	0.39	6.37	1.20	0.84	8.81	0.00	3.21	1.75	3.84	0.00	8.80
					e %	4.46	72.39	13.62	9.54		0.00	36.48	19.89	43.63	0.00	
50	El Sherka 3	650.4	406	7.00	ppm	14.13	73.20	14.58	16.00		0.00	68.40	17.68	195.20	0.00	
					epm	0.36	3.18	1.20	0.80	5.54	0.00	1.93	0.37	3.20	0.00	5.50
					e %	6.54	57.41	21.63	14.43		0.00	35.06	6.70	58.23	0.00	
51	El Sherka 2	800.41	503	7.10	ppm	24.21	91.58	11.66	12.80		0.00	80.00	4.21	234.24	0.00	
					epm	0.62	3.98	0.96	0.64	6.20	0.00	2.25	0.09	3.84	0.00	6.18
					e %	10.01	64.21	15.46	10.32		0.00	36.46	1.42	62.12	0.00	
52	Heipis El Kharga 22	416.3	261	7.20	ppm	9.34	34.87	15.55	11.20		0.00	34.20	28.67	122.00	0.00	
					epm	0.24	1.52	1.28	0.56	3.59	0.00	0.96	0.60	2.00	0.00	3.56
					e %	6.66	42.18	35.58	15.58		0.00	27.06	16.77	56.17	0.00	
53	El Kharga 6	476	300	6.96	ppm	17.72	41.25	17.01	12.00		0.00	42.75	66.00	97.60	0.00	
					epm	0.45	1.79	1.40	0.60	4.25	0.00	1.20	1.38	1.60	0.00	4.18
					e %	10.70	42.23	32.94	14.13		0.00	28.36	32.38	37.68	0.00	
54	Elbayadat 41	394.65	248	6.59	ppm	15.32	34.88	11.66	10.40		0.00	34.20	41.00	95.16	0.00	
					epm	0.39	1.52	0.96	0.52	3.39	0.00	0.96	0.85	1.56	0.00	3.38
					e %	11.59	44.76	28.30	15.35		0.00	28.52	25.29	46.19	0.00	
55	Zirzara	364.49	229	6.63	ppm	15.62	33.20	9.23	12.80		0.00	50.35	29.01	73.20	0.00	
					epm	0.40	1.44	0.76	0.64	3.24	0.00	1.42	0.60	1.20	0.00	3.22
					e %	12.35	44.51	23.41	19.73		0.00	44.01	18.75	37.24	0.00	
56	El Genah 6	379	239	6.74	ppm	16.70	34.87	9.23	12.80		0.00	49.40	25.11	85.40	0.00	
					epm	0.43	1.52	0.76	0.64	3.34	0.00	1.39	0.52	1.40	0.00	3.31
					e %	12.81	45.35	22.70	19.14		0.00	41.98	15.78	42.24	0.00	
57	Station water Port Said	647.03	407	7.83	ppm	16.70	80.00	16.04	16.80		0.00	118.75	41.02	112.24	0.00	
					epm	0.43	3.48	1.32	0.84	6.07	0.00	3.35	0.85	1.84	0.00	6.04
					e %	7.06	57.35	21.74	13.85		0.00	55.39	14.15	30.47	0.00	
58	El Genah 12	461	290	7.00	ppm	16.23	41.55	12.64	14.40		0.00	47.50	30.00	122.00	0.00	
					epm	0.42	1.81	1.04	0.72	3.98	0.00	1.34	0.63	2.00	0.00	3.96
					e %	10.45	45.37	26.10	18.08		0.00	33.76	15.77	50.47	0.00	
59	El Kharga 48	517.87	325	6.96	ppm	25.00	62.39	2.60	11.20		0.00	38.00	10.01	170.80	0.00	
					epm	0.64	2.71	0.21	0.56	4.13	0.00	1.07	0.21	2.80	0.00	4.08
					e %	15.53	65.72	5.18	13.57		0.00	25.93	5.05	67.84	0.00	
60	Um Elkosour	818	515	7.03	ppm	25.00	91.02	17.98	14.40		0.00	67.45	10.00	284.11	0.00	
					epm	0.64	3.96	1.48	0.72	6.80	0.00	1.90	0.21	4.66	0.00	6.77
					e %	9.43	58.22	21.75	10.59		0.00	28.08	3.08	68.84	0.00	
61	El Kantara 2	408.5	257	7.02	ppm	15.33	34.87	9.72	15.20		0.00	42.75	12.00	122.00	0.00	
					epm	0.39	1.52	0.80	0.76	3.47	0.00	1.20	0.25	2.00	0.00	3.45
					e %	11.33	43.71	23.05	21.91		0.00	34.86	7.24	57.90	0.00	

(*continued on next page*)

Appendix A (*continued*)

Sample	Well name	EC at 25 °C (mmohs/cm)	TDS (ppm)	pH	Unit	Cations K^+	Na^+	Mg^{++}	Ca^{++}	Sum	Anions NO_3^{--}	CL^-	SO_4^{--}	HCO_3^-	CO_3^{--}	Sum
62	Elbostan deep	730	459	6.70	ppm	14.00	44.01	32.07	32.80		0.00	60.80	88.00	180.70	0.00	
					epm	0.36	1.91	2.64	1.64	6.55	0.00	1.71	1.83	2.96	0.00	6.51
					e %	5.48	29.21	40.27	25.04		0.00	26.32	28.17	45.52	0.00	
63	El Qalaa	794	500	6.74	ppm	17.72	49.59	34.99	38.40		0.00	59.00	196.00	99.70	0.00	
					epm	0.45	2.16	2.88	1.92	7.41	0.00	1.66	4.08	1.63	0.00	7.38
					e %	6.13	29.11	38.84	25.92		0.00	22.52	55.33	22.15	0.00	
64	El Zohour deep	339.2	213	6.70	ppm	7.24	34.26	7.29	11.20		0.00	29.45	9.00	109.80	0.00	
					epm	0.19	1.49	0.60	0.56	2.83	0.00	0.83	0.19	1.80	0.00	2.82
					e %	6.55	52.55	21.15	19.76		0.00	29.45	6.66	63.90	0.00	
65	El Zohour Shallow	626.4	394	6.71	ppm	17.20	44.00	27.22	23.20		0.00	62.70	92.12	122.00	0.00	
					epm	0.44	1.91	2.24	1.16	5.75	0.00	1.77	1.92	2.00	0.00	5.69
					e %	7.67	33.26	38.91	20.17		0.00	30.70	33.36	34.77	0.00	

Appendix B

Chemical analysis of trace element (Fe) in groundwater samples of the Nubian sandstone aquifer in the study area.

Sample	Well name	Fe	Sample	Well name	Fe	Sample	Well name	Fe	Sample	Well name	Fe
43	El Sherka 1	1.3	49	Station water El Monira Elbalad	11	55	Zirzara	10	61	El Kantara 2	0.45
44	El Sherka 5	1.05	50	El Sherka 3	0.9	56	El Genah 6	3.8	62	Elbostan deep	4.2
45	Privat well (tolaib)	1.4	51	El Sherka 2	0.8	57	Station water Port Said	3.4	63	El Qalaa	8.3
46	Tolaib	0.9	52	Heipis El Kharga 22	0.95	58	El Genah 12	2.3	64	El Zohour deep	2.6
47	Elaisawia	0.95	53	El Kharga 6	2.6	59	El Kharga 48	1.95	65	El Zohour Shallow El Kantara 2	4.1
48	El monira Elbalad	0.65	54	Elbayadat 41	2.9	60	Um Elkosour Zirzara	0.6			

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