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Geology of groundwater occurrences of the Lower Cretaceus sandstone aquifer in East Central Sinai, Egypt

Assetto idrogeologico dell'Acquifero Sabbioso del Cretaceo Inferiore nel Sinai Centro-Orientale, Egitto

Saad Younes Ghoubachi

Riassunto: Il presente lavoro si è concentrato sull'effetto dell'assetto geologico rispetto alla circolazione sotterranea dell'Acquifero Sabbioso del Cretaceo Inferiore (Malha).

Nel presente lavoro, per la prima volta, questo acquifero è stato suddiviso in 3 unità in base alle caratteristiche litologiche. L'area di studio è disclocata da faglie normali con i settori ribassati posti in direzione nord. Le acque sotterranee scorrono dalle zone di ricarica a sud-est, verso nord-ovest, con un gradiente idraulico medio di 0,0035.

I parametri di falda dell'Acqufero Sabbioso del Cretaceo Inferiore sono stati determinati e valutati attraverso 7 prove di pompaggio effettuate su pozzi produttivi. L'Acquifero è caratterizzato da una potenzialità da moderata ad elevata.

Il volume calcolato dell'Acquifero (6300 km^2) nell'area di studio raggiunge circa 300 miliardi di metri cubi, mentre la ricarica stimata per la stessa falda raggiunge circa 44.500 m^3 / giorno con una ricarica annuale di 16 milioni di metri cubi / anno.

Il diagramma di Durov mostra come le acque sotterranee si siano evolute da $Mg\text{-}SO_4$ e Mg-Cl e che alla fine hanno raggiunto uno stadio finale dell'evoluzione rappresentato da un tipo di acqua Na-Cl. Questo diagramma aiuta anche a individuare la direzione del flusso delle acque sotterranee.

La salinità varia da 1.082 ppm (Shaira) a 1719 ppm (Nakhl) secondo la direzione di scorrimento della falda, verso nord.

Abstract: *The present study focused on investigating the impact of geological setting on the groundwater occurrences of the Lower Cretaceous sandstone aquifer (Malha). The Lower Cretaceous sandstone aquifer is subdivided into 3 units according to their lithological characters for the first time in this present work. The study area is dissected by normal faults with their downthrown sides due north direction. The groundwater flows from southeast recharge area (outcrop) to the northwest direction with an average hydraulic gradient of 0.0035. The hydraulic parameters of the Lower Cretaceous sandstone aquifer were determined and evaluated through 7 pumping tests carried out on productive wells. The Lower Cretaceous aquifer in the study area is characterized by moderate to high potential. The calculated groundwater volume of the Lower Cretaceous aquifer (6300 km^2) in the study area attains about 300 bcm, while the estimated recharge to the same aquifer reaches about 44,500 m^3/day with an annual recharge of 16 mcm/year.*

Expended Durov diagram plot revealed that the groundwater has been evolved from $Mg\text{-}SO_4$ and Mg-Cl dissolution area types that eventually reached a final stage of evolution represented by a Na-Cl water type. This diagram helps also in identifying groundwater flow direction. The groundwater salinity ranges from 1082 ppm (Shaira) to 1719 ppm (Nakhl), in the direction of groundwater movement towards north.

Keywords: *: Geology, Groundwater occurrences, Lower Cretaceous sandstone aquifer, Central Sinai, Egypt.*

Parole chiave: Geologia, modello idrogeologico concettuale, Acquifero Sabbioso del Cretaceo Inferiore, Sinai Centrale, Egitto.

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Introduction

Sinai is one of the most promising regions for development in Egypt due to its strategic location. The increasing population within Central Sinai especially Nakhl (wells nos. 1, 2, 3, 4 and 5), Wadi Shaira (wells nos. 6 and 7), El-Themed (well no. 8) and El-Kuntilla (well no. 9) (Fig. 1) has necessitated the high demand of groundwater development in the area. Groundwater represents the main source of water supply for local inhabitants, touristic activities and agricultural projects (WRRI 2001). The Lower Cretaceous sandstone aquifer (Malha) is differentiated herein into three water bearing units, A, B and C from top to base for first time, depending on its sand percentage calculated from the records of the Natural Gamma-ray.

Several geomorphologic, geologic and hydrogeologic studies were carried out in Central Sinai area and have been discussed by many authors (e.g. Shata 1956, Said 1962, El-Shazly et al. 1974, Hammad 1980, El-Shamy, 1983; El-Ghazawi, 1989, Hassanin 1997, Ali, 2006, Ghoubachi, 2006, 2010, 2012). The present paper aims to elucidate the hydrogeological conditions of the Lower Cretaceous sandstone aquifer depending on the new hydrogeological and hydrological data

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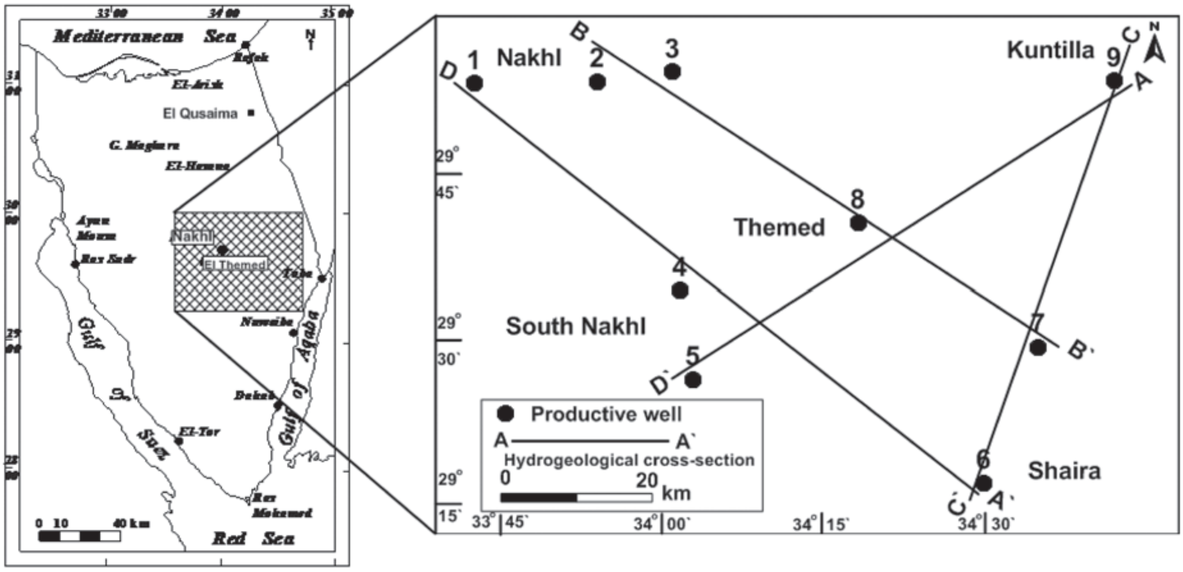

Fig. 1 - Location, well sites and cross sections trends, East Central Sinai, Egypt.

Fig. 1 - Localizzazione, pozzi e andamento delle sezioni trasversali nell'area Centro Orientale del Sinai, Egitto.

for 9 deep drilled wells as well as hydrochemical analyses of representative groundwater samples.

The present study is mainly based on the data of geophysical well logging and pumping tests carried out in the deep drilled productive wells in the study area, as well as the other published information and hydrochemical analyses of 5 representative groundwater samples.

Location and climate

The study area is located in the east central Sinai and occupies an area of about 6,300 km^2 representing about 10% of Sinai Peninsula. It is located between longitudes 33°40´ and 34°45´E and latitudes 29°10´ and 30°00´ N (Fig. 1).

The climatic conditions of study area belong to the arid belt and characterized by extreme dry conditions associated with very hot summers and cold winters in the period (1983-1993). In winter, the air temperature ranges from 16.4 °C to 20.4°C. In summer, the air temperature ranges from 21°C to 5.4°C. The average evaporation rate is 10.5 mm/day. The main annual rainfall varies from 17.7 mm at the west of the study area (Ras Sudr) to 97.1 mm at north outside the study area (El Qusaima) (WRRI 2001).

Geomorphology

According to Hassanin (1997), the area of study is built geomorphologically into two units as the following (Fig. 2):

1. The structural plateau (watershed area) occupies the majority of the study area and represented by El-Tih plateau, El-Egma plateau, southern mountains and hilly area. The surface of these units is built of Cretaceous and Eocene limestone beds, and is strongly dissected by complicated drainage lines, which debouch northward (Wadi El-Arish). They represent the watershed areas. They play principal roles in recharging the Lower Cretaceous sandstone aquifer and creating the main catchment areas of the existing hydrographic basins. The nine selected wells are located on this unit.
2. The low land areas represent the water collector areas in the hydrographic basins and intermountainous plains. They collect the surface water runoff and permit to recharge to the groundwater aquifers.

Geology

The outcrop of the investigated area is described in the geological map of Sinai at a scale 1:500,000 performed by Conoco (1987) and is shown in Fig. 3. The study area is built of Precambrian basement and sedimentary rocks ranging in age from Cretaceous to Quaternary. The Quaternary deposits are composed of sand dunes and wadi deposits. The basement rocks crop out in east of the study area due to the Gulf of Aqaba Uplift. The Lower Eocene Thebes Formation extensively covers the Egma plateau, which is locally called Egma limestone. Paleocene deposits including Esna shale Formation. The Upper Cretaceous is represented by Sudr chalky limestone Formation; Matulla Formation, which is composed of limestone; Wata Formation, composed of dolomitic limestone. Halal Formation belongs to the Cenomanian age and is composed of limestone (Fig. 4). In Fig. 4, the data of post Nubia sandstone formation were used WRRI (2001), while the Lower Cretaceous sandstone Formation was differentiated in the present work depending on the Natural Gamma-ray from geophysical well logging.

Lower Cretaceous is represented by Malha Formation, as it has been introduced by Abdallah et al. (1963). This formation is recorded in the subsurface in the study area and exposed on the surface east of the study area (Fig. 3). This formation is

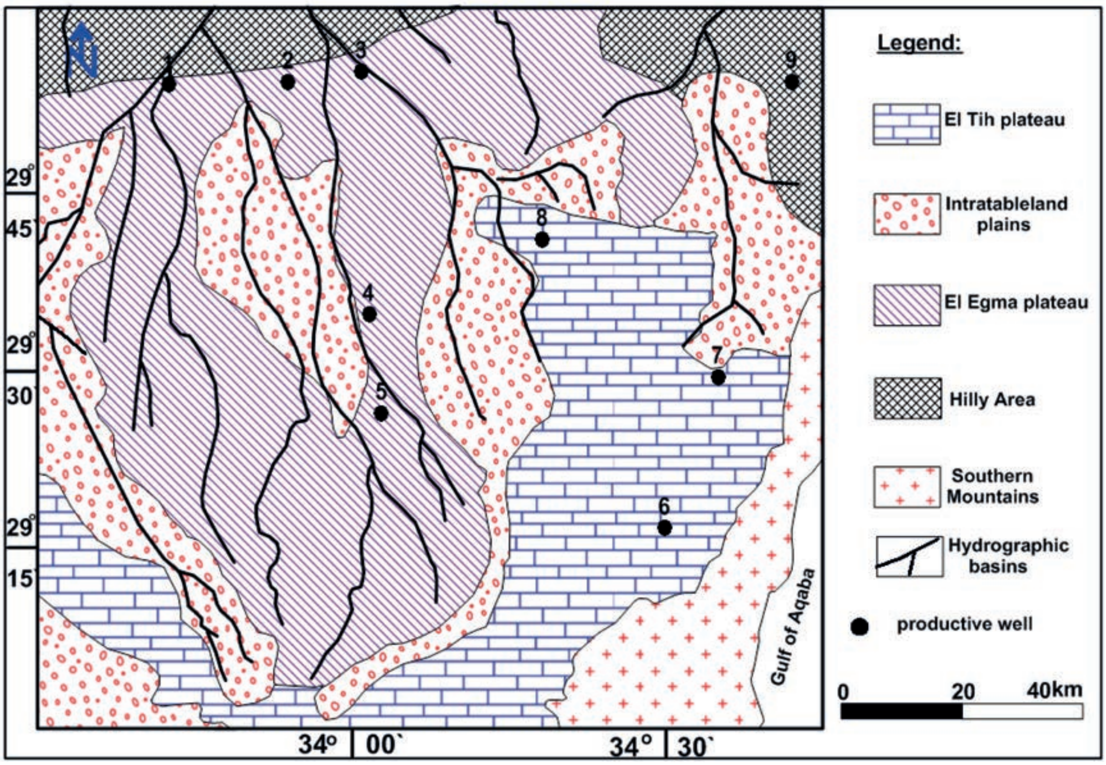

Fig. 2 - Geomorphological map of the east central Sinai (Hassanin, 1997).

Fig. 2 - Carta Geomorfologica della zona Centro Orientale del Sinai (Hassanim, 1997).

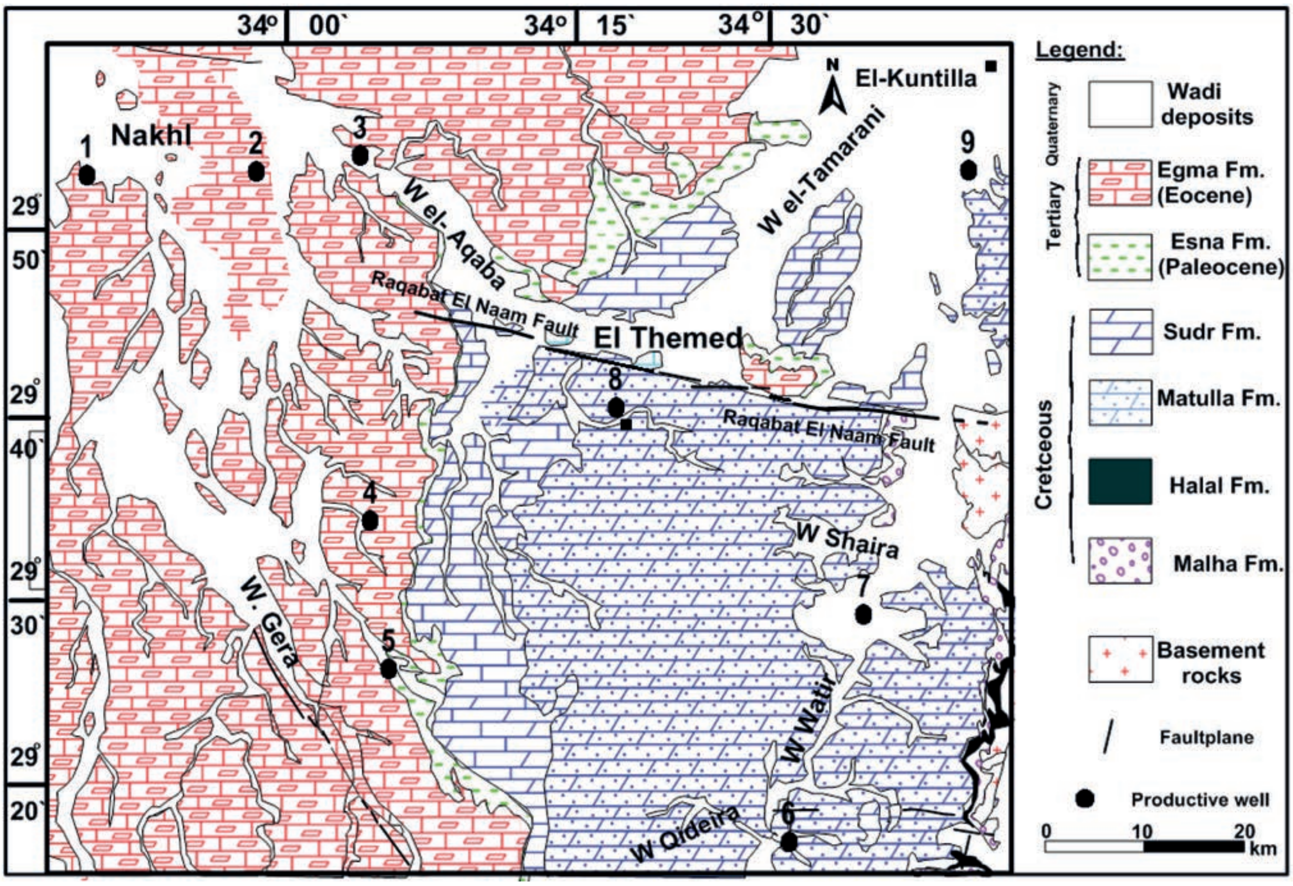

Fig. 3 - Geological map of the east central Sinai (Conoco, 1987).

Fig. 3 - Carta Geologica della zona Centro Orientale del Sinai (Conoco, 1987).

DOI: 10.7343/as-2016-241

conformably overlying the Jurassic sediments and conformably underlying the Halal Formation. Generally, it is assigned to the Lower Cretaceous age (Abdallah et al., 1963).

Malha Formation is encountered in the subsurface in all deep-drilled wells in the study area. The top surface of the Malha sandstone Formation is recorded at depths range from 397 mbsl (meter below sea level) at well no. 4 to 56 masl (meter above sea level) at well no. 8 illustrating gradually dipping towards the northwest direction (Fig. 4). The eastern part of the study area represents a horst structure form (Fig. 5). This formation is mainly composed of ferruginous sandstone, vari-colored, medium to coarse grained with clay interbeds. The sandstone of Malha Formation was deposited under river environment according to grain size analysis (Hassanin, 1997).

The regional structure in the area of study is represented by Raqabat El-Naam fault. This fault runs east-west direction (Fig. 3) and extends for a distance 200 km from Dead Sea in east to Gebel El Raha in west and throwing in north direction. The Raqabat El-Naam fault is formed a group of normal faults which led to the generation of horsts and grabens of various sizes and displacements (Fig. 4). These faults truncate rocks ranging in age from Pre-Cambrian to Lower Eocene. The vertical displacements of these faults range from 250 m to 500 m (Fig. 6). These faults are highly affected on the hydrogeological conditions in the study area.

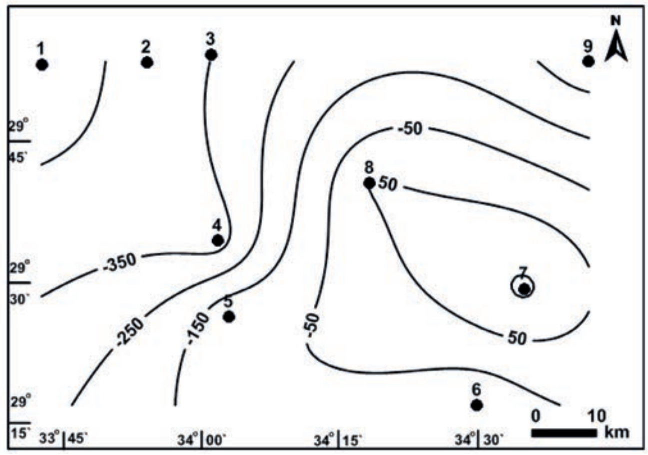

Fig. 5 - Top surface contour map of the Malha Formation (meter sea level).

Fig. 5 - Isolinee del tetto dell'acquifero della Formazione Malha (in metri sul livello del mare).

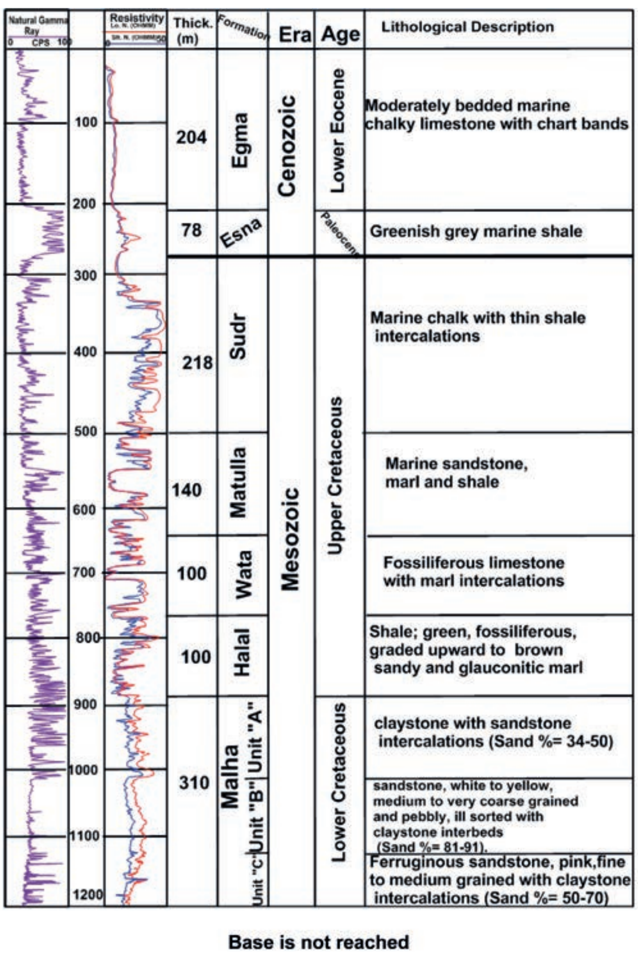

Fig. 4 - Composite lithostratigraphic section in south central Sinai (well no.1).

Fig. 4 - Sezione litostratigrafica di materiali compositi nel Sinai centro orientale (pozzo n° 1).

Materials and methods

To achieve the main objectives of this work, 9 geophysical well logging charts (Gamma ray and resistivity) were used in the present study. These charts were interpreted in order to evaluate the aquifer properties and drawn the hydrogeological cross sections. Collected technical data on wells drilled in the studied area including geographical coordinates, surface elevation, water depth and discharges of wells were used. Analysis of seven pumping tests data (constant discharge tests) was carried out in order to calculate the Lower Cretaceous sandstone aquifer hydraulic parameters (transmissivity, hydraulic conductivity and effective porosity) using GWW software program (Braticevic and Karanjac 1995) with Cooper and Jacob method (1946).

Five water samples were collected after sufficient time of pumping to insure that the sample represents the original groundwater source. Electric Conductivity of these samples (E.C.) was measured insitu. The collected water samples were subjected to various chemical analysis in the Desert Research Center to determine the major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and major anions (HCO_3^-, SO_4^{2-}, and Cl^-).

Result and discussion

Lithological classification

In the present work, the average sand percentage of the penetrated thickness of Malha Formation in the study area is computed from the records of the well logs obtained from WRRI (2001) (Gamma ray log). It is clearly noticed that the highest sand percentage attains 78 % of the penetrated thickness (well no. 1), while the minimum sand percentage is reported to be as 62 % of the penetrated thickness in well no. 8 (Tab. 1).

DOI: 10.7343/as-2016-241

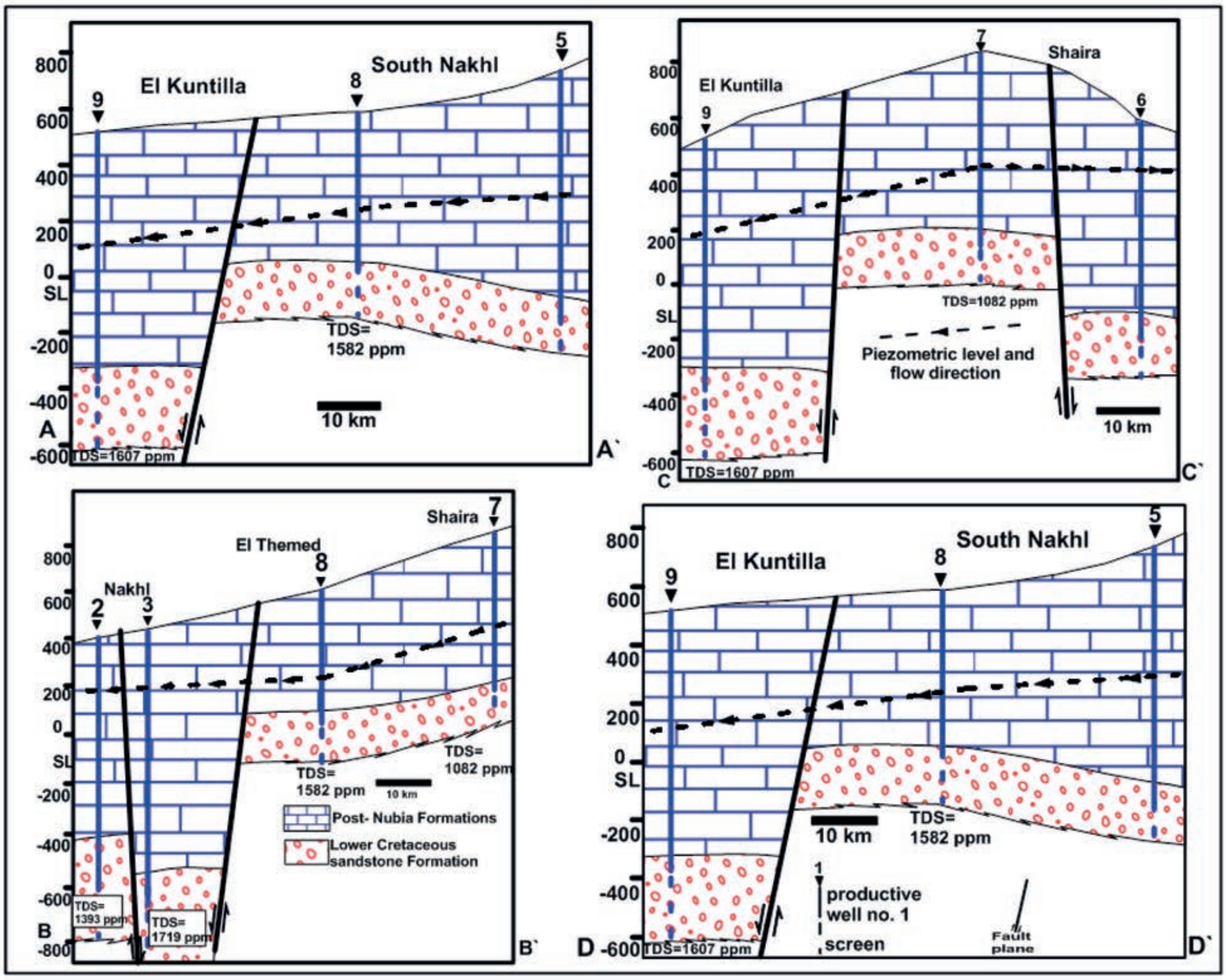

Fig. 6 - Hydrogeological cross-sections (A-A', B-B', C-C' and D-D`) in study area (trends in Fig. 1).

Fig. 6 - Sezioni idrogeologiche (A-A', B-B', C-C' e D-D') nell'area di studio (gli andamenti sono rappresentati in Fig.1).

Tab. 1 - Hydrogeological data of the Lower Cretaceous Aquifer in study area.

Tab. 1 - Dati idrogeologici dell'Acquifero del Cretaceo Inferiore, nell'area di studio.

Well No.	Well name	Total depth (m)	Depth to water (m)	Water level (MSL)	Screen interval (m)	Penetrated thickness (m)	Sand %	Salinity (TDS) (ppm)
1	Seal El Atam	1150	214	200	950-1150	240	78	-
2	Nakhl 6	1190	234	191	1007-1188	270	52	1393
3	Haraba	1285	220	210	1048-1210	275	76	1719
4	Jica 2	1260	423	234	1102-1245	241	73	-
5	Jica 4	1130	536	239	920-1130	230	69	-
6	Shaira K52	920	141	421	768-905	235	68	-
7	Shaira k83	830	455	380	768-816	238	77	1082
8	Themed 2	747	376	224	559-733	250	62	1582
9	Kuntilla 2	1125	323	188	900-1125	235	68	1607

*Not reached to bottom of Lower Cretaceous

DOI: 10.7343/as-2016-241

The Lower Cretaceous sandstone Formation (Malha) can be subdivided in the study area into three lithological units (A, B, and C from top to base respectively) depending upon the sand percentage calculated from the records of the natural gamma ray. Lithological unit "C" is mainly composed of fine to medium grained ferruginous sandstone with claystone interbeds. The average sand percent of this zone attains 63%. This unit directly overlies the Jurassic sandstone aquifer of high groundwater salinity. In the study area, the all productive wells are not reached this deep unit. Lithological unit "B" is built up of medium to very coarse grained sandstone with average sand percentage 86%. Accordingly, this unit represents fresh sandstone and the majority of the productive wells tapping this unit in the study area. The lithological unit "A" represents the upper unit of the Malha Formation and underlies Halal Formation. The average thickness of this unit attains 82 m. The lithological unit "A" is essentially composed of claystone with sandstone intercalations. The average sand percentage of this unit reaches 41 %. This lithological unit is detected as water bearing formation in the study area.

Hydrogeological conditions

The Lower Cretaceous sandstone (Malha Formation) aquifer is exposed on the surface in east of the study area (Fig. 3). It overlies directly the Jurassic sandstone aquifer and underlies the Halal limestone Formation. It exists under confined conditions (Fig. 6). In the study area, the Lower Cretaceous water-bearing formation (Nubia sandstone) is represented by the Malha Formation of Aptian-Albian age and composed of sandstone with subordinate interbeds of sandy siltstone and claystone and kaolinitic pockets. The tracing of the top surface of Malha sandstone aquifer can be the drawn the hydrogeological cross-sections (correlation chart) (Fig. 6). The correlation chart of lithologic logs revealed that the area of study is dissected by normal faults. These faults are related to the Aqaba system with downthrown to the north direction. These faults are highly affecting the groundwater movement and its quality.

The groundwater of the Lower Cretaceous sandstone aquifer occurs under confined conditions. The investigated aquifer is hydraulically connected with the underlying Jurassic sandstone aquifer in wells nos. 3, 6 and 9 due to the faulting, where the Malha sandstone aquifer comes in contact with each other as a result of faulting displacement (Fig. 6).

The penetrated thickness of the Lower Cretaceous sandstone aquifer ranges between 230 m (well no. 5) and 275 m (well no. 3) (Tab. 1). In general, it increases towards the northeast direction. The variation in thickness is essentially attributed to the structural deformation in the study area, where the minimum thickness (recorded at well 5) is located along the upthrown side of the recorded fault (Fig. 6). The active erosion processes minimize its thickness. On the other hand, the maximum thickness recorded in well no.3 is located along the graben structure side of the recorded fault, where it was not subjected to probably the erosion processes.

Groundwater flow

The depth to the groundwater in the Lower Cretaceous sandstone aquifer ranges from 141 mbgl (meter below ground level) in well no. 6 to 536 mbgl (well no. 5) in El-Egma plateau area (Tab. 1). The potentiometric map (Fig. 7) indicates that the highest observed potentiometric level at 421 m asl (meter above sea level) was observed at the well no. 6 at Shaira area, while the lowest level of 188 m asl was observed at El-Kuntilla area well (well no. 9). The lowest water level of well no. 9 is attributed to the location of the well in downthrown side of the detected fault (Fig. 6). The map also shows that the groundwater in the Lower Cretaceous aquifer system flows from its southeastern recharge area (outcrop of Malha Formation) near the Gulf of Aqaba to the northwest direction. The calculated hydraulic gradient ranges from 0.005 in recharge area to 0.002 m/m in discharge area.

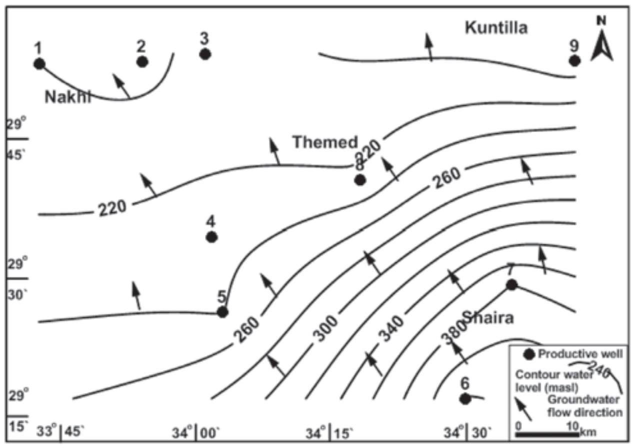

Fig. 7 - Piezometric surface map of the Lower Cretaceous sandstone aquifer.

Fig. 7 - Carta della superficie piezometrica dell'Acquifero Sabbioso del Cretaceo Inferiore.

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Aquifer tests

The aquifer tests of the Lower Cretaceous sandstone aquifer in east Central Sinai area are estimated based mainly on the

DOI: 10.7343/as-2016-241

Tab. 2 - Hydraulic parameters of some wells tapping the Lower Cretaceous aquifer.

Tab. 2 - Parametri idraulici di alcuni pozzi captati nell'Acquifero del Cretaceo Inferiore.

Well No	Productivity m^3/day	Maximum Drawdown (m)	Transmissivity m^2/day	Penetrated aquifer Thickness (m)	Hydraulic Conductivity m/day	Effective Porosity (%)
2	1200	-	596	270	2.2	19
3	1200	-	414	268	1.5	17
4	552	-	109	206	0.5	13
6	1200	6.48	242	220	1.1	16
7	720	3.87	742	220	3.4	21
8	984	10.22	289	250	1.1	16
9	1200	1.85	723	236	3.1	20

interpretation of the constant discharge pumping tests. The results of the hydraulic parameters are listed in Tab. 2.

Transmissivity (T)

The estimated transmissivity is based on the interpretation of pumping tests for seven-wells tapping the Lower Cretaceous sandstone aquifer. The original raw data (WRRI 2001) obtained through this work are analyzed by using Cooper and Jacob method (1946) and GWW computer program (Braticevic and Karanjac 1995). The values of specific drawdown Δ (s/Q) are plotted versus the corresponding time (t) on single logarithmic paper and a straight line is drawn through the plotted points. The slope of the straight line determines the specific drawdown difference Δ (s/Q) per log cycle of time (Fig. 8). The transmissivity is expressed by the following equation:

$$T = 2.3/4\ p\ \Delta\ (s/Q)$$

Where T is the transmissivity in (m^2/ day), (s/Q) is the specific drawdown difference per log cycle of time, Q is the constant discharge in (m^3/day) and s is the head drawdown in (m).

The results show that the transmissivity values of the studied aquifer ranges from 109 m^2/day (well n°4, south Nakhl) to 742 m^2/day (well n°7, Wadi Shaira) as shown in Tab. 2. The high transmissivity of well n°7 is attributed mainly to the high sand percent and effective porosity. The majority of transmissivity values of the concerned aquifer indicates that it is characterized by moderate potential (50-500 m^2/day), except the wells nos. 2, 7 and 9 have a high potential (>500 m^2/day) according to Gheorhge (1979) classification.

Hydraulic conductivity (K)

The hydraulic conductivity is expressed by the following equation:

$$K = T / D$$

Where the K Is the hydraulic conductivity in (m/day), T Is the transmissivity in (m^2/day) from the pumping method and D Is the aquifer thickness in (m). The aquifer hydraulic conductivity ranges from 0.5 m/day (well no. 4, south Nakhl) to 3.4 m/day (well no. 7, Shaira area).

Effective porosity (Φ_{eff})

The effective porosity of the Lower Cretaceous aquifer is determined by substitution of hydraulic conductivity in Martoz equation (1968). The effective porosity is obtained by the following equation: $\Phi_{eff} = 0.462 + 0.045 \mathrm{Ln}\ k$

Where Φ_{eff} is the effective porosity in decimal and k, the hydraulic conductivity in centimeters per second.

The effective porosity of the studied aquifer ranges from 13% (well no. 4) in south Nakhl to 21% (well no. 1) in Shaira area (Tab. 2).

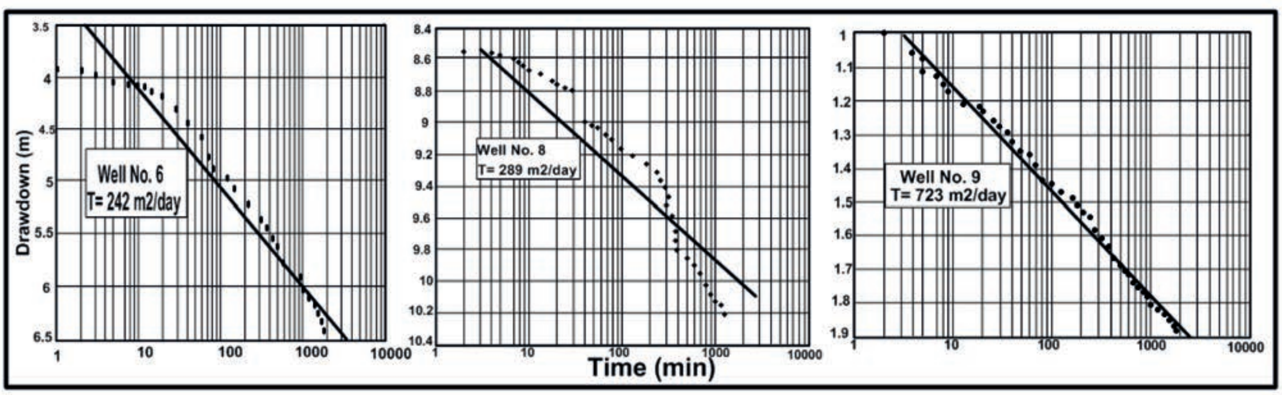

Fig. 8 - Time-Drawdown curve by using Cooper and Jacob method (1946).

Fig. 8 - Curve Tempi-Abbassamenti usando il metodo Cooper e Jacob (1946).

Groundwater quantity of the Lower Cretaceous aquifer in study area

The estimated groundwater quantity of the Lower sandstone aquifer in the concerned area depends principally on the thickness and effective porosity of the studied aquifer. It is obtained by the following equation:

$$Q = D*A*\Phi_{eff}$$

Where Q is the storage capacity of the aquifer in m^3, Φ_{eff} is the average effective porosity in decimal, D is the average aquifer thickness in meter and A, the aquifer area in m^2.

The groundwater quantity of the studied aquifer attains 300 bcm, although only a small fraction of this water can be pumped. A large part of the water in this aquifer is fossil, and dating using 14C, indicates an age reaching 22,000 years (Abd El Samei and Sadek 2001).

Recharge of Lower Cretaceous aquifer

The Lower Cretaceous aquifer in central Sinai is recharged by infiltration of local rainfall through its outcrops along the face of El-Egma, El-Hazin plateau in south Sinai. Dames and Moore (1985) estimate the recharge to the Lower Cretaceous aquifer system to be about 90,000 m^3/day.

In the present work, the potentiometric contour map (Fig. 7) shows that the groundwater flows from southeast to northwest direction. This indicates that the recharge area of the studied aquifer is located at south. Darcy's (1856) is used to calculate groundwater recharge according to the following equation:

$$R = T*I*L$$

where R is the amount recharge of the aquifer in m^3/day, T is the average transmissivity of the aquifer in m^2/day (445 m^2/day), I is the average hydraulic gradient (0.002), and L is the length of the front to recharge area (50,000 m).

In the present work, the estimated recharge of the Lower Cretaceous aquifer in study area reaches about 44,500 m^3/day. The annual recharge is 16 mcm/year (million m^3/year).

Hydrochemistry

Five groundwater samples collected from productive wells tapping Lower Cretaceous sandstone aquifer in east central Sinai were analyzed for the major elements (Tab. 3). Sampling was carried out in May, 2016. They will be described herein through the following:

Groundwater salinity

The groundwater salinity of the Lower Cretaceous sandstone aquifer (Malha) reveals a great variation reflecting the effect of the facies changes, the structural effect and the hydrochemical processes. The groundwater salinity of this aquifer varies from fresh water of 1082 ppm (well no. 7) to brackish water of 1719 ppm (well no. 3). The low groundwater salinity is related to that this well no. 7 located in the upthrown side of the fault (Fig. 6), where the faults are generally accompanied by the presence of best groundwater especially on their upthrown sides (Yousef and El-Saady, 1964). The high salinity of well no. 3 is essentially attributed to that this well is located in graben structure form.

Fig. 9 shows the distribution of groundwater salinity map of the studied aquifer. This map shows that the groundwater flows from south towards the north direction coinciding with the groundwater flow direction the north (Fig. 7).

Tab. 3 - Chemical analyses of groundwater samples (May, 2016).

Tab. 3 - Analisi chimiche di campioni di acque sotterranee (Maggio, 2016).

Well No.	EC μmhos/cm	TDS ppm	Units	Cations				Total epm	Anions			Total epm
				Ca^{++}	Mg^{++}	Na^{+}	K^{+}		HCO_3^-	SO_4^-	Cl^-	
2	2176	1393	ppm	120	62.21	240	50	22.83	112	445	420	22.94
			epm	5.99	5.12	10.44	1.28		1.84	9.26	11.84	
			epm%	26.24	22.43	45.73	5.60		8.02	40.37	51.61	
3	2800	1719	ppm	152	77.82	340	30	29.52	168	475	560	28.43
			epm	7.58	6.40	14.78	0.76		2.75	9.89	15.79	
			epm%	25.68	21.68	50.07	2.57		9.67	34.79	55.54	
7	1790	1082	ppm	89.6	73.87	170	14	18.3	164	300	352	18.87
			epm	4.47	6.08	7.39	0.36		2.69	6.25	9.93	
			epm%	24.43	33.22	40.38	1.97		14.25	33.12	52.63	
8	2472	1582	ppm	150	90.9	270	10	26.97	335	504	390	26.98
			epm	7.49	7.48	11.74	0.26		5.49	10.49	11.0	
			epm%	27.77	27.73	43.53	0.97		20.35	38.88	40.77	
9	2510	1607	ppm	133	47.5	364	20	26.89	217.2	434	500	26.66
			epm	6.64	3.91	15.83	0.51		3.56	9.03	14.1	
			epm%	24.69	14.54	58.87	1.90		13.34	33.83	52.83	

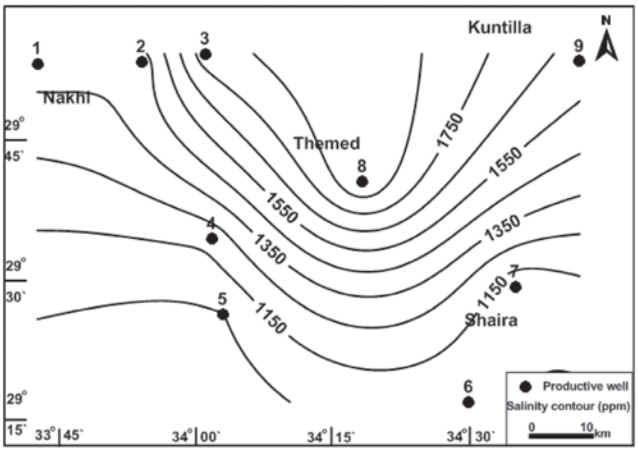

Fig. 9 - Groundwater salinity map of Lower Cretaceous aquifer in the study area.

Fig. 9 - Carta della salinità dell'Acquifero del Cretaceo Inferiore, nell'area di studio.

Ion dominance

The ion concentrations, the sodium and chloride dominate the other ions in the groundwater samples of Lower Cretaceous sandstone aquifer. The sequence of ion dominance of both cations and anions in the water follows the order $Na^{+} > Ca^{2+} > Mg^{2+}$ and $Cl^{-} > SO_4^{2-} > HCO_3^{-}$. So, the chemical water type is sodium chloride. The magnesium exceeds the calcium only in well no. 7 and has ion dominance order $Na^{+} > Mg^{2+} > Ca^{2+}$ and $Cl^{-} > SO_4^{2-} > HCO_3^{-}$. The magnesium exceeds calcium in this well attributed mainly to this well near the basement rocks of Gulf of Aqaba. These rocks are very rich in mafic minerals and the leaching of magnesium ions leads to the increase of magnesium ions in groundwater.

Genetic classification of groundwater mineralization

Expanded Durov diagram (Durov, 1948) is used to give more information about the hydrochemical facies and evolution of groundwater quality when compared with other graphical methods (Lloyd and Heathcote, 1985). It helps in identifying hydrochemical facies or water types, groundwater flow direction and can indicate mixing of different water types, ion-exchange and reverse ion-exchange processes.

Fig. 10 shows the spatial distribution of the different hydrochemical facies within the Lower Cretaceous sandstone aquifer in study area. The study area is located within the dissolution and discharging (end point water) areas. The hydrochemical facies with no dominant anion or cation (type 5) in El Themed area (well no. 8) of the middle of the study area along the mixing line indicate that waters exhibiting simple dissolution or mixing. The hydrochemical type 8 occurs in the northeastern area (well no. 7) and dominated by chloride and magnesium. It frequently represents mixing area. The hydrochemical type 9 occurs in the wells nos. 2, 3 and 9 and dominated by chloride and sodium representing the discharging area.

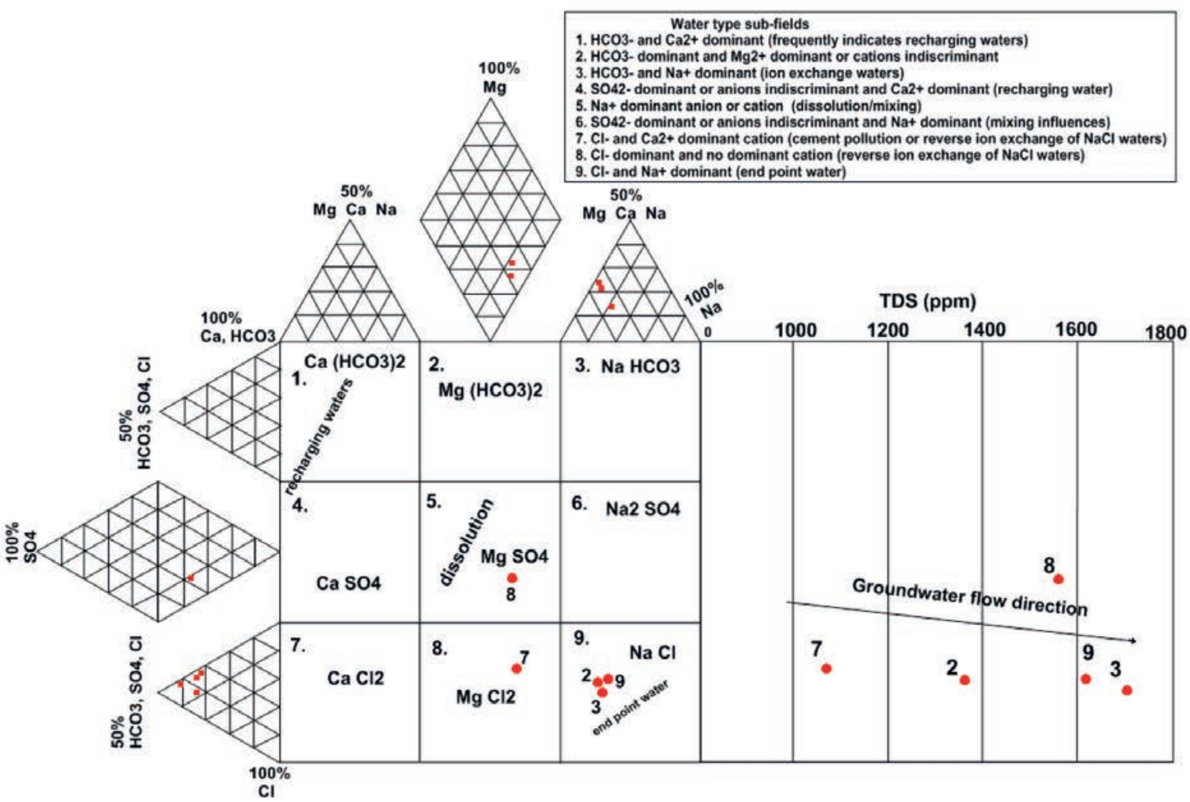

Fig. 10 - Expanded Durov diagram of groundwater samples.

Fig. 10 - Diagramma di Durow dei campioni di acqua sotterranea analizzati.

This figure can be used to determine the groundwater flow direction by plotting salinity of wells in expended figure. It is noticed that the dissolution area of the Lower Cretaceous aquifer has low groundwater salinity, while the end point water has high groundwater salinity. This is attributed to the increase of groundwater salinity with groundwater flow direction due to the dissolution and leaching of salts.

Recommendations

The extracted groundwater from the Lower Cretaceous sandstone aquifer (Malha sandstone aquifer) in the study area is very expensive. This is related to the majority of the pumps being installed at a depth of about 300 m below ground surface. It is recommended that the groundwater of this aquifer is only used in drinking purpose by using desalination stations to remove excess salts and iron. The unit "B" has a high sand percent (90%) with few clay intercalations, while the other units (A and C) have highly clay intercalations. It is recommended that the new drilled productive wells should be tapping the unit "B" of fresh sandstone.

Conclusions

The Lower Cretaceous sandstone aquifer (Malha) is differentiated into three lithological units (A, B and C) depending upon the sand percent calculated from the records of the Natural Gamma Ray. The calculated groundwater volume of the Lower Cretaceous aquifer (6300 km^2) in the study area attains about 300 billion m^3. In the present work, the estimated recharge of the Lower Cretaceous aquifer in study area reaches about 44,500 m^3/day. The groundwater salinity of the Lower Cretaceous sandstone aquifer varies from fresh water of 1082 ppm to brackish water of 1719 ppm and increases towards the northwest direction coinciding with groundwater flow.

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