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Monitoring of Groundwater Salinity for Water Resources Management in Irrigated Areas of Al-Jouf Region, Saudi Arabia

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ABSTRACT
Groundwater salinity is an important limiting factor to sustainable irrigated agriculture in Saudi Arabia. The total groundwater salinity depends on the aquifer geology and its chemical characteristics. The main objective of this study was to monitor groundwater salinity for water resources management in irrigated areas of Al-Jouf Region of Saudi Arabia. A total of 117 water samples were collected from randomly selected small, medium and large agricultural farms from the whole region. The water samples were mainly analyzed for major cation and anions. The total groundwater salinity in less than 1000 mg L^{-1} in the whole region and falls in the category of medium to high salinity and medium to high sodicity water. Inter-ion relationship is very poor between major cations and anions. The EC and SAR relationship is very poor (R^2 = 0.038). About 91% of groundwater is of sodium chloride type waters and the remaining 9% is that of sodium sulfate type water. The relationship between simple SAR and calculated SARs is very strong (R^2 = 0.988 and 0.983). The results showed a replenishment of groundwater aquifer with the fresh water intrusion. In conclusion, to achieve higher water use efficiency, improvement water management practices such as application of leaching requirements, adoption of improved irrigation methods (drip and sub-surface irrigation) and proper crop selection need to be followed for increased agricultural production in the region.

Key words: Groundwater, salinity, inter-ion relationship, sodicity, water classification, electrical conductivity, sodium adsorption ratio

INTRODUCTION
In Saudi Arabia, demand for irrigation water is increasing due to agricultural expansion for increasing agricultural productivity to meet the food and fiber requirements of increasing population. As such, there is a lot of stress on groundwater exploration to meet the growing water needs not only for agriculture sector but also for non-irrigation uses such as domestic, industrial and other development sectors. The groundwater sources in Saudi Arabia are not only scared but also non-renewable (Al-Tokhais, 2013) with minimal recharge from the limited rainfall received in the country (Lin, 1984).

Irrigation water salinity is one of major factors limiting the optimal use of available water resources for irrigation in arid regions of the world. Some investigators reported ground quality deterioration with special reference to total salt concentration resulting either from over-pumping or over exploitation of groundwater aquifers in different regions of the country such as Al-Hassa Oasis spring and drainage water (Hussain and Sadiq, 1991; Al-Hawas, 2002), Wadi Al-Yamaniyah (Bazuhair and Alkaff, 1989), Al-Qassim Region (Faruq *et al.*, 1996), Saudi Ground water chemistry (Mee, 1983) and chemical composition of ground waters of Saudi Arabia (MAW., 1985;

El-Din *et al*., 1993). Jun *et al*. (2005) applied hydrogeological characterization and isotope techniques to identify the location source and to trace the level of groundwater contamination by nitrate.

Chowdhury and Al-Zahrani (2015) estimated the non-renewable groundwater reserves around 259.1-760.6 billion cubic meters (BCM) with an effective annual recharge of 886 million cubic meters (MCM). He also reported the total internal renewable water upto 2.4 BCM year^{-1}. They also reported the water demand for various uses as 18.51 BCM in 2009. However, out of this 83.5% was used in agriculture. On the other hand, water demand for agriculture decreased by 2.5% between 2004 and 2009, while there was 2.1 and 2.2% per year increase in water needs for domestic and industrial sector, respectively. While, the annual domestic water consumption increased from 1391 (609-2164) to 3818 (1687-7404) m^3/subscriber from 1999-2008. Besides, the industrial water demands also increased from 56-713 MCM/year from 1980-2009.

Currently, the aquifer system in the Wadi Sirhan Basin is being exploited only in Saudi Arabia. According to an estimate, there were only 80 wells in the Wadi Sirhan withdrawing up to 2.5 million cubic meters of water per year which were mainly located in the central depression with the development of new agricultural activities (ACSAD., 1983). According to Abderrahman (2006), the number of wells in Wadi Sirhan increased to around 1,000 in 1982 which increased to more than 1,500 in 1986 especially in the Tubarjal-Al Isawiyah area in Saudi Arabia. This resulted in increased groundwater withdrawal approximately from 100 MCM year^{-1} in 1984 up to 1,000 MCM year^{-1} in the mid 1990s. Furthermore, with the expansion of agricultural activities after 1996, the total water withdrawal from the aquifer in Al Jawf Province increased from 1,900 MCM in 2003-3,500 MCM in 2004 (UN-ESCWA and BGR., 2013).

The main objective of this study was to monitor groundwater salinity subjected to varying degrees of water withdrawal to meet the growing water needs of agricultural expansion in order to improve groundwater management to avoid water quality degradation in Al-Jouf Region of Saudi Arabia.

Study location: The An Nafud Desert in Northern Saudi Arabia is separated from the Syrian Desert (Badiyet esh Sham) by the Hammad Plateau, which extends across the borders of Iraq, Jordan, Saudi Arabia and Syria (Khouri, 1982). On the basis of surface water drainage and the directions of groundwater flow, six hydrogeological basins were defined in the Hammad Plateau as (1) Wadi al Miyah, (2) Eastern Hammad, (3) Central Hammad, (4) Wadi Sirhan, (5a) Azraq, (5b) Sabkhat Munq'a or Rutba and (6) Sabkhat al Moh (ACSAD., 1983). The Tawil-Quaternary Aquifer System (Wadi Sirhan Basin), extending from the eastern boundaries of the Basalt Aquifer (South-East) towards the Sakaka-Al Jawf area, constitutes the South-Western region of the Hammad Plateau.

Study area: The Tawil-Quaternary Aquifer System consists off the southern part of a large depression along the eastern edge of the Jordan Uplift (Wadi Sirhan Depression), where the thick Paleogene and Neogene-Quaternary sediments were accumulated. The shape of the whole Wadi basin is due to its geomorphologic landscape and was divided into three main regions namely; The central topographic depression is located in a North-West/South-East direction at an altitude of 500-600 m above sea level, the Western Widyan area is 900-1,100 m above sea level, the origin of the main tributaries of the Wadi Sirhan drain and the basalt plateau which is 800-900 m above sea level and extends over 220 km from the Jebel al Arab region into Saudi Arabia (ACSAD., 1983).

Based on the boundaries of the present basin, the total area is a round 44,000 km^2, out of this about 80% (35,000 km^2) lies in Saudi Arabia and the remaining 20% (9,000 km^2) lies in Jordan.

Some of the outcrops present in the basin include Quaternary-Neogene undifferentiated outcrops (10,000 km^2), volcanic outcrops (12,000 km^2), Cretaceous-and Paleogene-age outcrops (20,000 km^2) and Silurian-and Early (UN-ESCWA and BGR., 2013). The General stratigraphic sequence of Paleozoic rocks in Al-Jouf Region is presented in Fig. 1.

Age			Formation	Generalized lithologic description	Thickness (Type or reference section) (m)	Major stratigraphic divisions
Cenozoic	Qyaternary and tertiary		Superficial deposits	Gravel, sand and silt		
Cenozoic	Miocene and pliocene		Kharj	Limestone, lacustrine limestone, gypsum and gravel	28	Miocene-pliocene-clastcs
			Hofuf	Sandy marl and sandy limestone; subordinate calcareous sandstone. Local gravel beds in lower part	95	
			Dam	Marl and shale; subordinate sandstone, chalky limestone and coquina	91	
			Hadrukh	Calcareous, silty sandstone, sandy limestone; local chert	84	
	Eocene	Lutetian	Dammam	Limestone, dolomite, marl and shale	33	Upper cretaceous and eocene carbonates
		Ypresian	Rus	Marl, chalky limestone and gypsum; common chert and geodal quartz in lower part Dominantly anhydrite in subsurface	56	
	PA-LEO-CENE	Thanetian Montlan?	Ummer radhuma	Limestone, dolomitic limestone and dolomite	243	
			Possible disconformity			
Mesozoic	Caetaceous	Maestrichtian Campanian	Aruma	Limestone; subordinate dolomite and shale. Lower part grades to sandstone in northwestern and soutern areas of outcrop	142	
		Turonian? Cenomanaian	Wasia (sakaka sandstone of northwest Arabia	Sandstone; subordinate shale, rare dolomite lenses	42	Middle cretaceous clastics
		Aptian Barremian	Biyadh	Sandstone; subordinate shale	42	Late lower cretaceous clastic
		Hauterivian	Buwaib	Biogenic calcarenite and calcarenitic limestone interbedded with fine sandstone in upper part	18	
		Valanginian	Yamama	Biogenic-pellet calcarenite, subordinate aphanitic limestone and biogenic calcarenitic lilmestone	46	Upper jurassic and early lower cretaceous carbonates
		Berriasian	Sulaiy	Chalky aphanitic limestone; rare biogenic calcarenite and calcarenitic limestone	170	
	Jurassic	Tithonian	Hith	Anhydrite	90	
			Arab	Calcarenite, calcarenitic and aphanitic limestone, dolomite and some anhydrite. Solution collapse carbonate breccia on outcrop due to loss of interbedded anhydrite	124	
		Kimmeridgian	Jubaila	Aphanitic limestone, dolomite; subordinate calcarenite and calcarenitic limestone. lower part candstone between 20°N and 22°N	±118	
			Hanifa	Aphanitic limestone, calcarenitic limestone and calcarenitic	113	
		Oxfordian Callovian	Tuwaik mountain	Aphanitic limestone, subordinate calcarenitic limestone and calcarenitic. Abundant corals and stromatoporoids in upper part	203	
		Callovian? Bathonian Bajocian	Dhruma	Aphanitic limestone and shale; subordinate calcarenite. Dominantly sandstone south of 22°N and north of 26°N	375	Lower and middle jurassic clastics and carbonates
		Toarcian	Marrat	Shale and aphanitic limestome; subordnate sandstone	103	
	Triassic	Upper	Minjur	Subordnate; some Shale	315	Permo-triassic clastics
		Middle	Jailh	Sandstone aphanitic limestone and shale; subordinate gypsum	326	
		Lower	Sudair	Red and green shale	116	
Paleozoic	Perlan	Upper	Khuff	Limesione and shale domiantly sandstone South of 21°N	171	
		Lower Undated	Wajid	Sandstone, gravel and basement erratics (Recognized only in southwertern Saudi Arabia) and northerh yemen	950 Calculated	Early paleozoic clastics
			Precambrian basement complex			
	Devo-nian	Lower	Jauf	Limesione shale and sandston	299	
	Odo-vician and silurian		Tabuk	Sandstone and shale	1,072	
	CAM-BAIAH		Saq – Umm sahrn, Ram, Quweira, Siq	Sandstone	+600	

Fig. 1: General stratigraphic sequence of Paleozoic rocks in Al-Jouf Region (Source: UN-ESCWA and BGR., 2013)

Climate of Al-Jouf Region: The Tawil-Quaternary Aquifer System is situated in an arid region with a mean annual precipitation of 35-120 mm with average temperature ranging from 16-21°C. The annual evapo-transpiration was estimated as 1.460-1.680 mm. The area receives an average annual rainfall of less than 50 mm along the Southern Jordanian border mostly in the form of infrequent and short rain storms. The Potential Evaporation (PE) is more than 3,500 mm year^{-1}, whereas the actual evaporation is more than 90% of total rainfall received in the area (UN-ESCWA and BGR., 2013).

MATERIALS AND METHODS

The study was carried in irrigated areas of Al-Jouf region of Saudi Arabia during 2013-2014 cropping season. A total of 107 groundwater samples were collected from randomly selected agriculture farms in the region. These include small (5-10 ha), medium (20-25 ha) and big size farms (50-100 ha) at various locations in the region. The main cultivated crops were alfalfa, Rhoades grass, wheat, barley, vegetables and different types of fruit trees. The main criteria of water sample collection was that the well under investigation was running at least for 2-3 h to obtain a representative groundwater sample from each randomly selected agriculture farm. The groundwater samples were collected in 1 L capacity sterile plastic bottles, sealed properly and stored in an ice chest before delivering to the analytical laboratory for chemical analysis.

Water analysis: All the water samples were analyzed for different cations and anions. These include macro-elements (N, P, K, Ca, Mg, Na) and anions (CO_3, HCO_3, Cl, SO_4). In addition to the above water quality criteria, the Sodium Adsorption Ratio (SAR) was determined according to USDA (1954), Ayers and Westcot (1985) and APHA, AWWA, WEF (1998).

Data analysis: The data was analyzed statistically according to the procedures given in SAS (2010).

RESULTS AND DISCUSSION

Chemistry of groundwater: The ranges of minimum, maximum and mean values of different water quality parameters were 870, 550 and 719 dS m^{-1} (EC), 139.41, 339.81 and 193.07 mg L^{-1} (Ca), 62.17, 93.26 and 68.86 mg L^{-1} (Mg), 482.79, 1080.53 and 682.61 mg L^{-1} (Na), 430.10, 1368.50 and 806.48 mg L^{-1} (K), 85.43, 170.86 and 127.06 mg L^{-1} (HCO_3), 4.80, 196.92 and 84.19 mg L^{-1} (SO4), 53.18, 194.98 and 129.01 mg L^{-1} (Cl), 6.47, 16.22 and 10.80 (SAR), 32.10, 60.92 and 45.06% (Na), 7.89, 17.92 and 12.59 (adj. R_{Na}), 15.49, 34.11 and 23.67 (adj. SAR) and 7.99, 18.47 and 12.72 (ESP) for minimum, maximum and mean values, respectively (Table 1). However, the detailed chemical composition of groundwater samples is given in Table 2. Overall, chemistry of groundwater showed that total water salinity in very low and is fit for irrigation including the other purposes such as domestic, industrial and hospitals etc. The concentration of

Table 1: Overall range of minimum, maximum and mean values of some water quality parameters in Al-Jouf Region, Saudi Arabia

GW wells	Parameters (mg L^{-1}) EC	HCO_3	Ca	Mg	Na	K	Cl	SO_4	SAR	Na (%)	Adj RNa	Adj SAR	ESP
Maximum	870	170.86	339.81	93.26	1080.53	1368.50	194.98	196.92	16.22	60.92	17.92	34.11	18.47
Minimum	550	85.43	139.41	62.17	482.79	430.10	53.18	4.80	6.74	32.10	7.89	15.49	7.99
Mean	719	127.06	193.07	68.86	682.61	806.48	129.01	84.19	10.80	45.06	12.59	23.67	12.72

GW: Ground water, EC: Electrical conductivity, SAR: Sodium adsorption ration

Table 2: Chemical composition of groundwater of some selected agriculture farms in Al-Jouf Region, Saudi Arabia

Well	EC	EC1	Ca	Mg	Na	K	$HC0_3$	CO_3	SO_4	Cl	SAR	Na (%)	Ca+Mg
1	820.00	0.82	11.74	7.67	40.00	24.00	0.00	2.40	2.50	4.50	12.84	47.95	19.41
2	550.00	0.55	7.39	5.12	35.00	15.00	0.00	2.40	0.70	3.80	14.00	55.99	12.51
3	570.00	0.57	8.26	5.12	38.00	11.00	0.00	2.40	0.60	4.00	14.69	60.92	13.38
4	690.00	0.69	8.70	7.67	28.00	17.00	0.00	2.20	0.40	4.20	9.79	45.63	16.37
5	730.00	0.73	11.30	7.67	33.00	22.00	0.00	2.40	1.80	4.20	10.71	44.61	18.98
6	630.00	0.63	8.26	7.67	29.00	27.00	0.00	2.20	0.60	5.00	10.27	40.32	15.93
7	580.00	0.58	6.96	7.67	36.00	19.00	0.00	2.00	1.40	4.00	13.31	51.70	14.63
8	790.00	0.79	10.43	7.67	29.00	21.00	0.00	2.00	1.20	4.50	9.64	42.58	18.11
9	690.00	0.69	7.39	7.67	35.00	23.00	0.00	2.20	1.40	4.20	12.75	47.90	15.06
10	670.00	0.67	7.39	7.67	32.00	22.00	0.00	2.00	2.10	3.30	11.66	46.33	15.06
11	620.00	0.62	7.39	5.12	32.00	22.00	0.00	1.80	2.00	3.50	12.80	48.12	12.51
12	630.00	0.63	7.39	5.12	25.00	22.00	0.00	2.20	0.90	3.50	10.00	42.01	12.51
13	780.00	0.78	10.00	5.12	32.00	17.00	0.00	2.40	1.00	4.00	11.64	49.91	15.12
14	810.00	0.81	10.87	5.12	37.00	20.00	0.00	2.00	2.40	4.00	13.09	50.70	15.98
15	640.00	0.64	7.83	5.12	32.00	15.00	0.00	2.10	1.60	3.00	12.58	53.39	12.94
16	600.00	0.60	7.39	5.12	23.00	21.00	0.00	2.20	1.10	3.00	9.20	40.70	12.51
17	590.00	0.59	7.39	5.12	25.00	16.00	0.00	2.40	0.90	2.70	10.00	46.72	12.51
18	580.00	0.58	7.39	5.12	22.00	18.00	0.00	2.40	0.80	2.70	8.80	41.90	12.51
19	580.00	0.58	7.39	5.12	23.00	18.00	0.00	2.00	1.30	2.70	9.20	42.99	12.51
20	590.00	0.59	7.39	5.12	25.00	18.00	0.00	2.40	0.80	3.00	10.00	45.04	12.51
21	770.00	0.77	11.74	5.12	22.00	22.00	0.00	2.20	1.60	3.50	7.58	36.15	16.85
22	750.00	0.75	7.39	5.12	28.00	21.00	0.00	2.00	2.10	2.70	11.20	45.52	12.51
23	590.00	0.59	7.39	5.12	21.00	23.00	0.00	2.20	1.40	2.70	8.40	37.16	12.51
24	610.00	0.61	8.26	5.12	21.00	20.00	0.00	2.00	1.50	2.70	8.12	38.62	13.38
25	770.00	0.77	11.30	5.12	25.00	22.00	0.00	2.00	2.00	3.50	8.73	39.42	16.42
26	780.00	0.78	11.74	7.67	25.00	21.00	0.00	2.00	1.60	4.00	8.02	38.22	19.41
27	770.00	0.77	11.74	7.67	26.00	20.00	0.00	2.00	1.80	3.80	8.35	39.75	19.41
28	690.00	0.69	10.00	7.67	24.00	23.00	0.00	1.80	2.20	3.30	8.07	37.11	17.67
29	730.00	0.73	10.87	7.67	25.00	20.00	0.00	1.60	2.70	3.00	8.21	39.34	18.54
30	730.00	0.73	10.87	7.67	26.00	19.00	0.00	2.00	2.00	3.30	8.54	40.92	18.54
31	770.00	0.77	11.74	7.67	24.00	20.00	0.00	1.80	1.80	3.80	7.70	37.85	19.41
32	770.00	0.77	11.74	7.67	21.00	25.00	0.00	2.00	1.60	4.00	6.74	32.10	19.41
33	730.00	0.73	11.30	7.67	21.00	23.00	0.00	2.20	1.30	3.80	6.82	33.35	18.98
34	740.00	0.74	11.74	7.67	22.00	25.00	0.00	2.00	2.70	3.00	7.06	33.13	19.41
35	710.00	0.71	10.87	7.67	30.00	16.00	0.00	2.20	2.20	3.00	9.85	46.48	18.54
36	760.00	0.76	11.74	7.67	22.00	24.00	0.00	2.00	1.60	4.00	7.06	33.63	19.41
37	670.00	0.67	10.00	5.12	34.00	16.00	0.00	2.20	2.00	3.30	12.37	52.22	15.12
38	720.00	0.72	10.87	7.67	28.00	22.00	0.00	1.80	2.50	3.50	9.20	40.85	18.54
39	760.00	0.76	11.74	7.67	32.00	13.00	0.00	2.00	2.00	3.50	10.27	49.68	19.41
40	660.00	0.66	10.00	5.12	26.00	19.00	0.00	2.20	1.80	3.00	9.46	43.25	15.12
41	640.00	0.64	9.13	5.12	23.00	17.00	0.00	2.40	0.60	3.30	8.62	42.40	14.25
42	620.00	0.62	8.70	5.12	22.00	21.00	0.00	2.00	1.80	2.70	8.37	38.73	13.81
43	680.00	0.68	10.43	5.12	21.00	20.00	0.00	2.20	1.20	3.30	7.53	37.14	15.55
44	680.00	0.68	10.43	5.12	26.00	14.00	0.00	2.00	1.30	3.30	9.32	46.80	15.55
45	640.00	0.64	9.13	5.12	25.00	17.00	0.00	2.20	1.80	2.50	9.37	44.45	14.25
46	580.00	0.58	7.83	5.12	23.00	20.00	0.00	2.20	1.10	3.00	9.04	41.11	12.94
47	580.00	0.58	7.39	5.12	25.00	17.00	0.00	2.20	1.40	2.50	10.00	45.87	12.51
48	660.00	0.66	10.00	5.12	25.00	16.00	0.00	2.20	2.40	2.00	9.09	44.55	15.12
49	670.00	0.67	10.00	5.12	36.00	12.00	0.00	1.60	2.00	3.50	13.10	57.04	15.12
50	700.00	0.70	11.30	5.12	26.00	20.00	0.00	1.90	2.90	2.70	9.07	41.65	16.42
51	560.00	0.56	7.39	5.12	21.00	16.00	0.00	2.20	1.10	2.30	8.40	42.42	12.51
52	810.00	0.81	8.70	5.12	41.00	14.00	0.00	2.00	2.20	3.50	15.60	59.58	13.81
53	800.00	0.80	8.70	5.12	28.00	35.00	0.00	2.00	2.30	4.20	10.66	36.45	13.81
54	770.00	0.77	8.70	5.12	31.00	26.00	0.00	2.40	2.30	4.20	11.80	43.78	13.81
55	790.00	0.79	9.13	5.12	23.00	31.00	0.00	2.00	1.50	4.20	8.62	33.70	14.25
56	630.00	0.63	9.13	7.67	47.00	0.00	0.00	1.60	1.80	3.70	16.22	73.66	16.80
57	760.00	0.76	16.96	5.12	27.00	19.00	0.00	2.60	2.80	3.30	8.13	39.66	22.07
58	730.00	0.73	8.70	5.12	26.00	35.00	0.00	2.00	2.30	4.00	9.89	34.75	13.81
59	770.00	0.77	8.70	5.12	23.00	21.00	0.00	2.00	1.00	3.60	8.75	39.78	13.81
60	780.00	0.78	9.13	5.12	30.00	22.00	0.00	2.00	1.50	4.00	11.24	45.29	14.25
61	760.00	0.76	8.70	5.12	31.00	26.00	0.00	2.60	1.10	4.20	11.80	43.78	13.81

Table 2: Continue

Well	EC	EC1	Ca	Mg	Na	K	HCO_3	CO_3	SO4	Cl	SAR	Na (%)	Ca+Mg
62	790.00	0.79	8.70	5.12	36.00	20.00	0.00	2.40	0.20	5.20	13.70	51.57	13.81
63	790.00	0.79	8.70	5.12	36.00	21.00	0.00	2.20	1.00	4.70	13.70	50.84	13.81
64	760.00	0.76	8.70	5.12	33.00	18.00	0.00	2.20	0.90	4.20	12.56	50.92	13.81
65	780.00	0.78	8.70	5.12	36.00	21.00	0.00	2.40	0.70	4.80	13.70	50.84	13.81
66	770.00	0.77	8.70	5.12	23.00	26.00	0.00	2.40	1.70	3.00	8.75	36.62	13.81
67	780.00	0.78	8.70	5.12	24.00	18.00	0.00	2.20	0.00	4.20	9.13	43.00	13.81
68	760.00	0.76	12.61	5.12	23.00	21.00	0.00	2.00	0.50	5.00	7.73	37.26	17.72
69	780.00	0.78	9.13	5.12	22.00	23.00	0.00	2.20	0.10	4.50	8.24	37.13	14.25
70	800.00	0.80	9.13	5.12	29.00	23.00	0.00	2.80	0.20	5.50	10.87	43.78	14.25
71	810.00	0.81	9.13	5.12	36.00	26.00	0.00	2.40	0.10	5.00	13.49	47.22	14.25
72	810.00	0.81	9.13	5.12	34.00	20.00	0.00	2.40	0.00	5.30	12.74	49.82	14.25
73	780.00	0.78	9.13	5.12	37.00	12.00	0.00	2.60	3.10	1.50	13.86	58.50	14.25
74	790.00	0.79	8.70	5.12	33.00	26.00	0.00	2.00	2.10	4.00	12.56	45.32	13.81
75	770.00	0.77	9.13	5.12	28.00	17.00	0.00	2.00	0.80	4.00	10.49	47.26	14.25
76	810.00	0.81	9.13	5.12	38.00	19.00	0.00	2.80	1.00	4.20	14.24	53.34	14.25
77	760.00	0.76	8.70	5.12	25.00	31.00	0.00	1.80	2.00	4.00	9.51	35.81	13.81
78	780.00	0.78	9.13	5.12	25.00	20.00	0.00	2.40	0.90	3.50	9.37	42.20	14.25
79	700.00	0.70	9.13	5.12	27.00	28.00	0.00	2.80	1.70	3.30	10.12	38.99	14.25
80	770.00	0.77	8.70	5.12	26.00	23.00	0.00	2.00	2.10	4.00	9.89	41.39	13.81
81	790.00	0.79	9.13	5.12	37.00	21.00	0.00	2.60	2.00	3.50	13.86	51.21	14.25
82	780.00	0.78	8.70	5.12	29.00	26.00	0.00	2.00	1.70	4.00	11.04	42.14	13.81
83	760.00	0.76	8.70	5.12	27.00	22.00	0.00	1.80	1.50	3.80	10.27	42.99	13.81
84	720.00	0.72	9.57	5.12	30.00	24.00	0.00	1.80	3.70	2.30	11.07	43.68	14.68
85	690.00	0.69	9.57	5.12	37.00	27.00	0.00	2.20	4.10	2.50	13.66	47.03	14.68
86	650.00	0.65	9.57	5.12	25.00	18.00	0.00	1.60	2.60	2.50	9.23	43.34	14.68
87	710.00	0.71	9.57	5.12	31.00	20.00	0.00	1.60	2.90	3.00	11.44	47.20	14.68
88	720.00	0.72	10.00	5.12	39.00	20.00	0.00	1.80	3.60	3.00	14.19	52.62	15.12
89	690.00	0.69	9.57	5.12	30.00	21.00	0.00	1.80	3.50	2.50	11.07	45.68	14.68
90	810.00	0.81	11.74	5.12	35.00	20.00	0.00	1.80	3.60	3.00	12.06	48.71	16.85
91	670.00	0.67	10.87	5.12	30.00	21.00	0.00	1.80	2.40	3.30	10.61	44.79	15.98
92	760.00	0.76	10.87	5.12	40.00	21.00	0.00	2.00	3.00	3.80	14.15	51.96	15.98
93	680.00	0.68	9.57	5.12	33.00	19.00	0.00	1.60	1.70	4.30	12.18	49.49	14.68
94	740.00	0.74	10.87	5.12	33.00	23.00	0.00	1.60	2.70	4.00	11.67	45.84	15.98
95	800.00	0.80	10.87	5.12	35.00	22.00	0.00	1.60	2.80	4.00	12.38	47.96	15.98
96	700.00	0.70	10.87	5.12	30.00	20.00	0.00	1.60	2.60	3.50	10.61	45.47	15.98
97	770.00	0.77	11.30	5.12	39.00	18.00	0.00	1.80	2.40	4.30	13.61	53.12	16.42
98	870.00	0.87	12.17	5.12	40.00	20.00	0.00	1.60	3.10	4.30	13.60	51.75	17.29
99	710.00	0.71	10.00	5.12	32.00	26.00	0.00	2.00	2.50	3.80	11.64	43.77	15.12
100	800.00	0.80	11.30	5.12	41.00	29.00	0.00	2.20	3.30	4.30	14.31	47.44	16.42
101	820.00	0.82	11.74	5.12	40.00	17.00	0.00	2.00	2.10	4.50	13.78	54.16	16.85
102	800.00	0.80	11.74	5.12	40.00	22.00	0.00	2.20	2.60	4.30	13.78	50.73	16.85
103	650.00	0.65	10.00	5.12	32.00	20.00	0.00	2.20	2.00	3.50	11.64	47.68	15.12
104	680.00	0.68	10.00	7.67	30.00	12.00	0.00	1.80	0.70	4.30	10.09	50.27	17.67
105	660.00	0.66	10.00	5.12	26.00	13.00	0.00	1.40	0.60	4.00	9.46	48.05	15.12
106	690.00	0.69	10.00	5.12	31.00	12.00	0.00	2.00	0.80	4.00	11.28	53.34	15.12
107	810.00	0.81	10.00	5.12	40.00	21.00	0.00	1.80	2.80	4.00	14.55	52.55	15.12

EC: Electrical conductivity, SAR: Sodium adsorption ratio

all major cations is also within permissible limits according to Ayers and Westcot (1985). This study findings agree with the results many previous investigations who reported groundwater salinity variations either due to over water withdrawal or low water recharge of aquifer in different regions of Saudi Arabia (Hussain and Sadiq, 1991; Al-Hawas, 2002; Bazuhair and Alkaff, 1989; Faruq *et al*., 1996; Mee, 1983; MAW., 1985; El-Din *et al*., 1993).

Ground water classification: Ground water in the irrigated areas of Al-Jouf Region was classified using different water classification schemes to determine its use for sustainable irrigated agriculture for optimal crop production.

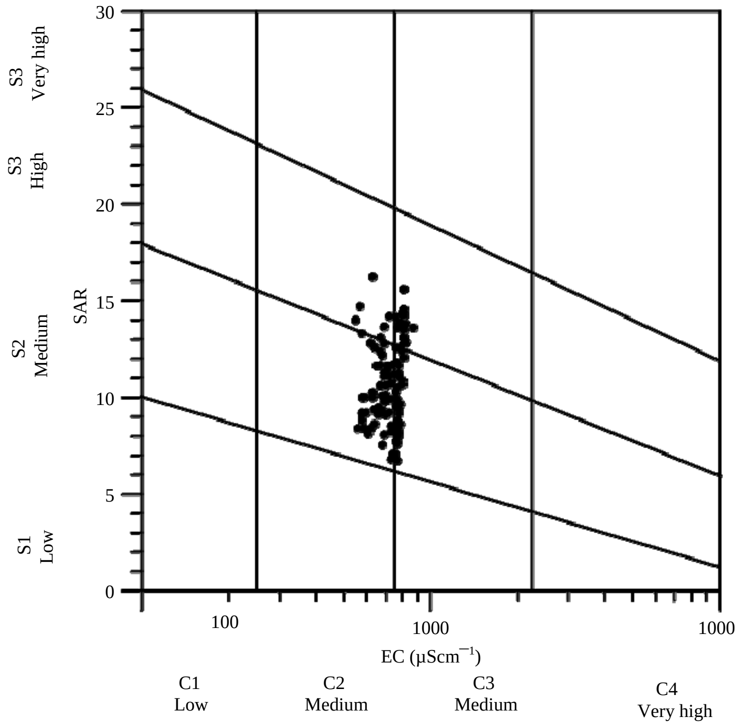

Fig. 2: Classification of ground water salinity based on USDA (1954) method for irrigation

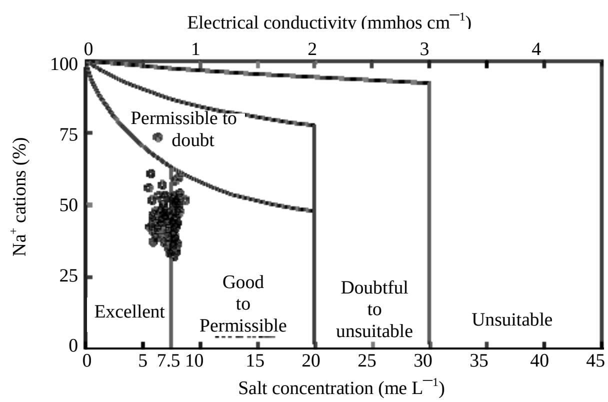

Fig. 3: Classification of ground water salinity according to Wilcox (1948)

The groundwater salinity classification based on Water Classification Criteria of USDA (1954) showed that the groundwater salinity falls in the category of medium to high salinity and medium to high sodicity classification (Fig. 2). This indicate that irrigation with this type of groundwater is likely to develop some soil salinity and sodicity problems with minor adverse effects on crop productivity, if proper water management practices such leaching requirements, proper crop selection and adoption of improved irrigation systems (drip and sub-surface irrigation). The groundwater salinity classification based on Wilcox (1948) criteria falls under the category of excellent to good class (permissible limit) when the total groundwater salinity is less than 1 dS m^{-1} and the Na percentage ranges between 25 to around 60 as shown in Fig. 3. However, according to

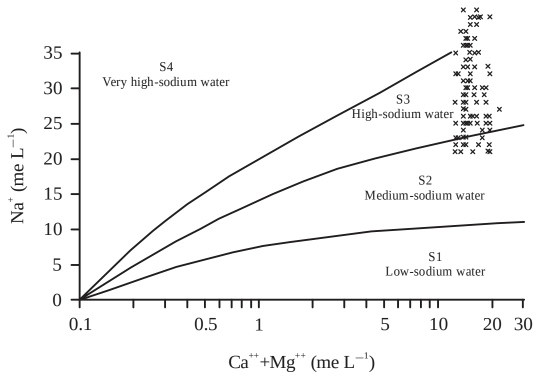

Fig. 4: Classification of ground water salinity according to Wilcox (1955)

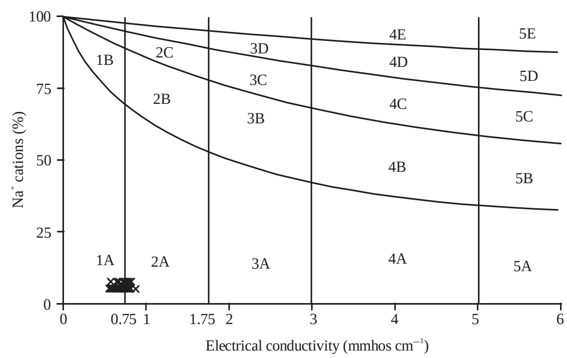

Fig. 5: Classification of ground water salinity according to Thorne and Thorne (1951)

the revised water classification scheme of Wilcox (1955), based on Na to Ca+Mg ratio, the groundwater salinity ranged between medium-sodium water to very high sodium water class (Fig. 4). This classification scheme indicates the development of minor soil sodicity problems in irrigated land with this type of water. In another water classification scheme (Thorne and Thorne, 1951), the groundwater salinity of Al-Jouf Region is categorized as IA which means that all the groundwater samples falls in the category of safe limits for irrigation purposes without any adverse effects on land and crop productivity (Fig. 5).

A Multi-Rectangular Diagram (MRD) of chemical analysis of groundwater salinity was prepared by using the Niaz Well Data method (Ahmad *et al*., 2003) to category all the ground water samples based on the relationship between all the major cations (Ca, Mg, Na+K) and anions [(CO_3+HCO_3), Cl, SO_4] (Fig. 6). It provided a variable picture of groundwater salinity in the whole Al-Jouf Region. Base on the relationship between (CO_3+HCO_3) and major cations, about 70% water samples falls in the category of Na+K-(CO_3+HCO_3) type water, 20% in Ca-(CO_3+HCO_3) and 10% under Mg+(CO_3+HCO_3) type water. While, based on the relationship between SO_4 and major cations (Ca, Mg, Na+K), around 65% water samples were found as (Na+K)-SO_4 type water and 20 and 15% in Mg-SO_4 and Ca+SO_4 type water, respectively. Also, when the relationship between Cl and major cations was considered, about 70% groundwater samples were classified as Na+K-Cl type water, 20% as Ca-Cl type water and 10% as Mg-Cl type water for irrigation purposes. Overall, it was noticed that most of the groundwater samples are in safe limits when the total water salinity is

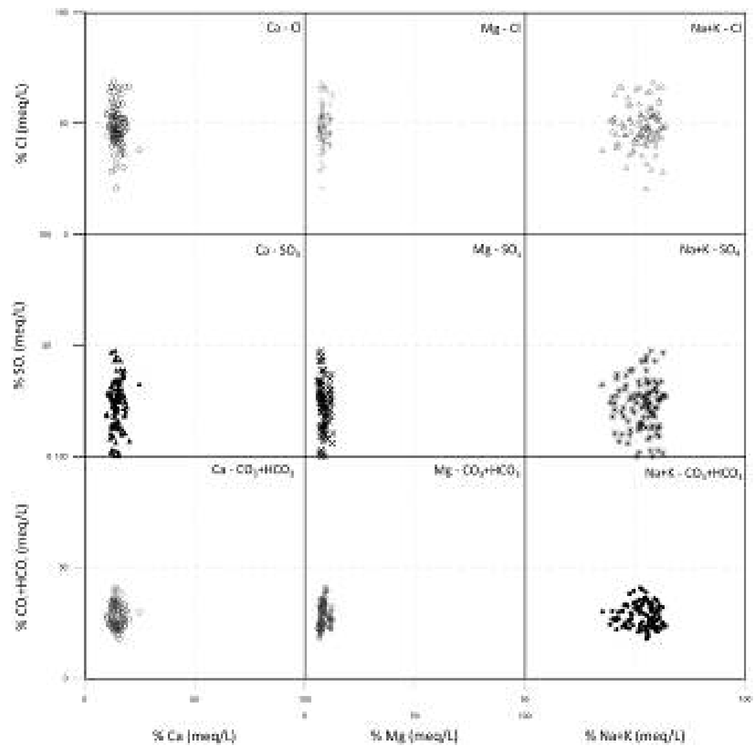

Fig. 6: Multi-Rectangular Diagram (MRD) of chemical analysis of ground water according to Niaz Well Data Method (Ahmad *et al*., 2003)

considered for irrigation purpose. These results are similar to those reported by Ayers and Westcot (1985), who reported that groundwater salinity classification depends on the cationic and anionic ratio of groundwater and their inter-relationship.

In order to classify the groundwater from another perspective, Hydrochemical Facies Evolution Diagram (HFED) diagram was developed by following the method of Gimenez-Forcada (2010), which showed that all the groundwater samples of Al-Jouf region were classified as medium salinity category water containing substantial amount of all the major cations and anions such as Ca, Mg, Na, K, Cl, SO4 and CO_3+HCO_3 (Fig. 7). Generally, CO_3 ion is mostly absent or present only in negligible amounts in majority of the groundwater samples in the region, but it combines mainly with HCO_3 ion to determine the carbonate equilibrium in soil-water solution after irrigation. The data in Fig. 7 also illustrates that the groundwater seems to be replenished with the fresh water in the aquifer. Overall, the data analysis that around 90% groundwater samples fall in the category of sodium chloride water and the remaining 10% are classified as sodium sulphate waters. Similar findings were reported by Ayers and Westcot (1985) and MAW (1985), who stated that groundwater salinity is influenced by the aquifer geology and its characteristics.

Inter-ion relationship: Based on the regression analysis (Fig. 8), inter-ion relationship is very poor between Ca vs Cl (R^2 = 0.021), Na vs Cl (R^2 = 0.106), Mg vs Cl (R^2 = 0.017) and K vs Cl (R^2 = 0.065). Similarly, the relationship between SO_4 and major cations is also very poor as

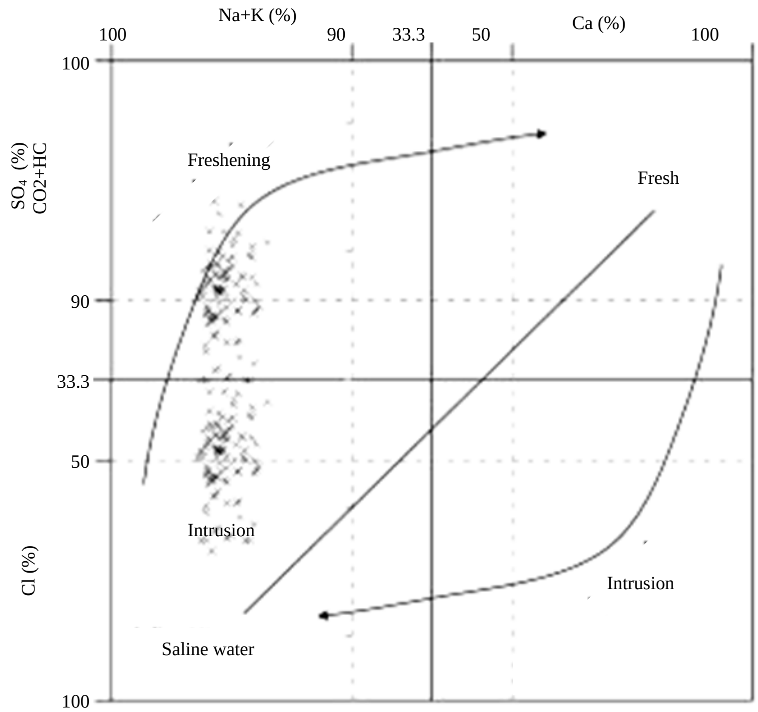

Fig. 7: HFED Diagram of chemical analysis of ground water salinity according to Gimenez-Forcada (2010)

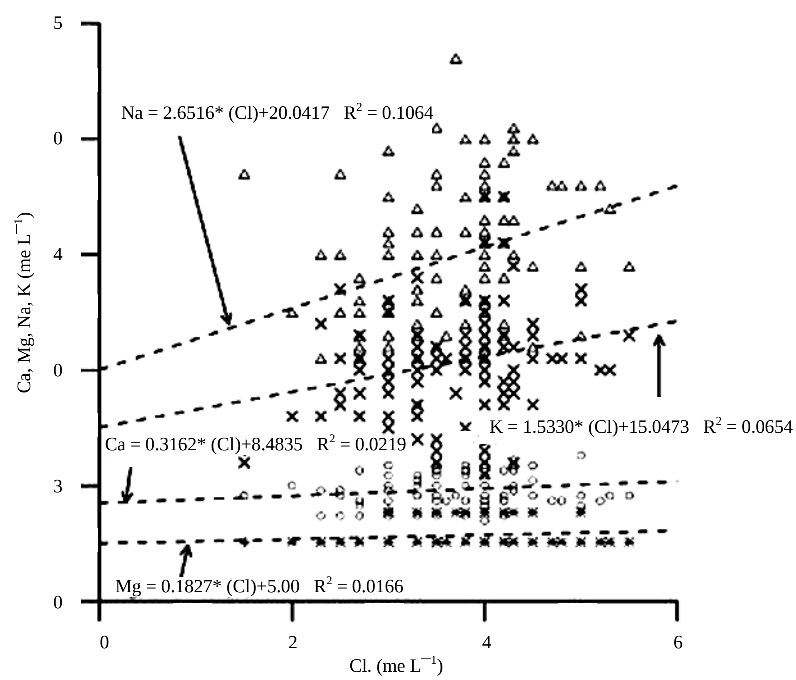

Fig. 8: Relationship between Cl and major cations of ground water in Al-Jouf Region

indicated from low values of R^2 i.e.. Ca vs SO_4 = 0.167, Mg vs SO_4 = 0.001, Na vs SO_4 = 0.095 and K vs SO_4 = 0.045 as indicated in Fig. 9. The relationship between HCO_3 and the major cations followed the same trend as that observed with other anions such as Cl and SO_4. The R^2 values were very low between HCO_3 vs Ca (0.038), HCO_3 vs Mg (0.018), HCO_3 vs Na (0.001) and HCO_3 vs K (0.002) as shown in Fig. 10. Overall, the poor relationship between all the major cations and anions may be attributed to overall low total groundwater salinity in Al-Jouf Region which may be primarily due to the characteristics of geological formation and the aquifer chemistry in the region. The study results are similar to those of Abderrahman (2006), who concluded that inter-ion relationship is generally poor in low salinity groundwater in many aquifers of Saudi Arabia.

Relationship between SAR vs calculated adj.SAR and adj.R_{Na}: It can be seen from the data in Fig. 11 that simple Sodium Adsorption Ratio (SAR) of groundwater is strongly related to the calculated adj.SAR (R^2 = 0.988) and adj.R_{Na} (R^2 = 0.983). The calculated values of adj.SAR are significantly higher when compared to adj.R_{Na}, because the adj.R_{Na} takes into account the precipitation and dissolution reactions of Ca ion with other anions (HCO_3, SO_4 and Cl) present in the groundwater where only the Mg ion is considered for determining the other calculated SARs values of the groundwater. On the other hand, adj.R_{Na} provides a true picture of the sodicity status of soil-water solution after irrigation which shows its adverse effects on plant growth under irrigation. The results of the study are identical to those reported by Ayers and Westcot (1985), who concluded that dissolution and precipitation reactions between Ca, Mg, Na and K with different anions (HCO_3, Cl, SO_4) present in water determine the sodicity status of groundwater aquifer.

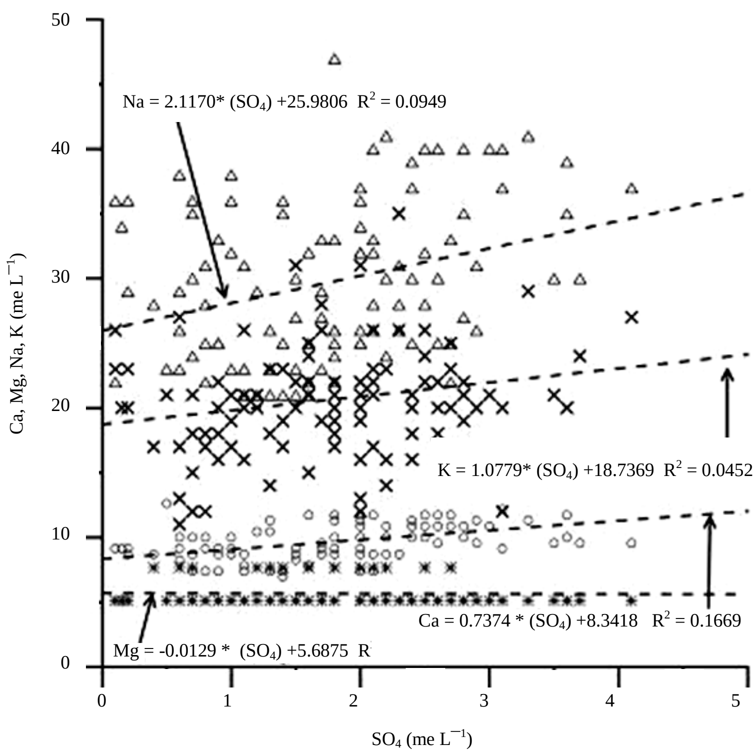

Fig. 9: Relationship between SO_4 and major cations of ground water in Al-Jouf Region

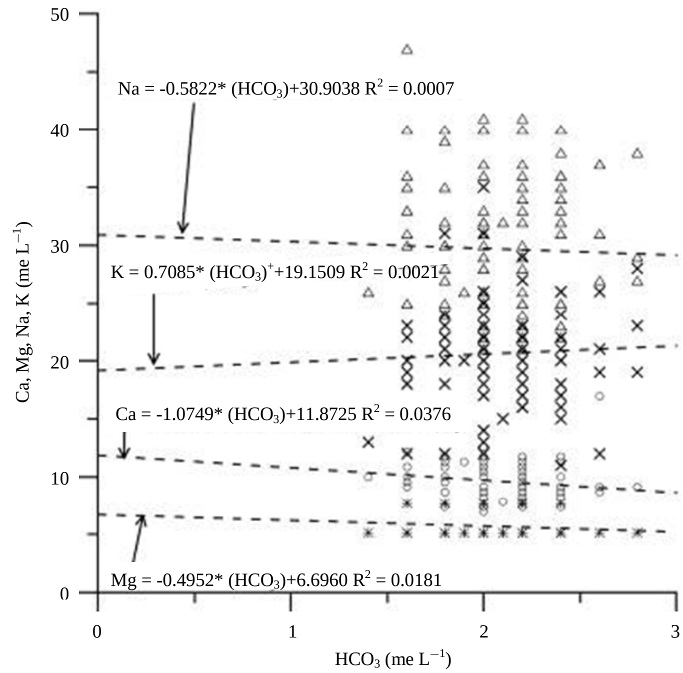

Fig. 10: Relationship between HCO_3 and major cations of ground water in Al-Jouf Region

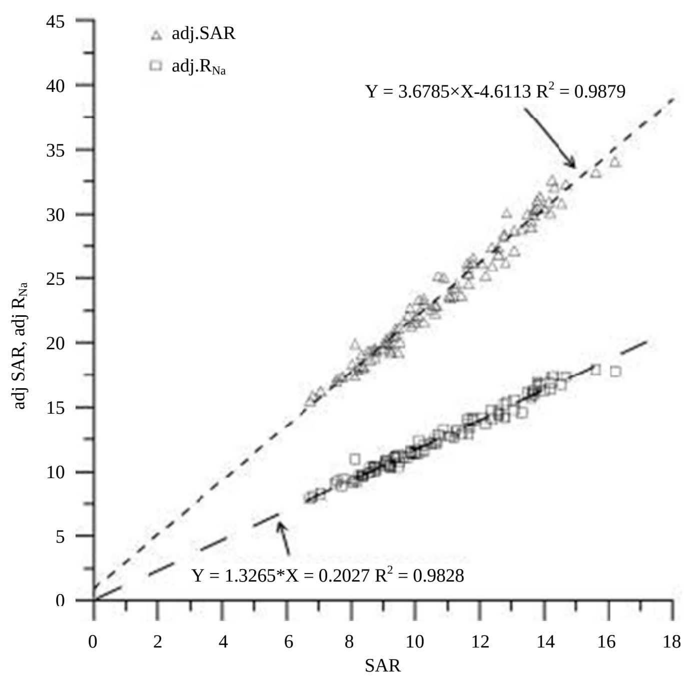

Fig. 11: Relationship between SAR vs calculated adj.SAR and adj.R_{Na} of ground water in Al-Jouf Region

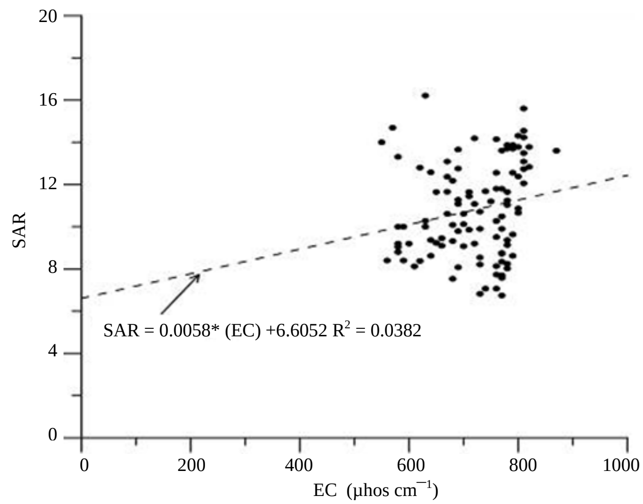

Fig. 12: Relationship between EC and SARs of ground water in Al-Jouf Region

Relationship between EC and SARs of groundwater: The relationship between Electrical Conductivity (EC) and Sodium Adsorption Ration (SAR) of ground water in Al-Jouf Region is very poor as indicated from low value of coefficient of determination (R^2 = 0.038) as shown in Fig. 12. This suggests that the SAR of groundwater is independent of the total water salinity. These findings agree with those of Ayers and Westcot (1985), who found poor relationship between EC and SAR in low salinity underground waters in irrigated regions of the world.

CONCLUSION

Overall the total groundwater salinity in less than 1000 mg L^{-1} in the whole region. The groundwater salinity falls in the category of medium to high salinity and medium to high sodicity classification according to the established standards for irrigation. Inter-ion relationship is very poor between major cations and anions. The EC and SAR relationship is very poor (R^2 = 0.038) due to overall low groundwater salinity. About 91% of groundwater is in the category of sodium chloride type water and the remaining 9% is that of sodium sulfate type water. The relationship between simple SAR and calculated SARs is very strong as shown from high R^2 values. The results showed replenishment of groundwater aquifer with the fresh water. In order to achieve higher water use efficiency, improvement water management practices such as application of leaching requirements, adoption of improved irrigation methods (drip and sub-surface irrigation) and proper crop selection need to be followed for increased agricultural production in the region.

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