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HYDROCHEMICAL APPRAISAL OF GROUNDWATER IN THE KHARTOUM REGION, SUDAN

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The groundwater chemistry of Khartoum State between longitudes 32° 15' - 33° 00'E and latitudes 15° 10' - 16° 00'N was evaluated and assessed using different hydrogeological methods. Groundwater in the region occurs in two hydraulically interconnected aquifers: the siliciclastic sediments of the Cretaceous Omdurman Formation and the mostly unconsolidated sediments of the Cretaceous-Tertiary-Quaternary Umm Ruwaba Formation. The analysis of the flow system indicated a regional flow direction towards the northwest, with a local flow regime towards the east. Assessment of groundwater chemistry showed negative correlation between the exchangeable ions, Na-Ca. This means an ion exchange process is active. The strong correlations between Na⁺ and Cl⁻ ions, TDS and EC indicate that salinization is related to the increase of concentration of these ions. Dissolution of evaporites is suggested by positive correlations between Ca, Mg and SO₄. Groundwaters were classified into three hydrochemical facies, Ca-Mg-HCO₃, Ca-SO₄-HCO₃ and Na-Ca-SO₄-Cl. The spatial distribution of these facies and hydrochemical sections indicates that the anionic facies changes in the flow direction from HCO₃ to SO₄ and finally to Cl. The cationic facies is mostly affected by the ion-exchange process of calcium and magnesium by sodium. Mixing is an active process that has affected the water facies in the region.

INTRODUCTION

Khartoum is the capital of Sudan. It lies at the confluence where the White Nile and Blue Nile meet to flow northward as the River Nile. The Khartoum region comprises the three towns of Khartoum, Omdurman, Khartoum North and their suburbs. It is located between longitude $32^{\circ} 15'$ - $33^{\circ} 00'E$ and latitudes $15^{\circ} 10'$ - $16^{\circ} 00'N$ (Figure 1). It covers a surface area of some 66,000 km². Since its foundation in 1820, Khartoum has been the headquarters of the central government. It is the center for all political, economical, commercial, agricultural, industrial, and cultural activities of Sudan. By the end of the Second World War, the three towns witnessed a steady increase in population at a rate of some 2.1% up to the mid 1950s. Thereafter this rate has increased to some 3% up to the end of the 1960s of the last century. From the beginning of the 1980s, a sharp and accelerating increase in population growth has taken place. In the last two decades more rural exodus has taken place, and influxes of Sudanese people and other African refugees of civil wars came to settle in the Khartoum region seeking security, food and shelter. A population of some 15 million is putting increasing stress on the natural resources of this part of Sudan. Up to the end of the 1970s, the three towns were dependent for their water supplies on the rivers; in remote rural areas some dug wells and few boreholes were used. As result of the increasing water demand, surface waters needed higher capacity units for water treatment. The treatment of river water to be fit for human and industrial use faced a lot of problems and shortages in the materials and chemicals needed, on one hand, and the areas remote from the rivers needed pipelines and pumps to carry the water to where needed. The water authorities thus found it more feasible to use groundwater to meet these demands. Since then more groundwater has been used in Khartoum region.

The main objective of this paper is to carry out a hydrochemical appraisal of groundwater in Khartoum region. This includes the determination of the general water quality, major ionic constituents, hydrochemical facies and water types, geochemical processes responsible for changes, and variations in the groundwater quality.

MATERIALS AND METHODS

The hydrogeological inventories were collected during fieldwork carried out in the period June-September 2003. Borehole data were obtained from the Hydrogeological Information Centre of the Ministry of Irrigation, Khartoum. Complete hydrogeological records were used in this evaluation, in addition to lithological logs describing the material encountered in the boreholes. The sampling procedure involved collecting groundwater samples in polyethylene bottles after pumping the sampled well for at least 30 minutes. This was done to remove groundwater stored in the well and to obtain representative samples. Groundwater temperature, pH, and electric conductivity (EC) were measured in-situ using portable Karl Kolb measuring units. The samples were further analyzed for major anions and cations using standard methods (American Public Health Association/ American Water Works Association/ Water Pollution Control Federation, APH/AWWA/WPCF/, 1989). The chemical data were reviewed and checked for its ionic balance. All records with ion balance greater than 6 % were rejected. The data are shown in Table 1.

GEOLOGICAL SETTING

The study area lies in the northwestern part of the Blue Nile Rift (Salama, 1985, 1997). It forms an intra-continental basin, whose axis is NW-SE and is bordered by Precambrian Basement

Complex at its southwestern and northern parts. This basin is a result of a rift system that has been activated several times (Fairhead, 1979; Schull, 1988). The rapid rates of uplift and subsidence have assisted in filling the basin with a thick sequence of siliciclastic sediments (Vail, 1974; Salama, 1985; 1997). E-W and N-W striking normal faults are the most prominent structures cutting the sedimentary sequence. Geological mapping and geophysical surveys suggest several hundreds of meters of downthrow on these faults. (Mula, 1971; Vail, 1978; Mula et al., 1993). The Basement Complex is the oldest rock unit cropping out in the study area. Granites and granite gneisses are the main types of rocks forming the basement in the study area.

The Omdurman Formation is deposited unconformably over the Basement Complex in Khartoum area. It crops out all over the western and northwestern parts of the region (Figure 1). The sedimentary sequence of the Omdurman Formation comprises sandstones, mudstones and conglomerates. Late Cretaceous (Albian-Cenomanian) age was assigned to Omdurman Formation (Schrank and Awad, 1990).

The sediments of the Umm Ruwaba Formation were deposited unconformably over the Basement Complex and the Omdurman Formation and occupy the triangular area between the White and Blue Niles and they extend to the southeast (Figure 1). It also crops out in small areas east of the Blue Nile and east of the Nile River. The Umm Ruwaba Formation is synonymous to the Gezira Formation (Adamson and Williams, 1980). In the study area, the Umm Ruwaba Formation is comprised of unconsolidated gravels, sands, silts and clays. Smectite is the dominant clay mineral in both the upper and lower parts of the formation, where it forms about 54-98% of the clays, followed by kaolinite, which forms 2.5-46% (Awad and Bireir, 1993). These sediments show rapid vertical and lateral facies changes indicating fluvial, deltaic and lacustrine environments. Calcareous materials are very common as a matrix in sandy sediments and as nodules (Kankar) in clayey sediments. Their distribution tends to increase towards the southwest. Salama and others (1999) interpreted these calcareous materials as products of successive processes of evaporation and leaching by floods in environments that were favorable for deposition of carbonates. The thickness of the Umm Ruwaba Formation increases away from the White Nile, where it reaches about 79 meters at the southwestern part of the study area. The Umm Ruwaba Formation was assigned to the Tertiary-Quaternary (Bireir, 1993)

GROUNDWATER FLOW

Groundwater level varies from 304 to 360 m above mean sea level (Figure 2). A prominent feature in the water level configuration is the natural groundwater trough at the east. The average hydraulic gradient is about 2.7 m/km and attains 7.6 m/km near the local cone of depression in the middle of the area. The hydraulic gradient to the west is about 0.58 m/km, and about 1.1 m/km at the northeastern part of the area. The hydraulic conductivity in the study area varies from 0.12 m/day to 7.82 m/day, with a mean value of 2.78 m/day (Awad, 2002). It generally increases from east to west, with an exceptional zone of low hydraulic conductivity in the midwest. This zone coincides with the Fiteihab Basin, where the mudstone to sandstone ratio is greater than 4 (Hussein, 1992). Transmissivity values show a very high variability from 8.7 to 490 m²/day, with a mean value of 171.6 m²/day (Awad, 2002). The values of storativity vary on the order of 10⁻¹ to 10⁻⁴, and these values show an increase towards the west. A relatively low storativity zone occurs at the southeast, extends to west and may reflect semi-confined conditions (Awad, 2002).

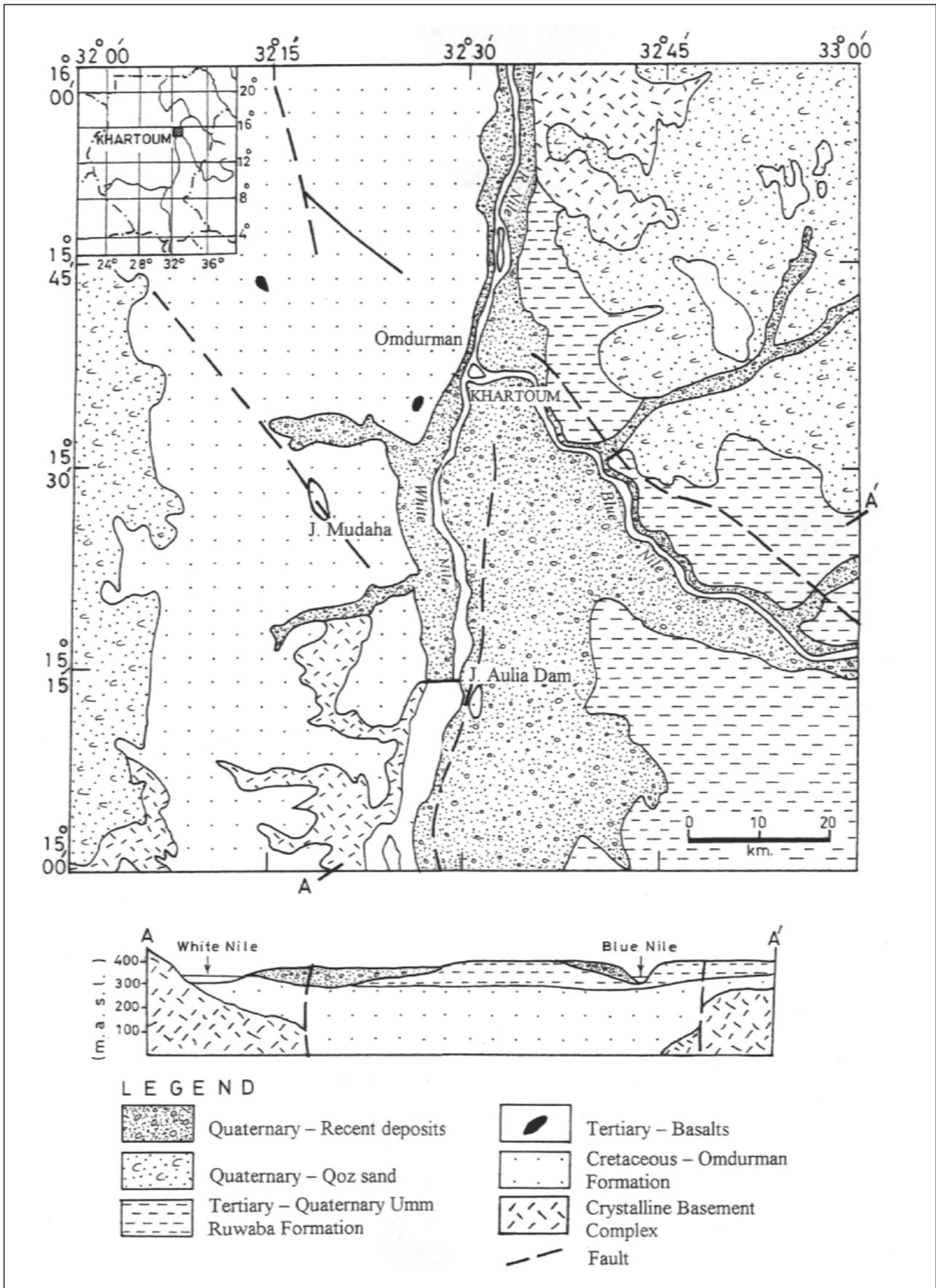


Figure 1. Simplified geological map of the study area (modified after GRAS, 1988).

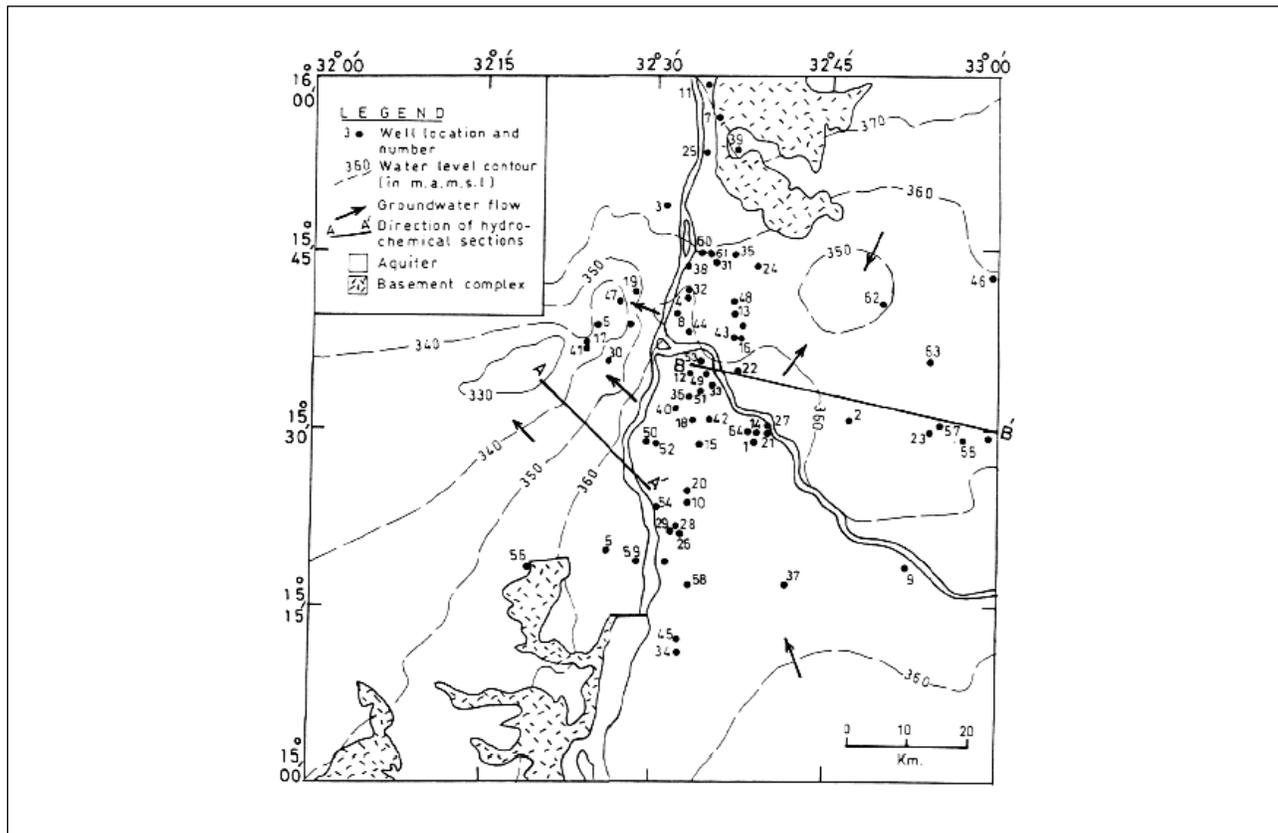


Figure 2. Groundwater level contour map (in meters a.m.s.l.).

Very limited or no recharge from direct precipitation is expected due to the topography, as rainfall runs off quickly towards the Niles, and due to high clay content and superficial sediments covering the upper aquifer (Boushi, 1972). The Nile rivers are the main source of groundwater recharge in the area (Saeed, 1976; Haggaz and Kheirallah, 1988; Geyh et al., 1995).

Major Ionic Constituents

The total dissolved solids varies from 184 to 3600 mg/L, and the electrical conductivity has a mean value of 732 $\mu\text{s}/\text{cm}$ and a maximum value of 2450 $\mu\text{s}/\text{cm}$ (Tables 1 and 2). TDS increases from the southeast to the northwest following the regional flow direction (Figure 3). Two high TDS zones are noted, one is located at the far east where TDS values reach more than 1200 mg/l, and the other is located at the mid south, where TDS reaches more than 2000 mg/l. The high TDS zone at the eastern part may be related to the local groundwater trough, where dissolved and leached materials are expected to precipitate, leading to groundwater salinization. The high TDS zone at the southeastern part of the area is related to agricultural practice, where the Soba scheme is located. The other local anomalous zones of high TDS may be caused by lithological changes in the aquifer materials, where calcareous nodules (kankar) are common at the upper parts of Umm Ruwaba Formation, and clayey horizons at Omdurman Formation.

The dominant cation is sodium, which has a mean concentration of 105 mg/l, followed by calcium and magnesium, which have mean concentrations of 41 and 19 mg/l respectively. Bicarbonate is the dominant anion, having a mean concentration of 244 mg/l, followed by chloride which has a mean of 78 mg/l. Sulphate has a wide range of concentrations, and the minimum value is 1 mg/l and the maximum is 1000 mg/l. Potassium and nitrate occur in very minor amounts, their mean concentrations are 4 and 3 mg/l respectively (Table 2).

Table 1. Chemical composition of collected water samples, Khartoum Region
(EC in $\mu\text{S}/\text{cm}$, TDS and ionic concentration in mg/L)

Well No.	Depth (m)	Depth to water (m)	Screened interval (m)	pH	EC	TDS	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	NO ₃
1	214.9	22.8	180.2- 192.3	8	640	460	45	10	70	10	160	100	70	1
2	86.3	37	54.2- 67.5	8.3	1260	910	55	45	200	10	330	290	120	1
3	88	23	55.3- 65.3	7.2	1600	930	60	25	200	5	240	450	20	1
4	76	18.1	60.4- 65, 71.6- 75.6	7.8	1550	960	50	25	300	5	220	450	200	50
5	135.7	31.7	30.2-56.6	8.3	270	200	32	15	16	2	140	23	16	1
6	123.4	59.7	78.0-83.2, 95.7-97.9	7.7	800	680	60	50	160	2	368	160	170	1
7	80	7	60.1- 64.8, 74.1- 78.6	8	330	240	35	15	10	5	135	15	40	1
8	92.9	16.7	74.9-84.5	7.9	400	260	51	20	48	2	212	45	56	1
9	106.7	19.8	75.2- 80.6, 94.4- 99.2	7.8	427	348	46	20	43	2	198	109	12	1
10	62.5	16.1	36.6-46.9	8.1	335	200	33	12	20	2	136	34	20	1
11	70.7	15.9	51.8-64	8	960	640	60	30	115	10	270	190	105	5
12	79.3	15.5	51.4-62.9	8.2	470	410	20	15	75	5	120	145	10	5
13	92.9	26.2	62.5-68.6, 82.3-88.4	7.5	1020	985	82	32	78	2	335	95	115	1
14	88.4	13.8	67.1-79.3	7.8	275	185	30	10	10	2	125	20	5	1
15	141.8	22.7	121.9-133.5	8.1	562	489	38	23	72	4	188	131	54	1
16	106.7	25.9	75.3-81.1, 93.6-99.4 112.8-118.9, 122.3- 128.4	8.3	669	502	36	24	47	11	186	54	77	1
17	137.2	49.3	138.7-144.8, 160.1- 166.2	8.1	510	382	54	16	35	2	198	45	28	1
18	176.8	22.6	103.7-109.8, 129.4- 135.5	7.8	1007	755	65	26	120	2	266	80	139	1
19	144.8	31.3	19.4-30.4	8	500	410	51	24	45	6	228	48	66	24
20	36.5	11.9	40-45	8	499	338	48	14	43	1	317	20	8	1
21	45.7	16.4	67.4-76.5	7.9	345	203	26	12	25	3	143	50	16	1
22	91.4	12	90.2-95	8.3	263	330	22	11	50	5	122	74	13	1
23	126.5	19.8	76.1-88.2	6.8	1691	924	43	27	227	23	366	180	217	1
24	109.6	31.6	42.1-59	7.2	384	269	35	16	22	3	207	6	15	4
25	64	13.9	40.2-51.8	8.7	1004	672	15	17	142	1	342	109	39	1
26	61	15.2	46.7-53.2	8.2	458	270	30	21	23	1	171	17	22	1
27	54.8	16.8	41.5-48.9	7.1	501	442	34	13	45	11	183	28	26	6
28	57.1	14.6	37.8-43.5	8.2	458	190	30	21	23	1	171	17	22	1
29	60.9	15.8	183.2-189.1, 195.1- 200	7.3	599	220	44	23	65	3	372	10	12	1
30	210.9	70.1	78-88.4	8.4	309	320	36	5	35	6	183	37	9	1
31	96	21	65.5-70.1	7.8	540	345	72	16	40	1	185	64	63	1
32	73.2	24.4	85.4-90.6, 96.8-102.6	7.8	1007	460	65	26	120	1	317	80	139	1
33	116.1	0	79.1- 84.9	7.4	304	320	36	11	10	2	183	1	10	8
34	94.5	18.5	9.8-55.6, 63.9-69.7	7.2	798	360	50	23	85	6	256	51	128	4
35	73.1	16.1	65.2-71	7	1692	952	34	37	324	8	305	316	248	1
36	91.5	0	128-140.2	7.2	680	510	24	23	58	5	293	39	11	1
37	155.5	22.4	60-6470-78	7.5	1430	1001	42	20	235	3	171	100	327	5
38	82	20	48.4-59.9	6.7	736	327	18	15	127	5	256	45	105	4
39	69.2	25.7	30.18-40.54	7.5	366	220	16	9	77	4	183	21	50	1
40	50.3	14.8	120.4-126.5, 150.9- 157	8.7	748	248	7	6	170	1	390	68	47	1
41	172.3	66	30.18-41.76	8	641	480	60	12	90	3	305	65	84	1
42	53.3	13.5	92.9-104.5	6.6	634	360	45	12	65	2	122	45	94	1
43	123.4	23	54.9-67.1	6.3	420	291	68	5	38	1	236	18	42	1
44	85.4	10.1	97.3-108.5	8.1	562	335	38	23	72	4	159	131	54	1
45	118.6	15.3	143.3-155.5	7.7	644	558	58	22	53	5	329	50	13	3
46	160	23.8	137.2-149.4	8	300	200	28	2	51	2	83	15	69	1
47	157	36.1		8	500	280	51	24	45	6	207	48	66	1

Ionic Relationships

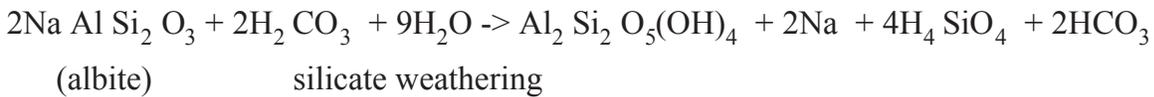
The relationships between the measured hydrochemical parameters may help to identify the main processes contributing to groundwater salinization. A correlation matrix was calculated for different pairs of major ions, TDS, EC, and pH (Table 3). Strong positive correlations ($r > 0.75$) exist between TDS, EC, Na^+ , Cl^- , and SO_4^{2-} . These relationships indicate that groundwater salinization is a result of increasing Na^+ and Cl^- concentrations due to evaporation. Positive correlation between Ca^{2+} , Mg^{2+} and SO_4^{2-} suggests that the effect of cation exchange and the process of dissolution of evaporitic minerals are active. Moderate correlation exists between

Table 2. Summary statistics of measured parameters (EC in μ s/cm, ionic concentrations in mg/l).

Statistics	pH	EC	TDS	Ca	Mg	Na	K	HCO ₄	SO ₅	Cl
Mean	7.70	763.83	520.02	40.71	19.44	104.89	4.71	244.35	100.76	77.90
Standard Error	0.07	57.41	39.01	2.07	1.28	14.15	0.53	11.88	18.69	9.61
Median	7.8	628	410	38	17	65	4	228	50	54
Mode	8	562	200	60	16	10	5	317	45	20
Standard Deviation	0.54	455.64	309.60	16.47	10.12	112.31	4.18	94.30	148.31	76.24
Kurtosis	-0.45	1.92	2.54	-0.20	1.76	13.70	7.96	0.01	22.13	2.44
Skewness	-0.43	1.38	1.41	0.28	1.13	3.06	2.47	0.59	4.19	1.59
Range	2.4	2187	1560	75	49	710	22	454	999	328
Minimum	6.3	263	185	7	2	10	1	83	1	5
Maximum	8.7	2450	1745	82	51	720	23	537	1000	333

SO₄²⁻ and Cl⁻, supporting the process of dissolution.

The scatter diagram of (Ca + Mg) vs (HCO₃ + SO₄) (Figure 4) shows that with the exception of few samples, the groundwater in the study area lies along and below the equiline. This indicates that silicate weathering is a major reaction taking place. In this reaction:



This process continues with the flow path. The Na vs Ca scatter diagram (Figure 5) shows that the sample points are above and below the 1:1 equiline. The samples below the equiline indicate ion exchange process. Those above the line show silicate weathering.

The scatter diagram of Na vs Cl (Figure 6) shows that most of the sample points are on and below the 1:1 equiline suggesting the process of evaporation and halite dissolution, respectively (Jankowski and Acworth, 1977). The Na/Cl ratio vs EC scatter diagram (Figure 7) is almost horizontal. This means that the Na/Cl ratio does not change during the increase of EC, suggesting an increase in Na and Cl concentrations by the process of evaporation.

The cation contribution to groundwater by silicate weathering is also estimated by the (Na + K)/total cation index (Sarin et al., 1989). The (Na + K) vs total cation (TC) scatter diagram (Figure 8) of the study area shows sample points along and above the (Na + K) = 0.33 TC line, and sample points below the (Na + K) = 0.5 TC line. The first suggests that the cations in the groundwater have been derived from silicate weathering. The second suggests that the slightly lower concentration of (Na + K) is likely caused by Ca/Na exchange process. This exchange process might have reduced the amount of Na in the groundwater.

Hydrochemical Facies

Table 3. Pearson's correlation matrix.

	pH	EC	TDS	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	NO ₃
pH	1.000										
EC	-0.316	1.000									
TDS	-0.289	0.927	1.000								
Ca	-0.139	0.158	0.238	1.000							
Mg	-0.107	0.506	0.532	0.351	1.000						
Na	-0.236	0.904	0.842	-0.003	0.365	1.000					
K	-0.279	0.367	0.382	0.036	0.121	0.222	1.000				
HCO ₃	-0.252	0.626	0.600	0.201	0.490	0.572	0.212	1.000			
SO ₄	-0.115	0.775	0.749	0.129	0.384	0.890	0.155	0.348	1.000		
Cl	-0.308	0.844	0.788	0.188	0.449	0.807	0.293	0.418	0.604	1.000	
NO ₃	-0.037	0.215	0.206	0.063	0.070	0.220	0.103	-0.015	0.276	0.224	1.000

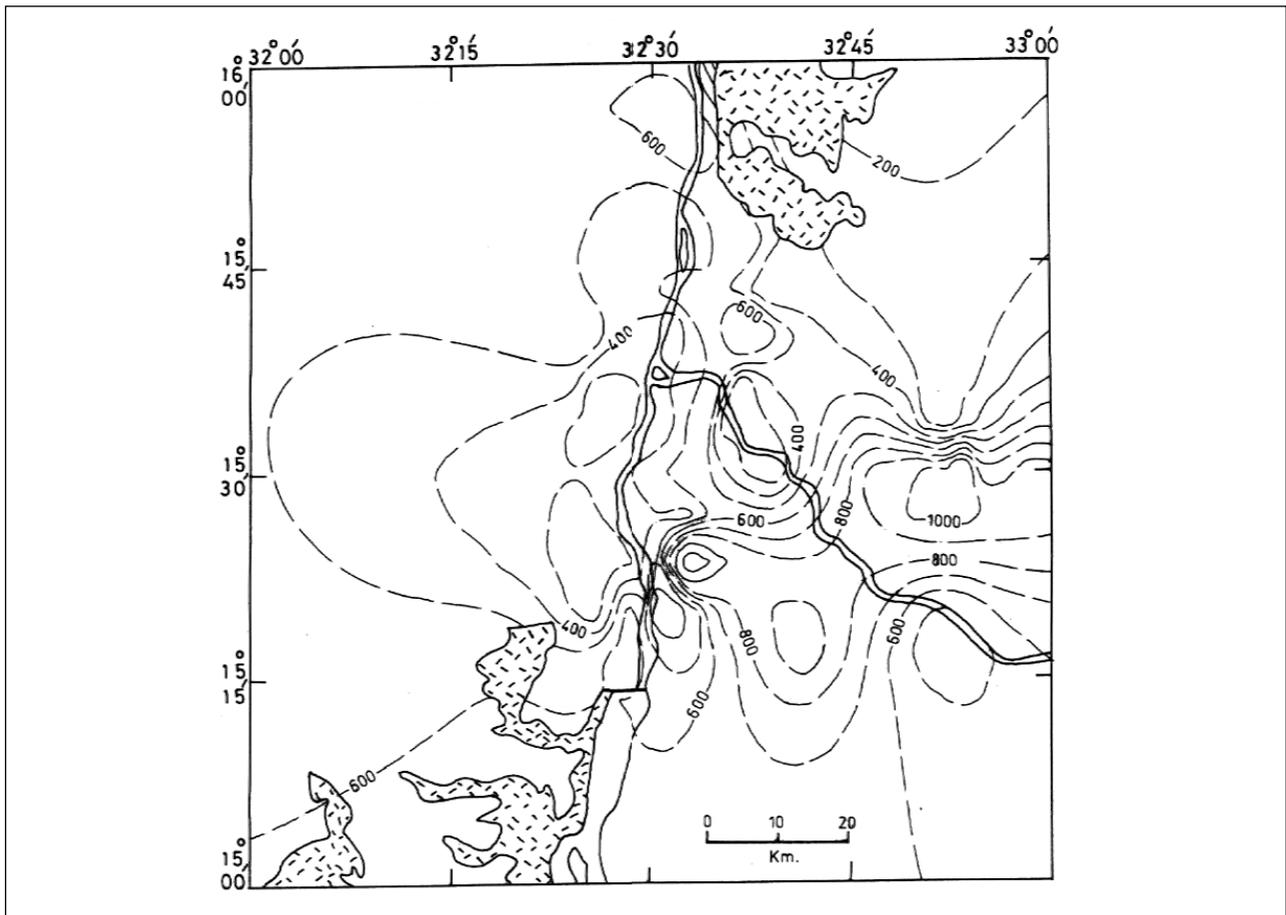


Figure 3. Spatial distribution of total dissolved solids (in mg/l).

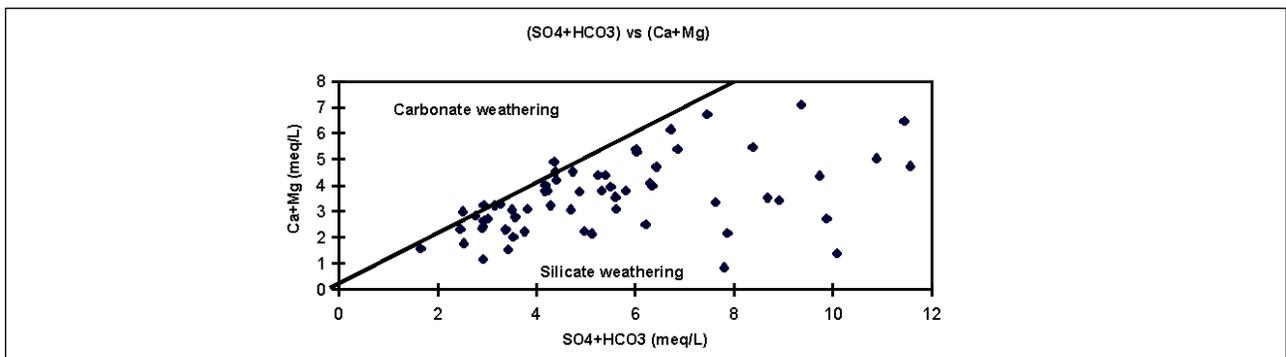


Figure 4. Scatter diagram of (Ca + Mg) vs ($\text{HCO}_3 + \text{SO}_4$)

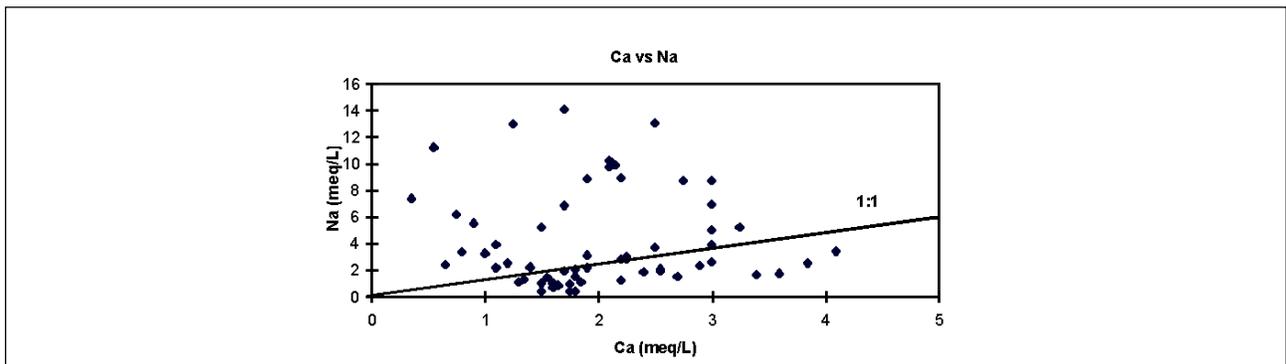


Figure 5. Scatter plot of Ca vs Na.

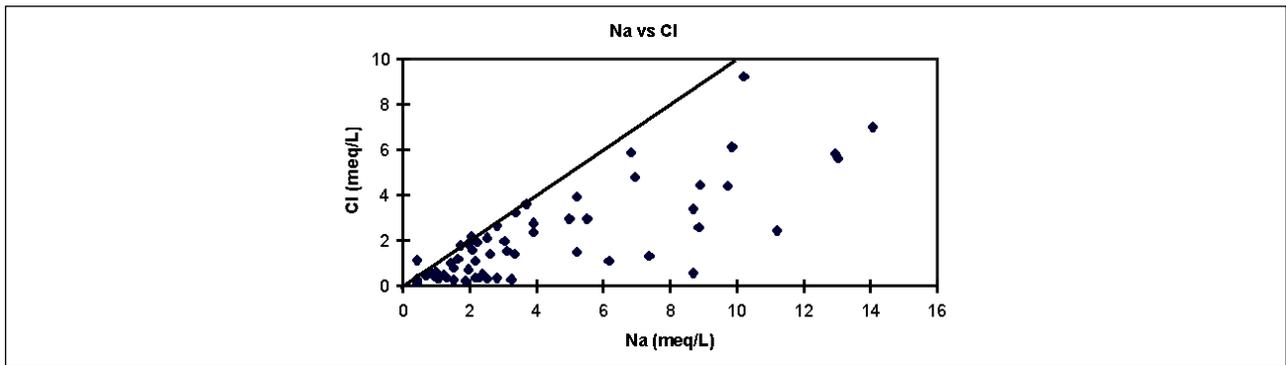


Figure 6 Scatter plot of Na vs Cl.

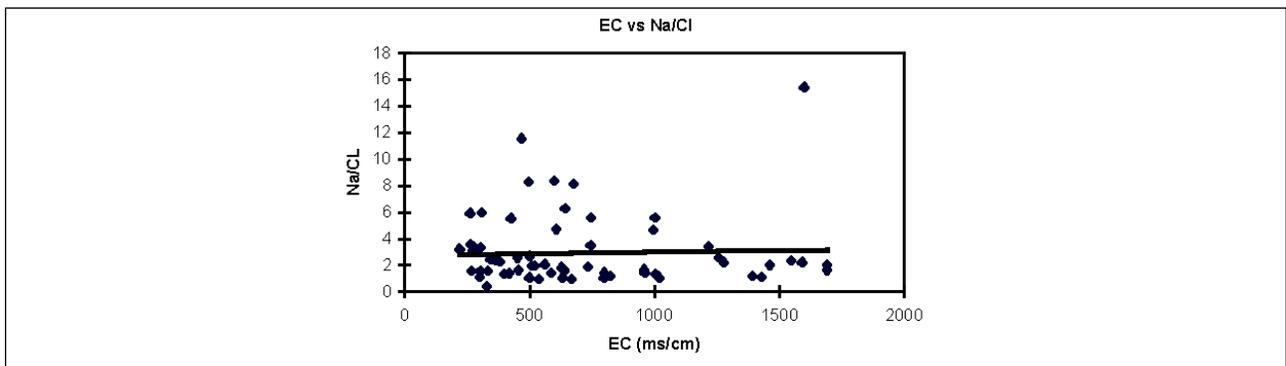


Figure 7. Scatter plot of EC vs Na/Cl ratio.

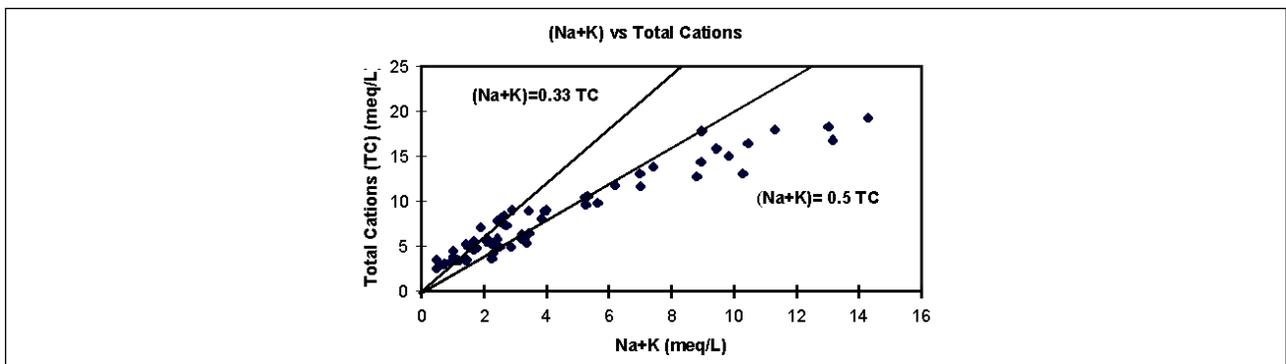


Figure 8. Scatter plot of (Na + K) vs total cations.

The results of groundwater classification using a trilinear diagram is shown graphically in Figure 9. About 50% represents Ca-Mg-HCO₃ facies, and about 35% characterizes waters having no dominant cation-anion pair. The rest of the samples have a composition dominated by alkalis and strong acids (Na-K-SO₄-Cl). The spatial distribution of facies (Figure 10) shows that the Ca-Mg-HCO₃ facies lies at the middle and extends north south along the Niles. This confirms the recharge of groundwater from the Nile waters in the study area (Table 1). The Na-K-SO₄-Cl facies dominates the eastern, southeastern parts, and isolated zones at the north. This facies may have resulted from the process of precipitation of dissolved evaporitic minerals.

CONCLUSIONS

The groundwater chemistry of Khartoum state was evaluated and assessed by different methods and techniques. The following conclusions were drawn:

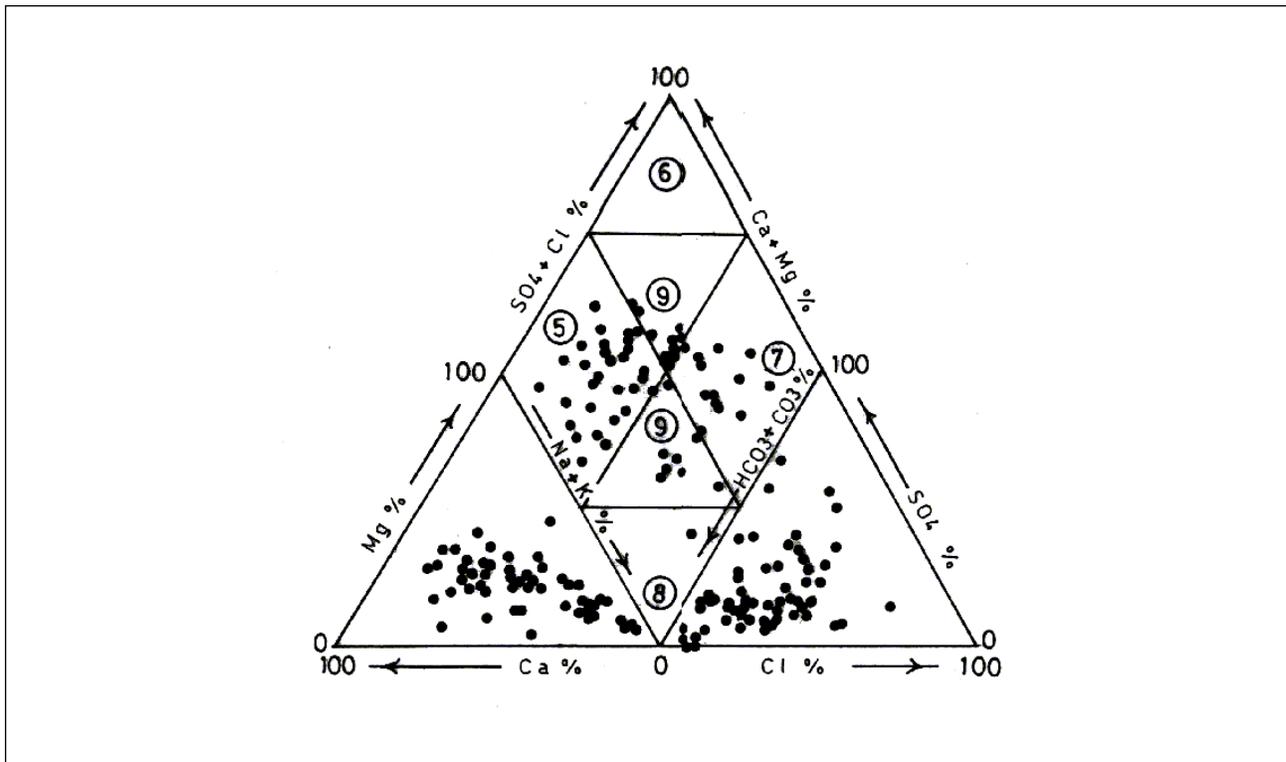


Figure 9. Hill-Piper diagram (concentrations in meq%).

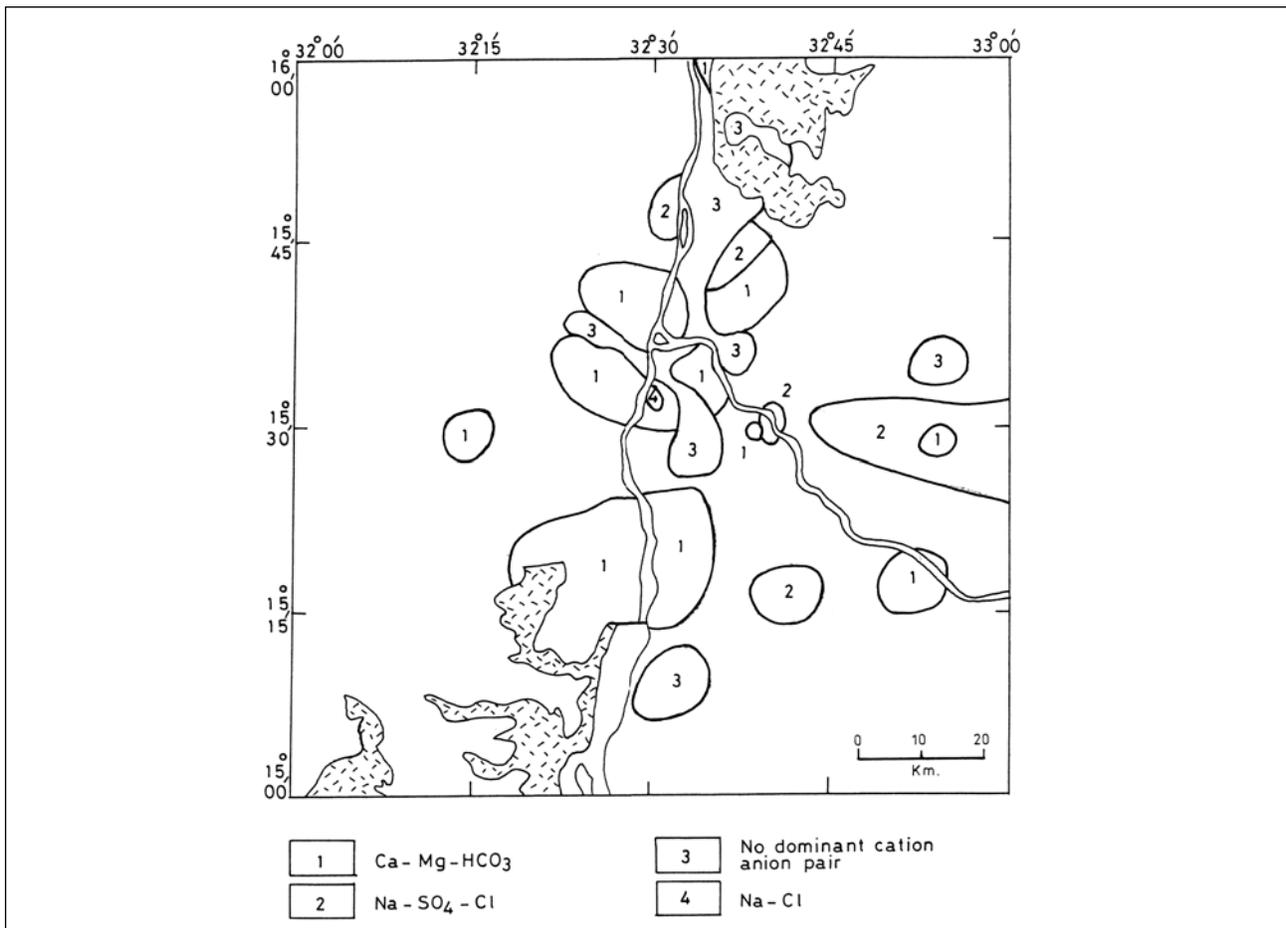


Figure 10. Spatial distribution of hydrochemical facies.

- The total dissolved solids varies from 184 to 3600 mg/L TDS. It generally increases from the southeast to the northwest following the regional flow direction. Two high TDS zones are noticed, one is located at the far east, and the other one is located at the mid south of the study area.
- The cationic relationship is $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^-$.
- The anionic relationship is $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-}$
- The ionic relationships indicated that the main chemical processes controlling the variation and change in groundwater quality in the study area are silicate weathering, evaporation, dissolution and ion exchange processes.
- Groundwater was classified into three hydrochemical facies, Ca-Mg-HCO₃, Ca-SO₄-HCO₃ and Na-Ca-SO₄-Cl. The spatial distribution of these facies and hydrochemical sections indicates that the anionic facies changes in the flow direction from HCO₃⁻ to SO₄²⁺ and finally to Cl⁻. Recharge water comes mainly from the Blue Nile, White Nile and main River Nile. The cationic facies is mostly affected by ion-exchange process of calcium and magnesium by sodium.
- Mixing is an active process that has affected the water facies in the region.

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