MAJOR IONS GEOCHEMISTRY AND ENVIRONMENTAL ISOTOPE STUDY OF THE NUBIAN AQUIFER SYSTEM, DAKHLA OASIS, WESTERN DESERT, EGYPT

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الخلاصة :

يُظهر التركيب الهيدروكيميائي للخزان الجوفي النوبي في الواحات الداخلة وجود مياه ذات أصل بحري (NaCl) مختلطة مع المياه المتسربة ذات الأصل الجوي ($Na_2 SO_4$). والسِّحنات الهيدروكيميائية هي صوديوم – كالسيوم – كلوريد – كبريتات، لأنَّ الماء الجوي المتسرب يُخفف ويُختلط ويُزيح المياه ذات الأصل البحري من بين مسامات الخزان الجوفي. ويتكوَّن التركيب الكيميائي للمحلول، نتيجة إذابة مكونات الصخور بواسطة المياه المتسربة واختلاطها مع المياه الأصلية تحت ظروف الأكسدة والاختزال. وتدل السِّحنات الهيدروكيميائية، والحدّ الفاصل بين الماء البحري والماء الجوي على أن اتجاه سريان المياه الجوفية من الجنوب الغربي إلى الشمال الشرقي عبر منخفض الواحات الداخلة. ويدل حساب معامل التشبع لمعادن الأنهيدريت، والأراجونيت، والكاليست، والدولوميت، والماغنسيت على أنها تقع تحت منطقة التشبع، مع احتمال ذوبان هذه المعادن في الماء.

أثبتت دراسة النظائر المشعة المستقرة أنَّ الماء الجوفي يقع على خط الرمل – التبخر ($\delta D = 2.9 * \delta^{18}O - 54$). بينما أثبتت دراسة النظائر المشعة النشطة أن عنصر التريتيوم أقل من (2.6 Tu)، وهذا يدل على أنه لا يوجد تسرب حديث للمياه يصل إلى الخزان الجوفي نتيجة معدل التبخير العالي. وباستخدام (كربون– 14)، وجد أن عمر المياه الجوفية أقل من 14000 سنة قبل الميلاد، أي ما بعد الزمن المطير.

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ABSTRACT

Among the hydrochemical studies, the original marine solution of the NaCl type and the continental Na_2SO_4 type of meteoric genesis, are the dominant water types in the Nubian sandstone aquifer. The hydrochemical facies of sodium–calcium–chloride–sulfate are due to leaching, mixing, dilution processes, and removal of the marine solution by meteoric flows under oxidation–reduction potentialities. The hydrochemical facies and marine–meteoric boundaries show that the groundwater flows from SW to NE across the Dakhla depression. The determination of the saturation index (SI) indicated that anhydrite, aragonite, calcite dolomite, and magnesite are undersaturated with respect to the groundwater, and the minerals might dissolve.

The studies of stable isotopes reveal that the groundwater samples are plotted exactly along the sand-evaporation line ($\delta D = 2.9^* \delta^{18}O - 54$). Radioactive isotopes show that tritium values fall below 2.6 Tu, which indicates that no recent infiltration water reached the aquifer due to high potential evaporation. The application of carbon-14 dating indicates that the age of the groundwater is < 14 000 years B.P., *i.e.* of post-pluvial time.

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INTRODUCTION

The Dakhla Oasis constitutes one of the main five distributed oases in the Western Desert, Egypt. The Dakhla Oasis with respect to its water supplies is large and suitable for land reclamation. It is a relatively narrow NW–SE depression that lies between Farafra and Kharga Oases to the north-west and south-east, respectively. The narrow depression extends to about 25 km in width along the northeast southwest direction and about 55 km in length along the northwest southeast direction, and nearly occupies the area between latitudes 25°30′ – 26°40′ N and longitudes 27°30′ – 29°00′ E, as shown in Figure 1.

Surface and subsurface geological studies of the Dakhla Oasis were carried out by different authors, among them references [1–7]. Hydrogeological and hydrological studies of Nubian aquifers in Western Desert of Egypt, were carried out in

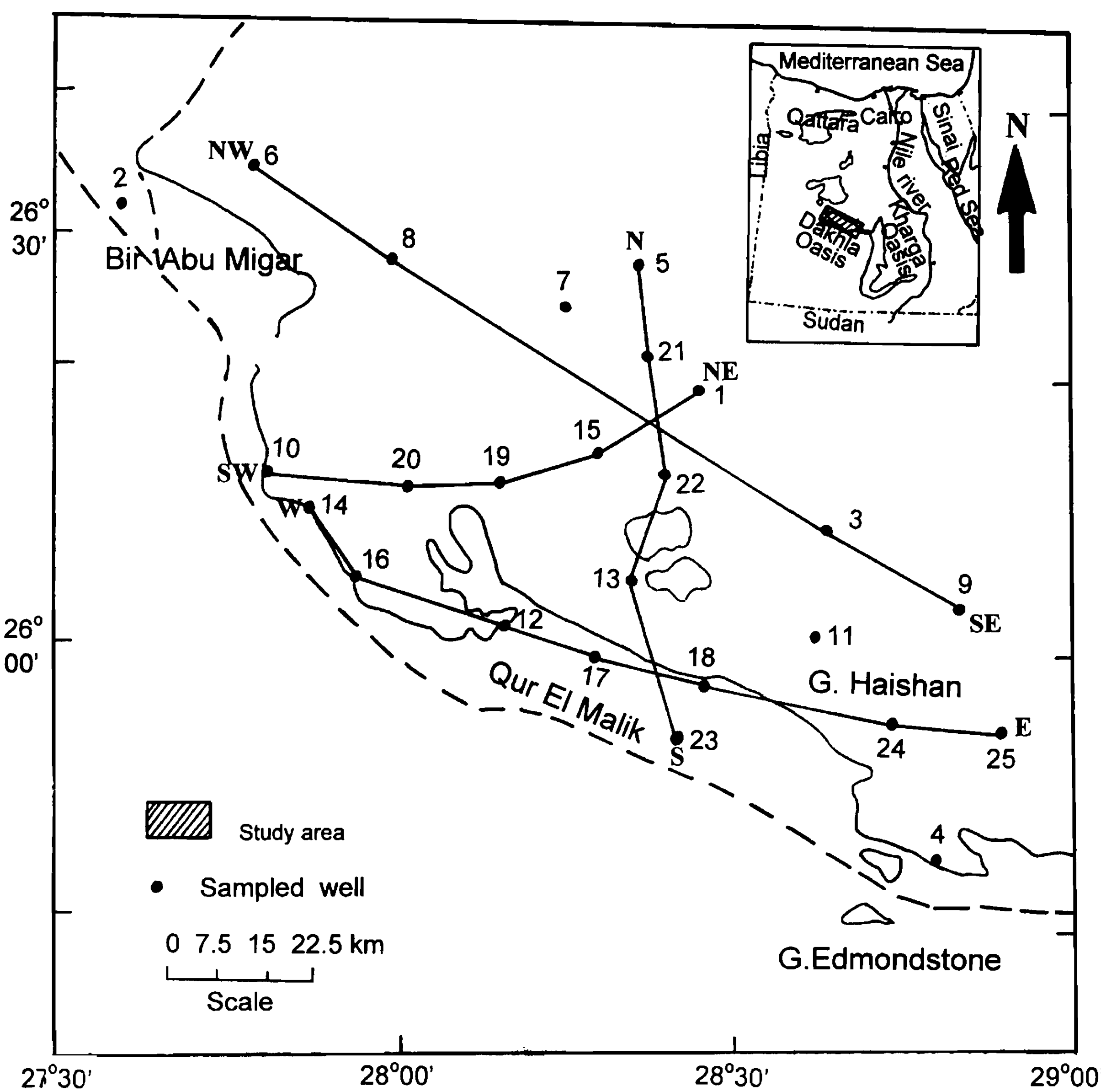

Figure 1. Location map of the groundwater sampled wells in Dakhla Oasis.

references [8] and [9]. General hydrochemical studies of the Dakhla Oasis were carried out in [10], while [11] and [12] gave results of hydrogeochemical variation of different zones in the Nubian aquifer system. General isotope studies in Southern Egypt [13] showed that the groundwater age of the Oases in the New Valley were more than 20 000 years B.P.

Several wells, with a range of depths from 400 to 800 m, were drilled by the Egyptian General Desert Development Organization (E.G.D.D.O.). In addition, a great number of hand-dug wells are distributed throughout the depression. All goundwater wells are used for land reclamation.

The present work deals with the detailed hydrochemical and isotopic characters of the deep aquifer in Dakhla Oasis (Nubian Aquifer System).

GENERAL SURFACE GEOLOGY

Stratigraphy

Detailed geological studies were carried out by[1, 6, 7, and 14]. They showed that the Dakhla Oasis is covered by upper Cretaceous – Lower Eocene rocks to Quaternary sediments as shown in Figures 2 and 3.

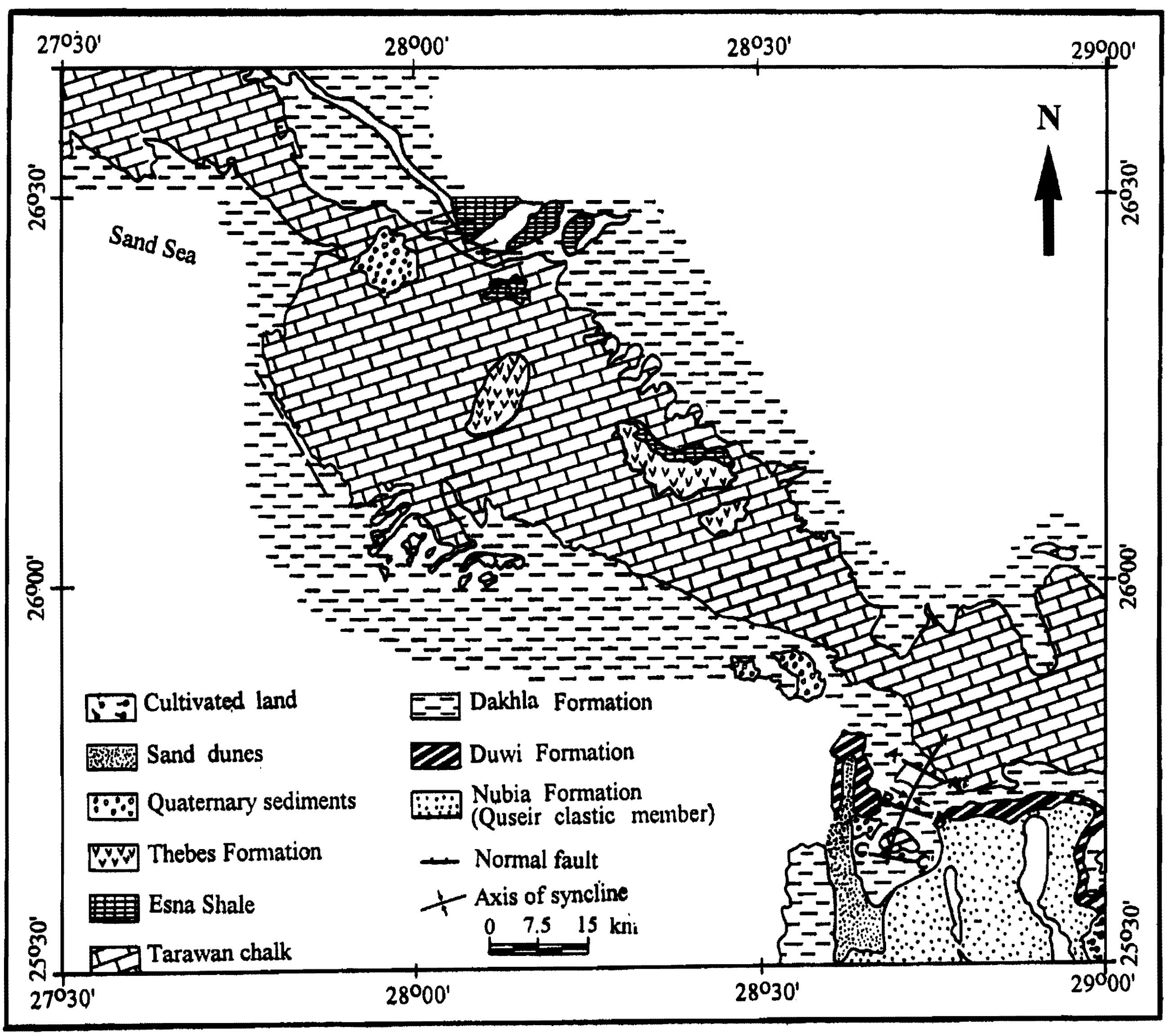

Figure 2. Geological map of the studied area. (Modified after reference [7]).

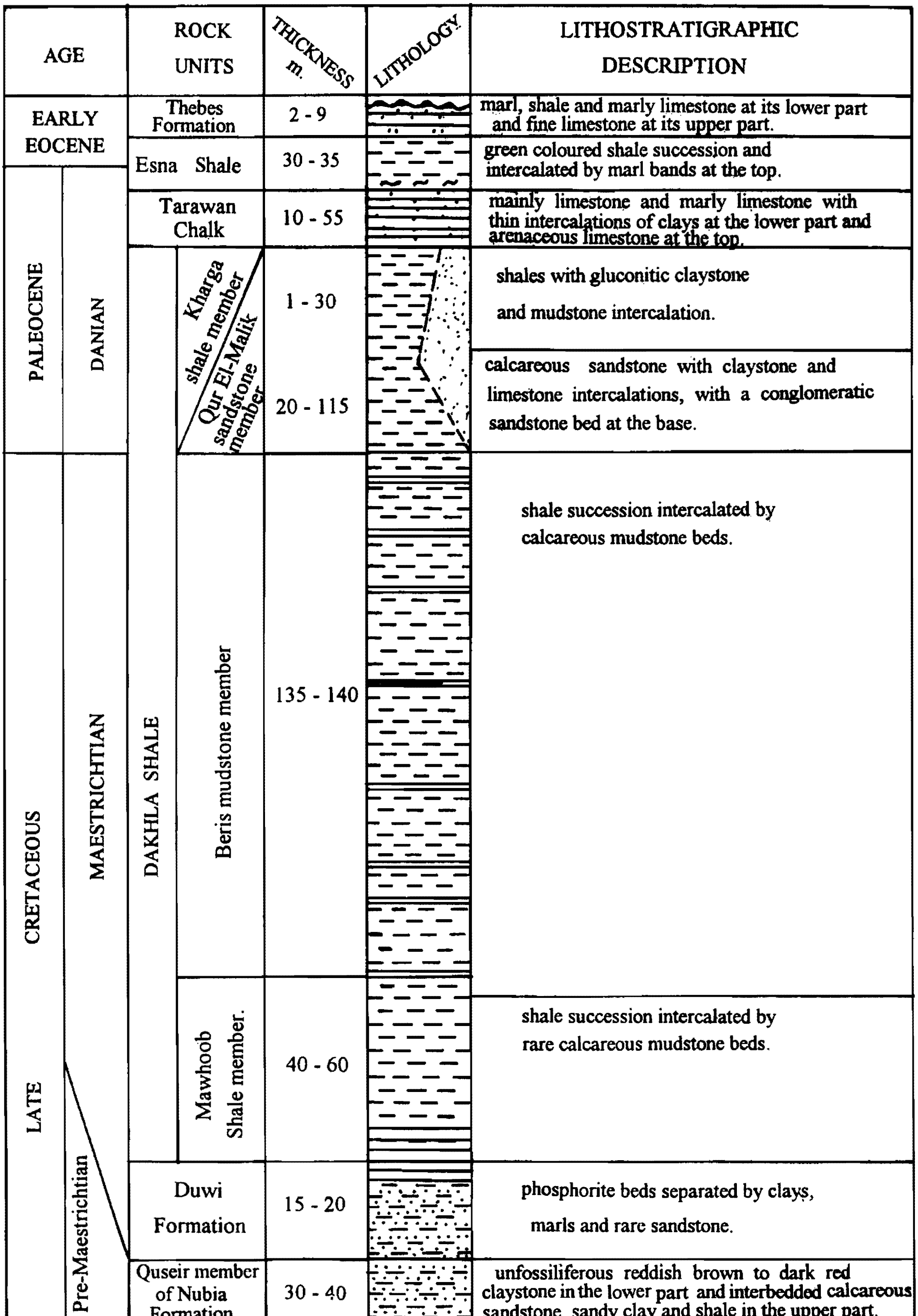

Figure 3. Stratigraphic column of the studied area. (Modified after reference [7]).

Upper Cretaceous – Lower Eocene rocks

The Nubia Formation. The stratigraphic succession underlying the phosphate bearing Duwi Formation is considered as one formation called the "Nubia Formation", and is subdivided into two members. The lower member is correlatable with Taref Sandstone Member [4], while the upper member is equivalent to the Quseir Shale [6] of the Dakhla Oasis area.

The Quseir Member is nonfossiliferous and reaches about 30 meters thickness. It is composed of reddish brown to dark red claystone in the lower part and interbedded calcareous sandstone, sandy clay and shale in the upper part. It conformably underlies the Duwi Formation and its equivalent sequence in the Dakhla Oasis was dated to uppermost Campanian or Lower Maestrichtian age [1] and [14].

The Duwi Formation. The succession (15m. thick in average) is composed of phosphorite beds separated by clays, marls, and rare sandstones. The top of the formation is marked by a dolostone bed (110 cm). In Dakhla Oasis, the formation is dated as Lower Maestrichtian age.

The Dakhla Formation. The term "Dakhla Shale" was first introduced by [14], for the shale section overlying the Duwi Formation and underlying the Tarawan Chalk in the Dakhla Oasis area. [4] and [7] classified the formation into the following members from Lower to Upper (Figure 3).

(*a*) The Mawhoob Shale Member (40 – 60m thick): It conformably overlies the Duwi Formation and is composed of a shale succession intercalated by rare calcareous mudstone beds. This member is considered to be of Middle Maestrichtian age.

(*b*) The Beris Mudstone Member (about 135m thick): It is composed of a shale succession intercalated by calcareous mudstone beds. This zone is considered to be of latest Maestrichtian age.

(*c*) The Kharga Shale Member: It forms the upper part of the Dakhla Formation exposed along the stretch between the Edmonstone and the Qur El-Malik. In the latter area the member wedges out, and the Qur El-Malik sandstone member directly underlies the Tarawan Chalk (Figure 3). This member attains its maximum thickness (115m) in the eastern part of the studied area. The member is composed of shales with glauconitic claystone and mudstone intercalation and it is considered to be of Danian age.

(*d*) The Qur El-Malik Sandstone Member: It is the unique stratigraphic succession that crops out between the Tarawan Chalk and the Kharga Shale Member with thickness ranging between 1m and 30m. Further to the west, the Kharga Shale Member disappear and the member conformably overlies the Beris Mudstone Member. The member is composed of calcareous sandstone with claystone and limestone intercalations. At the base, a conglomeratic sandstone bed is noticed.

The Tarawan Chalk. This succession (10 – 55m thick) is composed mainly of limestone and marly limestone with thin intercalations of clays at the lower part and arenaceous limestone at the top. This zone is assigned to Upper Middle Landenian age.

The Esna Shale. The Esna Shale is distinguished in the northern part of the study area (Figure 2) by its green colored Shale Succession (30 – 35m thick), and is intercalated by marl bands at the top.

The Thebes Formation. This formation is composed of marl, shale and marly limestone at its lower part and fine limestone at its upper part. The formation conformably overlies the Esna Shale. In some local areas, the Thebes Formation overlies unconformably the Tarawan Chalk.

Quaternary Sediments

The Quaternary sediments cover local areas in the northern part of El-Kharafish – El-Mingar Plateau, and the foot of the Dakhla – Abu Mingar scarp. The following facies are represented by the Quaternary sediments.

Interbedded Sands and Limestones. The succession unconformably overlies the Tarawan Chalk or the Esna Shale. Laterally the limestone wedge out and the succession becomes only sands. The sands are characterized by small scale cross-bedding, wavy bedding, and parallel bedding.

Travertine Silts and Sands. These occur as small patches or as intercalations within the sands. They are analogous and comparable to similar deposits at the Kharga scarp and in other places in south Egypt [15].

Interbedded Silts and Sands. The thickness of these facies ranges between 2 – 15m, unconformably overlying the Quseir Shale (at the foot of the scrap) or the Tarawan Chalk (on the top of the plateau). It is composed of interbedded very fine sands and silts. Cross-bedding, ripple marks, and mud cracks are occasionally mentioned.

Structures

The structure of the study area is very simple. The beds are nearly horizontal with minor faults AA, BB, and CC (Figure 2) having limited vertical displacements, located in the southeastern part of the study area. A series of small faults were observed west of Qur El-Malik, where they dip towards the northeast. All these are nearly vertical and of the normal type. The downthrows of these faults range from 15m to 25m. At the eastern part of the study area (Edmonstone area), a broad syncline with NE – SW axial trend and plunging towards the northeast is recorded. These faults and folds were also recorded by [1], [6], and [7].

SUBSURFACE GEOLOGY OF THE NUBIAN AQUIFER SYSTEM

The Dakhla Oasis is a typical arid zone of the desert type, where mean annual precipitation is less than 30 mm/y, but the evaporation rate is expected to exceed that of rainfall ranging about 80 mm/y. Consequently, a deficiency of water supplies from surface runoff always exists.

Gravimetrical and airborne magnetometric studies for the Dakhla depression were carried out by E.G.D.D.O. The aim of the studies was to investigate the maximum thickness of the Nubian Sandstone and its groundwater potential. Idris [3] estimated that the maximum depth of sediments overlying the basement complex ranges from 1200 – 1400m.

Ten lithological zones have been differentiated [5, 16] in the penetrated non-fossiliferous Nubian sediments of the Dakhla Oasis by means of their electrical properties. In reference [12], the lithological and the structural cross sections were constructed to correlate and to throw light on the facies changes at different localities of the Dakhla depression. Figures 4*a–d*, show four main water-bearing sandstone horizons separated by well marked shaly beds, classified from upper downwards as: *a, b, c,* and *d*. The shale interbeds increase in thickness upwards, westwards in the penetrated Nubian succession of the Dakhla Oasis and divide each of these sandstone horizons into zones, and even locally into subzones. The shale intercalations attain maximum thickness in synclinal troughs and minimum in anticlinal crests (Figure 4*a*). The uppermost horizon is overlain by a shaly bed with an average thickness of 110 m constituting the floor of the depression. As a matter of fact, water is drawn from the deep horizons, where the average depth of most of drilled wells is 800m. In the NE–SW cross section (Figure 4*b*), the shale interbeds are highly developed to subdivide the water-bearing sandstone horizons A and B from upper downwards into A1, A2, A3, B1, and B2. Consequently, lack of geoelectrical data introduces difficulties for further subdivision of the water-bearing sandstone horizons C and D into zones. It is obvious that the intensity of undulations in sediments in the cross-section (Figure 4*c*) parallel to structural axes, decreases in a nearly N–S trend. The Nubian facies consist of non-fossiliferous multi-colored well-sorted fine grained quartz, interbedded with calcareous gypseous shales containing disseminated sulfides, mostly pyrite.

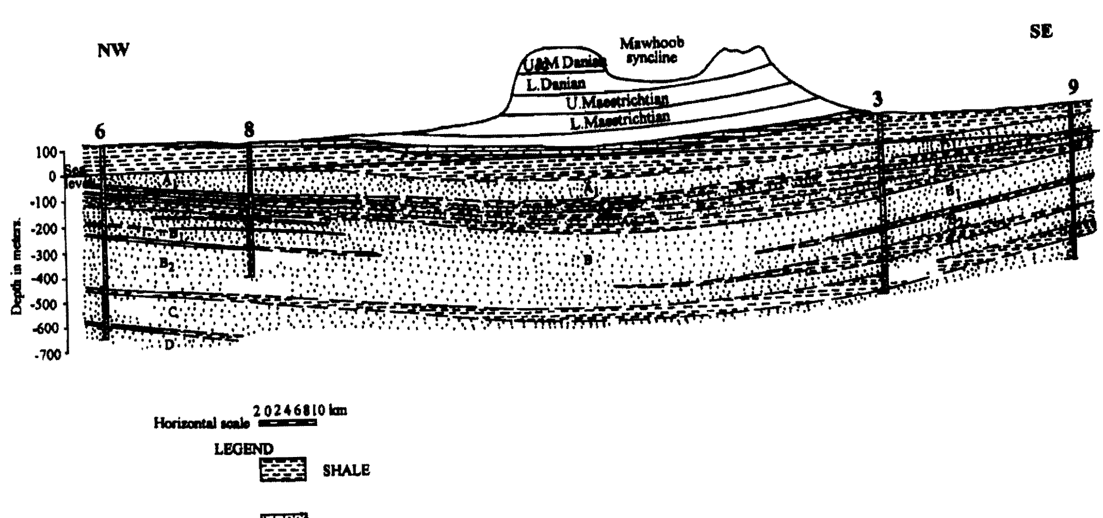

Figure 4(a). Hydrogeological cross-section of the Nubia Formation of Dakhla Oasis along the NW–SE line.

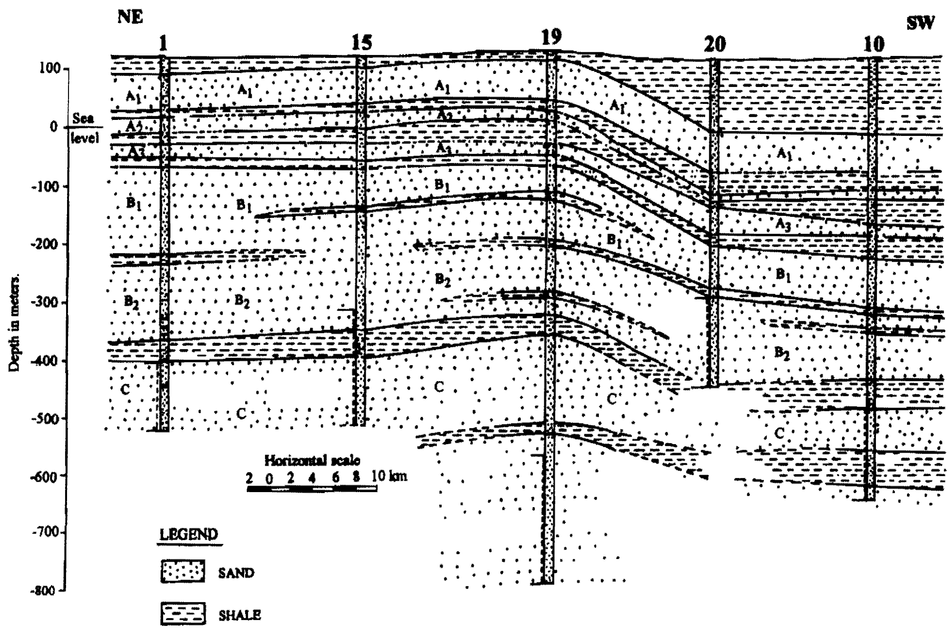

Figure 4(b). Hydrogeological cross-section of the Nubia Formation of Dakhla Oasis along the NE–SW line.

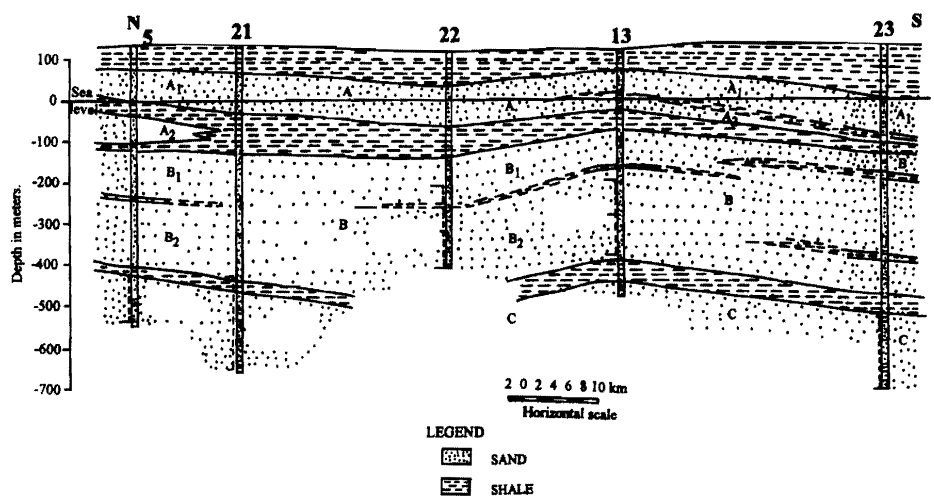

Figure 4(c). Hydrogeological cross-section of the Nubia Formation of Dakhla Oasis along the N–S line.

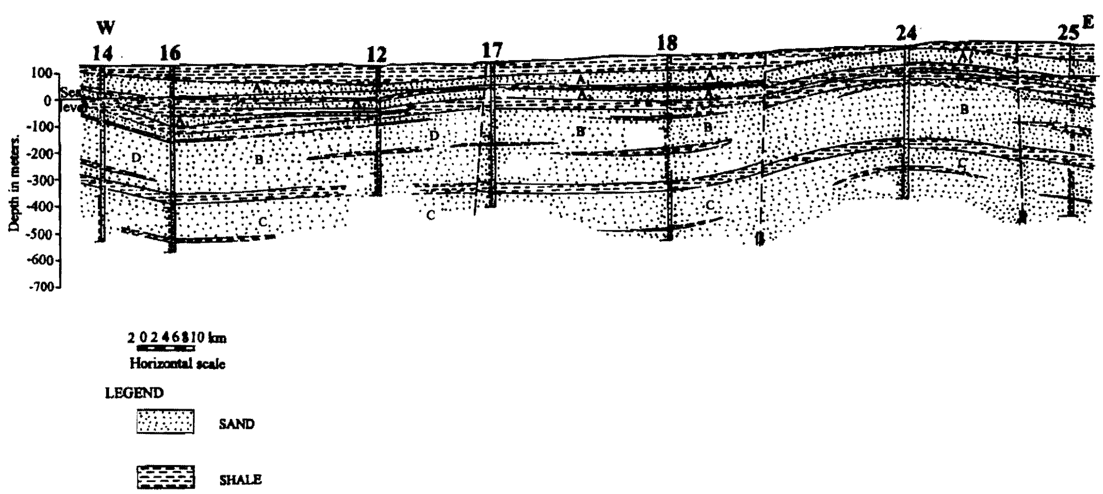

Figure 4(d). Hydrogeological cross-section of the Nubia Formation of Dakhla Oasis along the W–E line.

HYDROCHEMICAL CHARACTERS

Water samples were collected for chemical analysis from 25 wells, and for isotopic studies from 18 wells of the deep water-bearing sandstone, of the Nubian aquifer system in Dakhla Oasis (Figure 1). Chemical analysis of all samples showed the dominant ions to be Na^+, Ca^{2+}, Cl^-, and SO_4^{2-} (Table 1). Therefore, the groundwater can be classified as sodium–calcium–chloride–sulfate facies.

Trilinear diagram (Figure 5) permits the cations and anions composition of the studied groundwater samples to be represented on a single graph, in which major groupings or trends in the water samples can be seen. The plot of the chemical analyses on the trilinear diagram showed that the studied samples are located in the field where no cation–anion pair exceeds 50%, except 9 samples located in the field of non-carbonate alkali (primary salinity) of more than 50%.

Table 1. Chemical Composition of the Groundwater Samples in Dakhla Oasis. (Expressed in mg/l).

Well No.	pH	TDS	E.C.	Cations				Anions		
		mg/l	μ mhos/cm	K^+	Na^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-
1	7.9	910	1300	17	147	40	54	298	182	38
2	7.1	360	520	10	39	17	32	76	79	73
3	7.4	720	1030	15	115	28	48	236	140	32
4	7	320	460	9	37	17	29	74	73	53
5	7.3	920	1320	15	175	27	55	296	190	52
6	7.6	690	990	15	115	25	51	235	137	34
7	7.8	908	1300	17	180	30	72	332	190	62
8	8.8	750	1070	13	131	23	52	221	154	68
9	6.7	826	1180	14	156	22	53	261	173	44
10	7.6	450	640	16	50	24	33	76	105	121
11	7.8	510	730	9	60	21	52	116	114	108
12	6.7	340	490	13	41	17	41	90	85	70
13	7.6	560	800	16	66	26	55	122	105	150
14	6.8	490	700	12	62	22	50	108	144	83
15	7.5	695	990	20	78	28	67	141	156	148
16	7	410	590	7	48	21	37	89	56	125
17	7.2	470	670	9	58	24	44	103	99	107
18	8.4	430	620	6	53	23	42	94	99	93
19	7.7	700	1010	20	79	29	68	142	157	150
20	7.7	575	825	18	65	27	51	109	131	136
21	7.9	910	1300	17	164	35	63	315	186	35
22	7.8	735	1050	17	115	31	59	219	146	93
23	7.8	450	645	8	56	24	43	98	99	100
24	7.4	415	595	9	49	19	31	95	94	81
25	6.9	573	820	12	97	20	41	168	123	49
Max.	8.8	920	1320	20	180	40	72	332	190	150
Min.	6.7	320	460	6	37	17	29	74	56	32
Mean	7.496	604.68	865.8	13.36	89.44	24.8	48.92	164.56	128.7	84.2
Standard Deviation	0.509	194.74	277.8064	4.0813	46.349	5.5603	11.729	85.632	39.01	38.5584

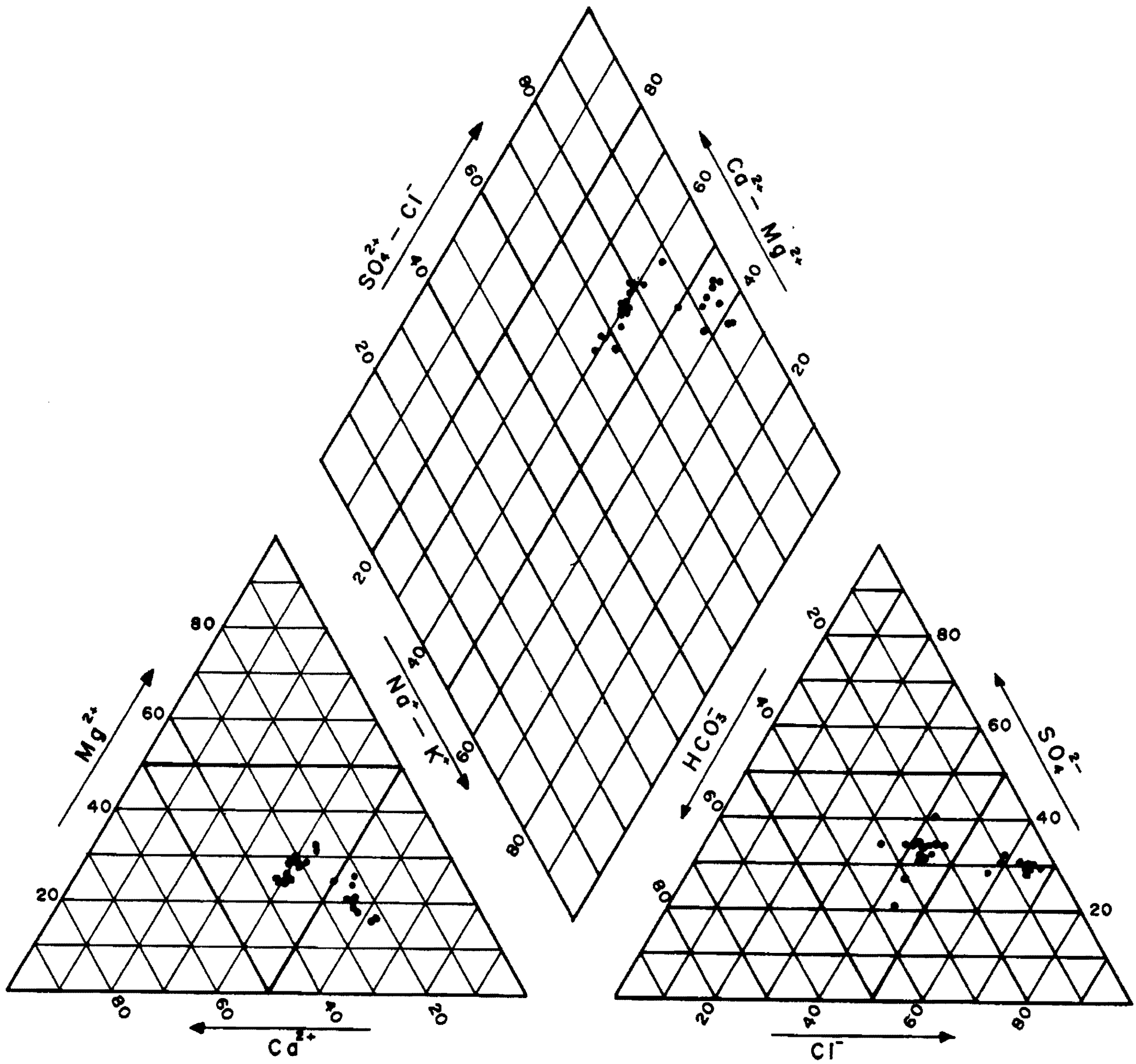

Figure 5. Trilinear diagram showing chemical composition of groundwater in Nubian aquifer of Dakhla Oasis.

Moreover, the ionic contents of the studied samples were plotted on a Durov's diagram (Figure 6) which displayed an apparent genetic relationship between the samples in spite of the disparity in the pattern of their chemical composition. The trend towards no dominant anion or cation, indicates that the groundwater exhibits simple dissolution or mixing processes. Moreover, few samples exhibited chloride and calcium as dominant, suggested a reverse ion exchange of $Na^+ - Cl^-$ waters.

Ion Exchange

Several chemical processes have been identified in controlling the major ion chemistry. These include: ion exchange of Na^+ on the solids for Ca^{2+} and Mg^{2+} in solution; dissolution of carbonate minerals in response to cation exchange; sulfate reduction; and methane fermentation.

The studied samples show a linear increase in both K^+ and Cl^-, and Na^+ and Cl^- as shown in Figures 7 and 8 respectively. This is because of the diffusion of Cl^- from the shale, which caused a charge imbalance in water. Also, the trend in Na^+ in the aquifer is attributed to the diffusion of Na^+ from the shales. Therefore, the trend in Na^+ and Cl^- are controlled by diffusion from the interbedded shaly layer. The dominance of Na^+ and Cl^- in the water samples was explained as the results of NaCl dissolution. It is clear that the concentration of Cl^- increases with the distance from the recharge area, also T.D.S.

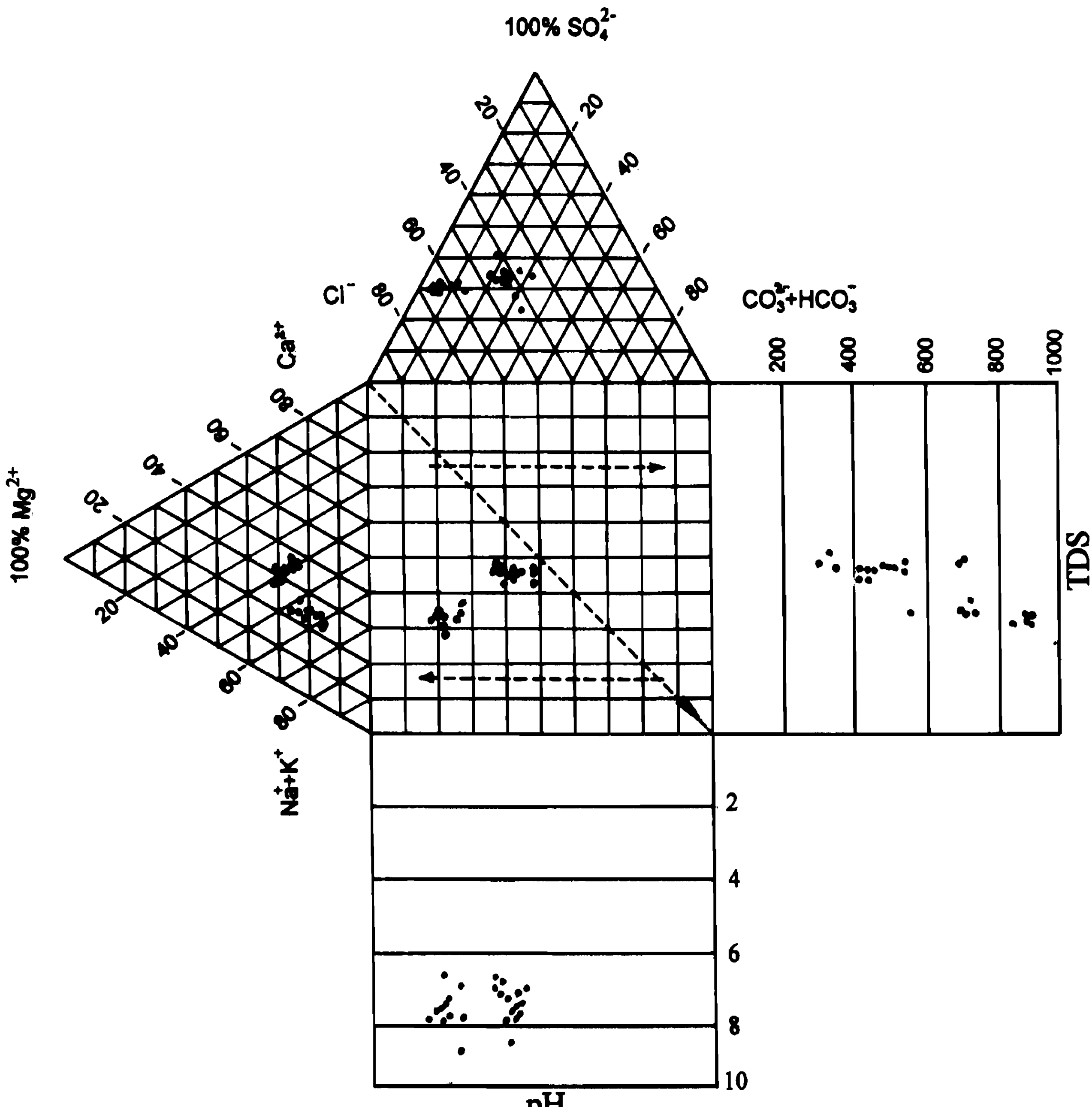

Figure 6. Durov's diagram showing general chemical character of groundwater in Nubian aquifer of Dakhla Oasis.

increases in the direction of groundwater flow from southwest to northeast direction. Also, El-Shazly and Tewfik [11] in their hydrochemical studies of Dakhla Oasis, attributed the increase in the salinity of water upwards, to the evaporation processes under arid climatic conditions.

Saturation Indices

The most common use of saturation index (SI) is in describing the extent to which a particular solution is supersaturated or undersaturated with respect to a particular solid phase.

Therefore, theoritical saturation states of anhydrite, aragonite, calcite, dolomite, gypsum, halite, magnesite, and P_{CO2} were calculated for water samples using the computer program PHREEQE [17]. The results are summarized in Table 2. The determination of saturation index (SI) values indicated that aragonite, calcite, and dolomite are undersaturated with respect

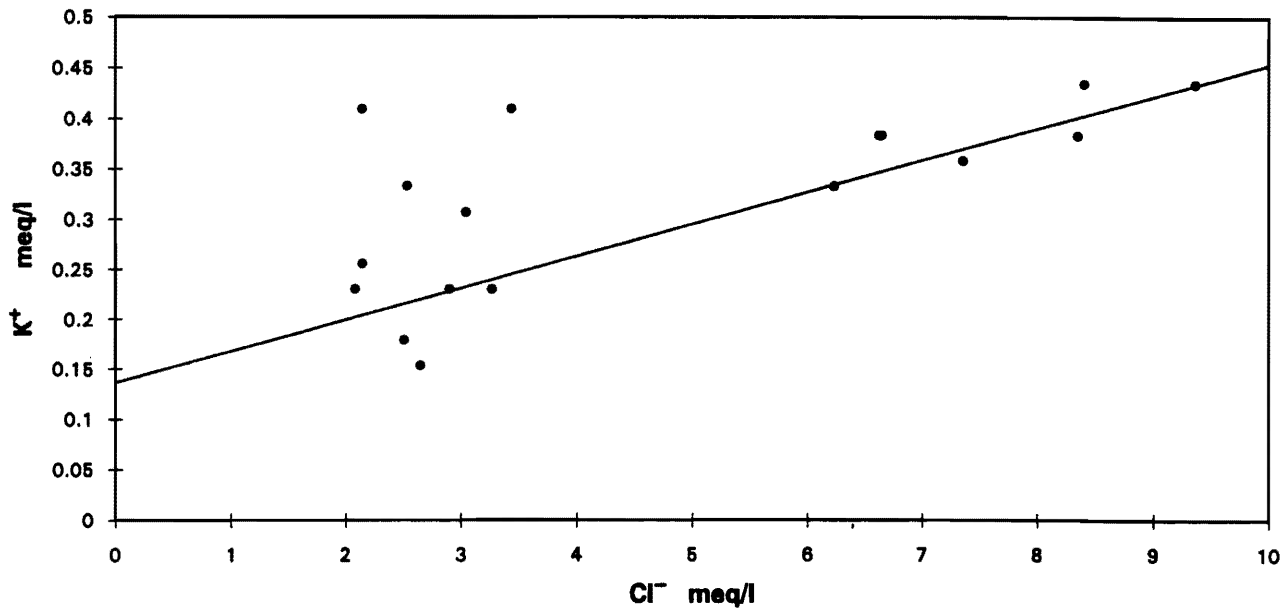

Figure 7. Potassium and chloride concentrations for groundwater analyses in Dakhla Oasis.

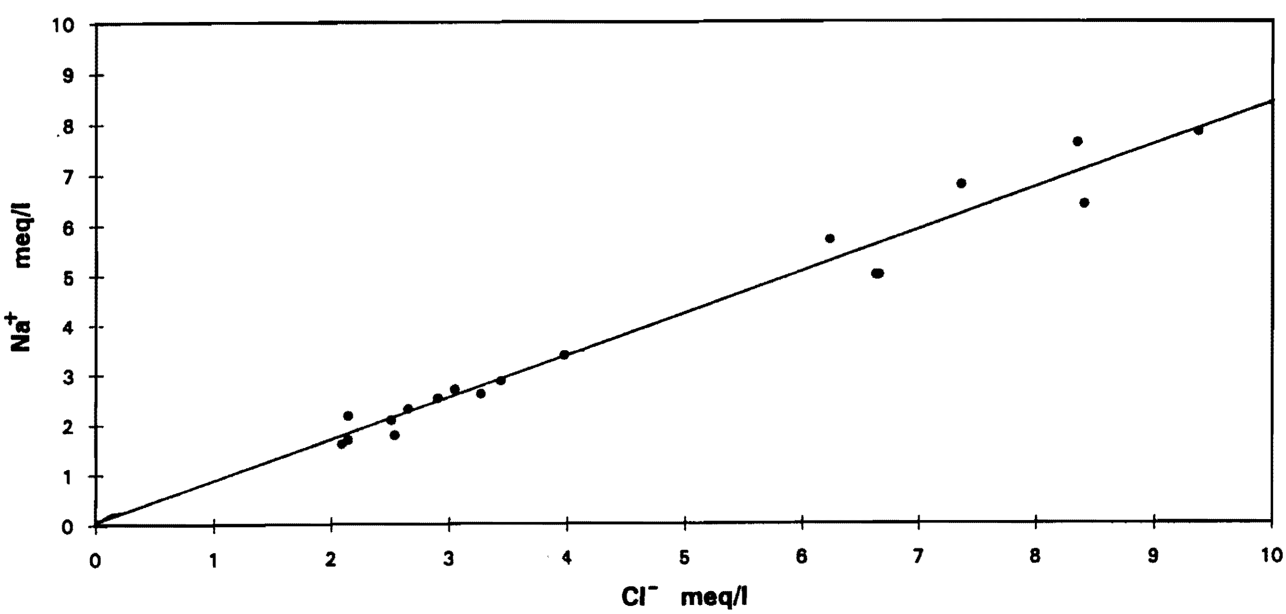

Figure 8. Sodium and chloride concentrations for groundwater analyses in Dakhla Oasis.

to the groundwater and these minerals might dissolve very slowly or not at all. It was found that 7 samples out of 25 (28%) have positive saturation indices, which means that the minerals might precipitate but cannot dissolve. Based on the observed SO_4^{2-} distributions and calculated (SI) values, it can be concluded that the behavior of SO_4^{2-} is not constrained by gypsum solubility.

The calculated log P_{CO2} values range from -1.82 to -4.04 which is near the P_{CO2} of the earth atmosphere ($10^{-3.5}$ atm). The trend in P_{CO2} is similar to that of HCO_3^- as log P_{CO2} is calculated from pH values and carbonate concentrations.

Environmental Isotope

Stable Isotopes (Deuterium and Oxygen-18)

Stable isotopic content of D and ^{18}O of the studied groundwater samples are plotted on the conventional δ-diagram (Figure 9). The δD and $\delta^{18}O$ show a range of variation from -80.68 to -60.01 and from -10.52 to -5.54 respectively as

Table 2. Saturation Indices of the Groundwater Samples from Dakhla Oasis.

Well No.	Anhydrite	Aragonite	Calcite	Dolomite	Gypsum	Halite	Magnesite	P_{CO2}	Log P_{CO2}
1	–1.787	–0.435	–0.294	–0.326	–1.589	–5.976	–0.622	4.67E-04	-3.33
2	–2.174	–0.997	–0.86	–1.558	–2.003	–7.121	–1.293	6.56E-03	-2.18
3	–1.876	–0.964	–0.826	–1.46	–1.699	–6.182	–1.229	1.37E-03	-2.86
4	–2.258	–1.325	–1.185	–2.197	–2.065	–7.144	–1.604	5.66E-03	-2.25
5	–1.753	–0.897	–0.756	–1.437	–1.55	–5.901	–1.27	2.57E-03	-2.59
6	–1.88	–0.795	–0.653	–1.241	–1.673	–6.17	–1.175	8.35E-04	-3.08
7	–1.651	–0.18	–0.042	–0.052	–1.463	–5.85	–0.604	9.87E-04	-3.01
8	–1.828	0.654	0.794	1.64	–1.636	–6.149	0.254	9.13E-05	-4.04
9	–1.766	–1.513	–1.375	–2.715	–1.584	–6.01	–1.934	9.31E-03	-2.03
10	–2.101	–0.338	–0.199	–0.124	–1.913	–7.014	–0.518	3.22E-03	-2.49
11	–1.886	0.018	0.155	0.345	–1.709	–6.762	–0.405	1.84E-03	-2.74
12	–2.066	–1.344	–1.205	–2.372	–1.883	–7.025	–1.76	1.53E-02	-1.82
13	–1.943	–0.101	0.04	0.133	–1.736	–6.689	–0.494	3.71E-03	-2.43
14	–1.831	–1.181	–1.04	–2.054	–1.628	–6.768	–1.602	1.34E-02	-1.87
15	–1.724	–0.135	0.006	0.019	–1.521	–6.563	–0.576	4.64E-03	-2.33
16	–2.293	–0.832	–0.694	–1.208	–2.11	–6.962	–1.108	1.36E-02	-1.87
17	–2.001	–0.626	–0.489	–0.804	–1.83	–6.828	–0.911	7.50E-03	-2.12
18	–2.017	0.455	0.592	1.362	–1.846	–6.904	0.175	3.80E-04	-3.42
19	–1.73	0.017	0.16	0.295	–1.51	–6.545	–0.446	2.79E-03	-2.55
20	–1.892	–0.127	0.017	0.102	–0.1.672	–6.737	–0.496	2.56E-03	-2.59
21	–1.731	–0.478	–0.334	–0.579	–1.512	–5.894	–0.826	4.01E-04	-3.40
22	–1.826	–0.155	–0.011	0.044	–1.606	–6.197	–0.526	1.36E-03	-2.87
23	–2.047	–0.21	–0.066	–0.039	–1.827	–6.841	–0.555	1.50E-03	-2.82
24	–2.175	–0.822	–0.679	–1.226	–1.955	–6.906	–1.128	3.12E-03	-2.51
25	–1.99	–1.449	–1.305	–2.579	–1.77	–6.374	–1.855	5.91E-03	-2.23
Max.	–1.651	0.654	0.794	1.64	–1.463	–5.85	0.254	1.53E-02	-4.04
Min.	–2.293	–1.513	–1.375	–2.715	–2.11	–7.144	–1.934	9.10E-05	-1.82
Mean	–1.929	–0.55	–0.041	–0.721	–1.732	–6.54	–0.9	4.36E-03	-2.62
Standard Deviation	0.177	0.585	0.585	1.167	0.183	0.429	0.585	0.0044	0.552

displayed in Table 3. Generally, across the continent, the content of the heavy stable isotopes deuterium and oxygen-18 in the water vapor decrease, because these isotopes condense preferably by precipitation and remain preferably in the fluid phase by evaporation, as compared with the light isotopes. According to [13], as $\delta D = 8 \times \delta^{18}O + 10$, this means that a meteoric water line exists. The plot of groundwater of Sahara area, exhibited the same values where the ratio between D and ^{18}O has the same slope. The slight increase in deuterium, is due to the different climatic conditions, $\delta D = 8 \times \delta^{18}O + 5$, which represents the Paleometeoric water line.

The content of D and ^{18}O of the groundwater samples fits exactly with the Paleometeoric water line, which is greatly decreased on the account of the remote Atlantic Ocean line. The groundwater normally has no continuous discharge, probably due to the effect of evaporation. This means that the groundwater will be enriched linearly with the heavy isotopes, since these tend to remain in the fluid phase. However, the studied groundwater samples plotted exactly along the sand-evaporation line (Figure 9) with a slope equal to $\delta D = 2.9 \times \delta^{18}O - 54$ [13]. The intersection-point of the sand-evaporation line and the paleometeoric water, line, represents exactly the content of groundwater of the study aquifer, which indicates that the groundwater is not affected by evaporation. The uniformly highly negative relationship between δD and $\delta^{18}O$ suggested that the evaporation is mostly higher than the precipitation.

Radioactive Isotopes (Tritium and Carbon-14)

Tritium and Carbon-14 are radioactive isotopes. Tritium is an isotope of hydrogen having mass-3, half-life 12.26 years, and β-radiation of maximum energy 18.1 MeV (million electron volt). Carbon-14 is a radioactive isotope of carbon. It emits β-radiation with a maximum energy of 156 MeV and has a half-life of 5730 years.

Table 3. Environmental Isotope Data of the Groundwater Samples in Dakhla Oasis.

Well No.	$\delta^{18}O$ ‰ SMOW	δD ‰ SMOW	Tritium Tu	$\delta^{13}C$ ‰ PDB	^{14}C ‰ Recent	^{14}C-Ages Years B.P.
1	–5.54	–60.38	5.76 ± 0.32	–7.5	31.8 ± 0.4	8100 ± 100
2	–10.52	–78.20	0.86 ± 0.33	–9.9	7.5 ± 0.7	19600 ± 800
3	–7.52	–68.30	5.90 ± 0.32	–7.6	57.4 ± 0.6	3200 ± 100
4	–10.00	–76.73	1.10 ± 0.16	–6.6	35.9 ± 0.3	6900 ± 100
5	–4.78	–60.01	4.43 ± 0.34	–	–	–
6	–7.84	–70.94	3.2 ± 0.15	–14.8	96.4 ± 0.9	Recent
7	–5.78	–64.39	4.50 ± 0.30	–11.9	60.3 ± 0.3	2800 ± 100
8	–7.59	–72.44	2.26 ± 0.22	–15.2	108.8 ± 0.7	Recent
9	–6.05	–63.74	1.80 ± 0.32	–	–	–
10	–9.70	–78.19	2.46 ± 0.33	–	–	–
11	–8.87	–77.07	1.80 ± 0.25	–9.7	39.3 ± 1.5	6800 ± 300
12	–10.18	–80.68	1.78 ± 0.24	–12.5	74.0 ± 0.7	1100 ± 100
13	–8.29	–67.33	1.78 ± 0.23	–5.0	68.8 ± 0.5	1800 ± 100
14	–9.88	–78.87	4.43 ± 0.25	–11.3	45.3 ± 1.1	5100 ± 200
15	–7.92	–74.74	4.66 ± 0.34	–6.8	50.4 ± 0.81	4200 ± 100
16	–9.01	–74.95	2.65 ± 0.34	–11.3	46.3 ± 0.5	4900 ± 100
17	–9.83	–77.93	2.16 ± 0.21	–	–	–
18	–9.20	–75.15	0.83 ± 0.33	–9.2	63.3 ± 0.5	2400 ± 100

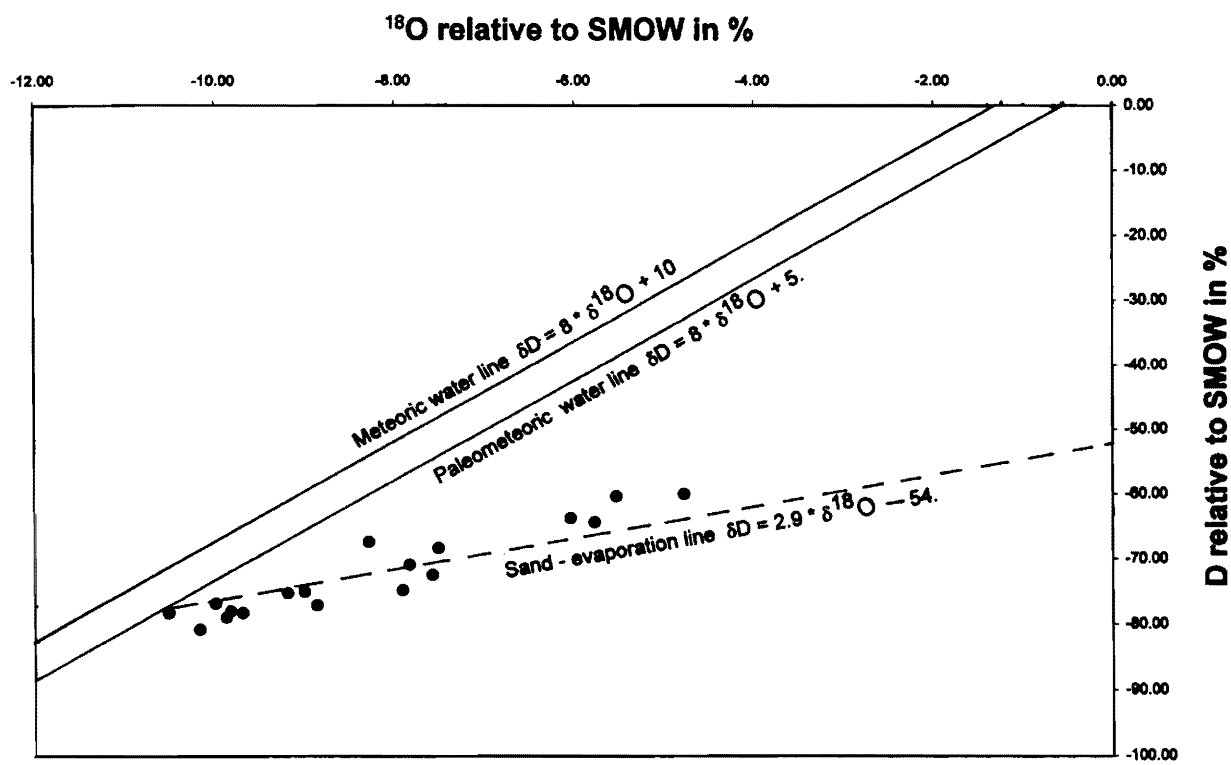

Figure 9. δD/δ¹⁸O ratio of the groundwater analyses in Dakhla Oasis. (Modified after reference [13]).

Most of the studied groundwater samples have tritium values below 2.6 Tu as shown in Table 3, which actually indicates that no recent infiltration water reaches the Nubian aquifer. This conforms with the local climatic conditions, in which the evaporation is higher than the precipitation. But, a few groundwater samples have tritium values ranging from 3–5 Tu (Table 3), indicated that a modern recharge of water occurred during the past 50 years in some locations. The application of carbon-14 dating to groundwater, shows great promise as an inventory technique, and as a means of contribution to the basic knowledge of groundwater accumulation and movement.

The use of carbon-14 dating of groundwater based on a simple geochemical model was first proposed in [18]. Münnich's proposal is based on the fact that soil zone carbon dioxide is of biogenic origin, resulting from the respiration of plant decay, and hence contains carbon-14 derived from the atmosphere. This biogenic carbon dioxide dissolves in infiltrating water and is carried down to the groundwater reservoir. Carbon-14 content will decrease due to radioactive decay and the fraction of the original remaining is a measure of the time since the water was cut off from the atmospheric carbon dioxide reservoir. The equation is:

$$t\,(\text{years}) = 8270\ln\frac{C_o}{C}$$

where 8270 is the mean life of carbon-14 in years, C_0 is the initial carbon-14 concentration and C is its concentration in the sample. The carbon-14 content is measured relative to the total carbon content of the sample, taking into consideration the origin of both the carbon-14 and the stable carbon of the groundwater sample.

All the studied samples indicated that the groundwater was formed during several post-pluvial ages (< 14 000 years B.P.). But the water wells which exhibited a relatively high radiocarbon content, were interpreted as being contaminated from the atmosphere. The plot of oxygen-18 versus carbon-14 contents, as shown in Figure 10, reveals a significant relationship; that the groundwater which exhibited the lowest values of carbon-14 is depleted in stable isotope composition.

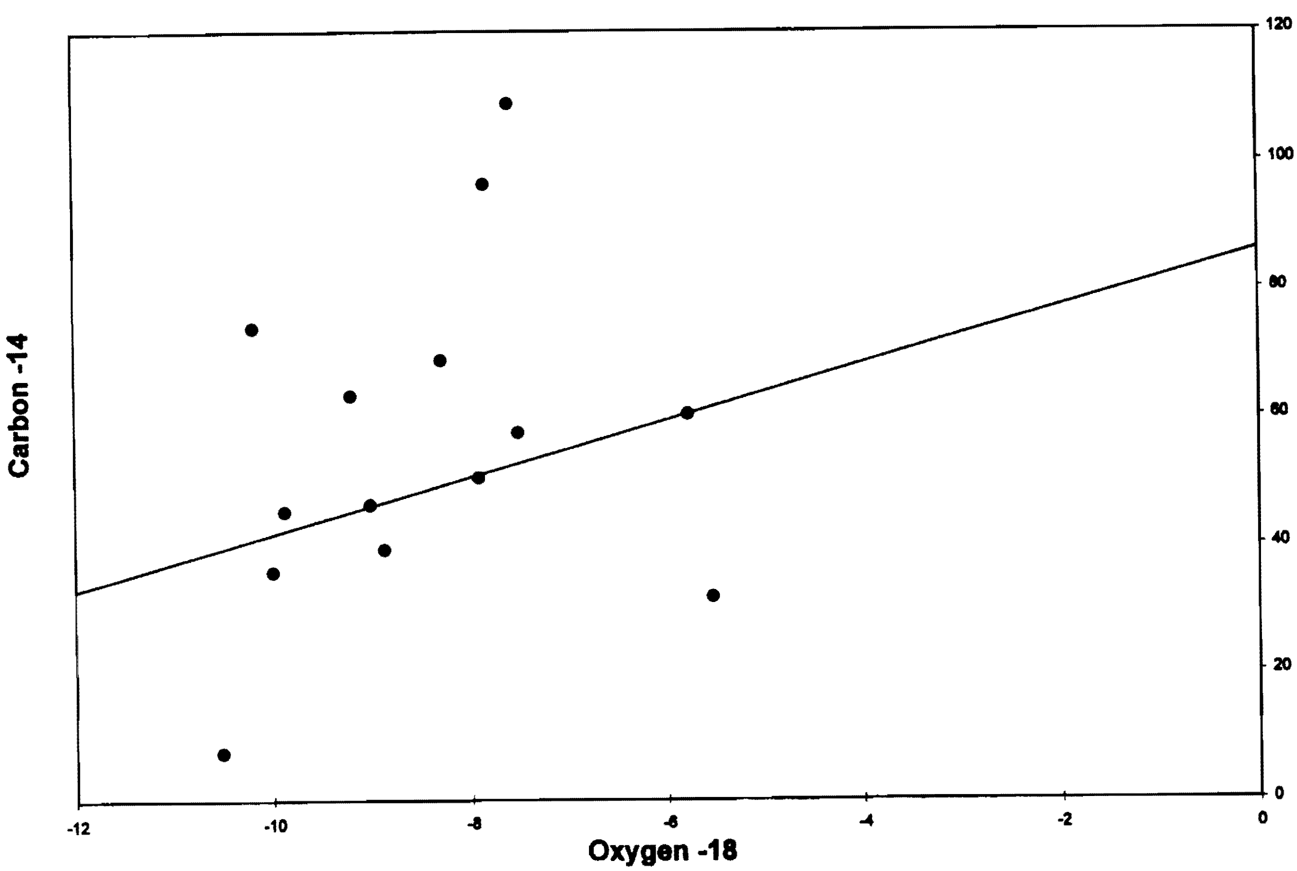

Figure 10. Carbon-14 and Oxygen-18 correlation of the groundwater analyses in Dakhla Oasis.

CONCLUSION

The Nubian aquifer system of Dakhla Oasis is divided into four water-bearing sandstone horizons. The present study reveals that the original marine solution of NaCl and the meteoric Na_2SO_4 water types are the dominant water types in this aquifer. The hydrochemical compositions indicate that the preserved marine solution has been subjected to dilution, dissolution, mixing processes, and removal by meteoric infiltration since the prevalence of continental conditions over the Western Desert.

The mean saturation indices (SI) for selected minerals such as anhydrite, aragonite, calcite, dolomite, and magnesite indicate that the groundwater is undersaturated with respect to these minerals, while calcite and dolomite are the most likely minerals to precipitate.

Analyses of δD along with $\delta^{18}O$ values show that the major groundwaters had been subjected to significant evaporation. From the Paleoclimatic point of view, the stable isotope analysis (δD and $\delta^{18}O$) show that the studied groundwater samples were formed by precipitation of Atlantic humid air masses transported by a western drift. The studied groundwater samples exactly plotted along a sand-evaporation line ($\delta D = 2.9 \times \delta^{18}O - 54$). The intersection-point of few samples with the paleometeoric water line ($\delta D = 8 \times \delta^{18}O + 5$) indicated that these water wells are not affected by evaporation. The radioactive isotopes (tritium and carbon-14) reveal that, most of the groundwater samples have tritium values less than 2.6 Tu, which indicate no recent infiltration water reaches the aquifer. The application of the carbon-14 dating indicates that the age of the groundwater is of post-pluvial time (< 14 000 years B.P.).

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