JKAU: Earth Sci., **vol. 16,** pp:121-139 (2005 A.D. / 1426 A.H.)

Hydrogeological and Hydrochemical Features of Wadi Adam, Makkah Al-Mukarramah Area

ALI M. SUBYANI
Faculty of Earth Sciences, King Abdulaziz University, Jeddah, Saudi Arabia

Received: 14/9/2004 Revised: 19/3/2005 Accepted: 24/5/2005

ABSTRACT. The aim of this research is to assess the groundwater quantity and quality potentials of Wadi Adam as an additional strategic future water supply for Makkah Al-Mukarramah area. Wadi Adam is one of the undeveloped Arabian Shield Wadis, located 50 km south of Makkah Al-Mukarramah city. This Wadi drains a catchment area of about 380 km^2 and receives a moderate amount of rainfall of about 160 mm $year^{-1}$. Water table map was constructed for the existing unconfined alluvial aquifer. The hydraulic gradient is about 0.008. Average transmissivity of 142 m^2 day^{-1} were calculated and the average storativity value is about 0.1, which indicated that the aquifer in this area is of moderate potential. The recharge rate to this basin, using chloride mass-balance method, is about 3×10^6 m^3/year. The amount of the natural discharge into the Red Sea is about 0.9 million m^3/year. The hydrochemical study indicated that the average total dissolved solids of the groundwater is 1500 mg/l. This means that this groundwater is suitable for irrigation and non-drinking purposes. Concentrations of trace elements are generally within the normal limits.

Introduction

The development of water resources programs in Saudi Arabia is the essential target of the government planning. Major wadis in Makkah Al-Mukarramah area, such as Fatimah, Naaman, and Khulais, have been developed and used for groundwater supply. The groundwater in these wadis is highly decreasing with time due to the scarcity of rain, extensive use for irrigation, domestic and industries. The search for development of new water resources in this area is considered among the top priorities as the consumption of water is rising with time, especially in Hajj and Omrah seasons. In the mean time most of water supply for Makkah Al-Mukarramah area (more than 90%) is obtained from desalination plants on the Red Sea (Sogreah, 1968; El-Khatib, 1980; Şen, 1983; Fourth and Fifth Development Plan, 1985, 1990).

Wadi Adam comprises a major undeveloped alluvial aquifer near Makkah Al-Mukarramah city. It is bounded by Latitudes 20º30' and 21º00'N and Longitudes 39º45' and 40º00'E. This wadi is located 50 km south of Makkah Al-Mukarramah city, Fig. 1. It constitutes a potential strategic water resource. It flows into the Red Sea after crossing the coastal plain. This wadi drains a part of the Hijaz Mountains scarp of the Arabian Shield, which extends from north to south parallel to the Red Sea. This basin drains a moderate area of about 380 km^2. The catchment area is characterized by moderate amount of annual rainfall of more than 160 mm. Few farms are distributed along the wadi. Local population activities in the basin are concentrated on grazing and agriculture. Kotb *et al.* (1990) studied the groundwater quality of Wadi Adam. They collected 23 samples from tributaries of the wadi and analyzed them for major ions. The dominant salts found were NaCl, $CaSO_4$ and $MgSO_4$. The total dissolved salts ranged between 454 and 32,818 mg/l. (These very high saline samples were taken from tributaries which are structurally isolated by Adam fault zone and do not represent the main channel). Other researchers concentrated on geological mapping (Pallister,1986; Matsah *et al.*, 2004).

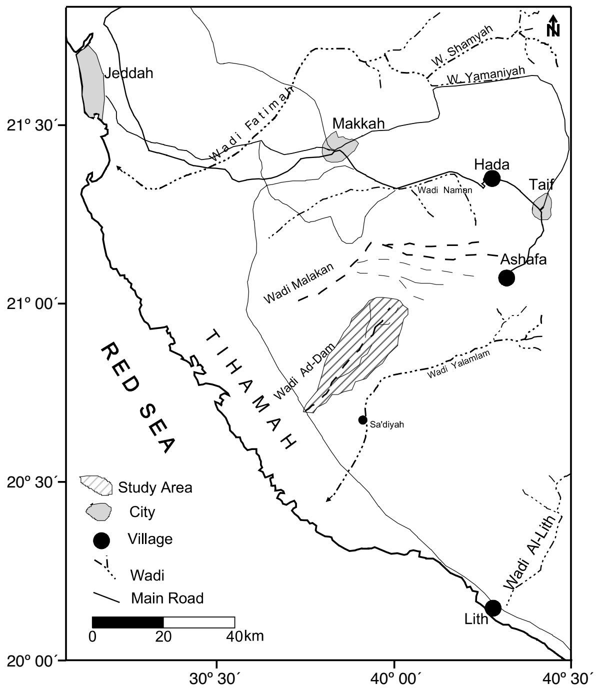

FIG. 1. Location map of Wadi Adam and adjacent area (after Subyani *et al.,* 2004).

This paper aims to study the hydrogeological and hydrochemical features of the unconfined alluvial aquifer of Wadi Adam. These features include groundwater occurrence and movement, aquifer hydraulic characteristics, and quantitative analysis of groundwater recharge and discharge volumes, quality and usability.

Geological Setting

Wadi Adam drains part of the Arabian Shield to the Red Sea across the coastal plain (Tihamah). The Arabian Shield comprises Precambrian crystalline, meta-volcanic and meta-sedimentary rocks with their associated plutonic equivalents, together with Tertiary and Quaternary basalt flows and alluvial sediments which cover part of the Precambrian rocks (Al Shanti, 1993). The following is a summary compilation of the geology of the study area based on the work of Brown *et al.* (1963); Pallister (1986), Ziab and Ramsay (1986), and Moore and Al-Rehaili (1989) (Fig. 2).

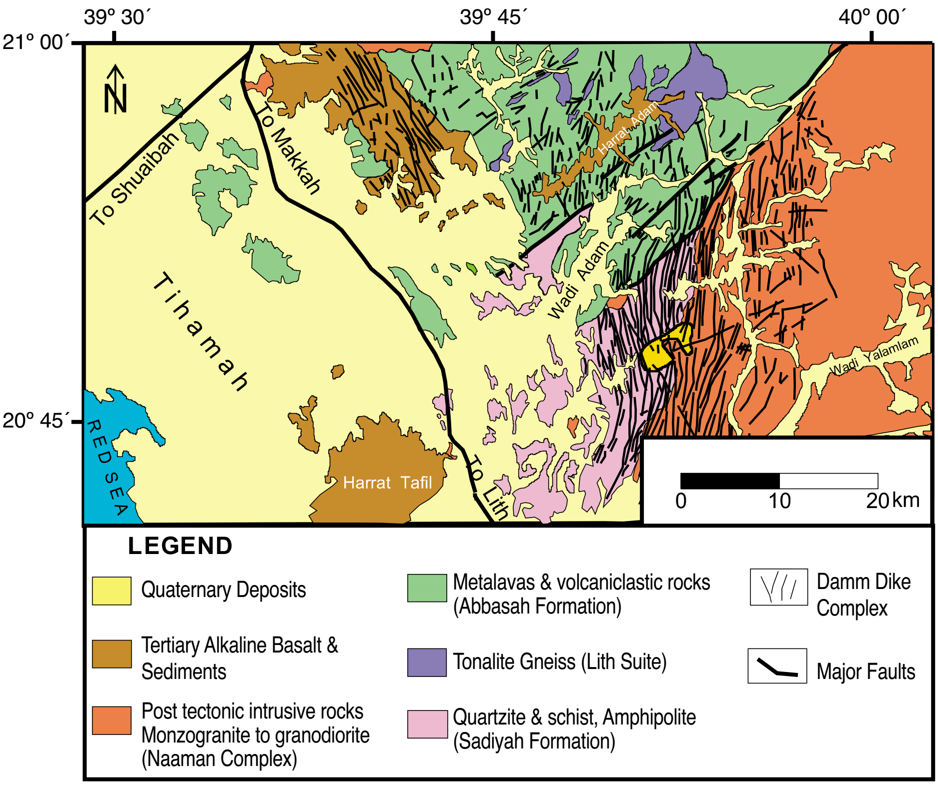

FIG. 2. Geologic map of Wadi Adam (after Pallister, 1986).

Precambrian Rocks

The late Precambrian rocks are classified into layered and intrusive rocks. The layered rocks consist of volcanic, volcanoclastic, and metamorphic rocks, which are intruded by igneous bodies.

In the southwest of the study area the oldest layered rocks, Sa'diyah Formation, consist of quartizite, schist, marble and amphibolite. This formation is mainly metasedimentary in nature and is located in the southern part of the study area (Fig. 2.). These rocks are locally interlayered with Baish group, and probably rank among the oldest units in the area. This formation was metamorphosed and suffered multiphase deformation during geological time.

In the eastern part of the study area, a post tectonic intrusive rock suit occurs and is called Naaman Complex. This complex is a northeast-trending, elongated granite-gneiss batholith. Most of the Shafa and Hada mountains belong to Naaman complex. This batholith intrudes rocks of the oldest layered units.

Abbasah Formation, in western side of Wadi Adam, consists of metamorphic lavas and associated volcaniclastic rocks that range in composition between basaltic and rhyolitic which are metamorphosed to paragneisses and schists (Smith, 1980). These rocks are isoclinally folded and correlated with Sa'diyah formation in the south of the study area. Pre-Kamil Suite, in the north of the study area, consists mainly of diorite to quartz diorite, metagabbro and gabbro rocks.

Tertiary Rocks

Two main rock units of the Tertiary rocks of Wadi Adam are Adam dike complex and Harrat Adam. Adam dike complex includes alkali basalt, Hawaiite, trachyte, dacite, and rhyolite dikes. Most of the dikes are parallel and mainly trend in the north-south direction. These dikes are also predominant downstream of the main channel of Wadi Adam, and they may affect the flow of subsurface water (Kotb *et al.*, 1990). Harrat Adam is an alkali basalt flow, which crops out in the northwest of Wadi Adam. It consists of olivine, olivine-plagioclase, and porphyritic basalt rock fragments. The lava flows are non-vesicular to moderately vesicular. Harrat Adam unconformably overlies Precambrian rocks (Fig. 2).

Quaternary Deposits

Quaternary deposits in the study area are bounded by and overlie the Precambrian rocks in the eastern parts of the study area. They are of continental origin, while in the alluvial plain these deposits start to overlap and mix with marine sediments and soils in the coastal zone. There is a general agreement among several authors that the coastal plain including both alluvial and marine deposits belongs to the Quaternary period (Brown *et al.*, 1963; Al Sayari and Zölt, 1978).

Alluvial deposits consist of unconsolidated sand, silt, and gravel deposited in the wadi channels and outwashed plains. They also occur as terrace deposits along Wadi Adam and as fan deposits close to the Red Sea shore as well as at the foot of the coastal hills. This soil unit is grayish yellow to brown in color, but has dark bluish color tone on satellite images due to the tarnished granodioritic gravels on the surface. The average thickness of these deposits increases from 2 m in the upstream of the wadi to 20 meters in the downstream near the main coastal road (Fig. 2).

Geological Structure

The recent geological studies have showed that the Arabian Shield has been deformed by a series of orogenic episodes and by younger major fault system. Uplifts and faulting have resulted in steep escarpment faces along the Red Sea coast through which numerous wadis cut down their valleys with torrents such as in deep valleys, these eventually move slowly across the coastal plain, and frequently reach the Red Sea. During the Tertiary time, Adam fault was activated along the north-western margin in the study area with north-west trend. The dikes trend mainly in the north-west direction. The eruption of basaltic flows in the area (Harrat) has occurred mostly along fissures with the dikes previously mentioned constituting their feeders.

Another faulting event occurred during Oligocene and Miocene which gave rise to the formation of the Red Sea Graben. The northwest-trending Quaternary faults are in the form of concealed fault zone parallel to Red Sea, which is related to Shua'iba fault. This fault has resulted in the formation of the sabkhas and extensive alluvial gravels in the lower course of wadi system (Matsah *et al*., 2004).

Rainfall Distribution

Over the study area, rainfall distribution is quite variable both in space and in time. The rainfall often occurs as thunderstorms of very high intensity during a local storm followed by dry periods. The rainfall data used in this paper were collected from the Hydrology division of the Ministry of Water and Electricity. The available rainfall records cover a period of 15-20 years. Some of the stations with long enough records of rainfall were chosen based on the following criteria: (1) that they provide a good spatial coverage of the region; (2) that they maximize the same monthly precipitation records; (3) that they have continuous monthly precipitation records; and (4) that they represent all different climatic conditions. Generally, rainfall in the study area is located under the influence of subtropical and orographic conditions.

The mean annual rainfall distribution presented in (Fig. 3), demonstrates the spatial variation of rainfall which strongly reflects the effect of topography, where the annual rainfall generally increases with elevation (orographic effect). Generally, the isohyetal lines passing through Adam basin range from 130 to 210 mm/year with a mean of 150 mm/year, which indicate that these basin areas receive reasonable amount of annual rainfall (Subyani, 2005).

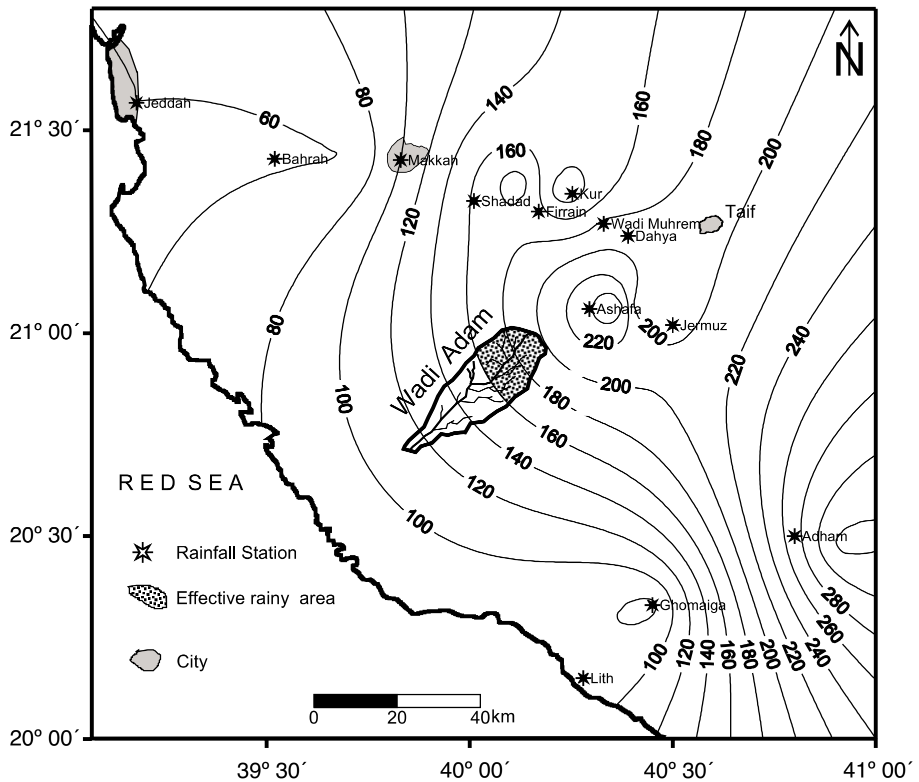

FIG. 3. Mean annual rainfall distribution over Adam basin.

Hydrogeological Features

Intensive hydrogeological fieldwork was carried out during the present study. The field activities covered Adam basin and included a well-point inventory, pumping tests and a collection of aquifer material samples for laboratory tests. A total of 16 wells are scattered along the main channel (Fig. 4). Details of the well inventory are given in Table 1. These wells are grouped into two cat-

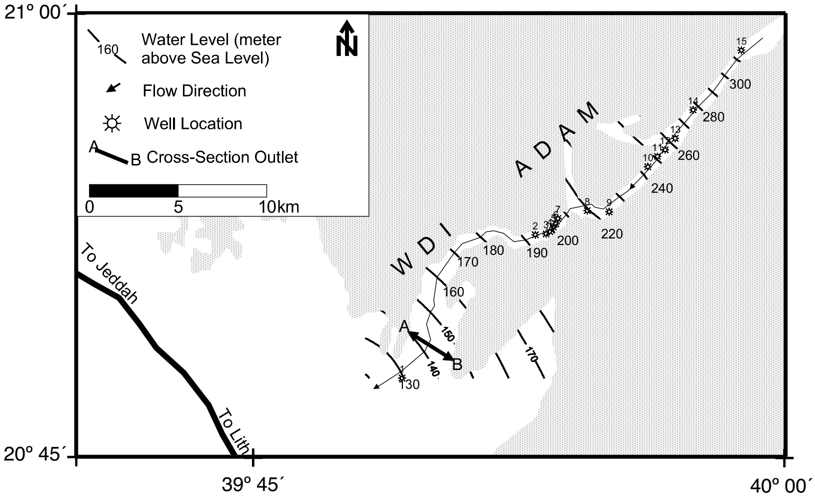

FIG. 4. Water table contour map of Wadi Adam.

TABLE 1. Well-point inventory of Wadi Adam.

Well no.	Easting (m)	Northing (m)	Elevation (masl)	Well type	Diam. (m)	Depth to water (m)	Total depth (m)	E.C	ph	Temp. (ºC)	Remark
1	583376	2304430	140	L	3	21.2	25	4300	7.48	33	Dp, 10hr
2	590892	2312509	203	L	3	9.46	22	3050	7.22	33	Dp, 10hr
3	591501	2312567	206	S	0.3	8.37	18.4	2570	7.3	33	Dp, 10hr
4	591700	2312700	208	S	0.3	uk	uk	2600	7.06	30	Dp, 10hr
5	591921	2312945	208	L	3	uk	uk	2530	7.2	32	Dp, 10hr
6	592047	2313128	209	S	0.3	7.66	uk	2790	7.25	35	Dp, 7hr
7	592162	2313431	212	S	0.3	7.4	uk	2590	7.22	26	Dp, 1hr
8	593820	2313875	226	L	3	6.45	10.35	2260	7.55	33	Dp, 6hr
9	595053	2313812	233	L	3	8.82	14	2370	7.4	32	Dp, 1hr
10	597235	2316344	252	L	3	9.5	15	1690	7.1	34	Dp, 6hr
11	597778	2316931	268	L	3	10.7	11.73	1570	7.12	37	Dp, 6hr
12	598211	2317302	272	L	3	uk	uk	1533	7.24	29.8	Dp, 6hr
13	598778	2317942	276	L	3	13.3	14.4	1880	7.06	37	Dp, 6hr
14	599784	2319547	292	S	0.3	15	20.7	1650	7.44	35	Dp, 6hr
15	602503	2322909	340	L	3	25	27	1280	7.89	39	Dp, 6hr
16	592953	2314303	225	S	0.3	8.24	uk				P

masl = meters above sea level, L = large-diameter well, S = small-diameter drilled borehole, P8 = piezometers, Uk = unknown, Dp = daily pumping, hrs = hours.

egories; large-diameter (hand-dug) and small diameter wells. Electrical conductivity, pH and temperature of groundwater were measured *in situ.*

Water Table

An adequate number of data points were found along the midstream parts of the wadi so contours could be drawn with a certain degree of accuracy. The data points comprise static water levels measured in the wells. It is obvious from the measured water table contour map of the Wadi Adam that the regional groundwater flow direction is towards the south-west following the major trend of the main wadi channel (Fig. 4). The gradient of the water level varies from one area to another depending on the pumping rates. Along the upper part of the wadi, the general hydraulic gradient is in the order of 0.01. This gradient decreases, however, in downstream of the wadi to 0.005, possibly reflecting an increase in the hydraulic conductivity of the aquifer material. There are no data points at the outlet of the wadi, which makes it impossible to draw contour lines beyond that area. The volume of groundwater flowing through any cross-section of the main channel can be calculated once the transmissivity of the aquifer material is estimated.

Hydraulic Properties of the Aquifer

It is essential in any groundwater study to determine the so-called hydraulic properties of the aquifer, also called formation constants. The constants that are involved comprise the hydraulic conductivity (K), transmissivity (T) and the storage coefficient (S). (T, S and K) appear in almost all text books of groundwater (Todd, 1980; Kruseman and de Ridder,1989).

Since hydraulic conductivity represents the ability of a porous medium to transmit water through its interconnected voids, certain relationships are expected to exist between hydraulic conductivity and statistical parameters that describe the particle size distribution of the material. Eleven soil samples were collected from Wadi Adam. Attempts of estimating the hydraulic conductivity by applying a method developed by Alyamani and Şen (1993) that incorporate the initial slope and intercept of the grain size distribution curve. The equation is expressed as:

$$K = 1300\,[I_0 + 0.025\,(d_{50} - d_{10})]^2$$

Where K = hydraulic conductivity (m/day); I_0 = x-intercept of the slope of the line formed by d_{50} and d_{10} of the grain size distribution curve (mm); d_{50} = average diameter of grain size (mm); and d_{10} = effective size (mm).

The hydraulic conductivity values obtained from the grain-size analysis for Wadi Adam are given on Table 2. The average hydraulic conductivity value calculated for Wadi Adam is 18 m/day, which is reasonable value for alluvial materials.

TABLE 2. Effective and mean sizes, uniformity coefficients and hydraulic conductivity calculated for soil samples from Wadi Adam.

Sample no.	Effective size d_{10} (mm)	Mean size d_{50} (mm)	60% size D_{60} (mm)	Uniformity coefficient (d_{60}/d_{10})	I_0	K (m/day)
S1	0.18	0.36	0.41	2. 3	0.12	20.2
S2	0.17	0.36	0.41	2.41	0.1	14.3
S3	0.18	0.36	0.41	2.28	0.1	14.2
S4	0.13	0.45	0.6	4.6	0.08	10.0
S5	0.17	0.33	0.4	2.35	0.07	7.1
S6	0.15	1	1.4	7.8	0.1	19.1
S7	0.25	0.7	1.2	4.8	0.15	33.8
S8	0.21	0.7	1.2	5.71	0.12	22.7
S9	0.17	0.7	1.2	7.06	0.08	11.3
S10	0.26	0.7	1.2	4.62	0.16	38.0
S11	0.15	0.63	0.93	6.2	0.08	11.0
Mean						**18.3**

The collected samples cannot be considered as real representatives of the aquifer material. Therefore, pumping test procedures may give reasonable results for aquifer properties (Alyamani and Şen, 1993).

Pumping Tests

Pumping tests were carried out in the study area and there are several methods available for pumping test data analyses. The choice of a certain method for a certain test is based mainly on how far the field conditions and aquifer type are closed to such a method, though almost all field conditions are far from ideal in the sense used by Theis (1935). Based on the above mentioned boundary conditions the following analytical methods were found most suitable such as Slope-matching method (Şen, 1986); Large-diameter wells (Papadopulos and Cooper's, 1967); Unconfined aquifers (Boulton's method, 1963); and Theis recovery method (1935).

The basis of each method, analysis of data and its ability to predict aquifer behavior can be obtained from the original papers as mentioned in references. Two tested wells were carried out for pumping and recovery tests. Table 3 shows the results from different methods, the average transmissivity vary from124 to 142m^2 day^{-1}. Using the criteria given by Gharghe (1979), it follows that the aquifer in this area is of moderate potential. On the other hand, the average storativity varies from 0.1 to 0.2, which is typical for unconfined aquifers.

TABLE 3. Transmissivity (m^2/day) and storativity values obtained for Wadi Adam.

Well no.	Slope matching method (Şen.)		Boulton method		Papadopulos & copper method		Recovery method	Average	
	T	S	T	S	T	S	T	T	S
1	–	–	118	0.29	130	0.12	–	124	0.21
2	247.7	0.11	46.8	0.11	166	0.09	109.4	142.5	0.1

Groundwater Recharge and Discharge

In arid regions, groundwater recharge is exclusively based on the rainfall, recharge determination is usually very difficult, because great changes in the spatial and temporal distribution of the hydrologic inputs and outputs lead to large uncertainties in determining the recharge either locally or regionally.

However, there is a relatively straightforward way of estimating groundwater recharge by considering the chloride ion as a tracer, which is concentrated by evaporation, and it is defined as a chloride mass-balance method (CMB) (Wood and Imes, 1995; Wood and Sanford., 1995; Flint *et al*., 2002). It has become a useful operational tool in determining the amount of recharge. This technique involves the using of chloride-ion concentration ratio in rainfall to chloride-ion concentration in groundwater.

In the chloride mass-balance method, recharge is computed from the following relationship:

$$q = R_{eff}\ Cl_p / Cl_{gw}$$

where q is the recharge (mm/year), R_{eff} is the effective rainfall (mm/year), Cl_p is the average chloride concentration of rainfall (mg/l), and Cl_{gw} is the average chloride concentration of groundwater.

In Adam basin, the average chloride concentration of the rainwater, Cl_p = 8 mg/l (this value were taken as an average of six rainfall samples around the study area) (Subyani *et al*., 2004). Chloride concentration in groundwater as shown in Table 4 represents down stream portion of Wadi Adam and does not meet the conditions of CMB method (Wood, 1999). However, an average of five groundwater samples in the mountains area as:, Cl_{gw} = 100 mg/l (Bazuhair *et al.*, 2002; Sharaf *et al.*, 2004). The average annual rainfall over the escarpment or effective rainy area between contour lines 160-200 mm, as shown in (Fig. 3), is about 180 mm yr^{-1}. The recharge rate, therefore, is about 18 mm yr^{-1}. This represents less than 10% of the annual rainfall, which means that more than 90% of rainwater is lost either as surface runoff or by evapotranspiration. These calculations are compatible with many studies in arid areas (Bazuhair *et al.*, 2002; Edmonds, 2002; Subyani, 2004).

In the study area, the annual recharge volume can be calculated as:

$$\text{Recharge Volume} = \text{Mean annual rainfall} \times \text{Effective area} \times \text{Recharge rate}$$

The effective area of the basin is taken as the moderate to high altitude areas in which most of the year rainfalls (about 45% of the basin). See (Fig. 3).

Hence, for Adam basin, the annual recharge can be calculated as:

$$\text{Recharge Rate} = 180\ \text{mm} \times (380 \times 0.45)\ \text{km}^2 \times 0.1 \approx 3 \times 10^6\ \text{m}^3\ \text{year}^{-1}.$$

Naturally, the groundwater in Wadi Adam is discharged into the Red Sea. The amount of this discharge volume has been estimated by Darcy's law to the portion of the aquifer at cross section. The cross-section extends for 3 km (Fig. 4). Using the average values of both the aquifer transmissivity (133 m^2 day^{-1}) and the hydraulic gradient near the cross section (0.006) yields an estimated flow rate of about 0.9 million m^3 annually. Artificial abstraction by pumping all wells in the Adam basin is about 198,000 m^3/year, which is very low compared to the natural discharge into the Red Sea.

Hydrochemical Features

Hydrochemistry is the subject that relates groundwater and its dissolved materials with the environment surrounding them, and therefore, it is considered an essential part of any hydrogeological study. The dissolved constituents in the groundwater can be very useful in indicating the geological evolution; the mode of the groundwater origin within the hydrological cycles; soil or rock mass influences and its influence on the borehole materials such as screen and casing.

During the fieldwork, 15 water samples were taken after intensive pumping of the wells in order to avoid any local contamination or evaporation. The samples were analyzed for the major ionic constituents Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}, and for the secondary and trace constituents such as Fe, Mn, Pb, As and others. The analyses were done in the laboratories of the Faculty of Earth Sciences using ICP-Optical Emission Spectrometer (OES), Optima 2000 DV, Perkin Elmer Instrument.

In addition, water temperature, electrical conductivity, and pH were measured *in situ*. Partial pressure of carbon dioxide (P_{CO2}) and saturation indices for calcite (SI_{cal}), dolomite (SI_{dol}), gypsum (SI_{gyp}) and halite (SI_{hal}) were computed, using "AquaChem" program developed by Waterloo Hydrogeologic (1999).

Results and Discussion

All the chemical analyses results for the major ions and the field of the groundwater samples in Wadi Adam were summarized in Table 4. which show the analysis of major constituents of the groundwater, in addition to the total dissolved solids (TDS), field electrical conductivity (EC), pH, and temperature. TDS in groundwater vary from 790 to 2750 mg/l with a mean and a standard deviation of 1500 and 507 mg/l, respectively. EC of the groundwater varies from 1280-4300 μS/cm with a mean and a standard deviation of 2311 and 767 μS/cm, respectively. The groundwater tends to be slightly balanced with pH values ranging from 7.2-7.6. On the other hand, the analysis results indicated that the chemical composition of the groundwater varies between low to moderate concentrations in most of the chemical constituents. In order to decipher the water type, the Durov diagram was used, (Fig. 5). Accordingly, Wadi Adam is characterized by a Ca^{+2}-SO_4^{-2} water type in its middle part and a Na+-Cl- water type in its lower part. This simple dissolution or water type change from calcium sulfate to sodium chloride water type distinctly matches the ion exchange and natural general flow of groundwater. In addition, Fig. 5 shows that there is systematic change in the major ions within the length of flow along the channel. This condition might reflect the active recharge area as shown in Fig. 3. (Lloyd and Heathcote, 1985; Wanielista *et al.*, 1997). Generally, the major ionic concentration of the groundwater shows the following general pattern as

$$Ca^{2+} > Na^{+} > Mg^{2+} > K^{+} \quad \text{and} \quad Cl^{-} > SO_4^{2-} > HCO_4^{-}$$

The saturation state of minerals in the water can be expressed by the saturation index (SI). When the SI < 1, the minerals will be dissolved; and when the SI is >1, the minerals will be deposited. SI indices of calcite and dolomite for the groundwater samples of Wadi Adam are shown in Table 4. All of the samples have positive calcite and dolomite indices, indicating a slight oversaturation. For halite and gypsum, all indices are negative, which indicates under-saturation state (Freeze and Cherry 1989).

Within the study area, the dissolution processes for calcite and dolomite would be considered with a relatively large reservoir of $CO_{2(g)}$ in the surficial zone. The high P_{CO2} values (Table 4) provide dissolved CO_2. That means the H_2CO_3 supplies the inputs in the calcite and dolomite dissolution (Freeze and Cherry 1989; Alyamani 1999). Figure 6 shows the regression line between total

TABLE 4. Chemical analysis of major ions of groundwater samples in Wadi Adam (mg/l).

Well no.	SO_4^{2-}	Cl^-	HCO_3^-	Na^+	Ka^+	Ca^{2+}	Mg^{2+}	TDS	E.C.	pH	Total hardness	P_{CO2}	SI_{cal}	SI_{dol}	SI_{gyp}	SI_{hal}
1	394.3	942.2	137	360	21.2	307.4	63.23	2746	4300	7.6	1028	–2.37	0.48	0.7	–0.8	–0.98
2	221.4	597.7	150	85	19.5	291.4	73.2	1976	3050	7.3	1029	–2.06	0.31	0.44	–1.01	–1.19
3	179.5	532.6	157	81	18.02	260.5	61.53	1724	2570	7.33	903	–2.12	0.38	0.55	–1.11	–1.29
4	191	539.6	163	79	18.3	257.7	66.64	1728	2600	7.25	917	–1.91	0.23	0.32	–1.1	–1.27
5	182.8	522.1	157.8	78.5	17.8	251.3	62.26	1686	2530	7.5	883	–1.89	0.09	–0.03	–1.11	–1.3
6	225.6	574.8	145	90	18.9	276.3	72.23	1886	2790	7.3	987	–2.09	0.33	0.51	–1.02	–1.19
7	191	539.7	150	75	18.2	249.7	62.5	1712	2590	7.35	880	–2.07	0.2	0.15	–1.08	–1.3
8	162	421.9	185	65	14.6	214.8	52.04	1452	2260	7.25	750	–2.29	0.63	1.07	–1.19	–1.37
9	172.9	451.8	220	68	13.8	221.2	53.02	1508	2370	7.36	770	–1.74	0.29	0.4	–1.16	–1.34
10	145.7	263.7	180	40	12.5	171.1	37.94	1094	1690	7.42	583	–1.83	0.13	0.03	–1.26	–1.44
11	122.7	233.8	202	38	12.3	149.5	36.48	988	1570	7.37	523	–1.78	0.19	0.22	–1.37	–1.53
12	130.9	223.2	195	36	12.8	151	34.05	990	1533	7.35	517	–1.96	0.21	0.16	–1.33	–1.53
13	141.6	321.7	221	45	13.6	187.1	37.94	1224	1880	7.26	623	–1.68	0.24	0.24	–1.26	–1.42
14	122.6	240.8	236	40	11.9	151.5	34.53	1024	1650	7.38	520	–2.03	0.56	0.93	–1.37	–1.54
15	103.7	186.3	200	35	10.8	120.2	25.29	792	1280	7.6	404	–2.55	0.89	1.57	–1.49	–1.63
Mean	179.2	439.5	179.92	81	15.61	217.4	51.53	1502	2311	7.4	754.467	–2.02	0.34	0.48	–1.18	–1.36
STD	69.5	201.6	31.3	79.8	3.3	58.9	15.7	507.3	767.2	0.11	210.4	0.24	0.215	0.433	**0.18**	**0.17**

TABLE 5. Chemical analysis trace elements of groundwater samples in Wadi Adam (mg/l).

Sample no.	Zn	Pb	Cd	Ni	Ba	Fe	Hg	Cr	Cu	U	Al	Li
1	0.072	0.002	0.002	0.004	0.099	0.007	0.197	0.003	0.017	0.004	0.0001	0.011
2	0.009	0.003	0.001	0.003	0.459	0.009	0.103	0.001	0.017	0.036	0.0001	0.01
3	0.058	0.009	0	0.003	0.52	0.007	0.078	0.001	0.016	0.03	0.0012	0.01
4	0.005	0.002	0.001	0.003	0.396	0.007	0.059	0.001	0.016	0.031	0.001	0.011
5	0.001	0.004	0	0.003	0.378	0.008	0.042	0.001	0.015	0.031	0.001	0.008
6	0.001	0.001	0	0.002	0.506	0.007	0.042	0	0.016	0.014	0.0001	0.009
7	0.001	0.002	0.001	0.003	0.465	0.008	0.022	0	0.016	0.034	0.001	0.01
8	0.459	0.006	0	0.003	0.339	0.006	0.008	0.001	0.008	0.04	0.0022	0.01
9	0.05	0.002	0.001	0.003	0.207	0.005	0.008	0.001	0.012	0.035	0.0022	0.01
10	0.008	0.011	0.001	0.002	0.347	0.007	0.0006	0.003	0.01	0.02	0.0046	0.004
11	0.012	0.014	0	0.003	0.291	0.007	0.0008	0.001	0.01	0.02	0.0056	0.007
12	0.009	0.014	0	0.003	0.293	0.006	0.0008	0.002	0.011	0.031	0.0062	0.008
13	0.013	0.012	0.001	0.003	0.226	0.008	0.0005	0.004	0.01	0.042	0.0036	0.09
14	0.076	0.019	0	0.002	0.225	0.008	0.0002	0.002	0.006	0.045	0.0055	0.009
15	0.015	0.005	0	0.003	0.134	0.007	0.0003	0.001	0.029	0.015	0.0081	0.008
Mean	**0.053**	**0.007**	**0.0005**	**0.003**	**0.33**	**0.007**	**0.037**	**0.001**	**0.014**	**0.031**	**0.0028**	**0.0091**
STD	**0.115**	**0.005**	**0.0006**	**0.0005**	**0.131**	**0.001**	**0.054**	**0.001**	**0.005**	**0.012**	**0.0025**	**0.0020**

dissolved solids and electrical conductance for 15 groundwater samples in Wadi Adam. This line gives the equation:

$$TDS = 0.65EC$$

The constant (*e.g.* A = 0.65) within the normal value in the literatures.

The fifteen groundwater samples were also analyzed for most toxic metals in milligram per liter and tabulated in Table 5. All of these trace elements concentration are generally acceptable within the normal limits according to the International and Saudi Standards.

Conclusion

Wadi Adam comprises a major undeveloped groundwater aquifer near Makkah area. This basin constitutes potential strategic water resource for Makkah Al-Mukarramah area. It drains a small catchment of about 380 km^2. This catch-

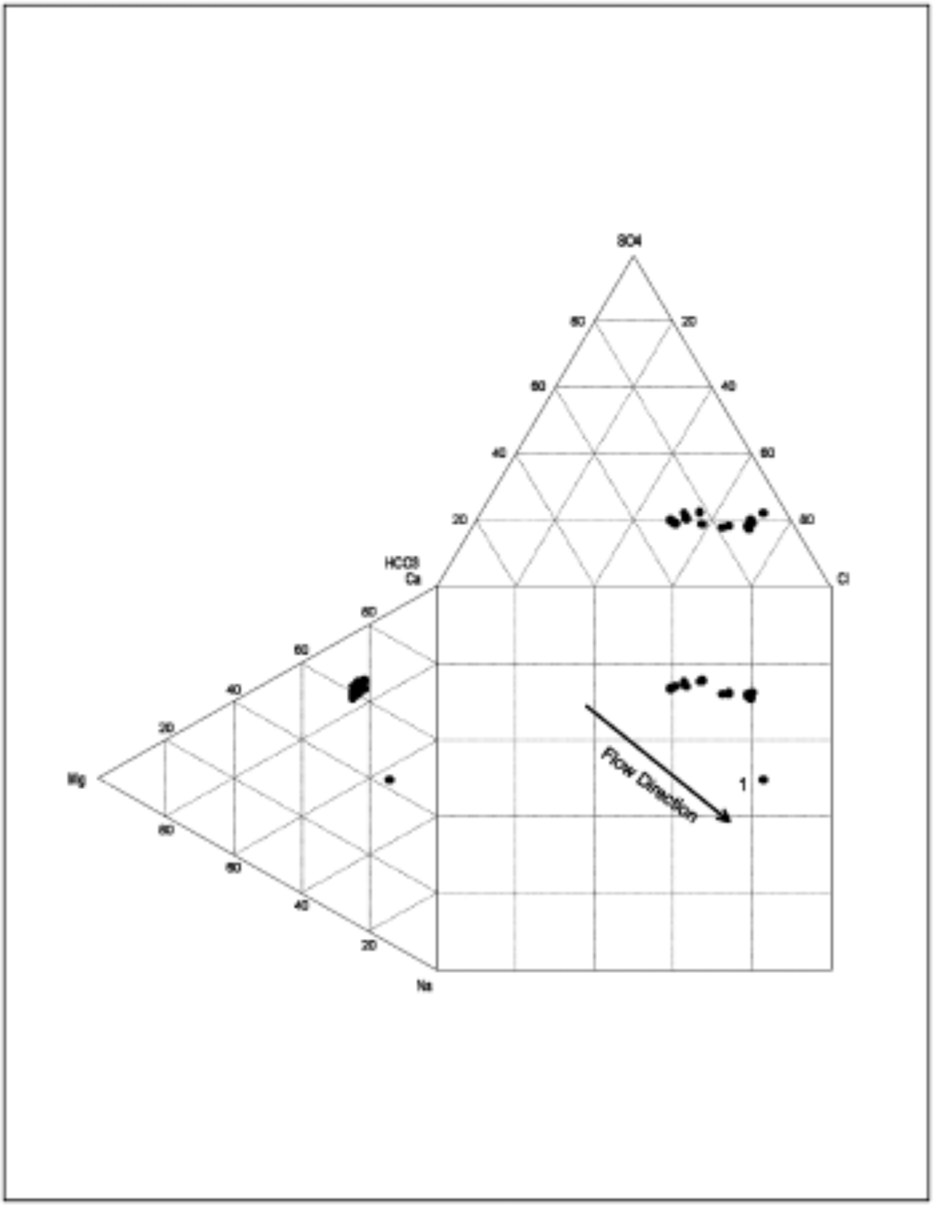

FIG. 5. Durov diagram for groundwater chemistry in Wadi Adam.

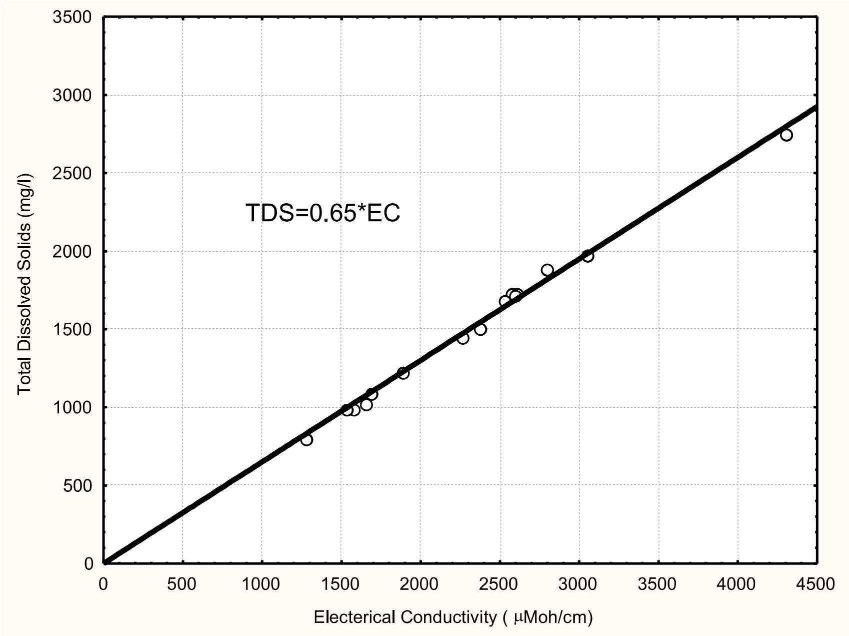

FIG. 6. EC-TDS relation of groundwater in Wadi Adam.

ment starts from the Hijaz Escarpment in the east to the Red Sea in the west. The average annual rainfall exceeds 180 mm in the mountains and decreases to 100 mm in the Red Sea coast.

Subsurface investigation indicated that water-bearing formations consist of alluvial deposits and top weathered zone of the basement rocks as an unconfined aquifer. More than 16 wells have been drilled in Wadi Adam abstracting about 550 m^3 day^{-1}. The Regional groundwater flow is toward the south and southwest and the average hydraulic gradient along the wadi is in the order of 0.008 and decreases slightly towards the downstream areas. From pumping test methods, the average transmissivity value is about 142 m^2 day^{-1}, and the storativity is about 0.1, which indicates that the aquifer is of moderate potential. The recharge rate to this basin, using chloride mass-balance method, is about 3×10^6 m^3 $year^{-1}$. The amount of the natural discharge into the sea is about 0.9 million m^3 $year^{-1}$.

Groundwater quality of Adam basin has been investigated for major cations and anions, and trace element analysis. Two types of groundwater exist; Calcium sulfate in the upstream and Sodium chloride in the downstream area. TDS range between 790 to 2750 mg/l. Analysis of trace elements shows that the concentration is less than the national and international standard limits.

References

Al-sayari, S. and **Zötl, J.** (1978) *Quaternary Period in Saudi Arabia*, Springer-Verlag, Wien, New York, p. 334.

Al-shanti, A. (1993) *Geology of the Arabian Shield* (Arabic), King Abdulaziz Univ. Publ., Jeddah, Saudi Arabia, p. 196.

Alyamani, M.S. and **Şen, Z.** (1992) Regional variation of monthly rainfall amounts in the Kingdom of Saudi Arabia, *J. KAU: Earth Sciences*, **6:** 113-133.

Alyamani, M.S. and **Şen, Z.** (1993) Determination of hydraulic conductivity from complete grain-size distribution curves, *Ground Water*, **31**(4): 551-555.

Alyamani, M.S. (1999) Salinity problem of groundwater in the Wadi Tharad Basin, Saudi Arabia, *GeoJournal*, **48:** 291-297.

AquaChem. (1999) *Aqueous Geochemical Analysis, Plotting and Modeling*, Waterloo Hydrogeologic, Inc. V.3.7.

Bazuhair A.S., Nassief, M.O., Al-Yamani, M.S., Sharaf, M.A., Bayumi, T.H. and **Ali, S.** (2002) *Groundwater Recharge Estimation in Some Wadi Aquifers of the Western Saudi Arabia*, King Abdulaziz City for Science and Technology; Project No. AT-17-63, Riyadh, Saudi Arabia.

Boulton, N.S. (1963) Analysis of data from non-equilibrium pumping test allowing for delayed yield from storage, *Proc. Inst. Civil Eng*., **26**(6693): 469-482.

Brown, G.F., Jackson, R.O., Bogue, R.G. and **MacLean, W.H.** (1963) *Geology of the Southern Hijaz Quadrangle, Kingdom of Saudi Arabia: DGMR*, Misc. Geologic Inves. Map I-210A, 1:500,000 scale.

Edmunds, W.M., Fellman, E., Goni, I.B. and **Prudhomme, C.** (2002) Spatial and temporal distribution of groundwater recharge in northern Nigeria, *Hydrogeology Journal*, **10:** 205-215.

El-Khatib, A. (1980) *Seven Green Spikes*, Ministry of Agriculture and Water, Riyadh, Saudi Arabia, p. 362.

Flint A.L, Flint, E., Kwicklis, A. and **Bodvarsson, G.** (2002) Estimation recharge at Yucca Mountain, Nevada, USA, comparison methods, *Hydrogeology Journal*, **10:** 180-204.

Freeze, A. and **Cherry, J.** (1979) *Groundwater*, Prentice Hall, New Jersey, p. 604.

Gharghe, A. (1979) *Processing and Synthesis of Hydrogeological Data*, Abacus Press, Tundridge Wells, Kent.

Kotb, H., Hussein, M.T. and **Zaidi, S.** (1990) Groundwater Quality of Damm Area, Saudi Arabia, *J. KAU: Earth Sciences*, **3:** 241-250.

Kruseman, G.P. and **De Ridder, N.A.** (1989) *Analysis and Evaluation of Pumping Test Data*, 4th ed., International Inst. for Land Reclamation and Improvement, Wageningen, The Netherlands.

Lloyd, J.W. and **Heathcote, J.A.** (1985) *Natural Inorganic Hhydrochemistry in Relation to Groundwater, An Introduction*, Oxford University Press, New York.

Matsah, M.I., Qari, M.H., Hegazi, A.M., Amlas, M. A. and **Hamimi, Z.** (2004) The Neoproterozoic Ad-Damm Shear Zone: Dextral Transpression in the Arabian Shield, Saudi Arabia, *Egypt. J. Geol.* (Under Publication).

Fourth Development Plan (1985) Ministry of Economic and Planning, Kingdom of Saudi Arabia.

Fifth Development Plan (1990) Ministry of Economic and Planning, Kingdom of Saudi Arabia.

Moore, T.A. and **Al-Rehaili, M.H.** (1989) *Geologic Map of Makkah Quadrangle, Sheet 21D, Kingdom of Saudi Arabia: DGMR*, Geoscience map GM-107C, 1:250,000 scale.

Pallister, J.S. (1986) *Geologic Map of Al-Lith Quadrangle, Sheet 20D, Kingdom of Saudi Arabia: DGMR*, Geoscience map GM-95, 1:250,000 scale.

Papadopoulos, I.S. and **Cooper, H.H.** (1967) Drawdown in a well of large diameter, *Water Res. Res.*, **3**(1): 241-244.

Saudi Arabian Dams and **Moore** (1988) Ministry of Agriculture and Water, Water resources development, Al-Lith Basin, Final Report, Vol. E.

Saudi Arabian Dams and **Moore** (2001) Hydrogeological Studies of Wadi Malakan Basin, Water and Sewage Authority of Makkah Al-Mukarramah, Final Report, 3 vol. (in Arabic).

Şen, Z. (1983) *Hydrology of Saudi Arabia, Symposium on Water Resources in Saudi Arabia*, Riyadh, P. A68-A94.

Şen, Z. (1986) Determination of aquifer parameters by slope matching method, *Groundwater*, **24:** 217-223.

Sharaf, M.A., Al-Yamani, M.S. and **Subyani, A.M.** (2004) *Regional Study of Rare and Trace Elements in the Groundwater of Major Wadi Basins (An Numan, Usfan, and Fatima) in Western Saudi Arabia and their Suitability for Various Purposes (Municipal, Agricultural and Industrial)*, Project No. 204/423, Final Report, King Abdulaziz Univ., Jeddah, p. 214.

Smith, J.W. (1980) *Reconnaissance Geology of At Tai'f Quadrangle, Sheet 21/40C*, *Kingdom of Saudi Arabia*, Saudi Arabian Deputy Ministry for Mineral resources Geologic Map GM-56, scale 1:100,000, 33p.

Sogreah (1968) *Water and Agricultural Development Survey for Area IV*, Final Report, Ministry of Agriculture and Water, Riyadh, Saudi Arabia.

Subyani, A.M. (1999) Topographic and Seasonal Influences on Precipitation Variability in Southwest Saudi Arabia, *J. KAU: Earth Sciences*, **11:** 89-102.

Subyani, A.M. (2004) Use of chloride mass-balance and environmental isotopes for evaluation of groundwater recharge in the alluvial aquifer, Wadi Tharad, Western Saudi Arabia, *J. Environmental Geology*, **46:** 741-749.

Subyani, A.M. (2005) Hydrochemical identification and salinity problem of groundwater in Wadi Yalamlam basin, Western Saudi Arabia, *J. Arid Environments*, **60:** 53-66.

Subyani, A.M., Bayumi, T.H., Matsah, M.I. and **Al-Garni, M.A.** (2004) *Quantitative and Qualitative Evaluation of Water Resources in Wadi Malakan and Wadi Adam Basins*, Makkah Area, Project No. 205/422, Final Report. King Abdulaziz Univ., Jeddah, p. 161.

Theis, C.V. (1935) The relation between the lowering of the piezometric and the rate and duration of discharge of a well using groundwater storage, *Trans. Am. Geophysical Union. Annl. Meet., 16th*, pp. 519-524.

Todd, D.K. (1980) *Groundwater Hydrology*, 2nd Ed., John Wiley and Sons, Inc, New York.

Torrent, H. and **Sauveplan, C.** (1977) *Orientation Map for Groundwater Exploration Related to Mineral Investigation in the Arabian Shield*, Bureau De Recherches Geologiques Et Minieres, Saudi Arabian Mission, BRGM Report 77 JED 13, Ministry of Petroleum and Mineral Resources, Jeddah, p.v6.

Wanielista, M., Kersten, R. and **Eaglin, R.** (1997) *Hydrology, Water Quantity and Quality Con*trol, 2nd Ed., John Wiley and Sons, Inc, New York.

Wood, W.W. (1999) Use and misuse of the chloride mass-balance method in estimating ground water recharge, *Groundwater*, **37:** 2-3.

Wood, W.W. and **Imes, J.L.** (1995) How wet is wet? Precipitation constraints on late Quaternary climate in the southern Arabian Peninsula, *J. Hydrol.*, **164:** 263-268.

Wood, W.W. and **Sanford, W.E.** (1995) Chemical and isotopic methods for quantifying groundwater recharge in a regional, semiarid environment, *Groundwater*, **33**(3): 458-468.

Ziab, A.M. and **Ramsay, C.R.** (1986) *Geologic Map of the Turabah Quadrangle, Sheet 21E, Kingdom of Saudi Arabia*, Saudi Arabian Deputy Ministry of Mineral Resources Geologic Map G.

الخصائص الهيدروجيولوجية والهيدروكيميائية لحوض وادي أدام ، منطقة مكة المكرمة

علي محمد الصبياني

قسم جيولوجيا المياه ، كلية علوم الأرض ، جامعة الملك عبد العزيز

جـــدة – المملكة العربية السعودية

المستخلص . يهدف هذا البحث إلى دراسة المصادر المائية كمًا ونوعًا في حوض وادي أدام ، حيث يقع مجمع وادي أدام حوالي ٥٠ كم جنوب مكة المكرمة ويصرف حوضًا مساحته حوالي ٣٨٠ كم^{٢} ، وبه عدة مزارع وبعض الآبار والتي تفي بحاجة السكان للأغراض المختلفة . وهذا الحوض يحده من الشرق خط توزيع المياه على قمم جبال السروات ، ومعدّل الأمطار السنوي يبلغ حوالي ١٦٠ ملم .

أنشئت خريطة لمستويات الماء للوادي مع حساب كمية التغذية بطريقة ميزان الكلور ، حيث بلغت حوالي ٣ مليون مترًا مكعبًا سنويًا ، وكمية المياه الخارجة من نهاية الوادي حوالي ٩ , ٠ مليون مترًا مكعبًا ، كما أجريت تجارب الضخ في وادي أدام ، حيث كان معامل النقولية ١٤٢ مترًا مربعًا يوميًا ومعامل التخزين ١ , ٠ .

أظهرت نتائج التحليل الكيميائي للماء الجوفي أن متوسط مجموع الأملاح الذائبة تبلغ حوالي ١٥٠٢ ملج/ لتر ، وهي صالحة للاستخدام الزراعي والبشري عدا الشرب ، أما العناصر الشحيحة والضارة ، فهي تحت المعدل المسموح به .