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Hydrogeology of the Saq Aquifer Northwest of Tabuk, Northern Saudi Arabia

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Abstract. Groundwater resources are precious commodity in general and for arid regions in particular. Their exploration, exploitation, protection and management play significant role in societal activities. In the Kingdom of Saudi Arabia, extensive aquifers are available in the Arabian Shelf. The Saq aquifer is one of the most important aquifers in the northwestern part of Saudi Arabia. It is made up of a Cambro-Ordovician sandstone formation, which extends over 1200 km in Saudi Arabia and northwards in Jordan. Groundwater occurs under unconfined conditions in the southwestern part and changes to confined conditions northward. The study area is located at about 50 km northwest of Tabuk, where many agricultural projects have been established depending on groundwater of the Saq aquifer for irrigation. The present study deals essentially with the hydrogeology of the Saq aquifer and the impact of extensive pumping on both groundwater levels and groundwater quality. Pumping and recovery tests were carried out in order to estimate the aquifer parameters. A total number of 192 groundwater samples were collected during the period 2000-2004 for quality investigation. Results of analysis of pumping test data showed that the average transmissivity and storativity are 1572 m^2/day and 2.86×10^{-4}, respectively. Values of average TDS of groundwater range between 540 and 670 mg/l, which indicate that it can be used safely for irrigation. The TDS values showed general decrease towards the northeastern part of the study area, in the direction of flow. Extensive pumping from 260 deep wells with an average discharge rate of 0.015 m^3/sec has resulted in continuous groundwater level drop since 1999 with an average rate ranges between 2.3 − 10.5 m/year. Additionally, the effects of pumping on the water quality for the period 2000-2004 were studied

using statistical analysis, which showed that there are no significant temporal variations of the major ion concentrations. It is strongly recommended to carry out groundwater management plan with the help of groundwater flow modeling where different scenarios for groundwater exploitation should be applied and the resulting drop of groundwater levels can be predicted.

Keywords: Hydrogeology, Saq aquifer, Groundwater, Saudi Arabia.

Introduction

Saudi Arabia is considered as one of the driest countries of the world, where rainfall is irregular and unpredictable. There are many ephemeral streams, which provide occasional recharge into the aquifers. These groundwater reservoirs are the most important water sources in the country**.** Such extensive aquifers occur within the depth of some sedimentary sequences in the Arabian Shelf. They constitute the eastern, central and western parts of the Kingdom of Saudi Arabia (KSA) with a total area of about 2/3 of the Kingdom (Fig. 1).

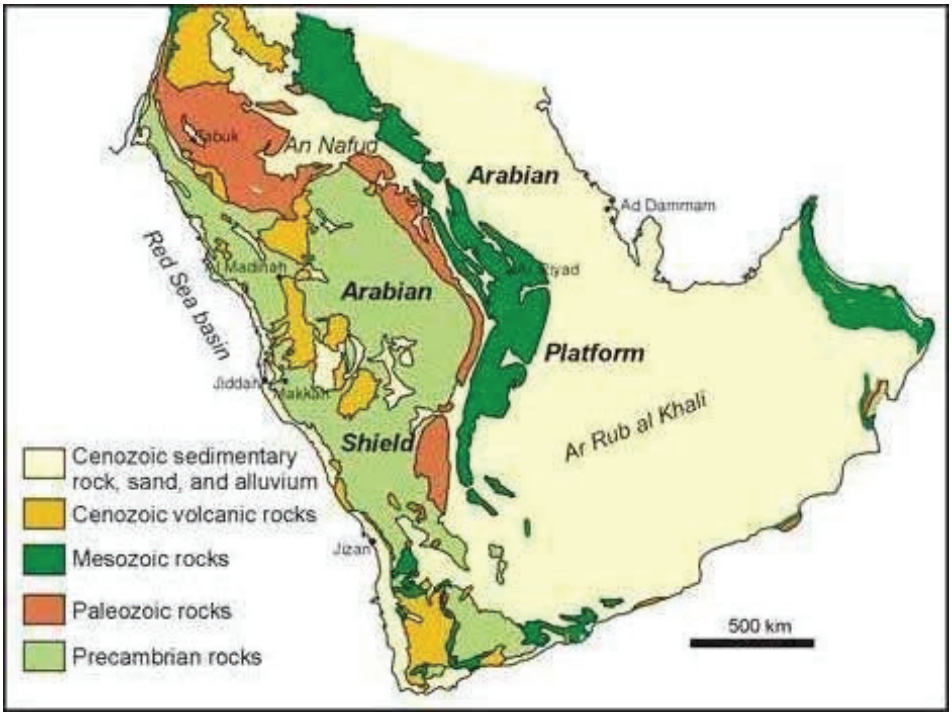

Fig. 1. Arabian Peninsula and the Arabian Shelf.

The Saq aquifer can be considered as one of the major aquifers in the Kingdom of Saudi Arabia. Different studies (Burdon, 1982; Jado and Zötl, 1984; Ministry of Agriculture and Water (MAW) 1984; Bureau de Récherches Géologigues et Miniéres (BRGM), 1985; Jerais, 1986; Segar, 1988; Sowayan and Allayla, 1989; Lloyd and Pim, 1990; Edgell, 1997) have shown that the Saq aquifer contains significant amount of fossil water, estimated to be about 280,000Mm^3, which is of 22000 to 28000 years old, with very little present-day recharge.

The study area is located within the arid belt of western Arabian Shelf, and it is about 50 km northwest of Tabuk City along the Tabuk-Jordan highway. It lies between latitudes 28° 00′ and 29° 00′ N and longitudes 36° 00′ and 36° 30′ E (Fig. 1). The study area is one of the most suitable locations for agricultural development, where groundwater is available mostly from the confined part of the Saq aquifer, through many small diameter wells (MAW, 1984).

Most of the area is cultivated by Tabuk Agricultural Development Company (TADCO), which drilled about 260 wells at an average depth of 750 m. Many of the wells are connected to circular sprinkler pivots, while others have two or three circular pivots for irrigation, which indicates that large amount of water is abstracted. All these wells penetrate and extract the water from the Saq aquifer.

Study Area

Topography of the Study Area

The investigated area is a peneplain, bounded by moderate to low relief of mountains in the east, west and south, while open to the north, where a very large catchment area is draining to the Tabuk basin. This drainage network extends southwards covering the Harrah (volcanic flow). As the basin is flat, there are main wadis that form the end of that large drainage area, namely Wadi Al-khadr and Wadi Abu Nishaifah to the east of Tabuk, and wadi Al-baggar to the west (Al-Sagaby, 1978). The elevation of the study area is around 700 to 800 m above mean sea level. The hills which are located in the west of the study area rise to an elevation of 150 to 200 m from the plain level (Al-Baradi, 2000).

Climate of Tabuk

The climate in the Tabuk area is of the continental type but is influenced occasionally by its proximity to the Mediterranean Sea (Şen,

1983). During the winter season, the penetration of cool Mediterranean air masses brings frontal rainfall events with high intensities. The maximum and minimum temperatures are about 47º C in summer and – 2º C in winter. While in summer, the average value is 28º C and 12º C in winter (Alsharan and others, 2001). The average annual rainfall is about 20 mm (Fig. 2), while the annual evaporation is almost 40 mm (Al-Sagaby, 1978).

This study aims to throw some light on the general hydrogeological conditions of the Saq aquifer to the northwest of the Tabuk area, concerning the groundwater occurrence, movement, aquifer parameters and groundwater quality. Moreover, the effect of extensive groundwater consumption from 1990 to 2004 was also discussed.

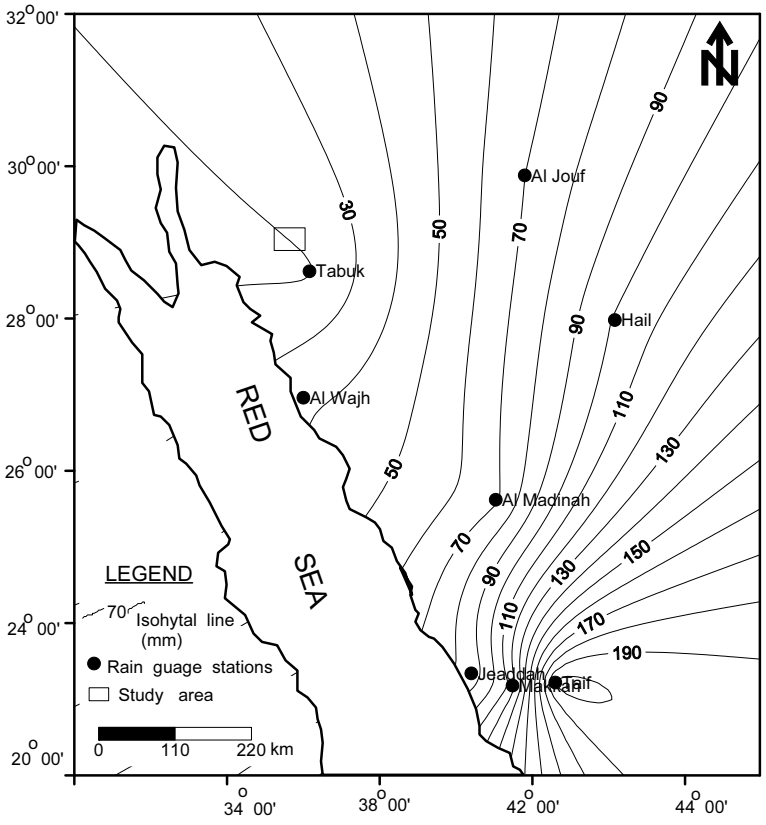

Fig. 2. Location map of the study area and the average annual rainfall.

Geological Setting

The study area lies within the sedimentary cover of the Arabian Peninsula. The general stratigraphic sequence in the study area is given in Table 1.

Table 1. General stratigraphic sequence of Paleozoic rocks in the Tabuk area.

PERIOD	FORMATION		MEMBER	THICKNESS (m)	LITHOLOGY
SILURIAN	QASSIM		TAWIL	65 – 550	Sandstone, medium to coarse grained, clay, siltstone.
			SHARAWRA	20	Siltstone
			QUSAIBA	50 – 280	Shale Shale, silty
			SARAH	150 – 400	Sandstone, fine grained shale
			MIDDLE SANDSTONES	150	Sandstone, clay, shale
			RAAN	20 – 50	Shale, siltstone
ORDOVICIAN			LOWER SANDSTONE	130 – 440	Sandstone, medium to coarse grained
			HANADIR	12.5 – 78	Clay, grey shale, siltstone
CAMBRIAN	SAQ	Upper	RAM and UMM SHAM SANDSTONE	200 - › 1200	Sandstone, fine to medium grained
		Lower	QUWEIRA SANDSTONE		Sandstone Medium to fine grained Sandstone, Coarse-grained Sandstone, fine, coarse-grained
			SAQ SANDSTONE		Conglomerate
PRECAMBRIAN					Basement rocks

The geology of the study area can be described under two categories as follows:

(a) The surface geology includes Quaternary deposits, which cover most of the study area. They consist mainly of silt and blown sand with

variable proportions of pebbles of limestone and basement complex. The thickness of silt ranges from 2 m to 25 m. The dominant rock successions in the area belong to the Qassim and Saq formations. The outcrops reach in some hills elevations ranging from 100 to 150 m above the ground level. The Saq Formation outcrop unconformabaly overlies a maturely peneplained surface of Precambrian crystalline rocks (Al-Laboun, 1982).

(b) The subsurface geology is represented by two general formations, namely: (1) Qassim Formation with a thickness of about 500 m, consisting of sandstone, shale and clay units of marine and continental origin, and (2) Saq Formation, which covers a very large area with thicknesses varying from one place to another, but it reaches 600 m within the study area. The Saq Formation has an Early Ordovician age (Edgell, 1997) and is composed of medium to coarse-grained quartz sandstone.

Hydrogeological Setting

The Saq aquifer is the largest most productive and most developed aquifer in the study area. Generally, it has a very large areal extension from the Jordanian border as far south as latitude 24° 30′ N and longitude 45° E, with a surface area of about 6500 km^2 (Jerais, 1986).

The thickness of this aquifer is variable but it changes according to geologic formations. It ranges from 200 m to 500 m in south and east of the study area, while in the northern part it ranges between 150 m and 500 m. However, in the central part of the area, its thickness varies between 450 m to 600 m (Tabuk Agricultural Development Company, personal communications).

The Saq Formation rests directly on the crystalline rocks of the Precambrian basement, and overlain by the lower part of the Qassim Formation. The effective porosity of this aquifer generally exceeds 15% with a range of 10 – 20% (King Fahd University Staff, 1987) The isotopic age of groundwater of the Saq aquifer varies between 22,000 and 28,000 before present, which indicates fossil water features (Edgell, 1997).

Groundwater Occurrence and Movement

The Saq aquifer constitutes the most important groundwater reservoir in the Arabian Peninsula. Figure 4 shows the SW-NE geological cross-section along the study area. It shows that the Quaternary deposits cover the Saq aquifer in the southwestern part, where the aquifer is under unconfined condition, while the Qassim Formation covers the northeastern part of the area where it is confined. Groundwater of this aquifer has been exploited since 1970 where the total depth of the drilled

wells reached 1223 m with an average value of 830 m (Tabuk Agricultural Development Company, personal communication).

At the present time, the total depth of the drilled wells ranges from 632 m to 1223 m in wells J39 and J28, respectively. The discharge rates are ranging from 804 to 1728 m^3/ day. The groundwater occurs at variable depths ranging between 42.3 m (well No. J40) and 104.98 m (well No. F9). The water level contour map for the year 2004 (Fig. 3) shows that the general direction of groundwater flow is towards northeast with an average hydraulic gradient of 0.0015.

Aquifer Parameters

Pumping and recovery tests were performed in four wells (A3, B2, B3, and C4) in order to define the aquifer parameters. These constant discharge tests and recovery tests were analysed using different methods and the results are given in Table 2. This table shows that the average transmissivity is 1572 m^2/day while the average storativity is 2.86×10^{-4}. The transmissivity value implies that the aquifer has a high potential and the storativity value is consistent with the confined condition of the Saq aquifer. According to the high potentiality of the aquifer, the total number of wells in the study area has increased from 136 wells in 1989 to 260 wells in 2004 to cope with the increasing demand of water for agricultural production (Tabuk Agricultural Development Company, personal communication).

Groundwater Quality

The study of water quality of the Saq aquifer is based on the results of detailed chemical analysis of 192 water samples collected from various localities in the study area during the period 2000-2004. The chemical study included measurement of the total dissolved solids (TDS), the major cations (Ca, Mg, Na and K), and major anions (HCO_3, Cl and SO_4). The results are given in Table 3 and illustrated in Fig. 4, which shows that TDS values in the Saq aquifer decrease from 630 mg/l in the southwestern sector of the study area to 420 mg/l at the northeastern sector. These TDS values indicate that the groundwater is fresh and safe for irrigation purposes. Additionally, this explains that the groundwater within the unconfined part of the aquifer and near to recharge area has more mineralization than the confined part. The mineralization is facilitated by the arid condition where very high evaporation rate leads to an increase of the salt concentration in the soil. Hence, recharge events may cause leaching of the readily soluble soil salts in the Quaternary deposits down into the Saq aquifer.

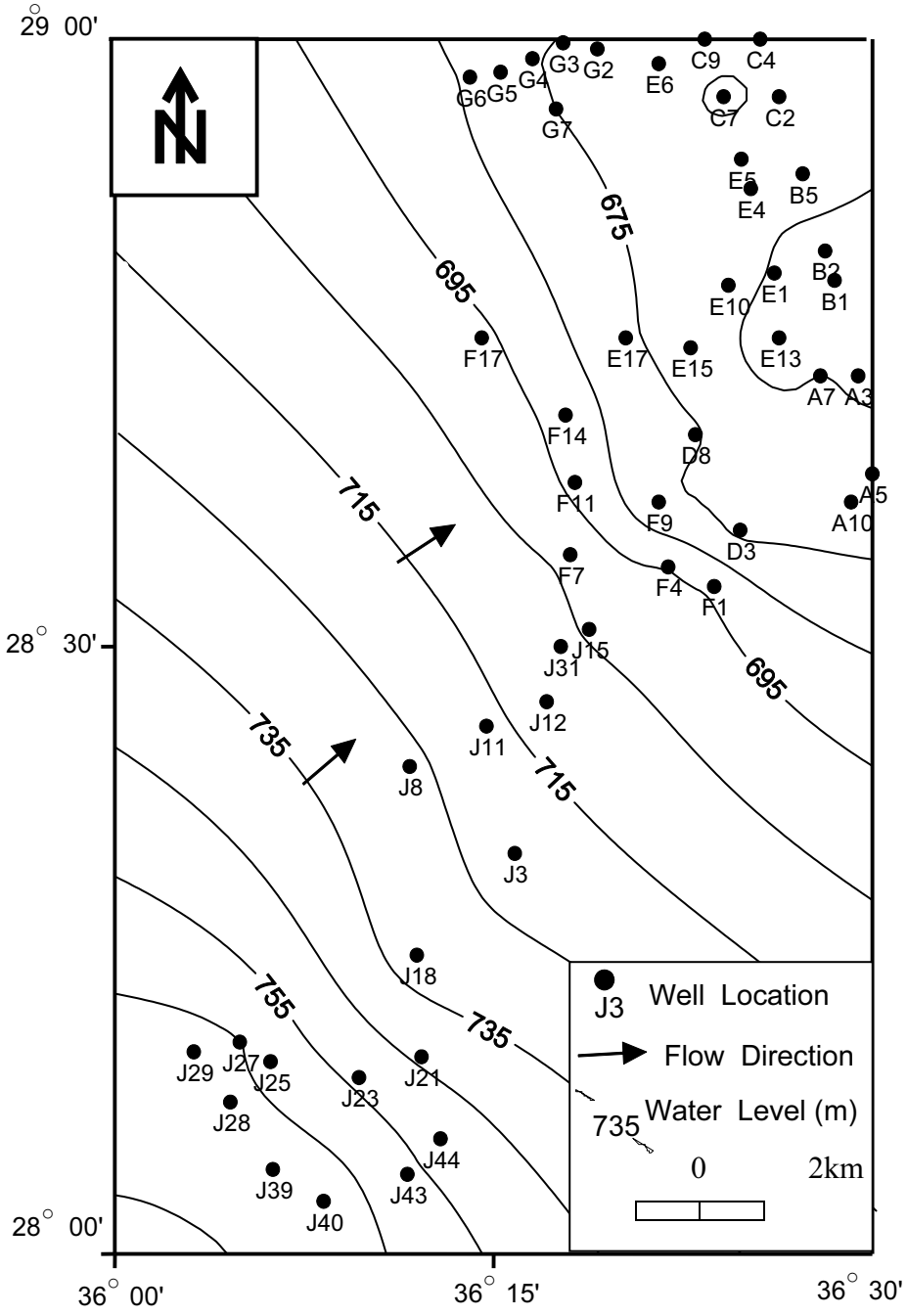

Fig. 3. Water level contour map of the study area in 2004.

Table 2. Transmissivity (T) and storativity (S) values of the Saq aquifer northwest of Tabuk.

Well No.	Theis Method		Jacob- Copper Method		Sen′ Method		Recovery Method T(m²/d)
	T(m²/d)	S	T(m²/d)	S	T(m²/d)	S	
A3	1728	$2.1X10^{-4}$	–	–	1730	$4.2X10^{-4}$	1560
B2	1580	$3.62X10^{-4}$	1430	$4.2X10^{-4}$	–	–	–
B3	1693	$3.00X10^{-4}$	1725	$2.67X10^{-4}$	1721	$2.86X10^{-4}$	–
C4	1400	$1.5x10^{-4}$	1397	$1.2X10^{-4}$	1387	$1.91X10^{-4}$	–

On the other hand, TDS values decrease towards the northeastern part of the study area, in the direction of flow. Therefore, the quality of groundwater improves in the confined part of the aquifer where the Hanadir Shale totally prevents the salt leaching from the Quaternary cover into the confined part of the Saq aquifer. Major ion concentrations of all the collected samples in 2004 (44 samples) are shown in a Piper's diagram (Fig. 5). Hydrochemical facies of groundwater in the Saq aquifer change broadly from a Ca-Na-Cl-HCO_3 type to a Na-Ca-Cl-HCO_3 (+ SO_4) type. The distribution of anions tends to be clustered in the ternary diagram and is dominated by Cl and HCO_3. Dominant cations are either Ca or Na. Na is the most dominant cation in most of the collected samples.

Effect of Heavy Pumping

In order to clarify the effect of pumping on the water levels in the Saq aquifer, three long-term observation wells data, namely, E1, B4 and F6 were used for monitoring groundwater levels for 6 years from January 1999 until the end of 2004. Figure 6 shows the monthly fluctuation of groundwater level in the study area during this period. It is noticed from Fig.6 that there are seasonal short-term and long-term fluctuations in the study area.

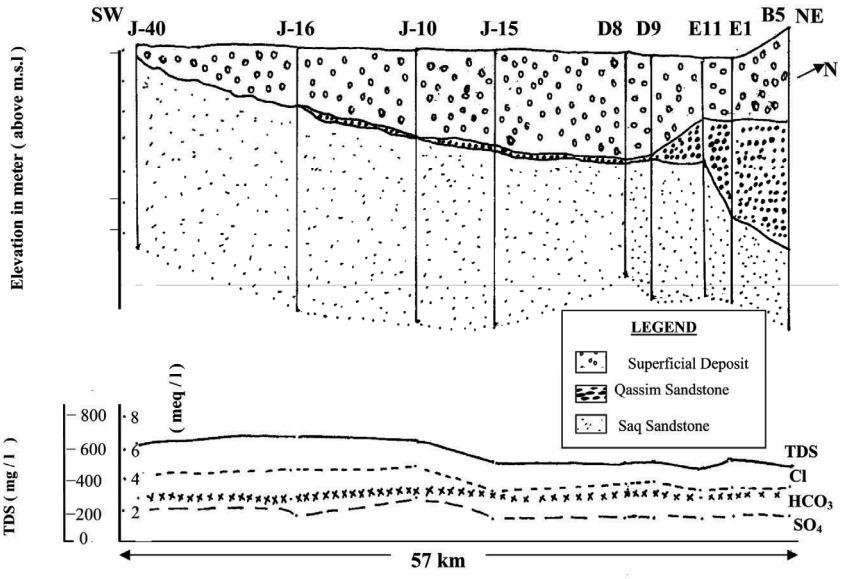

Fig. 4. SW-NE geologic cross-section and a hydrochemical profile along the study area.

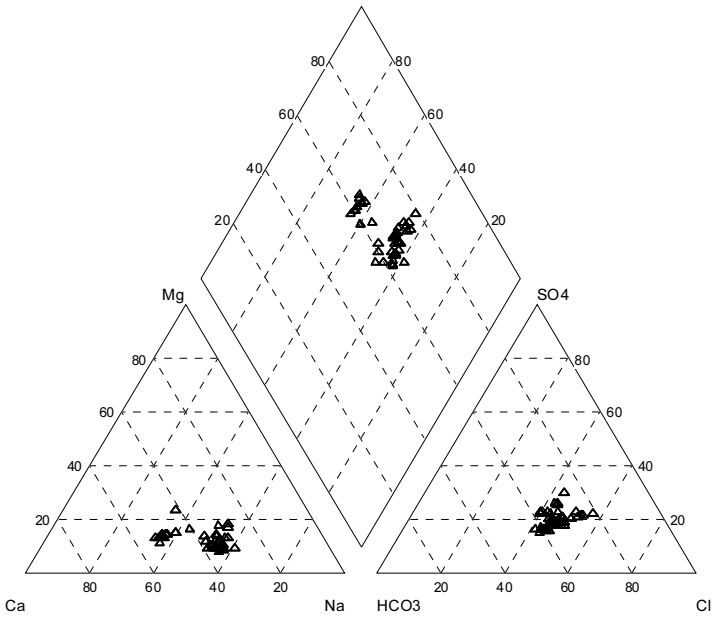

Fig. 5. Piper's diagram showing the general hydrochemical characteristics of the Saq aquifer.

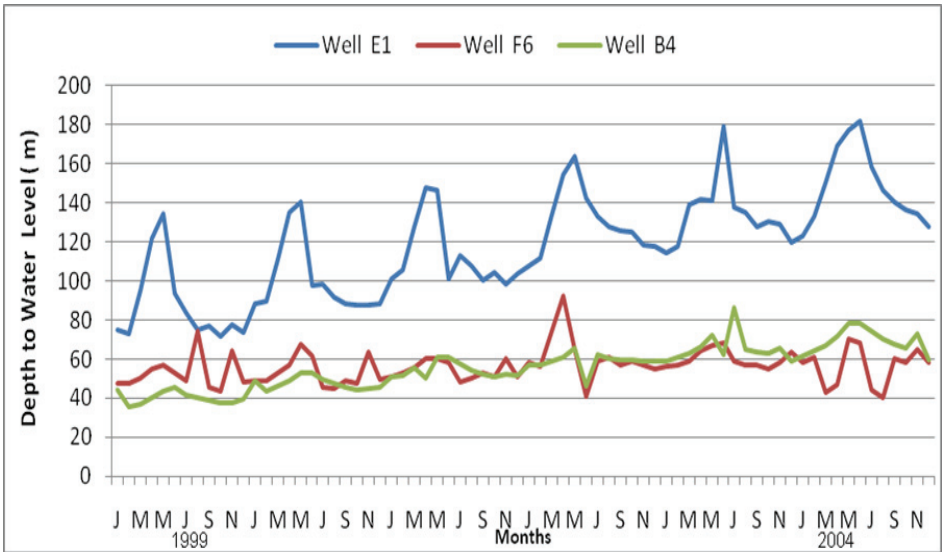

Fig. 6. Annual fluctuation of water levels in selected wells during the period 1999-2004.

In the seasonal short-term, the water level drops during the heavy pumping period which extends from April to May each year. This is due to use of water for wheat irrigation, which needs a lot of water. Also the short-term fluctuation occurs from October to November when the water is used to irrigate other types of vegetables. On the other hand, it is also noticed that the depth to groundwater increases with time, which implies a continuing water level drop in the area, with average drop rate of 2.3 – 10.5 m/year. The recharge of the Saq aquifer is low as compared with discharge that is clear from water level data of observation well No. E1, where the depth to groundwater increased from 75.50 m to 128.10 m. This is attributed to extensive pumping of groundwater for irrigation.

The effect of the heavy pumping on the water quality was also studied and some statistical analyses were carried out for a period 2000 - 2004. The results are presented in the form of arithmetic mean, median, mode, standard deviation and range as given in Table 3. It can be noticed from this table that the average, median and mode are more or less the same through the examined period.

Table 3. Summary of statistical analysis of the major ion concentrations (meq/l) and TDS(mg/l) for the time period 2000-2004.

Ion	Year	Average	Median	Mode	Standard Deviation	Range
Ca	2000	2.88	3.28	3.36	0.81	2.64
	2001	3.30	3.40	3.38	0.59	3.36
	2002	3.80	3.80	4.00	0.33	1.20
	2004	2.85	2.89	2.64	0.35	1.28
Mg	2000	1.57	1.4	1.40	0.58	2.32
	2001	1.05	0.99	0.96	0.19	0.86
	2002	1.38	1.40	1.60	0.54	2.97
	2004	1.18	1.16	0.96	0.31	1.04
Na	2000	3.53	3.48	5.22	0.95	3.7
	2001	4.47	5.33	2.43	1.64	5.07
	2002	2.64	2.51	2.17	0.52	2.00
	2004	3.22	3.11	3.00	0.36	1.38
K	2000	0.11	0.05	0.03	0.11	0.49
	2001	0.07	0.05	0.05	0.28	0.12
	2002	0.15	0.05	0.04	0.25	0.97
	2004	0.15	0.15	0.25	0.07	0.2
HCO_3	2000	2.99	3.00	3.00	0.53	2.75
	2001	2.83	2.80	2.80	0.35	1.92
	2002	2.74	2.50	2.50	0.60	2.50
	2004	2.81	3.00	3.60	0.92	3.28
Cl	2000	4.52	4.50	4.50	1.19	6.48
	2001	3.83	3.65	3.40	0.69	2.79
	2002	4.20	4.25	4.00	0.49	2.00
	2004	3.24	3.13	3.00	0.38	1.42
So_4	2000	1.43	1.43	1.55	0.39	1.32
	2001	1.64	1.73	2.05	0.37	1.12
	2002	2.39	2.57	2.57	0.72	3.43
	2004	1.40	1.10	0.86	0.82	3.00
TDS(mg/l)	2000	540.66	519.56	519.56	78.65	396.78
	2001	670.89	645.69	427.04	136.36	468.86
	2002	590.35	587.34	567.82	124.20	511.60
	2004	582.60	600.40	611.90	88.17	347.30

Moreover, it is clear that Ca, Na, SO_4 and Cl display the highest mode in the study area. Since the range of the ion concentrations is small, there is no significant variation in any major ion concentration. The standard deviation for all ions is more or less similar, which also implies that there is no significant variation. This interpretation shows that the ionic concentration of groundwater in the Saq aquifer is rather uniform, which means that there are no significant temporal variations caused by lowering the water level as a result of heavy pumping programs.

Well pumping can be considered as the major discharge from the Saq aquifer, where many drilled wells are used mainly to irrigate large areas of cultivated lands. All wells in the study area penetrate the Saq aquifer and many are used as center for pivot irrigation immediately around the well site. There are no historical records of the total water quantity, which is extracted from the existing wells in the study area. However, the water quantity as the total daily volume extracted from about 260 wells was estimated to be as 336960 m^3/day.

It is strongly recommended to carry out a detailed groundwater management plan with help of groundwater flow modeling where different scenarios for groundwater exploitation should be applied and the resulting drop of groundwater levels can be predicted.

Conclusions

The area overlying the Saq aquifer northwest of Tabuk is considered as the most important prolific locations for agricultural production of wheat and vegetables in the Kingdom of Saudi Arabia. The Saq aquifer is the major aquifer in this area where the groundwater is abstracted from depths ranging from 632 m to 1223 m. The Saq aquifer is unconfined in the southeastern part of the study area while it is confined in the northeastern part. It is characterized by an average transmissivity of 1572 m^2/day which indicates high potentiality while the average storativity is $2.86X10^{-4}$ indicating confined conditions. The groundwater flows toward northeast under an average hydraulic gradient of 0.0015. There is very limited local recharge in the unconfined part of the area. TDS average values range between 540 and 670 mg/l, which indicates that it can be used safely for irrigation. Heavy pumping of groundwater in the study area since 1999 has caused a continuous drop of water level with an average rate ranges between 2.3 − 10.5 m/year, but no significant temporal changes have been observed in the major ion concentrations. Statistical analysis confirmed that there is no clear change in the quality of water during the period from 2000 to 2004.

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هيدروجيولوجية متكون الساق المائي شمال غرب تبوك، شمال المملكة العربية السعودية

مسعود عيد الأحمدي

قسم جيولوجيا المياه – كلية علوم الأرض – جامعة الملك عبدالعزيز

ص.ب :٨٠٢٠٦ ، جدة ٢١٥١١، المملكة العربية السعودية

المستخلص. تعتبر مصادر المياه الجوفية بشكل عام ذات فائدة ثمينة جدا، وتزداد أهميتها في المناطق الجافة بشكل خاص، كذلك فإن استكشاف هذه المصادر واستغلالها وحمايتها وإدارتها تلعب دورًا أساسيًا في بناء النشاطات المختلفة.

في المملكة العربية السعودية تكون المتكونات المائية الواسعة متوفرة في الرف العربي، يعتبر متكون الساق المائي واحدًا من أهم المتكونات المائية الأكثر أهمية في الجزء الشمالي الغربي من المملكة العربية السعودية. وهو مكون من الحجر الرملي، و يتبع عصر الكامبري- أوردوفيشي، ويمتد على مدى أكثر من ١٢٠٠ كلم في المملكة العربية السعودية شمالآ حتى الأردن. توجد المياه الجوفية بشكل غير محصور في الجزء الجنوبي الغربي، وتتغير إلى حالة المحصورة شمالا. تقع منطقة الدراسة على بعد حوالي ٥٠ كلم تقريباً شمال مدينة تبوك، حيث أنشئت فيها العديد من المشاريع الزراعية معتمدة على المياه الجوفية من متكون الساق المائي لأغراض الري. إن الدراسة الحالية تتعامل أساسًا مع هيدروجيولوجيا متكون الساق المائي، وتأثير الضخ الجائر على كل من مستويات المياه الجوفية، ونوعيتها. أجريت اختبارات الضخ والتعويض من أجل تقدير خصائص المتكون المائي. تم جمع ٢٢٠

عينة من المياه الجوفية خلال الفترة ٢٠٠٠ – ٢٠٠٤م وذلك من أجل دراسة نوعية المياه. وقد أظهرت نتائج تحليل اختبار الضخ أن متوسط معامل النفاذية والنوقلية هي ١٥٧٢ م^{٢} / يوم، و٢,٨٦×١٠$^{-٤}$ على التوالي. أما قيم المواد الصلبة الذائبة في المياه الجوفية تراوحت ما بين ٤٢٠ و ٦٣٠ ملجم/لتر، وهو ما يشير إلى أنه يمكن استخدامها لأغراض الري بأمان. هذا وقد أظهرت قيم المواد الصلبة الذائبة أن هناك تناقص عام نحو الجزء الشمالي الشرقي من منطقة الدراسة في اتجاه التدفق. كذلك فقد اتضح أن الضخ من ٢٦٠ بئرا عميقآ بمتوسط معدل تصريف يبلغ ٠,٠١٥ م^{٣}/ ثانية، قد أدى إلى انخفاض مستمر في مستوى المياه الجوفية منذ عام ١٩٩٩ بمتوسط معدل بين ٢,٣ – ١٠,٥م/السنة. وبالإضافة إلى ذلك، فقد درس تأثير هذا الانخفاض على نوعية المياه للفترة ٢٠٠٠– ٢٠٠٤م باستخدام التحليل الإحصائي، حيث أظهرت الدراسة أنه لا توجد أي اختلافات واضحة في التركيزات الأيونية الأساسية. وعليه فإنه من المهم جدا القيام بخطة لإدارة المياه الجوفية بالاستعانة بنماذج سريان المياه الجوفية، حيث تستخدم فيها سيناريوهات مختلفة لاستغلال المياه الجوفية والتي ينبغي تطبيقها، حيث يمكن التنبوء بانخفاض مستويات المياه الجوفية.

الكلمات الدالة: الهيدروجيولوجيا، متكون الساق المائي، المياه الجوفية، المملكة العربية السعودية.