Hydrogeology and hydrochemistry of the aquifer system of Wadi An Numan, Makkah Al Mukarramah, Saudi Arabia

Mohammed Amin M. Sharaf

Abstract: The present study mainly deals with the hydrogeological and hydrochemical characteristics of the Wadi An Numan aquifer system in order to delineate the suitability of groundwater for municipal, agriculture and/or industrial usage.

The study area is situated in the western part of the Arabian Shield. Except with the Quaternary surficial deposits in the Wadi An Numan basin, the study area is covered mainly by late Precambrian plutonic rocks and minor amount (ca. 10%) of layered metavolcanic-metasedimentary rocks. The thickness of the Quaternary sedimentary fills composed of conglomerates, sandstones and mudstones in Wadi An Numan basin range from 3 to15 m in upstream areas to more than 50 m in the downstream. The highly weathered and fractured igneous and metamorphic bedrocks of An Numan basin are the ideal host for groundwater preservation.

There is a positive correlation between the SO_4 and Ca which indicate gypsum dissolution. Also, there is systematic change in the major ions within the length of flow along the main channel. The ions distribution maps show that the major constituents show increases in the downstream direction. The groundwater salinity is relatively low with EC measurements varied between 542 and 5400 µS/cm with an average of about 1539 µS/cm. Calcium-Chloride is the major water type in An Numan basin. Evaporation, recycling of irrigation water and chemical weathering reactions of silicate minerals are the dominant processes affecting the groundwater's chemical composition. The groundwater in the study area seems to be suitable for irrigation when compared with FAO quality criteria. The calculated values of SAR, Na (ppm), RSC, and Magnesium hazard indicate well to permissible use of groundwater for this aim..

Keywords: Saudi Arabia, Makkah District, Hydrology and hydrochemistry of Wadi An Numan, Groundwater aquifers in the western Arabian.

Mohammed Amin M. SHARAF ✉
Faculty of Earth Sciences, King Abdulaziz University
P.O. BOX 80206, Jeddah, 21589, Saudi Arabia
masharaf40@hotmail.com

Received: 25 december 2010 / Accepted: 26 february 2011

Riassunto: *Questo lavoro si occupa principalmente delle caratteristiche idrogeologiche e idrochimiche del sistema dell' acquefero del Wadi An Numan con lo scopo di definire la potabilità delle acque sotterranee per usi civili, per l'agricoltura e/o per l'industria.*

L'area di studio è situata nella parte orientale dell'Arabian Shield. Ad eccezione dei depositi Quaternari superficiali nel bacino del Wadi An Numan, l'area di studio è interessata prevalentemente da rocce plutoniche del tardo Precambriano e in parte minore (circa il 10%) da rocce metavulcaniche e metasedimentarie stratificate. Lo spessore dei depositi sedimentari Quaternari costituiti da conglomerati, arenarie e argilliti nel bacino del Wadi An Numan varia da 3 a 15 m nelle zone a monte, fino ad arrivare a 50 m in quelle più a valle. Le rocce ignee e metamorfiche del substrato, estremamente alterate e fratturate, nel bacino del Wadi An Numan, sono l'ambiente ideale per ospitare e conservare le acque sotterranee.

C'è una correlazione positiva tra SO_4 e Ca che indica la dissoluzione del gesso. Inoltre è presente un sistematico cambiamento nei maggiori ioni lungo tutto il flusso all'interno del canale principale. La rappresentazione della distribuzione degli ioni evidenzia che i costituenti maggiori mostrano un aumento nella direzione verso il basso. La salinità delle acque sotterranee è relativamente bassa: le misure di EC variano tra 542 e 5400 µS/cm con una media di 1539 µS/cm. L'acqua a base di Calcio/Clorite è il tipo più diffuso nel bacino del Wadi An Numan. Evapotraspirazione, riciclo dell'acqua da irrigazione, reazioni chimiche per l'esposizione agli agenti esogeni dei silicati sono i processi dominanti che interessano la composizione chimica delle acque sotterranee. Le falde nell'area di studio sembrano essere adatte quando vengono messe a confronto con i criteri FAO di qualità per l'irrigazione. I valori di rischio, calcolati su SAR, Na (ppm), RSC e Magnesio indicano che è consentito l'uso delle acque sotterranee per questo scopo.

Introduction and Geologic Setting

Location and climate

The study area lies within the western province of Saudi Arabia between latitudes 21º15' and 21º55' N and longitudes 39º15' and 40º30' E (Fig. 1). Three main basins are present in the western part of the Arabian Shield around Jeddah and Makkah cities i.e. Usfan, An Numan and Fatima (Fig. 1). An Numan basin includes: Dayqah, Arar, Rahjan and main channel of An Numan sub-basins which drain finally to the Red Sea coastal plain. Generally, the climate is typically arid and the rainfall is irregular and has a torrential nature. The rainfall occurs during the winter season, while in the autumn and spring the area is subjected to isolated events. The average annual rainfall is about 60 mm in the lowland areas, where, moving eastwards, rainfall increases to more than 170 mm/year. Such variation in the rainfall can be attributed to the orographic effects of the Red Sea escarpment.

DOI 10.4409/Am-027-11-0027

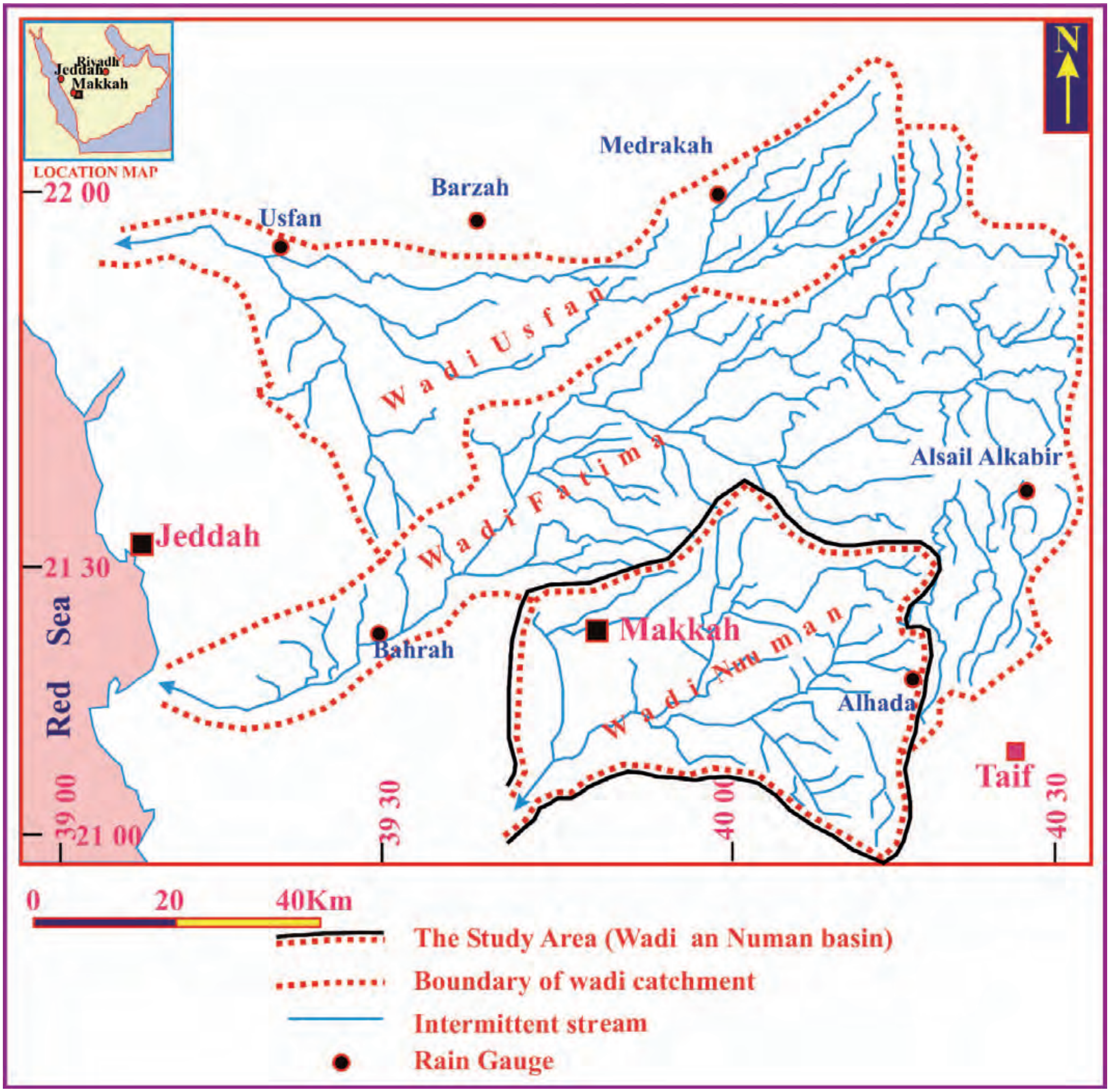


Fig. 1: *Drainage lines map of Makkah district showing the location of the studied Wadi An Numan Basin*

Previous Works

Several hydrogeological research activities were carried out in the study area since the early seventies.

Most of these works were concerned with the groundwater condition, aquifer characteristics and the groundwater quality in the wadi sediments (e.g. Italconsult, 1976; Al-Khatib, 1977; Al-Hajeri, 1977; Jamman, 1978; Al-Nujaidi, 1978; Al-Gamal and Sen, 1983; Mansour, 1984; Sharaf et al. 1988; Al Kabir, 1985; Basmci and Al-Kabir, 1988; Alyamani and Hussein, 1995; Alyamani et al. 1996; and Alyamani, 1999). A few studies concerned with the trace elements concentrations such as Mn, Pb, Si, Al, F and B in the groundwater are available (i.e. Bazuhair et al., 1992) outlined comprehensive investigations on groundwater condition included water chemistry within Khulais basin. Detailed hydrogeological and hydrochemical studies were carried out in Wadi Usfan by Sharaf et al. (2002). Several detailed studies regarding geological and geomorphological characteristics of the area around An Numan basin are available (e.g. Brown et al., 1963; Zaidi, 1983 and 1984; Moore and Al-Rehaili, 1989).

Objectives

The main objectives of this study are to clarify the concentration and distribution of the major ions and cations of the groundwater of An Numan basins. The main hydrochemical processes that affect the groundwater quality and the suitability of this water for agricultural uses are achieved.

Geomorphology and General Geology

An Numan basin originates mainly in the Hijaz Highlands. The drainage of the basins is generally well developed and the pattern is typically dendritic. Three distinctive geomorphologic zones in the study area are present, namely the mountainous region in the extreme east, the pediment region and the coastal plain. The mountainous region comprises mostly folded and faulted Precambrian rocks (Hijaz Highlands) and Tertiary lava flows (Harrat Rahat). They form a longitudinal block that extends from the north to the south. The pediments bound the mountainous region from the west and are marked by their elongated features, which trend in a westerly direction and sometimes appear as small knobs. The pediments are marked by a thin layer of alluvial and aeolian sediments resting on highly weathered surface of Precambrian rocks. The mountainous region is mainly a recharge area, while the pediment region may be considered as an area of surface flow.

Geology of Wadi An Numan

Wadi An Numan lies in the western part of the Arabian Shield of Saudi Arabia (Fig. 2A). Some detailed studies were carried out on the geology of Wadi An Numan within the general frame of Makkah district (e.g. Brown et al., 1963; Al-Rehaili and Moore, 1985; Moore & Al-Rehaili, 1989). According to the recent geologic map of Petter Johnson (2006) for the Arabian Shield, four rock units (from youngest to oldest) were recognized (Fig. 2B). These are: 1) The Precambrian Arabian Shield rocks; 2) The Cenozoic rocks (Cs); 3) The Cenozoic basalts (Cb), and 4) The Quaternary sediments. The detailed geologic map of Wadi An Numan area (Fig. 2C), shows the following rock units which are described from base to top as follows:

The unassigned Neoproterozoic rock units which are represented by: 1) The unassigned gabbros which are present only in the southern part of the study area; 2) The unassigned granitoids and diorite (Utg).

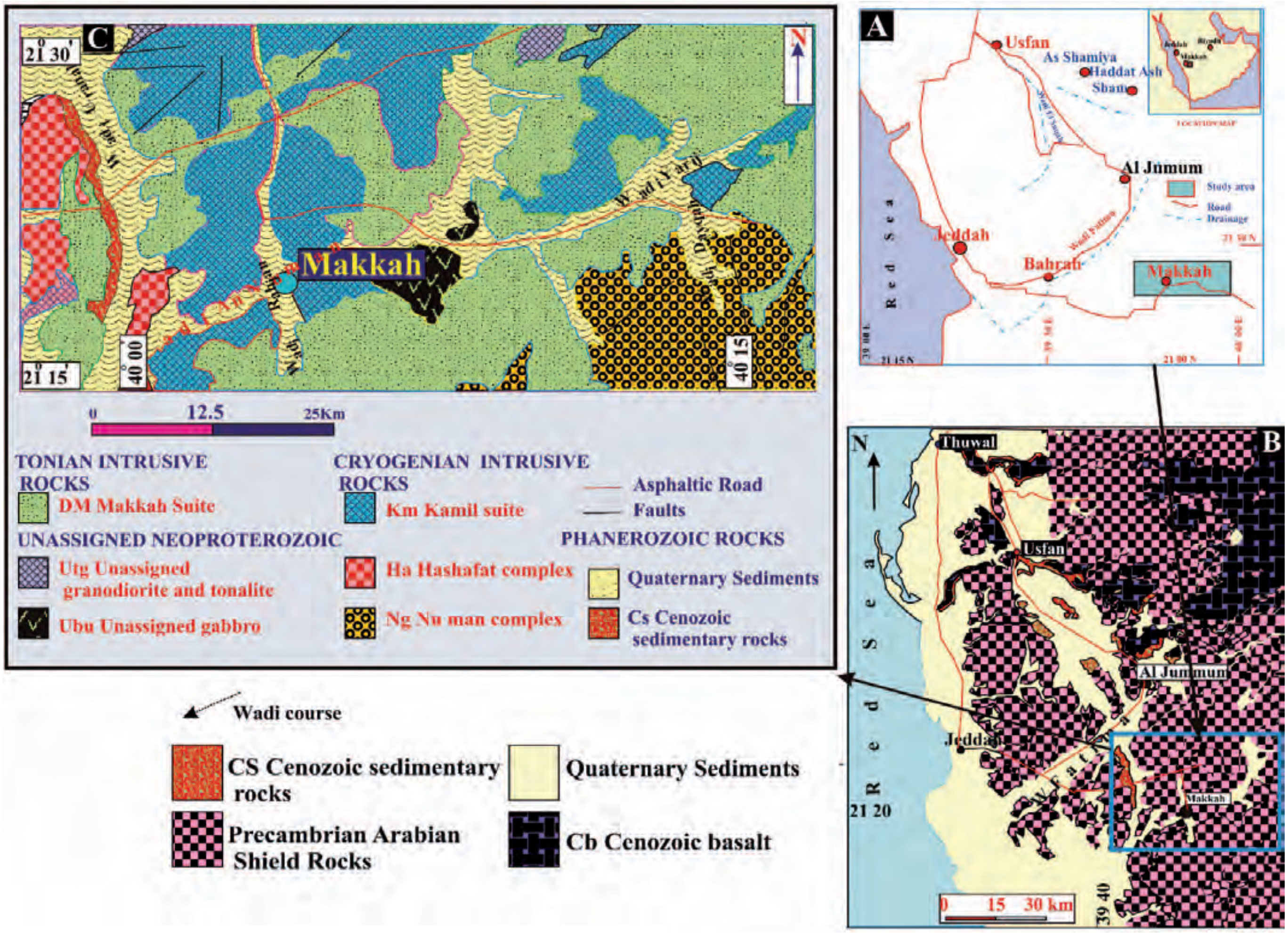


Fig. 2: *Geologic map of the study area (Modified after Johnson, 2006).*

DOI 10.4409/Am-027-11-0027

The Tonian intrusive rocks: these are represented by the Makkah suite (Dm) which is the main Precambrian rock unit in the study area. This suite consists of amphibolite-grade, deformed metamafic plutonic rocks and mostly crops out in the southern part of the Makkah batholith.

The Cryogenian intrusive rocks: these are represented by the following three units: 1) The Numan complex (Ng) which present in the southeastern corner of the mapped area of Wadi An Numan (Moore and Al-Rehaili, 1989). It consists of biotite monzogranite and hornblende-biotite monzogranite to granodiorite orthogneiss and subordinate massive granite, 2) The Hashfat complex (Ha) (Moore and Al-Rehaili, 1989) which is recorded only in the western part of the study area in the down stream of Wadi An Numan. It consists of granodiorite and monzogranite exposed in the Al Aqiq or Bahrah batholith (Moore and Al-Rehaili, 1989; Radain and others, 1989) in the southwestern part of the Jeddah terrane, adjacent to the Red Sea coastal plain, and, 3) Kamil suite (Km, Ramsay, 1986; Moore and Al-Rehaili, 1989) which is present in the central and in the western parts of the study area and it also dominated along both sides of the downstream of Wadi An Numan. It consists mainly from mafic, intermediate, and felsic plutonic rocks of calc-alkalic and locally trondhjemitic affinities.

The Cenozoic rocks (Cs): these are recorded only in the extreme western part of the study area. It is represented by the sedimentary Oligo-Miocene succession of sandstone, conglomerates, and mudstones of Ash Shumaysi Formation.

The Quaternary alluvial Deposits: which consist of well rounded pebble to boulder size conglomerate. These deposits are essentially recorded in steep-sided wadis. In these areas, the alluvial deposits are thin, while in the downstream parts, they are thick and composed of moderately well sorted gravel and medium to fine sand.

Tectonically, the Precambrian layered rocks were intensively folded and faulted, while the plutonic rocks appear less deformed. The Tertiary sedimentary rocks were faulted but not folded. The volcanic rocks of the Harrat Rahat are essentially undeformed. There are three main fracture sets; these are (i) north-northeasterly faults; (ii) east-northwesterly faults; and (iii) southeast trending faults of the Red Sea fracture system.

Hydrological setting

The climatic conditions all over the study area plays an important role in defining the hydraulic response of the watersheds and groundwater quality existing in the region. The most important factor affecting the groundwater chemistry is the rainfall in terms of its intensity and distribution as well as surface runoff that takes place along the main courses of the wadi basins. The rainfall varies from year to year and it often occurs as thunderstorms of very high intensity during a local storm followed by dry periods. Because of the high rainfall and high intensity, flash floods frequently take place. Consequently, many areas within the basins and along the coastal plain might be severely damaged by floods, resulting in very serious problems to the people to property.

Rainfall distribution over the study area was characterized in time and space. Data from the five rainfall gauges (Fig. 1, Tab. 1) were used to establish the rainfall distribution. This table shows that the variation of rainfall in the spatial dimension reflects the topographic effects, since the highest values were recorded at the highest stations (Medrakah, Alsail Alkabir, and Alhada, Fig. 2). The average monthly rainfall was computed in order to give an approximate idea of the seasonal variation in the local rainfall patterns. All effective rainfall is concentrated between November and April (with very minor exceptions in early May).

Quaternary sediments fill Wadi An Numan basin with a thickness ranging from 3 to15 m in upstream areas to more than 50 m further downstream. These are composed from conglomerates, sandstones and mudstones. The bedrocks of An Numan basin is composed from highly weathered and fractured igneous and metamorphic rocks providing another ideal host for groundwater preservation (Sharaf et. al., 2004). This shallow aquifer is also characterized by porosity between 14% and 30%, an average transmissivity of 140 m^2/day, and an average storativity of about 0.1 (Jamman, 1978; Es-Saeed et al.,

Tab. 1: *Average monthly rainfall for different rain gauges (mm).*

STATION NAME	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Elevation m.a.s.l
Alhada (1980-1992)	22.4	7.0	18.3	19.6	30.4	2.5	0	8.0	7.6	14.4	21.2	36.7	1940
AlsailAlkabir (1982-1993)	5.3	0.4	5.7	17.7	12.0	1.6	0.2	0.9	2.6	1.7	7.6	10.8	1230
Bahrah (1966-1997)	18.0	4.0	1.5	4.2	1.2	0	0	2.0	1.5	0.9	11.4	18.0	116
Barzah (1976-1997)	8.5	3.9	7.0	7.0	0.8	1.9	0.7	2.7	5.5	1.1	18.0	15.0	350
Medrakah (1966-1996)	16.6	3.9	7.7	23.2	9.0	1.1	4.0	3.5	13.6	7.9	12.9	7.1	710

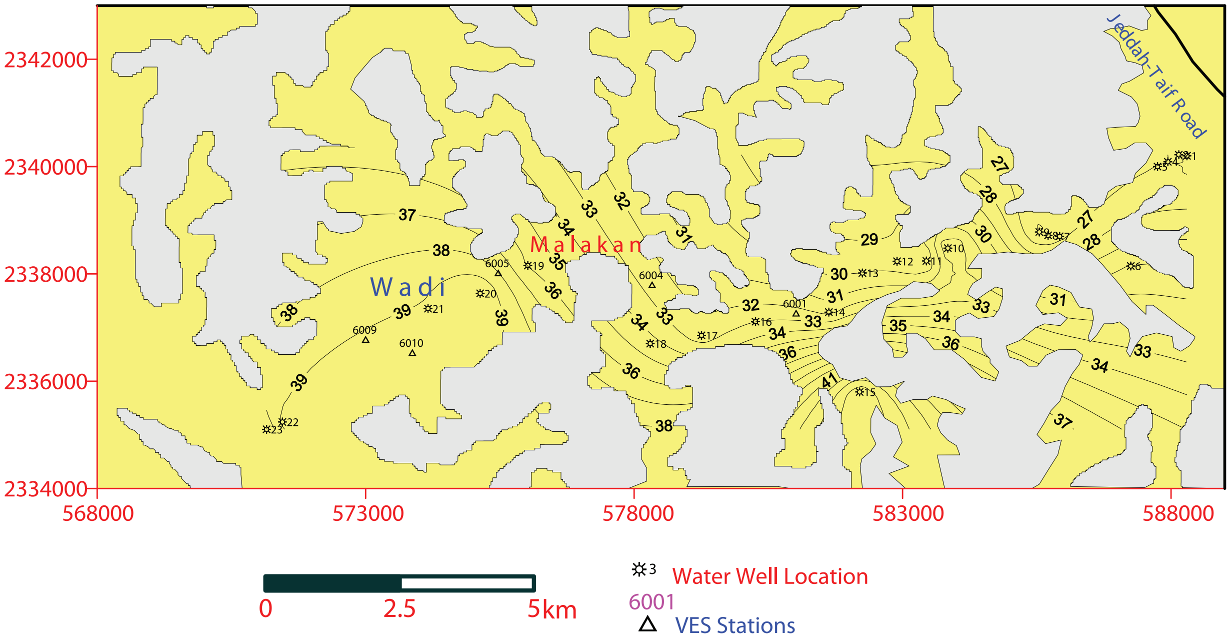


Fig. 3: *Water Depth map of Wadi An Numan basin.*

2004). All of these attributes indicate that the aquifer is unconfined with moderate potential.

The water depth map (Fig. 3) shows that the wells in the uppermost tributaries are nearly shallow while the wells within the main channel of wadi An Numan are deeper. The lowest water depth is 25m while the highest water depth within the downstream of the main channel of Wadi An Numan is about 39 m.

Groundwater Chemistry

The purpose of this section is to describe the groundwater chemistry and to identify and interpret the resulting chemical character of the groundwater. To achieve the hydrochemical evaluation, detailed studies of the composition of the groundwater were undertaken. The approach was to obtain chemical analyses reflecting as closely as possible the composition of the water in its original state by determining some parameters at the time of sampling.

Field Data Collection (Programme of Sampling and Methodology)

Sampling and analytical methods

A total of 65 groundwater samples were collected from the privately owned drilled wells within Wadi An Numan basin. These samples were scattered in four sub-basins (Fig. 4): 19 from the Wadi Dayqah (Table 2), 29 from the main channel of Wadi An Numan (Table 3), 4 samples from Wadi Arar (Table 4) and 13 samples from Wadi Rahjan (Table 5). During the field survey and sample collection, groundwater temperature, electrical conductivity (EC) and pH were measured at the well sites. Most of the groundwater samples were taken from intensively pumped wells in order to avoid any local contamination or change in chemistry caused by evaporation or gas exchange in the well itself. These water samples were analyzed by using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) in the laboratories of the Faculty of Earth Sciences, King Abdulaziz University, Jeddah, Saudi Arabia. The chemical analyses were performed for the cations Na^+, K^+, Ca^{2+}, Mg^{2+} and the anions HCO_3^- , CO_3^{2-}, SO_4^{2-}, Cl^-, NO_3^-.

On the other hand, to better undestand the basic analyses, the computer program "PHREEQE" was used to treat them for all the groundwater samples. This program computes activities of dissolved species, calculates the saturation indices. As the reactions involved are very much dependent on temperature and pH, the success of the model requires rather accurate temperature and pH data. For this reason, both elements were determined in the field to avoid changes due to storage.

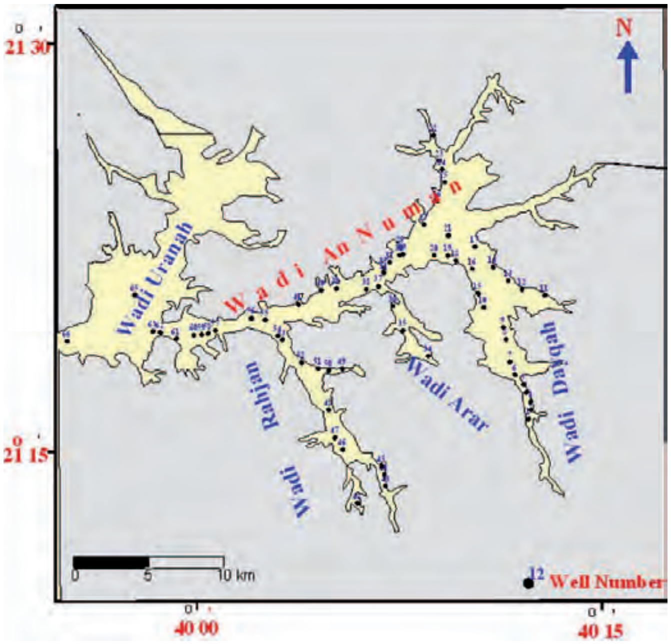


Fig. 4: *Well location map.*

DOI 10.4409/Am-027-11-0027

Water Chemical Analyses and Statistics

The water samples that were collected from the following sub-basins of Wadi An Numan, these are classified as follows: 19 samples from the Dayqah sub-basin (Tab. 2), 29 samples from the main channel of Wadi An Numan (Tab. 3), 4 samples from Wadi Arar sub-basin (Tab. 4) and finally 13 samples from wadi Rahjan sub-basin (Tab. 5). These chemical analyses were used to deduce the Durov and Trilinear diagrams as well as the statistics (Tab. 6) using the Aqua-Chem program (V.3.70).

pH of groundwaters of Wadi An Numan

The pH values of the groundwater of Wadi An Numan area ranged from 7.1 to 7.9. The minimum pH value indicated neutral water. The limit of the pH falls within the WHO (1971) recommended guideline for drinking water whereas the upper limit was within the range as shown in tables 2, 3, 4, 5, but for rural water supply which has pH range of 5.0 to 9.0 (WHO, 1984) it is adequate.

Description of the Groundwater Chemistry

Durov diagram

The main purpose of the Durov diagram is to show clustering of data points to indicate samples that have similar compositions (Hem, 1989). The Durov diagram of the chemical analyses of the water samples of the different areas (Fig. 5), revealed that the water types of Wadi Dayqah sub-basin are mainly of $CaCl_2$ types except analyses n^o 3, 4, 11, 12 (Tab. 2) which are of calcium bicarbonate types. Analyses n^o. 5, 7, 9, 10 are of calcium sulphate types. The chemical analyses of the main channel of Wadi An Numan sub-basin (Tab. 3) are of calcium chloride and calcium sulphate types with less frequent calcium bicarbonate types. Analysis n^o 64 is of NaCl and analysis n^o 65 is sodium sulphate water type. In Wadi Arar sub-basin (Tab. 4), the water types are mainly calcium chloride, calcium sulphate and calcium bicarbonate. In Wadi Rahjan sub-basin (Tab. 5), the water types are of calcium chloride and calcium sulphate with less frequent Na and Ca bicarbonates and Ca sulphates. From the Durov diagram we notice that the analyses of the main channel of Wadi An Numan are enriched in Cl and SO_4**.**

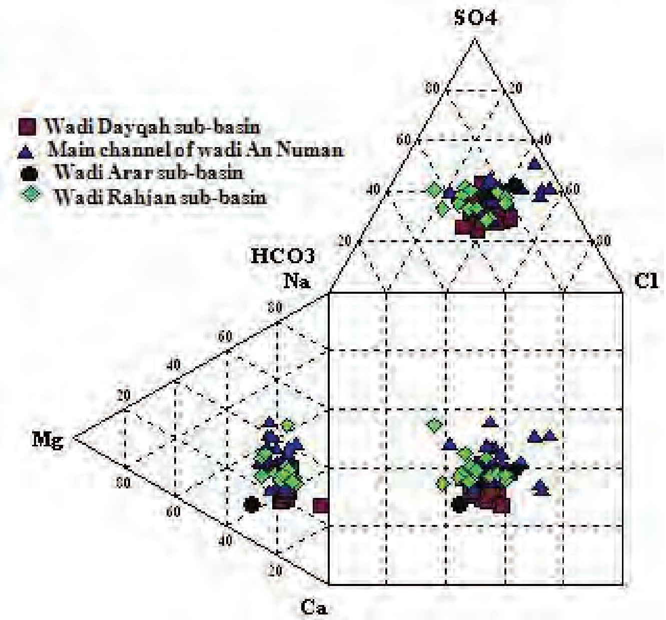


Fig. 5: *Durov Diagram of the chemical analyses of the water samples of the different sub-basins of wadi An Numan..*

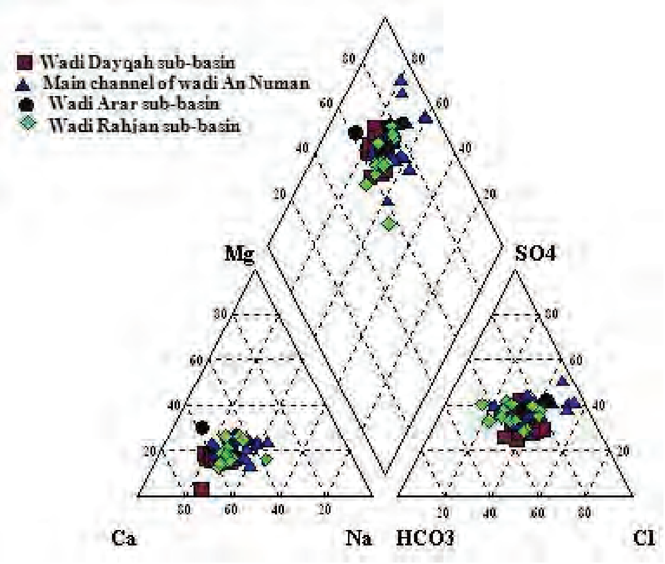


Fig. 6: *Trilinear diagram of the chemical analyses of the groundwater samples of the different sub-basins of Wadi An Numan..*

Trilinear diagram

The plotting of the analyses of the different sub-basins on the trilinear diagram (Fig. 6) revealed that, the groundwater within the study area is predominantly a mixture of calcium-sodium ions and the upper tributaries of Wadi Numan contains fresh water while downstream (main channel of Wadi An Numan, Wadi Rahjan and Wadi Arar) waters are brackish. This is due to the very slow interaction between the fractured crystalline rocks and the rainfall waters in the upstream (fresh water) while in the downstream, the water is interacted with the alluvial sediments as well as the highly weathered and fractured bed rocks which lead to the addition of CO_3, Na, Ca, K and Mg to the water with time leading to the formation of saline and brakish waters of HCO_3^- -Ca^{2+}- Na^+ -SO4^{2-} - Cl -Ca^{2+} type.

Areal distribution of major constituents

The chemical data indicate that, the cation composition ranges from Ca^{2+} to dominantly Na^+ and Mg^{2+} with relatively lesser amounts of K^+. Among the anions, Cl^- and SO_4^{2-} are dominant. The contour map of SO_4 (Fig.7A) shows the low concentration of SO_4 in the initial parts of the tributaries of Wadi Dayqah, Wadi Arar and Wadi Rahjan. The main channel of Wadi An Numan is of relatively higher SO_4 content. The downstream (the western part of the map) and Wadi Uranah are of highest SO_4 content. The Cl distribution contour map (Fig. 7B) show nearly the same distribution as SO_4 but the values of Cl are higher than that of SO_4. The $HCO_3 + CO_3$ map (Fig. 8A) show higher values in the initial tributaries of the sub-basin and decreases in the main tributaries as well as the main channel of Wadi An Numan. This may support the leaching of these two anions during the interaction between rainfall water and atmospheric CO_2. The Na distribution map (Fig. 8B) shows the same anomalies of Cl

Tab. 2: *Chemical analyses of groundwater of Wadi Dayqah sub-basin (mg/l)..*

No.	SO_4	Cl	HCO_3+CO_3	SO_3	Na	K	Ca	Mg	NO_3	EC	Ph	Temp.	Water Type
1	102.5	116.6	192.7	85.4	50.3	8.28	121	23.5	11	1910	7.6	34.6	$CaCl_2$
2	11.1	127.8	131.3	92.6	53.8	14.5	131	3.62	8	800	7.3	32.1	$CaCl_2$
3	139	113.8	213.5	115.8	52.9	6.75	121	21.8	6	963	7.28	34.6	$Ca(HCO_3)_2$
4	151	118.7	205.7	125.8	49.7	7.9	125	24	12	952	7.33	31	$Ca(HCO_3)_2$
5	293	155.7	231.6	244.2	70.1	9.13	186	29.7	55	1115	7.37	30.8	$CaSO_4$
6	196	146.6	193.9	163.3	53.4	8.14	150	27.5	40	1065	7.49	30.8	$CaCl_2$
7	187.6	118.7	212.2	156.3	61.5	6.65	135	22.5	59	1080	7.32	33.6	$CaSO_4$
8	145	137.6	188.9	120.8	51.7	7.74	129	23.7	32	1063	7.35	33.5	$CaCl_2$
9	174	106.8	197.6	145	56.5	6.91	129	22.3	34	1024	7.35	31.8	$CaSO_4$
10	178	111.8	211.6	148.3	59	7	131	20	96	1039	7.33	31.1	$CaSO_4$
11	118	104.7	185.1	98.3	67.6	7.5	95.2	16	17	920	7.53	31.1	$Ca(HCO_3)_2$
12	96	90.8	196.6	80.4	54.8	6.96	94.9	15.7	18	1250	7.5	31	$Ca(HCO_3)_2$
13	125	148.7	127.9	104.2	66.7	7.9	103	19.2	34	1358	7.43	30	$CaCl_2$
14	151	172.5	211	125.8	84	7.41	125	28.2	38	1330	7.36	36.8	$CaCl_2$
15	161	175	211	134.2	87	8	129	26	93	1366	7.72	32.4	$CaCl_2$
16	201	193.4	213.3	167.5	78.6	7.39	166	27.1	66	1330	7.77	31.6	$CaCl_2$
17	160	162.7	245.7	133.3	102.4	5.26	136	26.3	46	1280	7.56	33.4	$CaCl_2$
18	209	171.1	208.4	174.2	72.5	7.3	156	26.6	72	1360	7.55	33	$CaCl_2$
19	155	181.6	207.1	129.2	72.5	6.91	141	24	59	1320	7.37	38.1	$CaCl_2$

Tab. 3: *Chemical analyses of groundwater of the main channel of Wadi An Numan (mg/l).*

No.	SO_4	Cl	HCO_3+CO_3	SO_3	Na	K	Ca	Mg	NO_3	EC	Ph	Temp.	Water Type
20	152	167.6	209.6	126.7	72.4	6.83	140	23.9	75	1266	7.57	31.7	$CaCl_2$
21	215	193.4	293.9	179.2	104.4	4.08	155	34	45	1360	7.55	33	$CaCl_2$
22	380	293.3	359.8	316.7	167.7	257	157	50.2	67	2190	7.79	38	$CaCl_2$
23	520	319.1	392.5	433.3	150.1	4.44	245	79.8	52	2400	7.25	39	$CaSO_4$
24	440	330.3	340.5	366.7	146.3	4.42	230	68.9	72	2470	7.63	37	$CaCl_2$
25	380	272.3	353.1	316.7	139.4	7.06	196	72.7	53	2100	7.73	33	$CaSO_4$
26	160	127.8	230.4	133.3	58.8	7.68	126	22.2	60	2250	7.4	32.6	$Ca(HCO_3)_2$
27	280	221.4	305.6	233.3	110.6	5.55	159	56.2	53	1950	7.35	34.7	$CaCl_2$
28	249	172.5	233	207.5	111.1	5.69	115	41.4	53	1360	8.12	36.1	$CaSO_4$
29	266	153.6	213.6	221.7	85.8	6.91	155	27	70	1270	7.35	35.3	$CaSO_4$
30	289	206.7	299.2	240.8	115.4	4.95	153	47.7	88	1665	7.55	32.5	$CaSO_4$
31	260	176.7	242.1	216.7	93.2	6.6	157	33.5	66	1510	7.57	33	$CaSO_4$
32	239.5	178.8	242.2	199.6	87.8	6.54	155	32.3	67	1465	7.86	33	$CaCl_2$
33	233	173.2	222.8	194.2	85.1	6.39	152	29.6	67	1420	7.39	33.3	$CaCl_2$
38	209	85.2	266.2	174.2	101	3.12	98.6	16.6	76	1350	7.63	33.7	$Ca(HCO_3)_2$
39	226	179.5	224	188.3	90.4	5.94	148	32.6	68	1425	7.65	33	$CaCl_2$
40	224	190.6	201.8	186.7	91.1	6.19	146	33	79	1400	7.68	36.2	$CaCl_2$
41	290	159.3	191	241.7	132	10.7	87.6	37.2	85	1490	7.65	37	Na_2SO_4
55	219	209.5	181.2	182.5	96.3	6.04	142	31.3	84	1444	7.65	37.5	$CaCl_2$
56	225	195.5	189	187.5	97.1	5.47	134	33.1	81	1495	7.76	31.8	$CaCl_2$
57	290	191.8	187.7	241.6	88.6	5.85	140	31	79	1400	7.4	34	$CaSO_4$
58	270	201.9	175	225	83.8	5.86	148	29.6	560	1440	7.49	38.5	$CaCl_2$
59	210	185.7	182.4	175	108	5.89	124	25.4	67	1400	7.94	39.6	$CaCl_2$
60	260	171	186.2	216.7	117	5.58	111	22.6	51	1350	7.5	38.1	$CaSO_4$
61	680	653.6	155.3	566.7	161.5	6.57	400	98	264	2500	7.66	38	$CaCl_2$
62	372	307.3	166.8	310	139.6	6.14	188	43.3	132	2450	7.6	38.3	$CaCl_2$
63	495	523.7	159.2	412.5	148.2	6.88	311	67	111	2900	7.59	38.6	$CaCl_2$
64	1090	1086	157.5	908.3	492	6.74	419	160	293	5400	7.19	33.8	NaCl
65	1350	895.4	157.5	1125	500	9.68	432	150	327	5350	7.3	36	Na_2SO_4

DOI 10.4409/Am-027-11-0027

Tab. 4: *Chemical analyses of groundwater of Wadi Arar sub-basin (mg/l).*

No.	SO_4	Cl	HCO_3+CO_3	SO_3	Na	K	Ca	Mg	NO_3	EC	Ph	Temp.	Water Type
34	395	293.3	185	329.2	130	6.5	192	42.4	10	1433	7.4	32	$CaCl_2$
35	240	155.7	218.7	200	91.1	6.63	147	28	64	1140	7.64	38	$CaSO_4$
36	445	335.2	314.6	370.8	136.8	7.29	232	71.4	116	2340	7.59	36	$CaCl_2$
37	146	77.6	191.2	121.7	53.5	7.57	220	70.2	109	1954	7.58	38	$Ca(HCO_3)_2$

Tab. 5: *Chemical analyses of groundwater of Wadi Rahjan sub-basin (mg/l).*

No.	SO_4	Cl	HCO_3 +CO_3	SO_3	Na	K	Ca	Mg	NO_3	EC	Ph	Temp.	Water Type
42	181	52.4	248.9	151.2	108	4.32	75.9	20	90	988	7.9	33.7	$NaHCO_3$
43	191	192.7	249.9	159.2	76.8	10.3	139	44.4	23	1330	7.21	30.7	$CaCl_2$
44	165	167.6	236.9	137.3	86.2	7.79	109	40	36	1286	8.53	30.7	$CaCl_2$
45	225	103.4	227.7	187.5	88.9	5.42	103	36.3	115	1300	8.15	32.4	$CaSO_4$
46	160	81.7	191.3	133.3	59.5	6.79	97.1	24.4	52	960	7.42	35.8	$CaSO_4$
47	260	211.6	185	216.7	92.8	8.1	170	35.5	78	1500	7.43	34.1	$CaCl_2$
48	101	56.8	141	84.2	40.1	5.25	66	9.7	42	623	7.76	32.1	$Ca(HCO_3)_2$
49	89	44	151.6	74.2	37.2	6.64	68.6	8.9	18	542	7.57	31.6	$Ca(HCO_3)_2$
50	259	181.6	190.4	245.8	99.2	6.71	158	28.1	84	1500	7.18	33.7	$CaSO_4$
51	192	99.9	188.9	160	77.3	6.69	107	20.8	79	961	8.04	30.5	$CaSO_4$
52	120	83.8	165.7	100	52.2	6.51	93.3	14	30	830	7.92	33.2	$Ca(HCO_3)_2$
53	134	99.9	168.4	111.7	63.4	6.38	93.6	17.1	41	965	7.8	32	$CaCl_2$
54	216	193.4	174.7	180	86.9	6.59	142	29.4	63	1380	7.56	36.3	$CaCl_2$

Tab. 6: *Statistics of chemical analyses (65 samples, concentration in mg/l).*

Item	Minimum	Maximum	Average	St. Dev.
Ca	66	432	154.766	72.155
Mg	3.26	160	36.893	27.756
Na	37.2	500	101.466	77.288
K	2.57	14.5	6.753	1.735
HCO_3	127.9	392.5	214.36	54.221
SO_4	89.0	1350	262.252	205.664
SO_3	74.2	1125	219.007	171.415
NO_3	6	560	78.32	83.5
Cl	44	1085.8	205.075	173.17
Sum Cations	5.943	55.894	15.344	8.814
Sum Anions	5.579	55.945	14.758	9.099
Alkalinity	11.74	36.028	19.676	4.977

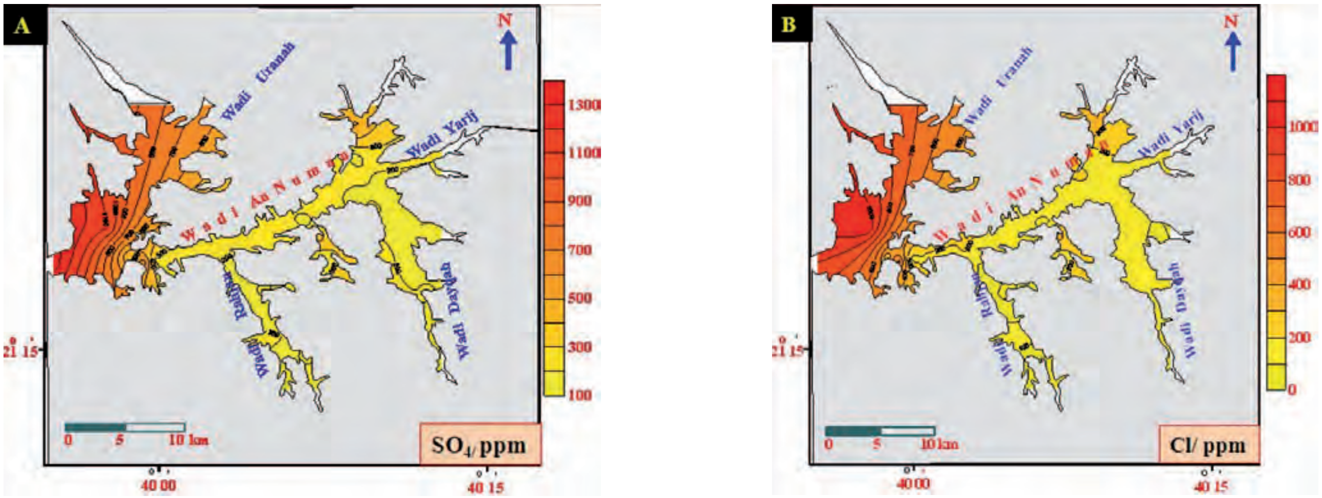


Fig. 7A, 7B: *Distribution contour maps of SO_4, Cl in Wadi An Numan basin.*

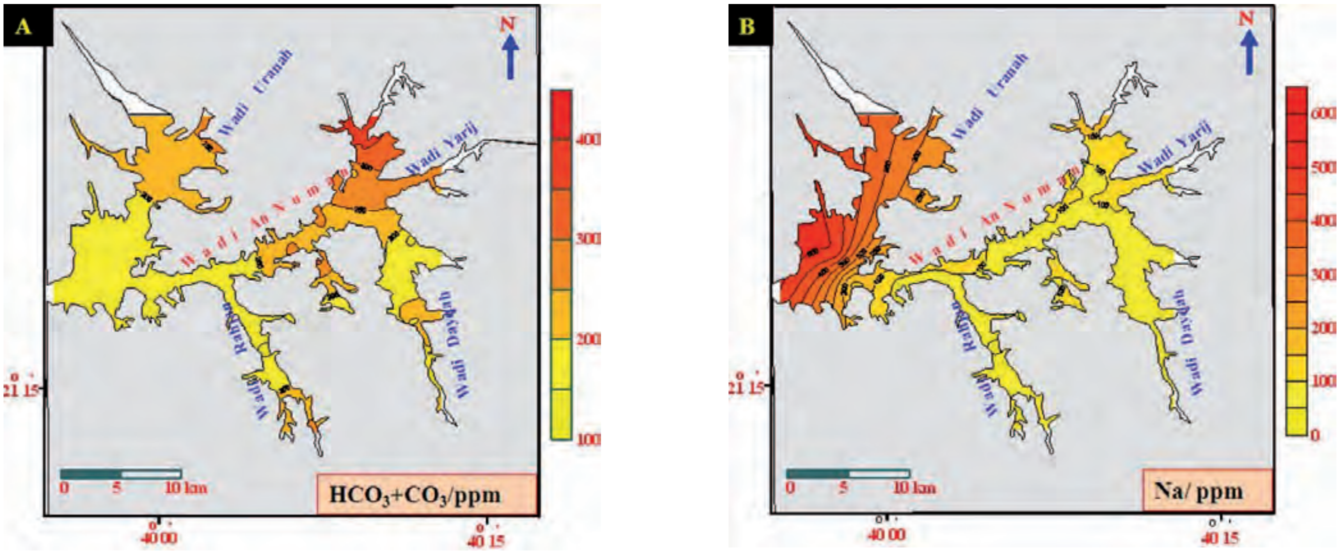


Fig. 8A, 8B: *Distribution contour maps of $HCO_3 + CO_3$ and Na in Wadi An Numan basin.*

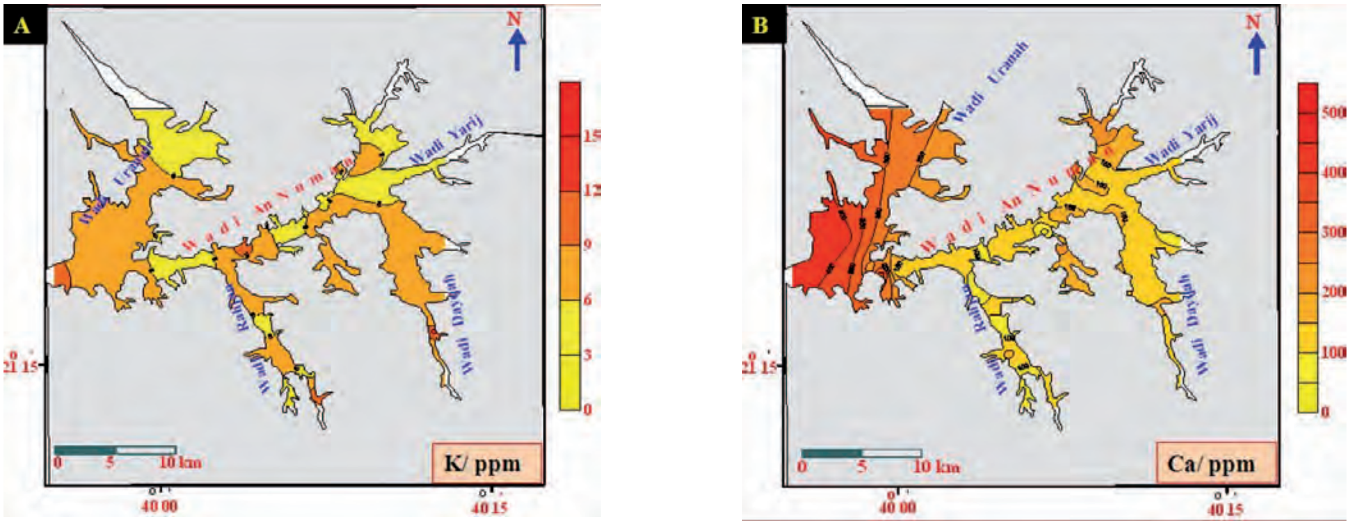


Fig. 9A, 9B: *Distribution contour maps of K and Ca in Wadi An Numan basin.*

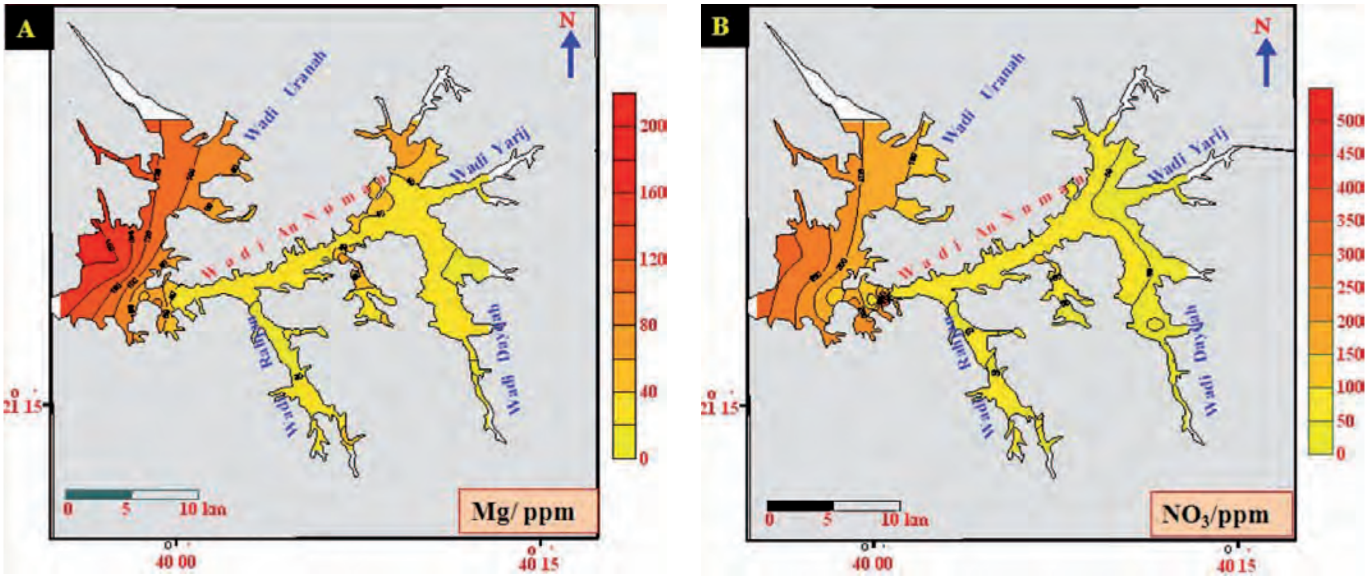


Fig. 10A, 10B: *Distribution contour maps of Mg and NO_3 in Wadi An Numan basin.*

(Fig. 7B) which indicates the good correlation between Na and Cl and their formation by NaCl dissolution.

The K distribution map (Fig. 9A) shows a complicated pattern not similar or even correlated with any other cations or anions. In this map, we notice the high K at the main parts of the tributaries then decreasing at the intersection between the tributaries and the main channel of Wadi An Numan and reaching its maximum values in isolated small areas. The Ca distribution map (Fig. 9B) is very similar to the HCO_3 & CO_3 map where the lowest values are recorded within the tributaries while the high values are recorded in the downstream of An Numan basin. The Mg and NO_3 distribution mapS (Fig. 10A, B) are similar to the other cations where they have the lowest concentration in the tributaries and upstream parts and the highest concentration in the downstream part. The high anomalies of the different cations and anions in Wadi Uranah may relate to: i) the progressive leaching of these cations and anions from the crystalline rocks of the tributaries and the main channel of Wadi An Numan, or ii) the progressive accumulation of cations and anions in the downstream area. The major ionic concentration of the groundwater shows the following general pattern:

$$Ca^{2+} > Na^{+} > Mg^{2+} > K^{+} \quad \text{and} \quad Cl^{-} > SO_4^{2-} > HCO_3^{-}$$

There is also a positive correlation between Na and Cl which indicate dissolution of NaCl (Fig. 11B). All the analyses are nearly of the same values of Na and Cl with exception of two wells. The variation diagram between Ca, Mg against $HCO_3 + CO_3$ (Fig. 11C, D) show nearly the same anomalies where there is a positive correlation with some odd values of the wells of the main channel of Wadi An Numan.

Groundwater Salinity

The variations in the groundwater salinity for the whole basin and sub-basins (e.g. Dayqah, Rahjan, Arar and along the main channel of Wadi An Numan) are illustrated in figure 7A, B and table 7. There is a positive correlation between EC and SO_4 and Cl (Fig. 12A, B), which indicates the dependence of EC values on the salinity. The groundwater salinity is evaluated on the basis of electrical conductivity (EC) in the investigated area. The EC measurements might be considered a rapid determination of the total dissolved solids (TDS) of a groundwater sample. The EC is preferred rather than its reciprocal, resistance, because it increases with the total concentrations of the ionized constituents in the water (Singh and Kalar, 1975), and should give a general indication of the total dissolved solids (TDS). The groundwater salinity probably tends to follow the general direction of the groundwater movement within the wadi catchment, and the lower EC is in the areas having greatest recharge. High saline waters were also found but less common and often concentrated rather in the downstream part of Wadi An Numan (Tabs. 2, 3, 4, 5). The minimum EC value is 542 while the maximum value is 5400 with an average value of 1554.26.

Variation Diagrams

The variations in the values of cations and anions are shown in table 6. The variation diagrams between SO_4 and Ca (Fig. 11A) revealed that there is a positive correlation between the SO_4 and Ca which indicates gypsum dissolution. This diagram shows also that the values of the main channel of Wadi An Numan have the highest Ca and SO_4 values while Wadi Rahjan values are the lowest. Also most of the SO_4 analyses range between 100 and 600 with some exception of the analyses of the main channel of Wadi An Numan and the analyses range in Ca content varies between 50 and 250 mg/l with some high exceptions of the values.

The hydrochemical processes

Evaporation, recycling of irrigation water and chemical weathering reactions of silicate minerals are the dominant chemical processes that influenced the groundwater evolution. The first two processes possibly worked collectively, which lead to precipitation of evaporitic salts in the irrigated fields around the production wells. Calcite, dolomite and gypsum are the dominant evaporite salts. These precipitated minerals flushed into the aquifers by flood - and rain waters as well as by irrigation waters. The effect of the rain water chemistry on the major hydrochemistry elements of An Numan groundwater indicates that most of the major constituents are relatively low in their concentrations and Ca^{2+} and HCO_3^{-} are the dominant ions (Tab. 8). The chemical composition of the rain that falls over the Wadi

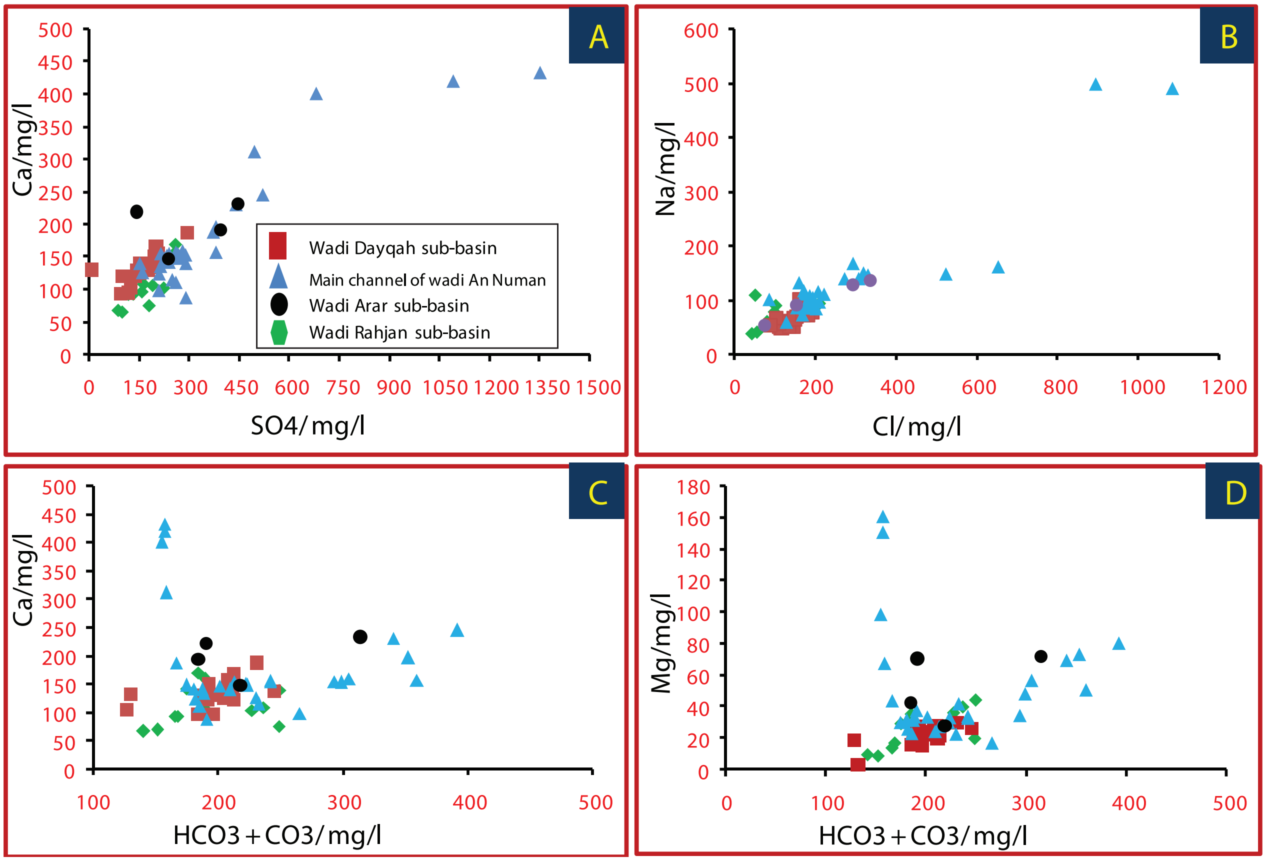


Fig. 11: *Variation diagrams between Ca vs SO_4 - Na vs Cl - Ca vs HCO_3 + CO_3 and Mg vs HCO_3+ CO_3 in Wadi An Numan basin.*

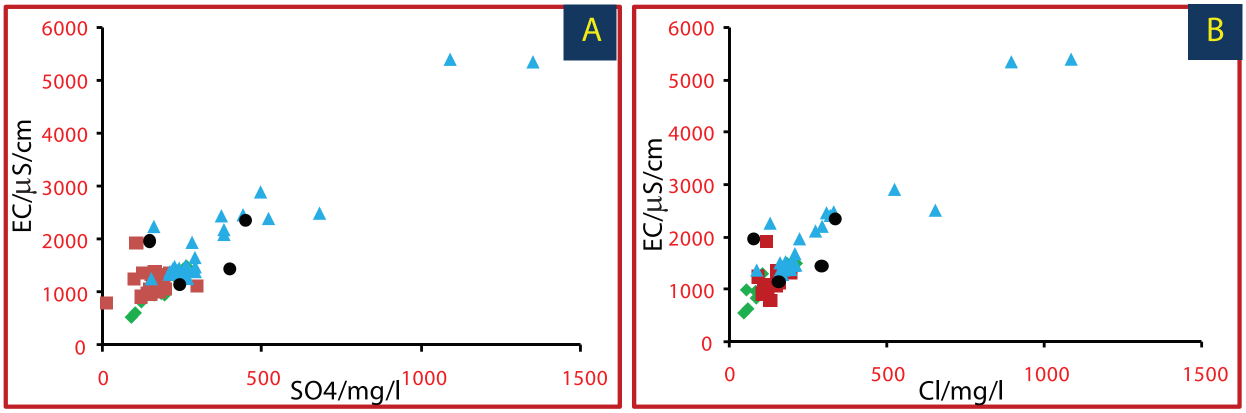


Fig. 12: *Variation diagrams between EC vs SO_4 and EC vs Cl in Wadi An Numan basin.*

Tab. 7: *The variation in groundwater salinity within An Numan basin in µS/cm.*

BASIN NAME	SUB-BASIN NAME	MAX.	MIN.	MEAN
WADI AN NUMAN	Dayqah	1366	800	1133
	Rahjan	1500	542	1089
	Arar	2340	1140	1717
	Main channel of Wadi An Numan	5400	1266	1982

catchment can be considered as an effective element for SO_4^{2-}, Cl and HCO_3^- contents in groundwater. This conclusion might be substantial since the availability of rocks containing minerals having these three elements in the wadi for weathering cannot explain the higher contents of these ions in the groundwater. Its effect, therefore, appears either directly during the recharge process as it infiltrates throughout the soil zone and/or due to chemical precipitation of various minerals such as calcite, dolomite, gypsum and halite in the superficial deposits and in the irrigated fields as a result of intensive evaporation processes.

Weathering of Silicate Minerals

The major reactive minerals for groundwater and recharge water (rainwater) are the Precambrian Arabian Shield rocks, evaporite salts as well as sediments derived from the parent rocks. The rate of weathering depends on the intensity of fracturing and fracture zones as well as on the rate of chemical reactions. In the different sub-basins of Wadi An Numan, andesine and oligoclase are the major sources of Na^+, whereas Ca^{2+}, Mg^{2+}, Fe^{2+} and K^+ have multiple mineral sources.

Weathering of biotite is a good example showing a release of Mg^{2+}, HCO_3 and K^+ to the groundwater. The most probable primary source of SO_4^{2-} is oxidation of pyrite (FeS_2) which is a widespread accessory mineral in igneous and metamorphic rocks of the Precambrian crystalline rocks on both sides of Wadi An Numan.

Evaporation Process and Recycling of Irrigation Water

Evaporitic salts have resulted from the intensive evaporation of irrigation water. It has been observed that the ion concentrations become higher at the edges of the wadi compared to the values observed in the central channel itself. This might be a result of recirculation of irrigation water applied to fields on terraces along the wadi flanks in the different sub-basins. Dolomite, calcite and gypsum are common evaporitic salts present in the surficial and soil

Tab. 8: *Chemical composition of rain water (after Alyamani and Hussein, 1995).*

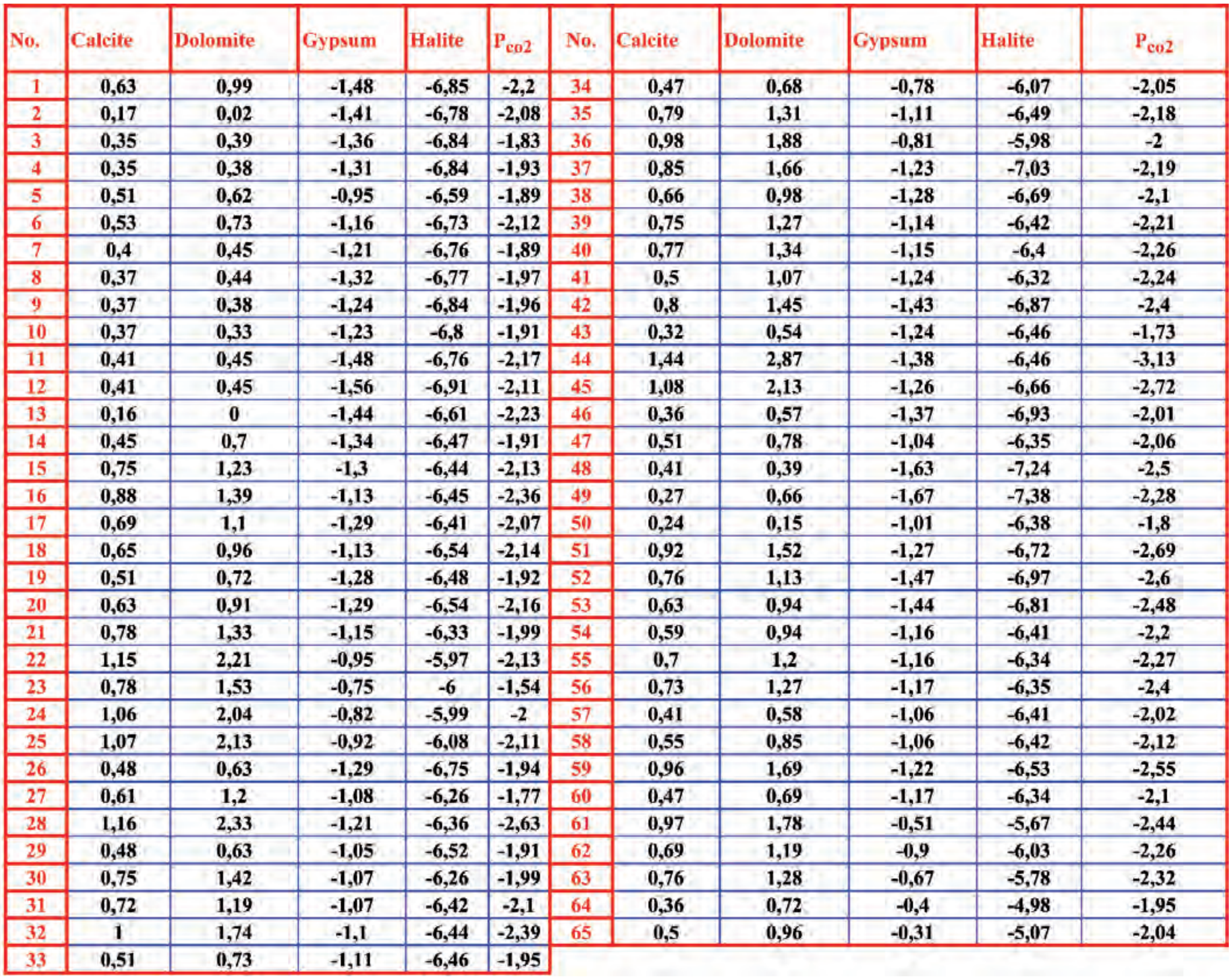
VARIABLE	UNIT		ALHADA	BAHRAH	ALSAILAL-KABIR
SO_4^{2-}	mg/l	Max.	5.30	6.24	4.80
		Min.	2.90	3.80	3.40
		Mean	4.10	5.3	4.10
Cl-	mg/l	Max.	7.80	6.90	9.20
		Min.	4.61	5.70	3.09
		Mean	6.0	7.90	5.90
HCO_3^-	mg/l	Max.	19.52	21.35	17.10
		Min.	11.60	11.59	12.20
		Mean	14.1	16.5	14.0
Na^+	mg/l	Max.	4.14	5.70	4.14
		Min.	1.61	2.50	1.61
		Mean	2.90	4.20	2.80
K+	mg/l	Max.	1.41	1.56	1.52
		Min.	1.02	1.02	1.02
		Mean	1.10	1.30	1.20
Ca^{2+}	mg/l	Max.	4.41	5.80	4.61
		Min.	2.81	2.81	3.01
		Mean	3.50	4.30	3.50
Mg^{2+}	mg/l	Max.	1.20	1.60	1.46
		Min.	1.10	1.10	1.10
		Mean	1.10	1.30	1.20
pH	-	Max.	7.40	7.40	7.45
		Min.	6.90	6.95	7.10
		Mean	7.10	7.20	7.30
EC	µS/cm	Max.	79.0	94.0	82.0
		Min.	62.0	66.0	62.0
		Mean	69.5	77.0	62.0

zones in these wadis. The relationship between Na and Cl ions (Fig. 9B) might be practically utilized to identify the concentration effects by evaporation (Eugster and Jones, 1979). Figure 9B shows a positive linear relationship which is maintained throughout most of the samples. The data points lie almost on or close to the halite dissolution line, indicating halite is probably the sole source of these two constituents. Halite absence from the soil and/or surficial deposits sample could be due to its extreme solubility (Gat, 1980). In the presence of CO_2 , the behaviour of these minerals presented in the wadi sediments as well as evaporite salts especially the carbonate minerals (calcite and dolomite) in the irrigated areas, is thought to be largely responsible for releasing these constituents particularly SO_4^{2-}, Ca^{2+} and Mg^{2+} and HCO_3 into the groundwater.

Dissolution and Precipitation of Minerals

Calculation of saturation indices using the PHREEQE program shows that almost all the waters within An Numan basin tend to precipitate calcite and dolomite, but are capable of dissolving gypsum and halite (Tab. 9). In Wadi An Numan the Pco2 values range from 10-3.13 to 10-1.84 but the majority of the samples fall between 10-2.4 and 10-1.7. These values are much higher than the 10-3.5 atm expected from contact with the natural atmosphere. The enhanced CO_2 content of the groundwater may be due to contact with the soil air which is often enriched with CO_2 which may liberated from calcite when attacked by H_2SO_4 where calcite is a widespread accessory mineral in Arabian Shield rocks and in the evaporitic salts.

Tab. 9: *Saturation indices for the groundwater samples in Wadi An Numan.*



No.	Calcite	Dolomite	Gypsum	Halite	P_{co2}
1	0,63	0,99	-1,48	-6,85	-2,2
2	0,17	0,02	-1,41	-6,78	-2,08
3	0,35	0,39	-1,36	-6,84	-1,83
4	0,35	0,38	-1,31	-6,84	-1,93
5	0,51	0,62	-0,95	-6,59	-1,89
6	0,53	0,73	-1,16	-6,73	-2,12
7	0,4	0,45	-1,21	-6,76	-1,89
8	0,37	0,44	-1,32	-6,77	-1,97
9	0,37	0,38	-1,24	-6,84	-1,96
10	0,37	0,33	-1,23	-6,8	-1,91
11	0,41	0,45	-1,48	-6,76	-2,17
12	0,41	0,45	-1,56	-6,91	-2,11
13	0,16	0	-1,44	-6,61	-2,23
14	0,45	0,7	-1,34	-6,47	-1,91
15	0,75	1,23	-1,3	-6,44	-2,13
16	0,88	1,39	-1,13	-6,45	-2,36
17	0,69	1,1	-1,29	-6,41	-2,07
18	0,65	0,96	-1,13	-6,54	-2,14
19	0,51	0,72	-1,28	-6,48	-1,92
20	0,63	0,91	-1,29	-6,54	-2,16
21	0,78	1,33	-1,15	-6,33	-1,99
22	1,15	2,21	-0,95	-5,97	-2,13
23	0,78	1,53	-0,75	-6	-1,54
24	1,06	2,04	-0,82	-5,99	-2
25	1,07	2,13	-0,92	-6,08	-2,11
26	0,48	0,63	-1,29	-6,75	-1,94
27	0,61	1,2	-1,08	-6,26	-1,77
28	1,16	2,33	-1,21	-6,36	-2,63
29	0,48	0,63	-1,05	-6,52	-1,91
30	0,75	1,42	-1,07	-6,26	-1,99
31	0,72	1,19	-1,07	-6,42	-2,1
32	1	1,74	-1,1	-6,44	-2,39
33	0,51	0,73	-1,11	-6,46	-1,95
34	0,47	0,68	-0,78	-6,07	-2,05
35	0,79	1,31	-1,11	-6,49	-2,18
36	0,98	1,88	-0,81	-5,98	-2
37	0,85	1,66	-1,23	-7,03	-2,19
38	0,66	0,98	-1,28	-6,69	-2,1
39	0,75	1,27	-1,14	-6,42	-2,21
40	0,77	1,34	-1,15	-6,4	-2,26
41	0,5	1,07	-1,24	-6,32	-2,24
42	0,8	1,45	-1,43	-6,87	-2,4
43	0,32	0,54	-1,24	-6,46	-1,73
44	1,44	2,87	-1,38	-6,46	-3,13
45	1,08	2,13	-1,26	-6,66	-2,72
46	0,36	0,57	-1,37	-6,93	-2,01
47	0,51	0,78	-1,04	-6,35	-2,06
48	0,41	0,39	-1,63	-7,24	-2,5
49	0,27	0,66	-1,67	-7,38	-2,28
50	0,24	0,15	-1,01	-6,38	-1,8
51	0,92	1,52	-1,27	-6,72	-2,69
52	0,76	1,13	-1,47	-6,97	-2,6
53	0,63	0,94	-1,44	-6,81	-2,48
54	0,59	0,94	-1,16	-6,41	-2,2
55	0,7	1,2	-1,16	-6,34	-2,27
56	0,73	1,27	-1,17	-6,35	-2,4
57	0,41	0,58	-1,06	-6,41	-2,02
58	0,55	0,85	-1,06	-6,42	-2,12
59	0,96	1,69	-1,22	-6,53	-2,55
60	0,47	0,69	-1,17	-6,34	-2,1
61	0,97	1,78	-0,51	-5,67	-2,44
62	0,69	1,19	-0,9	-6,03	-2,26
63	0,76	1,28	-0,67	-5,78	-2,32
64	0,36	0,72	-0,4	-4,98	-1,95
65	0,5	0,96	-0,31	-5,07	-2,04

Ion Exchange Reactions

Clay minerals are rich in Na^+ and groundwater in Ca^{2+}, with the result that exchange tends to replace the Ca^{2+} in the water with Na^+. The reverse process sometimes occurs and is called 'reverse ion exchange'. In Wadi An Numan groundwater, there is evidence that favours the occurrence of reverse ion exchange as is clear in figure 9B where the plotting of Na^+ versus Cl shows that Na^+ concentrations are in most cases less than would be expected if the groundwater were simply evaporated precipitation. The most likely explanation for this is loss of Na^+ by reverse ion exchange for Ca^{2+} and/or Mg^{2+}. This presupposes that the clay minerals contain exchangeable Ca^{2+}, derived from plagioclase weathering. However, clay minerals either montmorillonites and/or kaolinite, are final products of the chemical weathering processes.

DOI 10.4409/Am-027-11-0027

Tab. 10: *Values of EC, SAR, RSC, MH, B and TH for groundwater samples in Wadi An Numan. (EC= Electro conductivity (µS/cm); SAR = Sodium Adsorption Ratio (meq/l); RSC = Residual Sodium Carbonate (meq/l); MH = Magnesium Hazard (meq/l); TH = Total Hardness (mg/l), BH=Boron Hazard (mg/l))*

NO.	EC	SAR	RSC	MH	BH	TH	Cl/CO_3
1	910	1.1	-4.81	24.25	0.74	398.8	0.88
2	800	1.27	-4.68	4.36	0.46	342.2	1.51
3	963	1.16	-4.33	22.9	0.58	391.9	0.87
4	952	1.07	-4.84	24.04	0.54	410.9	0.89
5	1115	1.26	-7.93	20.84	0.66	586.8	1
6	1065	1.05	-6.57	23.21	0.5	487.7	0.76
7	1080	1.29	-5.11	21.55	0.7	429.8	0.89
8	1063	1.1	-5.29	23.25	0.51	419.7	0.95
9	1024	1.21	-5.03	22.18	0.61	413.9	0.51
10	1039	1.27	-4.72	20.11	0.55	409.5	0.64
11	920	1.69	-3.03	21.7	0.57	303.6	1.14
12	1250	1.37	-2.8	21.43	0.52	301.6	0.77
13	1358	1.58	-4.62	23.51	0.46	336.2	0.99
14	1330	1.77	-5.1	27.11	0.8	428.1	1.35
15	1366	1.83	-5.12	24.94	0.69	429.1	1.26
16	1330	1.49	-7.02	21.21	0.63	526.1	0.88
17	1280	2.11	-4.92	24.17	0.94	447.8	0.81
18	1360	1.41	-6.56	21.94	0.58	499.1	1.35
19	1320	1.61	-5.62	21.91	0.51	450.9	1.38
20	1266	1.49	-5.52	21.96	0.52	448	1.04
21	1360	1.97	-5.71	26.56	0.95	526.9	1.4
22	2190	2.87	-6.96	32.11	0.08	643.3	1.28
23	2400	2.13	-12.4	34.94	2.03	939.7	0
24	2470	2.17	-11.6	33.06	2.28	857.5	1.63
25	2100	2.16	-9.97	37.94	1.95	788.1	0.91
26	2250	1.26	-4.34	22.51	1.91	406	1.22
27	1950	1.92	-7.55	36.82	1.54	627.9	1.46
28	1360	2.26	-5.33	37.24	1.3	457.2	1.35
29	1270	1.67	-6.45	22.31	0.67	498.2	1.3
30	1665	2.09	-6.65	33.95	1.47	578.1	0
31	1510	1.76	-6.62	26.02	1.07	529.8	1.36
32	1465	1.68	-4.42	25.57	0.96	519.3	0
33	1420	1.65	-6.37	24.3	0.84	501.4	0
34	1433	2.21	-10.04	26.69	0.63	653.8	1.28
35	1140	1.81	-6.05	23.9	1.23	482.3	1.01
36	2340	2.01	-12.29	33.66	1.92	872.7	1.64
37	1554	0.8	-13.61	34.49	1.82	837.8	0.72
38	1350	2.48	-1.92	21.72	0.84	314.6	0.76
39	1425	1.75	-6.4	26.64	0.87	503.7	1.37
40	1400	1.77	-6.69	27.15	0.86	500.3	1.09
41	1490	2.98	-4.3	41.18	2.13	371.5	0.81
42	988	2.85	-1.35	30.28	1.66	271.7	0.01
43	1330	1.45	-6.49	34.49	0.79	529.5	1.4
44	1286	1.79	-4.85	37.69	0.83	436.5	1.34
45	1300	1.92	-4.39	36.75	0.94	406.3	0.83
46	960	1.4	-3.72	29.29	0.71	342.8	0.51
47	1500	1.69	-8.37	25.61	0.91	570.6	1.14
48	623	1.22	-1.78	19.5	0.56	204.8	0.36
49	542	1.12	-0.67	17.55	0.61	207.8	0
50	1500	1.91	-7.08	22.67	1.54	510.2	0
51	961	1.79	-3.95	24.27	0.79	352.8	0.81
52	830	1.33	-3.09	19.83	0.69	290.7	1.04
53	965	1.58	-3.32	23.15	0.76	304.1	0
54	1380	1.73	-6.64	25.45	0.93	475.5	1.4
55	1444	1.91	-6.69	26.65	0.93	483.3	1.44
56	1495	1.95	-6.31	28.94	1.09	470.7	1.41
57	1400	1.77	-6.46	26.74	1.01	477.1	0
58	1440	1.65	-6.95	24.8	0.93	491.4	1.44
59	1400	2.31	-5.29	25.24	1.25	414.1	1.08
60	1350	2.65	-4.35	25.13	1.42	370.2	1.06
61	2500	1.88	-25.48	28.77	3.98	1402	1.93
62	2450	2.39	-10.21	27.52	1.68	647.5	1.3
63	2900	1.99	-18.45	26.29	1.93	1053	1.84
64	5400	5.19	-31.49	38.63	4.03	1704	2.17
65	5350	5.28	-31.32	36.4	4.54	1695	1.78

Local Contamination

The NO_3^- ion concentrations are relatively high in the different sub-basins of Wadi An Numan. In general, the NO_3^- content of unpolluted groundwater seldom exceeds 10 mg/l (Rainwater and Thatcher, 1960). Presumably the NO_3^- where found in the studied areas is derived from leaching of products of organic decay by recharge and/or irrigated waters. In addition, excessive NO_3^- in groundwater may indicate leakage from the over use of agricultural chemicals fertilizer in sandy soils.

Suitability of Groundwater

Irrigation Water

The usual range for bicarbonate in irrigation water is 0-10 me/l (Ayers and Wescot, 1985). All of the groundwater samples fall below this range. Concentrations of sulphate vary between 89 and 1350 ppm with an average 262.252 ppm which are beneath the usual limits according to irrigation water standards. Chloride is another ion commonly found in irrigation waters. In general, waters with chloride values of below 30 me/l are considered to be good quality irrigation waters (Ayers & Westcot, 1985). All groundwater samples have pH value lower than the Ayers & Wescot (1985) irrigation water guidelines. Electrical conductivity (EC) values of groundwater samples are between 87–329 µS/cm and below the Ayers & Wescot (1985) irrigation limit.

Sodium content: EC and sodium concentration are very important in classifying irrigation water. The salts, besides affecting the growth of the plants directly, also affect soil structure, permeability and aeration, which indirectly affect plant growth (Singh et al., 2008). The sodium content (Na/ppm) in the area ranges between 37.2 and 500 with an average 101.466 (Fig. 13, Table 6).

Total Salt Concentration Hazard: according to the criteria provided in table 11, most of the groundwater in Wadi An Numan falls within the satisfactory limits. Most of the farmers within Wadi An Numan area are reliant upon private wells from which the water samples were collected.

Sodium Adsorption Ratio (SAR): table 10 shows that the calculated values of SAR for the groundwater in Wadi An Numan are low according to the recommended water classification for SAR (Lloyd and Heathcote, 1985). The high salt concentration in water leads to formation of saline soil, while the high sodium concentration leads to development of an alkaline soil (Singh et al., 2008). The sodium adsorption ratio (SAR) parameter evaluates the sodium hazard in relation to calcium and magnesium concentrations. The minimum SAR values of Wadi An Numan groundwater is 0.8 while the maximum is 5.28 and the average is 1.85. Wadi An Numan groundwater samples are of SAR values between 1 and 3 and EC values between 1000 and 3000 (Fig. 14). Most of the samples are located within the C3-S1 and C4-S1. Less frequent samples are present in the fields C2-S1 and C4-S2.

Residual Sodium Carbonate (RSC): another way to examine irrigation water is to estimate the residual sodium carbonate (RSC) as suggested by Eaton, 1950. According to Eaton (op.cit.) if the RSC < 1.25, the water is considered safe. On the other hand, if the RSC > 2.5 the water is not appropriate for irrigation. The computed values of RSC for the different sub-basins of Wadi An Numan are summarized in table 10. All the values are negative (< 1.25). The classifica-

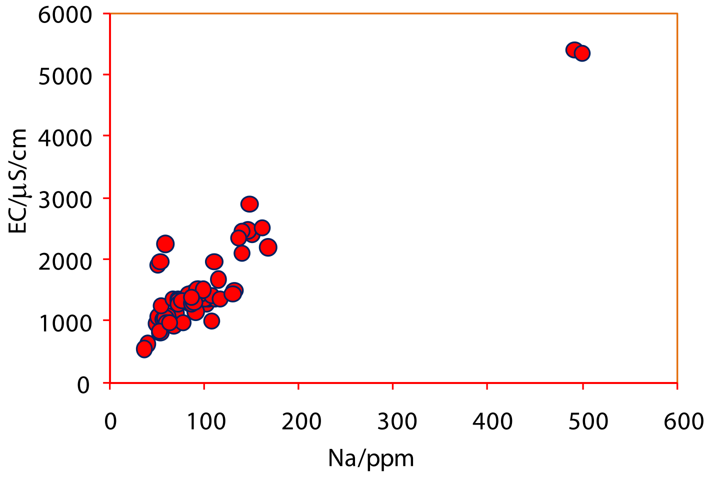


Fig. 13: *Relation between EC (µS/cm and Na (ppm).*

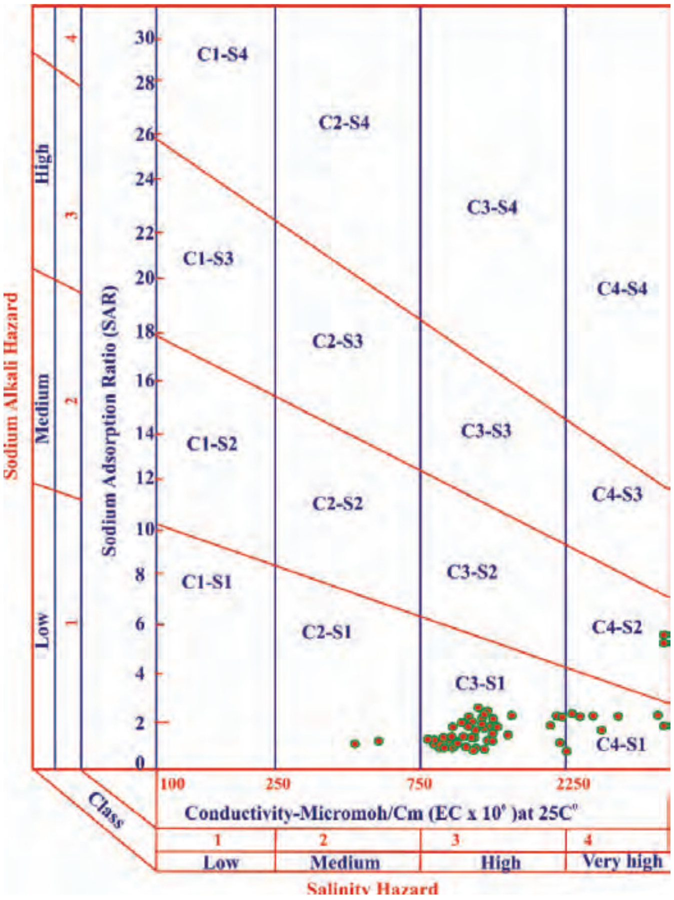


Fig. 14: *US Salinity classification of Wadi An Numan groundwater for irrigation (USLL, 1954).*

Tab. 11: *Guidelines for interpretation of water quality for irrigation and domestic uses.*

EC µS/cm		SAR (meq/l)		RSC (meq/l)		B (mg/l)		TH (mg/l)	
< 250	Low salinity	0-10	Low	<1.25	Suitable	< 1.0	Excellent	75	soft
250-750	Medium salinity	10-18	Medium	1.25-2.5	Marginal	1-2	Good	75-150	Moderately hard
750-2250	High salinity	18-26	High	>2.5	Not suitable	2-3	Permissible	150- 300	Hard
2250-5000	Very high salinity	>26	Very high			3-375	Doubtful	>300	Very hard
						>3.75	Unsuitable		

tion of the groundwater quality for irrigation according to this criterion indicates that all of the samples are of negative values below RSC value of 1.25 (Table 10). This indicates that water is suitable for irrigation uses. The RSC values in the range found can be used safely for irrigation purposes (Lloyd and Heathcote, 1985).

Magnesium Hazard (MH): Szabolcs and Darab (1964) proposed magnesium hazard (MH) value for irrigation water as given below

$$MH= Mg_2+/(Ca^{2+} + Mg^{2+}) *100$$

MH > 50 is considered harmful and unsuitable for irrigation use. The calculated values of Magnesium Hazard MH are presented in table 10. The analyzed groundwaters samples of Wadi An Numan have MH < 50 (Table 10) which indicates that, the groundwater is not harmful for irrigation and all the groundwater samples are fall within the accepted limits which in turn the water can be used safely.

Boron Hazard (BH): the most common ions which might cause a toxicity problem are chloride, sodium and boron. Boron is essential for plant growth in very small concentrations; however, it can become extremely toxic at concentrations slightly above optimum. With the exception of samples nos. 61, 64 and 65 of Wadi An Numan (Tab. 10), most of the groundwater falls within satisfactory limits.

Chloride effects: these pumps are often affected by certain constituents particularly chloride and carbonate. Chloride is most effective at concentrations greater than 300 mg/l. Its effect is to break down protective films of copper and aluminum alloys. The calculated Cl^-/CO_3^{2-} values (Tab. 10) show that all the groundwater samples are within the safe limits.

Groundwater Potability and Domestic Uses

Within Wadi An Numan, the groundwater generally tend to be very hard. This is because of the greater alkaline earth (Ca^{2+}, Mg^{2+}). However, water hardness in excess of 300 mg/l is tolerated by consumers. Soft water, with a hardness of less than 100 mg/l, may, on the other hand, have a low buffer capacity and so be more corrosive for water pipes. The safe NO_3^- limit for domestic water is set at 45 mg/l by standards. However, NO_3^- concentrations greater than 45 mg/l is undesirable in domestic water supplies because of the potential toxic effect on young infants

Discussion and conclusions

Hydrologically, the rainfall in the study area is irregular where the uppermost of the wadis received considerable amount of rainfall (170 mm/year), while the lowlands of the basins are among the driest parts in the region, with average annual rainfall not exceeding 60 mm. Quaternary sediments fill Wadi An Numan basin with a thickness ranging from 3 to 15 m in upstream areas to more than 50 m further downstream. This shallow aquifer is also characterized by a porosity between 14% and 30%, an average transmissivity of 140 m^2/day and an average storativity of about 0.1 (Jamman, 1978; Es-Saeed et al., 2004). All of these attributes indicate that the aquifer is unconfined with moderate potential.

There is a pronounced change in the major ions distribution along the main channel of wadi An Numan. This condition probably reflects an active recharge throughout the main channel or from the tributaries. The major ions and cations distribution maps show their increasing in the downstream direction. The only exceptions to this pattern were the HCO_3^- and K^+ ions, which did not display the pronounced down gradient increase of the other constituents.

The positive correlation between SO_4 and Ca indicate gypsum dissolution. The main channel of Wadi An Numan has the highest Ca and SO_4 values while Wadi Rahjan values are the lowest. The SO_4 range from 100 to 600 with some exception of the analyses of the main channel of Wadi An Numan. The Ca varies between 50 and 250 mg/l with some high exception of the values. The groundwater salinity is relatively low with EC measurements varying between 542 and 5400 µS/cm with an average of about 1539 µS/cm. Calcium-Chloride is the major water type in An Numan basin.

Evaporation, recycling of irrigation water and chemical weathering reactions of silicate minerals are the dominate processes affecting the groundwater's chemical composition. The first two processes possibly worked collectively and lead to precipitate evaporitic salts in the irrigated fields around the production wells. Calcite, dolomite and gypsum are the dominant evaporite salts. The groundwater in the study area seems to be suitable when compared with FAO quality criteria for irrigation. The calculated values of SAR, % Na, RSC, and Magnesium hazard indicate good to permissible use of groundwater for this purpose.

Acknowledgment: The author would like to thank the staff members of the project no. 204/423 funded by the Deanship of postgraduates and scientific research, King Abdullaziz University, Jeddah, Saudi Arabia.

References

Al Kabir, M. A.(1985) Recharge characteristics of groundwater aquifers in Jeddah-Makkah-Taif area. M.Sc. Thesis, Faculty of Earth Sci., King Abdulaziz Uni., Jeddah, Saudi Arabia.

Al-Gamal,S.A., and Sen,Z.(1983) Quantitative analysis of groundwater quality in Western Saudi Arabia. Proc. Int. Symp. Noordwijkuhout,

Al-Hajeri, F.Y.(1977) Groundwater studies of Wade Qudaid. Institute of Applied Geology, King Abdulaziz Uni., Jeddah, Saudi Arabia.

Al-Khatib,E.A.B.(1977) Hydrogeology of Usfan District. M.Sc. Thesis, Institute of Applied Geology, King Abdulaziz Uni., Jeddah, Saudi Arabia.

Al-Nujaidi,H,A.(1978) Hydrogeology of Wade Murawani- Khulais. M.Sc. Thesis, Institute of Applied Geology, King Abdulaziz Uni., Jeddah, Saudi Arabia.

Al-Rehaili, M. and Moore, T.A.(1985) Geogaphic map of the Makkah quadrangle, Sheet 21D,Kingdom of Saudi Arabia: Saudia Arabian Deputy Ministry for Mineral Resources, Map GM-84c.

Alyaamani, MS., and Hussein,M.T.(1995) Hydrochemical study of groundwater in recharge area, Wade Fatimah basin, Saudi Arabia. Geo Journal, 37.1, p:81-89.

Alyamani, M.S.(1999). Physio-chemical processes on groundwater chemistry, under arid climatic conditions,western province, Saudi Arabia. Proj. No. 203/418, King Abdulaziz Uni., Jeddah, Saudi Arabia.

Alyamani, M.S., Bazuhair, A. S., Bayumi, T. H., and Al-Sulaiman, K. (1996) Application of environmental isotope on groundwater study in the western province, Saudi Arabia. Proj. No. 005/413, King Abdulaziz Uni., Jeddah, Saudi Arabia.

Ayers R.S, Westcot D.W.(1985): Water quality for agriculture, FAO Irrigation and Drainage Paper No. 29, Rev. 1, U.N. Food and Agriculture Organization, Rome.Basmci, Y., and Al Kabir, M.A.(1988). Recharge characteristics of aquifers of Jeddah-Makkah-Taif region. Mathematical and Physical Sci., Vol. 222, p: 367-375.

Basmci, Y. and Al Kabir, M.A. (1988) Recharge characteristic of aquifers of Jeddah-Makkah-Taif region. Mathematical and Physical Sci., Vol 222, p367-375.

Bazuhair, A.S., Hussein,M.T., Alyamani,M.S., and Ibrahim,K.(1992) Hydrogeophysical studies of Khulais basin, western region, Saudi Arabia. Unpub. Report, King Abdulaziz Uni, Jeddah, Saudi Arabia.

Brown, G.F., Jackson, R.O., Bogue, R.G., and MacLean, W.H. (1963) Geology of the Southern Hijaz quadrangle, Kingdom of Saudi Arabia: Saudi Arabian Dir. Gen. Min. Res.Misc. Geologic Invest. Map I - 210A, 1:500,000 scale.

Durov, S. A. (1958): Natural waters and graphic representation of their composition. Dokl. Akad. Nurak SSSR, vol. 59, n. 1, 89-90.

Eaton, F.M. (1950): Significance of carbonates in irrigation waters. Soil Sci 39:123–133.

Es-Saeed M, Şen Z, Basamad A, Dahlawi A. (2004) Strategic groundwater storage in Wadi Numan, Makkah Region, Saudi Arabia. Saudi Geological Survey, Technical report-SGSTR- 2004-1.

Eugster, H.P., and Jones, B. F. (1979) Behavior of major solutes during closed-basin brine evolution. Am., Jourl. Sci., No. 279, p: 609-631.

Gat, J.R. (1980) The relationship between surface and subsurface waters. Water quality aspect in areas of low precipitation. Hydrol. Science, Bull. 25, p:257-267.

Hem, J.D. (1989) The Study and Interpretation of the Chemical Characteristics of Natural Water. 3rd edn. USGS Water Supply Paper 2254, US Geological Survey

Italconsult (1976) Detailed investigations of Wade Khulais basin. Unpub. Report. Ministry of Agriculture and Water, Riyadh, Saudi Arabia.

Jamman, A. M. (1978) Hydrogeology of Wadi An Numan, Saudi Arabia. Unpub M. Sc.Thesis, Faculty of Earth Sci., King Abdulaziz Uni., Jeddah, Saudi Arabia. M.Sc. Thesis, Institute of Applied Geology, King Abdulaziz Uni., Jeddah, Saudi Arabia.

Johnson, P. R. (2006) Explanatory notes to the map of Proterozoic geology of western Saudi Arabia, technical report SGS-Tr-2006-4.

Lloyd, J. A., and Heathcote, J.A. (1985) Natural inorganic hydrochemistry in relation to groundwater: An introduction. Oxford Uni. Press, New YorK p: 296.

Mansour, M. A. (1984) Evaluation of groundwater resources of Wade Fatimah by Numerical model. Unpub. M.Sc.Thesis, Faculty of Earth Sci., King Abdulaziz Uni., Jeddah, Saudi Arabia.

Moore, T. A., and Al-Rehaili, M.H. (1989) Explantory notes to the geologic map of the Makkah quadrangle, sheet21D, Kingdom of Saudi Arabia: Saudi Arabian Dir. Gen. Min. Res. Geoscience map GM-107C, 1:250,000 scale.

Piper, A. M. (1944): “A graphic procedure in the geochemical interpretation of water analyses”.

Radain, A.A., Al-Shanti, A.M.S., and Abdel-Monem, A.A.(1989) Age and petrochemistry of Bahrah granodiorite-granite complex, Jeddah-Makkah region, Saudi Arabia: Journal of King Abdulaziz University, Earth Sciences, v. 2, p. 147-167.

Rainwater, F.H., and Thatcher, L. L. (1960) Methods for collection and analysis of water samples. U.S.Geol. Survey, Water supply Paper 1454.

Ramsay, C.R. (1986) Geologic map of the Rabigh quadrangle, sheet 22 D, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Geologic Map GM-84, 49 p.

Sharaf, M. A, Alyamani MS, Subyani, A. M (2004) Regional study of the rare and trace elements in the groundwater of the major wadi basins (An Numan, Usfan, and Fatimah) in western Saudi Arabia and their suitability for various purposes. Project No. (204/423). King Abdulaziz University. Jeddah. Saudi Arabia.

Sharaf, M.A., Al-Bassam,A., Bayumi, T.H., and Qari,M. H. (2002) Hydrogeological and hydrochemical investigation of the Cretaceous- Quaternary sedimentary sequence east of Jeddah city. King Abdulaziz City for Science and Technology (KACST), Final Report, Riyadh, Saudi Arabia.

Sharaf, M. A., Farag, M. H., and Gazzaz, M. (1988) Groundwater chemistry of WadiUoranah- Alabdiah area. Western Province, Saudi Arabia, JKAU: Earth Sci. 1, 103-112.

Singh, T., and Kalar, Y.P. (1975) Specific conductance methods for an in situ estimation of total dissolved solids. Jour. AWWA, Vol. 67, No. 2 p: 99-100.

Singh, A..K., Mondal, G.C. Kumar, S.Singh, T. B., Tewary, B. K., Sinha, A. (2008): Major ionchemistry, weathering processes and water quality assessment in upper catchment of Damodar River basin, India. Environ Geol, 54:745–758.

Szabolcs I, Darab C.(1964): The influence of irrigation water of high sodium carbonate content of soils. In: Proceedings of 8th International Congress of Isss, Trans, vol II, pp 803–812.

USSL 1954: Diagnosis and improvement of saline and alkali soils. USDA Agr. Handbook No. 60, Washington DC

WHO (1984) Guidelines for Drinking Water Quality, Geneva.

Zaidi, S. (1983) Landform and geomorphic evolution of Wade Khulais area. Western Saudi Arabia. FES, Bull. 5, 153-156pp.

Zaidi,S.(1984) Geomorphology of Wadi Khulais area. FES, Res. Ser. No.18, 98p.