FALAJES OF UNITED ARAB EMIRATES: GEOLOGICAL SETTING AND HYDROGEOLOGICAL CHARACTERISTICS

Zeinelabidin S. Rizk

Geology Department, Faculty of Science, U. A. E. University
Al Ain, P. O. Box 17551, United Arab Emirates

الخلاصـة :

الفلج هو نهر من صنع الانسان يعترض المياه الجوفية عند أقدام الجبال ويحملها الى السطح لاستخدام مياهها في الأغراض الزراعية أساسا. هدف هذه الدراسة هو مناقشة تأثير المناخ والجيولوجيا والظروف الهيدروجيولوجية على كيمياء ونوعية وصلاحية مياه الأفلاج بالإمارات العربية المتحدة للأغراض المختلفة. فبالاضافة إلى البيانات التي تم الحصول عليها من وزارة الزراعة والثروة السمكية نُظمت رحلات حقلية في مايو ١٩٩٥ ومارس ١٩٩٦ إلى مناطق رأس الخيمة والفجيرة والذيد والعين لقياس تدفقات الأفلاج وجمع عينات من مياهها للتحليل الكيميائي. وقد تم جمع (٣٤) عينة مياه، جرى تحليلها بالنسبة لمحتواها من الأيونات الرئيسة كما تَمَّ قياس تدفقات الأفلاج التي تَمَّتْ زيارتها عند مخارجها الرئيسة.

تدلُّ نتائج الدراسة أنه في الفترة من ١٩٧٨ إلى ١٩٩٥ م تراوح تدفق الأفلاج السنوي في الإمارات العربية المتحدة بين ٩ إلى (٣١,٢) مليون متر مكعب بما يمثل (٢,٨) إلى (٧,٩٪) من المياه المستخدمة سنويا في الدولة. كما تمثل مواقع الأفلاج وطبيعة الخزان المائي الذي يغذيها والتسرب من قنوات تلك الأفلاج بالاضافة إلى متوسط المطر السنوي أهم العوامل التي تؤثر في كميات تدفقها. وينحصر وجود الأفلاج في الإمارات العربية المتحدة على سلاسل الجبال الشرقية والسهول الحصوية التي تحدها من ناحيتي الشرق والغرب. وتتميز مياه الأفلاج بتفاوت توصيلها الكهربي الذي يتراوح بين ٤٥٠ ميكروسيمنز على السنتيمتر في فلج عسمة بمنطقة الفجيرة و(١٠٩٤٠) ميكورسيمنز على السنتيمتر في فلج عين سخانة بمنطقة العين. وتدل خريطة توزيع الأملاح في مياه الأفلاج أنها تصل إلى أقل معدلاتها عند خط تقسيم مياه جبال عُمان الشمالية وتزداد في اتجاهي الشرق والغرب. كما لوحظ أن تركيز الأملاح الذائبة الكلية يتناسب طرديا مع طول الفلج في حالة الأفلاج الغيلية ذات القنوات المكشوفة نتيجة البخر الطبيعي من مياهها علاوة على تفاعل مياهها مع صخور القنوات التي تحملها. أما في حالة الأفلاج الداودية والحضورية ذات القنوات المغطاه فلا توجد علاقة مباشرة بين طول الفلج ودرجة التوصيل الكهربي لمياهه.

تتميز مياه الأفلاج الغيلية في الإمارات العربية المتحدة بارتفاع تركيز أيوني البيكربونات والماغنيسيوم مما يدل على أنها تحمل في الغالب مياه أمطار كما أنها تصرف صخورا غنية بالماغنيسيوم وهي صخور الأفيوليت التي تكون معظم سلاسل الجبال الشرقية. وطبقا لقيم التوصيل الكهربي ونسبة ادمصاص الصوديوم فإن معظم مياه الأفلاج التي تمت دراستها تتراوح من جيدة إلى مقبولة للأغراض الزراعية.

ABSTRACT

The falaj is a man-made stream which intercepts groundwater at the footslopes of mountains and brings it to the surface at a lower level for irrigation purposes. The objective of this study is to discuss the effect of climate, geology and hydrological conditions on the chemistry and quality of water in the U.A.E. falajes.

Between 1978 and 1995, total falaj discharges ranged from 9.0 to 31.2 × 10^6 m^3/yr, which represents 2.8 to 9.7% of the total water use in the country. The location, aquifer storage, seepage loss from falaj channels, and rainfall, are the main factors affecting falaj discharges in the U.A.E.

All U.A.E. falajes are confined to the northern Oman mountains and the surrounding gravel plains. The Electrical Conductance (EC) of falaj waters are generally low to medium, varying between 450 micro-Seimens per centimeters (μS/cm) in Falaj Asimah (Al Fujairah) and 10 940 μS/cm in Falaj Ain Sukhnah (Al Ain). Iso-EC map shows that the EC of falaj waters is minimal near the water divide of the mountains and increases to the east and west. In open-channel falajes (Al Gheli type), the EC increases with increasing falaj length, but in the tunnel-type falajes (Al Daudi type), EC is generally low irrespective to the falaj length. Falaj waters have high concentrations of Mg^{2+} because they drain magnesium-rich mantle sequence rocks of the lower Semail nappe. The Mg/(Ca+Mg) ratio is >0.5 in 27 falajes out of 33, indicating the dissolution of Mg-rich rocks which are the main constituent of the ultramafic rocks of the Semail ophiolites. These conditions also favor the precipitation of calcite ($CaCO_3$) and possibly huntite ($Mg_3Ca(CO_3)_4$) which can be altered later to magnesite ($MgCO_3$). According to EC and Sodium Adsorption Ratio (SAR), water of the Gheli falajes in ophiolitic rocks are good for irrigation, whereas the water in the Daudi and Hadouri falajes draining limestone rocks are fair to poor for irrigation purposes.

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INTRODUCTION

Until recently, falajes represented the main arteries of life in the eastern U.A.E. At their outlets palm oases have flourished, permanent communities were established, and an agricultural way of life was dependent upon their water. At the present time, falajes are part of the U.A.E.'s agricultural heritage. Recently, many of U.A.E. falajes have gone dry because of the low rainfall and excessive groundwater pumping. However, several falajes are still flowing and feeding, at least in part, the same but now larger, palm oases. The design, construction, and maintenance of active falajes are interesting features. The water-distribution systems of historical falajes still exist near Al Hili archeological garden in the Al Ain area.

The geological setting of U.A.E. falajes, the factors affecting their discharge and water chemistry, the chemical characteristics of falaj waters and their suitability for different uses are the main objectives of this study.

The study area lies in the eastern U.A.E., between Longitudes 55° 00′ and 56° 30′ E and Latitudes 24° 00′ and 26° 00′ N, covering an area of some 40 000 km^2 (Figure 1). The field work for this study was conducted during the May 1995 – March 1996 period. The local geological and geomorphological features within the study area were investigated, 34 water samples were collected for chemical analysis, and the discharges of sampled falajes were measured at their main outlets. Water samples were analyzed for major cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) and anions (CO_3^{2-}, HCO_3^{-}, SO_4^{2-}, and Cl^{-}) in the Food Control Laboratory of the Al Ain Municipality.

HISTORICAL PERSPECTIVE

The word Falaj (plural = Falajes), or Aflaj in Arabic, means the division of an ownership into shares among those who have water rights. A falaj also means a distinct irrigation system through which water is distributed among individuals who have a right to it.

In this study, a falaj is defined as a man-made stream which intercepts the groundwater table through a single or several wells at the footslopes of high mountains. It brings water to the surface through a tunnel which has a slope gentler than the natural hydraulic gradient. As a falaj intersects the ground surface, it splits into several branches (called *Awamid,* the Columns). These are narrow, deep, open, and cement-lined small channels which deliver water from the main tunnel of the falaj to farm lands and palm oases (Figure 2).

Despite similarities in design, it is hard to find two identical falajes. Falajes vary in width, length, water quality, discharge rate, and the nature of the ground which they run through. Before construction of the main well an expert (called *Al Baseer,* the Foresighter), depending on his experience, feeling, and guess, decides the site of the main well. This well (Umm Al Falaj = mother of the falaj) may reach a depth of 30 m, and decreases gradually in depth as the falaj approaches the ground surface. For each falaj there may be more than one Umm (mother), resembling upstream tributaries which carry water from a wide area to the main stream channel (tunnel of the falaj). Because these mountains typically receive up to 350 mm of rainfall per year, falajes are usually constructed in the piedmont zone. Shafts (vertical wells) are constructed about 20 m apart. If enough water is obtained, workers start connecting these shafts together through a tunnel, and a line of additional wells, of shallower depth, are dug. The length of the falaj tunnels depends on the ease of drilling in the rock opposite the mountainous area [1].

The falaj width ranges from 0.6 to 1.2 m and its height varies between 0.9 m and 2.1 m. Access, rock materials, falaj maintenance, and aeration are all facilitated through the shafts. The tunnel slope depends on the ground slope, ground material and groundwater depth.

In the past, falaj water was used for all purposes. Now their use is limited to irrigation. The distribution of the water of a falaj is a complicated process which depends on the stars at night, and sundial-based shares during the day. Water is divided among participants according to legal entitlement, nature of the soil, and farm needs. *Al Areef* (the Knowledgeable), is the person who is responsible for distribution of water among participants in return to a certain share in the water of the falaj. Al Areef is a trusted, experienced, and knowledgeable person who has to know the time interval between the disappearance of a star and appearance of another and their positions in the sky. He should also know how to measure shadow in the daytime.

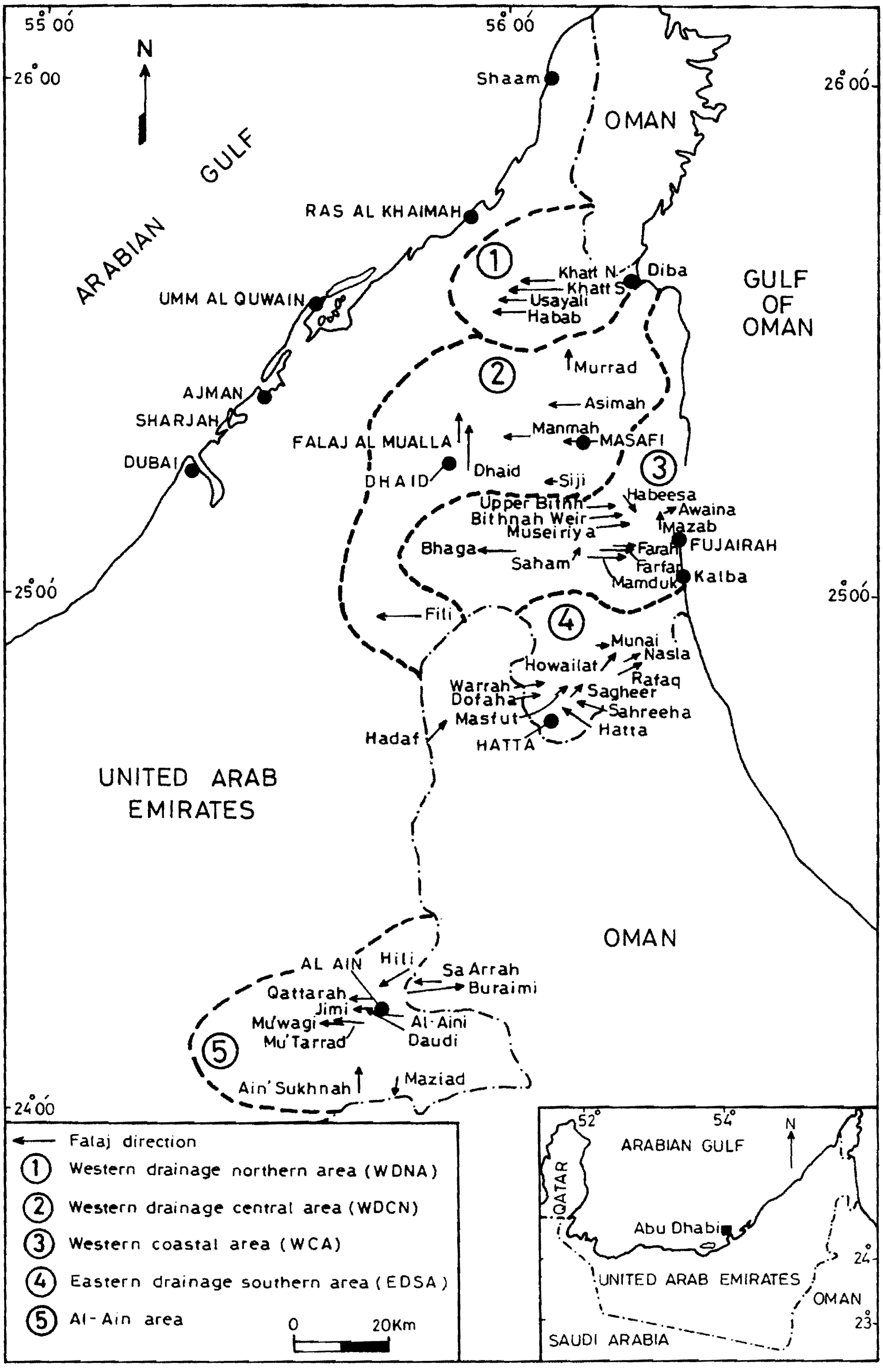

Figure 1. Location Map of the Study Area and the U.A.E. Falajes. The lengths of arrows represent falaj lengths.

GEOLOGY

In addition to the field survey, a study of topographic maps, aerial photographs, and satellite images enabled recognition of the following geomorphic divisions in the eastern U.A.E. (United Arab Emirates National Atlas), [2]: (1) mountains; (2) gravel plains; (3) linear and star dunes; (4) old and recent dunes; and (5) coastal sabkhas (Figure 3).

The eastern U.A.E. area is covered by a rock sequence ranging in age from the Triassic to the Quaternary (Figure 4). Lithology, geological structure, and climate are the main controls on the amount and quality of water flowing through the falajes.

Because the U.A.E. falajes are confined to the eastern mountains and gravel plains, the following is a brief discussion on the geology of both regions.

Mountains

The eastern mountains of the U.A.E. extend for 155 km between Shaam in the north and Al Ain in the south, with an average width of 10 km in the north, 38 km in the middle, and 27 km in the south. The elevations of the mountain peaks typically vary between 500 and 900 m above sea level. Some salient peaks, however, may reach an elevation of 2000 m. Within the U.A.E., these mountains are heavily dissected by 58 separate drainage systems, which vary in area between 5 km^2 (Wadi Dadnah, Al Fujairah) and 5000 km^2 (Wadi El-Peeh, Ras Al Khaimah).

The eastern mountains of U.A.E. can be divided into three major parts: (*a*) Rus Al Jibal massif in the north, (*b*) Diba zone in the middle, and (*c*) northern Oman mountains in the south.

The Rus Al Jibal massif consists predominantly of a carbonate sequence that ranges in age from Triassic to Lower Cretaceous. In general, the area is characterized by broad folding, block faulting, and complex local thrusting.

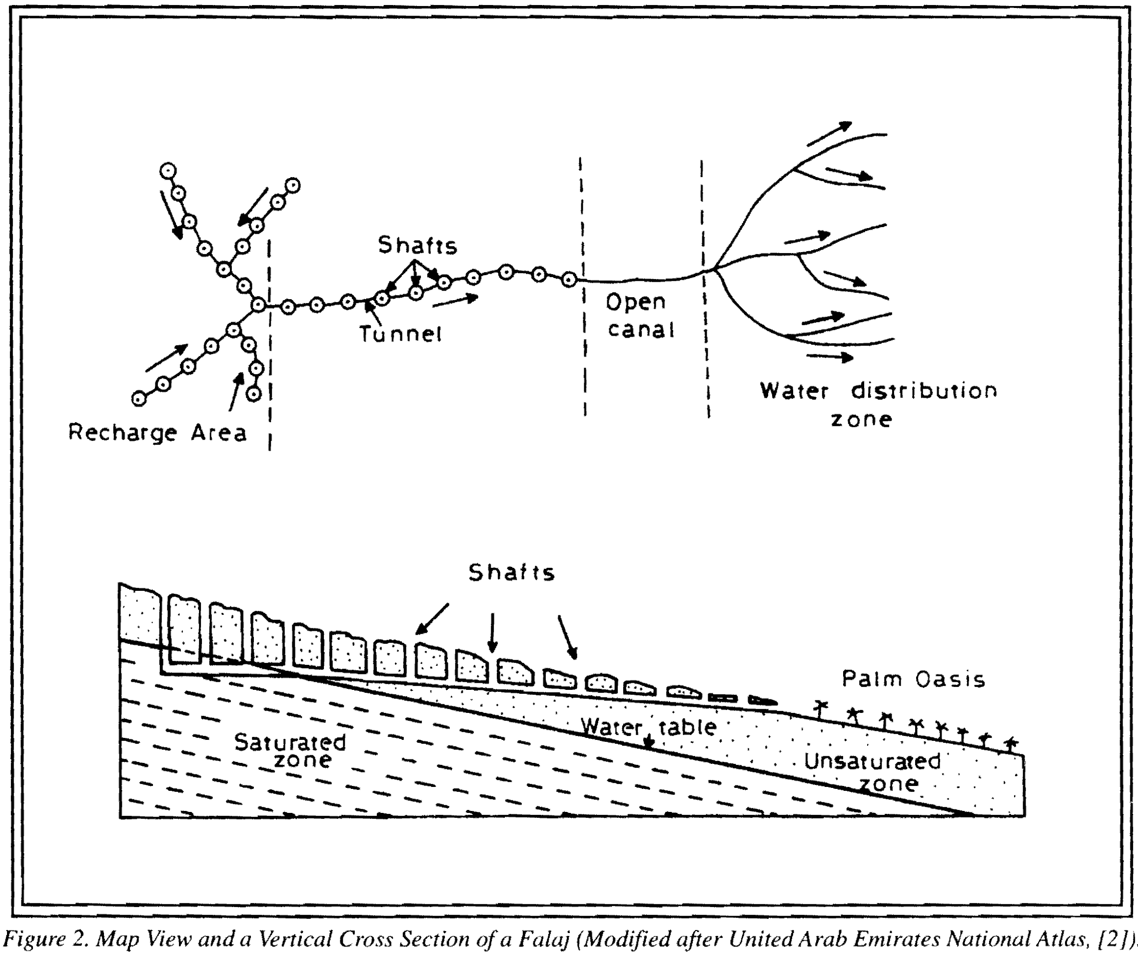

Figure 2. Map View and a Vertical Cross Section of a Falaj (Modified after United Arab Emirates National Atlas, [2]). NB: Vertical scale is exaggerated.

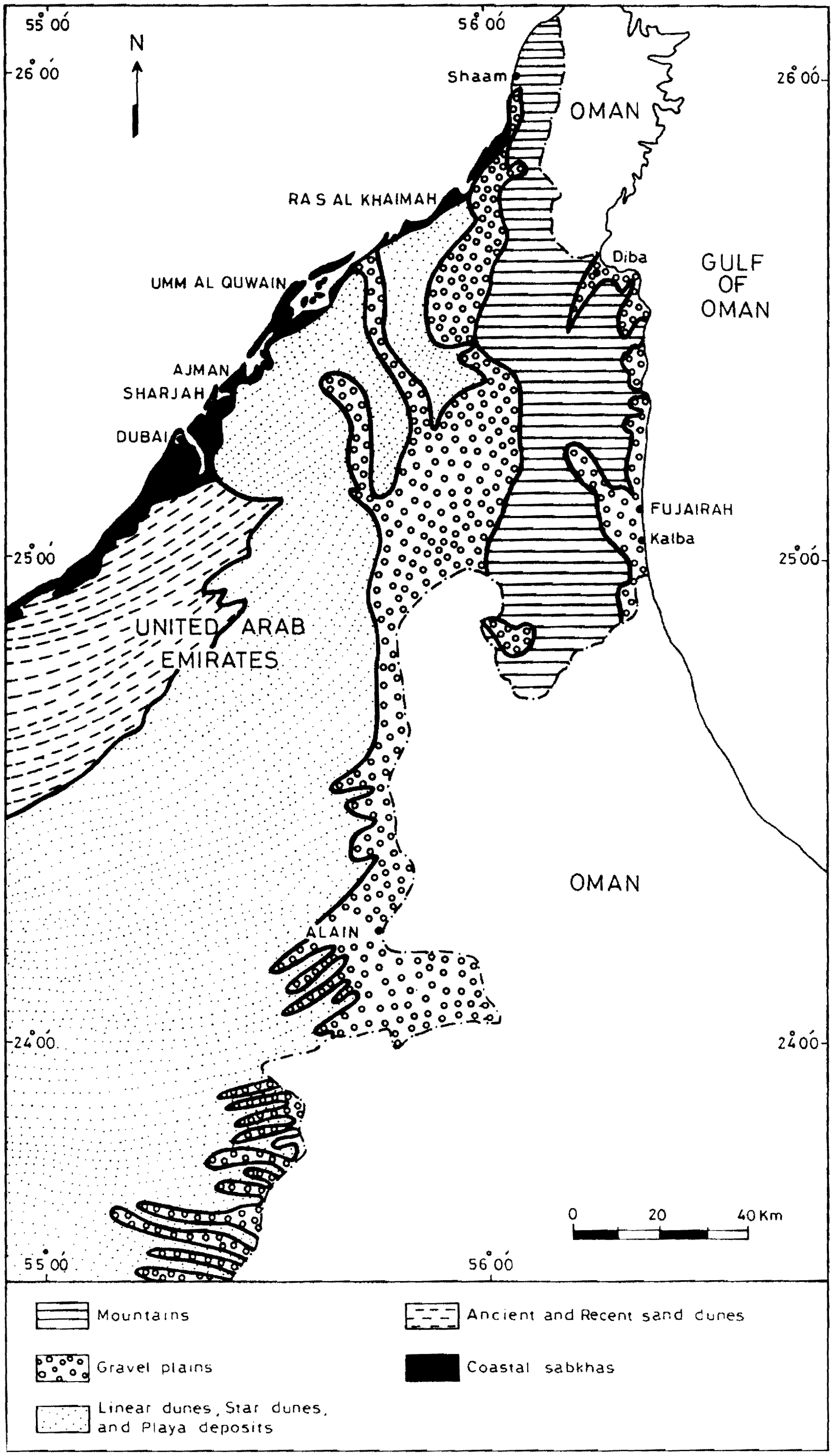

Figure 3. Geomorphological Map of the Study Area, Simplified from the United Arab Emirates National Atlas [2].

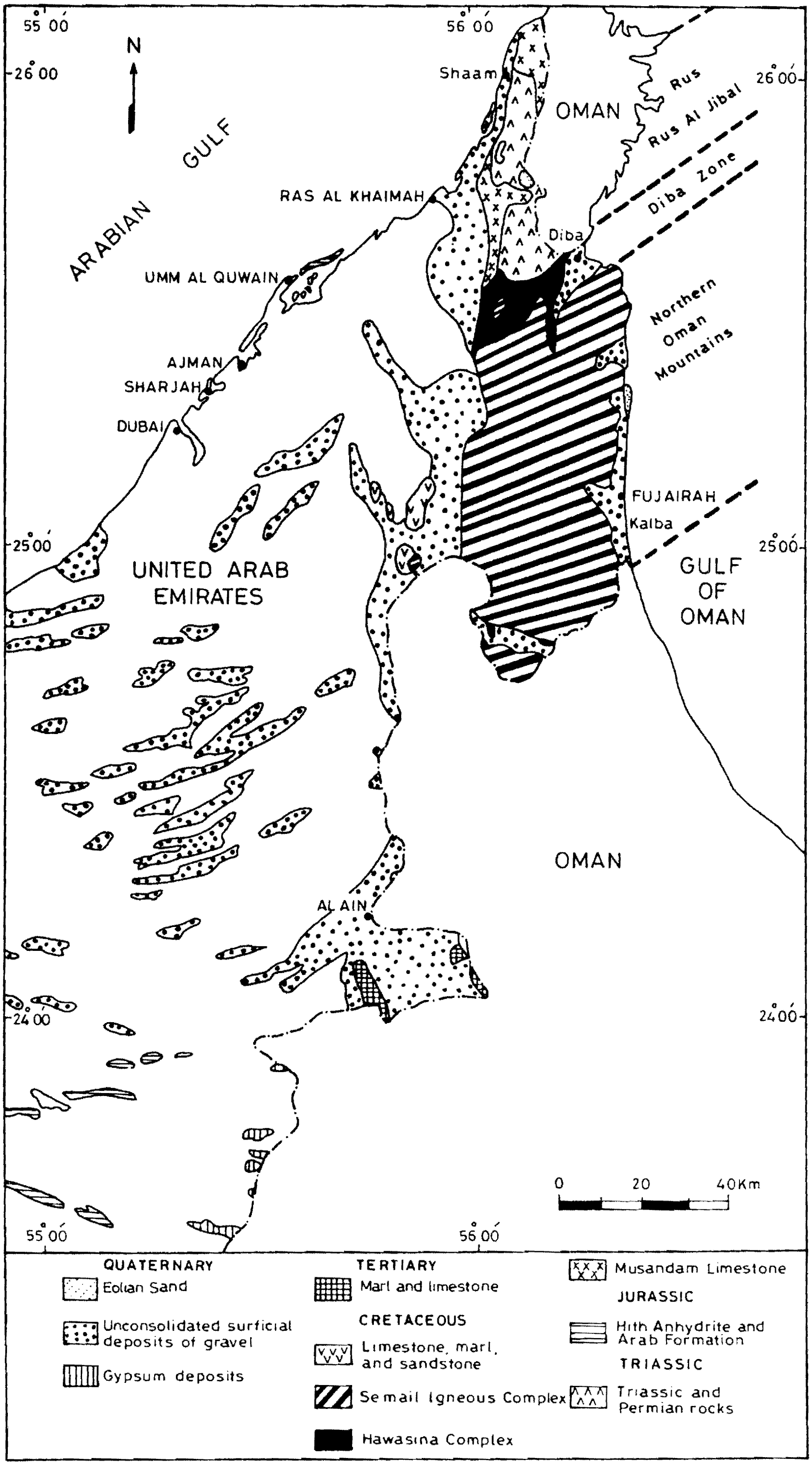

Figure 4. Geological Map of the Eastern U.A.E., Simplified from the United Arab Emirates National Atlas [2].

The Diba zone is an elongated NE–SW trending topographic depression, separating the Rus Al Jibal Musandum shelf in the northwest from the Semail ophiolite sequence in the southeast.

The northern Oman mountains comprise the northern part of the Semail ophiolite nappe which is composed of a repeated ophiolite sequence caused by internal low-angle thrust faults. The ophiolite complex is divided from base to top into: an ultramafic mantle sequence, layered peridotite, coarse-grained gabbros, fine-grained gabbros, sheeted dyke complex, and extrusive lavas.

Gravel Plains

Gravel plains bound the northern Oman mountains from the east and west. The eastern gravel plain is a narrow strip, 4 km (Al Fujairah) to 10 km (Kalba) wide, and 70 km long. It extends between Diba in the north and Kalba in the south, and is bounded by the Gulf of Oman on the east and the northern Oman mountains on the west.

The western gravel plains extend for some 160 km as a long, narrow strip from Ras Al Khaimah in the north to the Al Jaww plain, east of Al Ain city, in the south. The plains exist at the outlets of main wadis, which have the main control on their shape and width. They occupy the area between the northern Oman mountains on the east and the sand-dune fields on the west. The western gravel plains have a gentle slope from east to west with an average gradient of 0.001 [3].

The gravel plains are composed of alluvial sands and gravels, which gradually decrease in grain size from east to west. The continuity of the western gravel plain is locally interrupted by sand dunes and Al Fayah mountain range (Figure 3).

HYDROLOGY

Rainfall

The average annual rainfall in U.A.E. is 119 mm. However, in wet years (*e.g.*, 1981–1982) the mean annual rainfall was 282 mm, reaching >450 mm in some mountainous areas, whereas in dry years (*e.g.*, 1983–1984) the mean annual rainfall was only about 40 mm. During 1991–1992, the northern part of the study area received >220 mm of rain, and the southern part <100 mm (Figure 5). For this reason, the eastern mountains, which occupy only 5% of the total area of U.A.E., receive about 30% of the total annual rainfall [5]. This also explains why the falajes are clustered in the northern and eastern parts of the country.

To assess the wide spatial and temporal variations in rainfall, the Relative Variability (RV) and Inter-Annual Variability (IAV) were calculated for 12 meteorological stations within the study area for the longest period of records (Table 1):

$$\text{RV}\ (\%) = (\Sigma|\mu - x| \,/\, n\mu)\ 100, \text{ and}$$

$$\text{IAV}\ (\%) = (\Sigma|x_{i-1} - x_i| \,/\, \mu\ (n-1)\ 100,$$

where

μ = the arithmetic mean of annual rainfall for the longest period of records (mm/yr),

x = the mean annual rainfall (mm/yr), and

n = the number of years.

Table 1 includes the length of rainfall records, means, median values, RV, and IAV percentages for each meteorological station. The mean annual rainfall for the longest period of records ranged from 89.1 mm at Dubai Airport to 198.9 mm at Masafi. The median ranged from 77.1 mm/year at Dubai Airport to 143.2 mm/yr at Masafi. The RV of rainfall records varied between 44% at Al Burayrat meteorological station and 77% at Kalba station. The IAV of rainfall records varied between 57% at Diba station and 85% at Hibab station.

Discharge

Falaj discharges were measured with an Ott 1205-26 mini-current meter, which is equipped with an electronic revolution indicator. Every 10 cm across the falaj outlet, the number of revolutions in 40 seconds were counted at depths of 8 and 15 cm above the bottom. Flow velocities were obtained from rating tables provided with the instrument according to the formula: $V = 0.619\ N + 0.017$, where V is the velocity in meter per second, and N is the number of revolutions per second. The area of the outlet, which can be triangular, rectangular, or trapezoid, was measured by a staff. Discharge of each sector is then estimated by multiplying the average velocity by the area. Total falaj discharge is the sum of sector discharges. The accuracy of the used current meter is high and expected errors would not exceed 2 to 3%. The average annual values of falaj discharges in liters per second are listed in Table 2. Each of these values is an average of two measurements one during September–October (before rain) and the other during April–May (after rain).

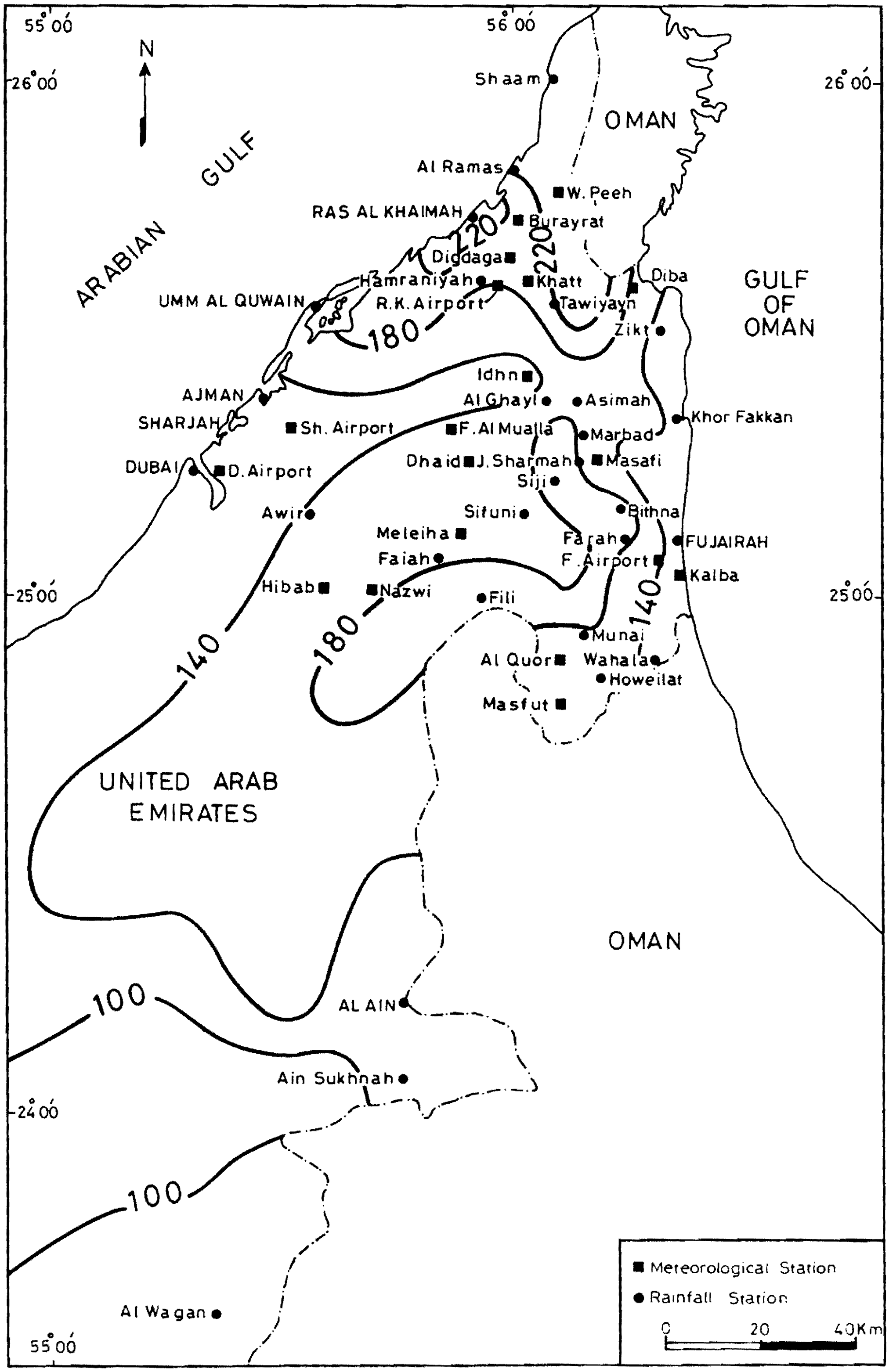

Figure 5. Isohyetal Map (mm) of the Eastern U.A.E. During the 1991–1992 Period (based on data from the Ministry of Agriculture and Fisheries [4]).

Table 1. Rainfall Records (mm) of 12 Meteorological Stations in Eastern U.A.E.

Abbreviations: Ave. = Average, Rel. Var. = Relative Variability, and Int. An. Var. = Inter-Annual Variability.

S. No. Meteo. Station	Rainfall in millimeters per year																								
	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
1 Al Ain					302.5	77.1	42.6	46.2	151.5	104.3	46.8	29.6	68.4	60.8	240.5	164.7	1.2	14.0	52.2	122.7	126.8	84.8	201.2	62.8	105.7
					202.2	23.2	57.7	54.1	51.2	4.0	53.5	70.7	31.9	39.5	140.2	64.4	99.1	86.3	48.1	22.4	26.5	15.5	100.9	37.5	5.4
					225.4	34.5	3.6	105.3	47.2	57.5	17.2	38.8	7.6	179.7	75.8	163.5	12.8	38.2	70.5	4.1	42.0	116.4	138.4	42.9	
2 Al Hibab					148.2	51.5	24.7	115.7	0.0	99.7	101.5	45.7	74.8	101.3	317.1	157.6	24.2	25.4	50.6	162.8	240.6	60.0	182.8	64.4	170.0
					42.6	54.1	80.9	10.1	105.6	5.9	4.1	59.9	30.8	4.3	211.5	52.0	81.4	80.2	55.0	57.2	135.0	45.6	77.2	41.2	64.4
					96.7	26.8	91.0	115.7	99.7	1.8	55.8	29.1	26.5	215.8	159.5	133.4	1.2	25.2	112.2	77.8	180.6	122.8	118.4	105.6	
3 Burayrat					197.6	75.8	14.1	330.5	295.4	234.7	72.3	84.3	147.6	77.9	297.0	216.1	21.2	57.8	25.2	148.6	176.0	96.2	126.4	77.2	164.6
					57.8	64.0	125.7	190.7	155.6	94.9	67.5	55.5	7.8	61.9	157.2	76.3	118.6	82.0	114.6	8.8	36.2	43.6	13.4	62.6	24.8
					121.8	61.7	316.4	35.1	60.7	162.4	12.0	63.3	69.7	219.1	80.9	194.9	36.6	32.6	123.4	27.4	79.8	30.2	49.2	87.4	
4 Diba	88.9	166.0	60.3	16.3	177.1	93.7	11.9	72.4	197.4	246.5	96.6	90.4	86.6	96.4	246.2	251.0	34.6	14.8	66.0	63.4	212.0	70.0	160.6	82.0	166.2
	25.8	51.3	54.4	98.4	62.4	21.0	102.8	42.3	82.7	131.8	18.1	24.3	28.1	18.3	131.5	136.3	80.1	99.9	48.7	51.3	97.3	44.7	45.9	32.7	51.5
	77.1	105.7	44.0	160.8	83.4	81.8	60.5	125.0	49.1	149.9	6.2	3.8	9.8	149.8	4.8	216.4	19.8	51.2	2.6	148.6	142.0	90.6	78.6	84.2	
5 Digdaga	66.6	118.6	28.5	9.8	177.5	54.3	99.8	0.0	240.3	218.9	72.1	87.2	145.8	105.5	267.9	275.0	22.2	34.8	54.2	152.2	162.1	88.0	174.0	106.8	193.4
	51.6	0.4	89.7	108.4	59.3	63.9	18.4	118.2	122.1	100.7	46.1	31.0	27.6	12.7	149.7	156.8	96.0	83.4	64.0	34.0	43.9	30.2	55.8	11.4	75.2
	52.0	90.1	18.7	167.7	123.2	45.5	99.8	240.3	21.4	146.8	15.1	58.6	40.3	162.4	7.1	252.8	12.6	19.4	98.0	9.9	74.1	86.0	67.2	86.6	
6 Dubai Airport	104.6	102.8	19.3	1.8	142.9	48.9	30.2	80.3	129.7	79.6	49.7	49.4	77.1	62.3	193.9	125.3	7.1	24.5	42.4	169.9	226.5	63.9	209.9	54.5	132.0
	15.5	13.7	69.8	87.3	53.8	40.2	58.9	8.8	40.6	9.5	39.4	39.7	12.0	26.8	104.8	36.2	82.0	64.6	46.7	80.8	137.4	25.2	120.8	34.6	42.9
	1.8	83.5	17.5	141.1	94.0	18.7	50.1	49.4	50.1	29.9	0.3	27.7	14.8	131.6	68.6	118.2	17.4	0.9	127.5	56.6	162.6	146.0	155.4	77.5	
7 Falaj Al Mualla	79.9	129.5	82.2	18.0	193.3	29.7	45.8	138.1	210.7	129.2	46.4	74.8	166.6	80.4	381.0	188.0	30.6	54.4	64.2	167.6	196.6	83.0	223.4	63.7	179.2
	42.4	7.2	40.1	104.3	71.0	92.6	76.5	15.8	88.4	6.9	75.9	47.5	44.3	41.9	258.7	65.7	91.7	67.9	58.1	45.3	74.3	39.3	101.1	58.6	56.9
	49.6	47.3	64.2	175.3	163.6	16.1	92.3	72.6	81.5	82.8	28.4	91.8	86.2	300.6	193.0	157.4	23.8	9.8	103.4	29.0	113.6	140.4	159.7	115.5	
8 Kalba	110.0	223.7	68.2	20.6	271.2	20.2	23.4	144.1	264.9	241.8	78.2	78.6	85.6	95.8	330.8	421.8	31.6	12.4	0.0	0.0	277.4	97.8	115.2	56.4	111.0
	17.2	96.5	59.0	106.6	144.0	107.0	103.8	16.9	137.7	114.6	49.0	48.6	41.6	31.4	330.8	294.6	95.6	114.8	127.2	127.2	150.2	29.4	12.0	70.8	16.2
	113.7	155.5	47.6	250.6	251.0	3.2	120.7	120.8	23.1	163.6	0.4	7.0	10.2	235.0	91.0	390.2	19.2	12.4	0.0	277.4	179.8	17.4	58.8	54.8	
9 Masafi	106.6	181.2	40.3	0.0	192.9	83.2	41.0	325.5	357.1	263.6	197.9	104.0	184.6	95.0	348.2	249.5	110.4	33.6	77.6	158.8	1242.4	65.0	291.0	79.8	143.2
	92.3	17.7	158.6	198.9	6.0	115.7	157.9	126.6	158.2	64.7	1.0	94.9	14.3	103.9	149.3	50.6	88.5	165.3	121.3	40.1	1043.5	133.9	92.1	119.1	55.7
	74.6	140.9	40.3	192.9	109.7	42.2	284.5	31.6	93.5	65.7	93.9	80.6	89.6	253.2	98.7	139.1	76.8	44.0	81.2	1083.6	1177.4	226.0	211.2	63.4	
10 Masfut	109.1	130.4	49.8	6.3	233.8	4.3	94.7	478.8	325.1	196.8	66.8	46.0	150.2	112.2	341.6	264.6	18.6	14.6	92.4	293.0	306.0	79.4	185.0	100.8	131.1
	44.2	22.9	103.5	147.0	80.5	149.0	58.6	325.5	171.8	43.5	86.5	107.3	3.1	41.1	188.3	111.3	134.7	138.7	60.9	139.7	152.7	73.9	31.7	52.5	22.2
	21.3	80.6	43.5	227.5	229.5	90.4	384.1	153.7	128.3	130.0	20.8	104.2	38.0	229.4	77.0	246.0	4.0	77.8	200.6	13.0	226.6	105.6	84.2	30.3	
11 Meleiha	120.0	209.8	58.8	3.9	198.6	65.4	8.6	134.6	275.9	133.9	69.9	58.1	78.5	136.3	259.6	249.6	56.4	6.2	80.8	190.2	208.0	66.8	250.7	57.8	158.1
	5.5	84.3	66.7	121.6	73.1	60.1	116.9	9.1	150.4	8.4	55.6	67.4	47.0	10.8	134.1	124.1	69.1	119.3	44.7	64.7	82.5	58.7	125.2	67.7	32.6
	89.8	151.0	54.9	194.7	133.2	56.8	126.0	141.3	142.0	64.0	11.8	20.4	57.8	123.3	10.0	193.2	50.2	74.6	109.4	7.8	141.2	183.9	192.9	100.3	
11 R. A. K. Airport										167.2	88.6	77.2	158.7	86.4	257.2	256.6	15.0	26.7	41.2	129.2	180.6	35.7	149.5	127.8	181.8
												46.5	35.0	37.3	133.5	132.9	108.7	97.0	82.5	5.5	56.9	88.0	25.8	4.1	58.1
												81.5	72.3	170.8	0.6	241.6	11.7	14.5	88.0	51.4	144.9	113.8	21.7	54.0	
12 Sharjiah Airport												72.2	125.1	82.1	241.5	189.5	12.0	17.6	55.1	171.6	170.4	65.2	193.3	39.9	132.6
												39.8	13.1	29.9	129.5	77.5	100.0	94.4	56.9	59.6	58.4	46.8	81.3	72.1	20.6
												52.9	43.0	159.4	52.0	177.5	5.6	37.5	116.5	1.2	105.2	128.1	153.4	92.7	

S.No.	Meteo. Station	Years	Period	Ave.	Median	Rel. Var.	Int. An. Var.
1	Al Ain	21	72–92	100.3	77.1	58.60	70.86
2	Al Hibab	21	72–92	105.6	99.7	58.56	84.98
3	Burayrat	21	72–92	139.8	126.4	44.24	66.67
4	Diba	25	68–92	114.7	90.4	55.16	66.60
5	Digdaga	25	68–92	118.2	105.5	55.85	68.76
6	Dubai Airport	25	68–92	89.1	77.1	57.99	66.11
7	Falaj Al Mualla	25	68–92	122.3	83.0	54.72	70.26
8	Kalba	25	68–92	127.2	95.8	76.81	66.67
9	Masafi	25	68–92	198.9	143.2	67.78	91.04
10	Masfut	25	68–92	153.3	112.2	65.01	69.97
11	Meleiha	25	68–92	125.5	120.0	57.37	64.76
11	R. A. K. Airport	16	77–92	123.7	128.5	46.06	67.49
12	Sharjiah Airport	14	79–92	112.0	103.6	56.11	77.26

Table 2. Geometric Parameters and Discharge of U.A.E. Falajes (liter per second) for the Period 1984–1996. Abbreviations: EDSA = Eastern Drainage Southern Area, WDNA = Western Drainage Northern Area, WDCA = Western Drainage Central Area, and ECA = East Coast Area.

Falaj No.	Falaj Name	Falaj Type	Width (m)	Length (m)	X. Area (m^2)	A. Area (m^2)	Discharge of U.A.E. Falajes in liters per second															
							1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	Ave. Dis. (l/s)	Mean Velocity (m/s)	Transit time (hr)
	EDSA																					
1	Shafgah	Gheli	0.70		0.185	0	19.00	0.00	0.00	43.00	34.00	20.00	20.00	0.00	43.00	0.00	22.00	20.00	42.00	20.23	0.11	0.00
2	Hadf	Gheli	0.40		0.130	0	12.80	6.10	8.00	20.00	13.00	5.00	5.00	9.00	20.00	10.00	15.00	10.00	22.00	11.99	0.09	0.00
3	Nasla	Gheli	0.70		0.160	0	57.00	4.00	9.00	85.00	68.00	67.00	36.00	0.00	10.00	0.00	12.00	1.00	15.00	28.00	0.18	0.00
4	Rafaq	Gheli	0.60	2500	0.150	1500	51.00	9.00	8.00	52.00	52.00	53.00	63.00	8.00	7.00	0.00	91.00	3.00	61.00	35.23	0.23	2.96
5	Munnai	Gheli	0.80	500	0.400	400	36.00	0.00	0.00	0.00	4.00	3.00	4.00	3.00	6.00	20.00	3.00	2.00	30.00	8.54	0.02	6.51
6	Howeilat	Gheli	0.45	3200	0.110	1440	12.90	7.00	6.00	89.00	2.90	54.00	46.00	3.00	20.00	20.00	14.00	12.00	45.00	25.52	0.23	3.83
7	Warah	Gheli	0.90	1000	0.160	900	11.00	0.00	0.00	24.00	72.00	10.00	0.00	0.00	30.00	20.00	0.00	52.00	10.00	17.62	0.11	2.52
8	Masfut	Gheli	0.80	1500	0.035	1200	12.00	0.00	0.00	6.00	0.00	0.00	0.00	0.00	10.00	13.00	80.00	27.00	30.00	13.69	0.39	1.07
9	Dofdaha	Gheli	0.45	1000	0.130	450	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	469.44
10	Sagheer	Daudi	0.45	1500	0.080	675	5.00	0.00	0.00	6.50	28.00	10.00	5.00	4.00	0.00	0.00	0.00	0.00	0.00	4.50	0.06	7.41
11	Sahreeha	Daudi	0.50	1500	0.080	750	7.00	0.00	0.00	4.60	18.00	12.00	16.00	12.00	0.00	0.00	0.00	0.00	0.00	5.35	0.07	6.23
	WDNA																					
12	Khatt North	Hadouri	0.65		0.098	0	17.00	14.00	7.20	7.10	21.10	11.00	16.00	16.10	17.00	25.00	10.00	20.00	40.00	17.04	0.17	0.00
13	Khatt South	Hadouri	0.60	1000	0.044	600	33.00	19.00	4.00	9.30	24.00	11.00	20.00	22.00	32.00	46.00	14.00	30.00	60.00	24.95	0.57	0.49
14	Hubhub	Daudi	0.50	500	0.100	250	55.00	35.00	26.00	53.00	55.00	31.00	35.00	26.00	50.00	52.00	22.00	17.00	48.00	38.85	0.39	0.36
15	Usayali	Daudi	0.45	3000	0.030	1350	53.00	3.70	2.20	2.00	3.00	2.40	3.00	2.00	4.00	2.00	3.00	2.00	1.00	6.41	0.21	3.90
	WDCA																					
17	Fili	Gheli	0.45	5000	0.194	2250	6.20	5.00	8.00	6.00	4.00	16.00	12.00	11.00	10.00	8.00	9.00	9.00	12.00	8.94	0.05	30.14
18	Asimah	Gheli	0.50	3000	0.030	1500	5.40	4.50	3.60	7.50	5.00	5.00	6.00	5.00	8.00	9.00	8.00	6.00	9.00	6.31	0.21	3.96
19	Murrad	Gheli	0.55	1500	0.120	825	0.00	8.00	6.00	10.00	10.00	37.00	11.00	10.00	11.00	13.00	11.00	13.00	11.00	11.62	0.10	4.30
20	Dhaid	Gheli	0.50	10000	0.100	5000	13.30	12.00	0.00	0.00	5.00	18.00	16.00	15.00	17.00	15.00	16.00	13.00	16.00	12.02	0.12	23.10
21	Siji	Gheli	0.72	500	0.060	360	3.00	2.00	3.00	4.00	4.00	4.00	4.00	4.00	0.00	0.00	0.00	0.00	0.00	2.15	0.04	3.87
22	Mualla	Gheli	0.55	3500	0.290	1925	8.00	8.00	8.00	6.00	8.00	10.00	10.00	10.00	9.00	8.00	9.00	8.00	10.00	8.62	0.03	32.73
23	Mannama	Daudi	0.30	3000	0.018	900	4.10	3.00	4.00	4.10	6.00	1.80	1.60	5.00	5.00	3.00	2.00	4.00	0.00	3.35	0.19	4.47
	ECA																					
24	Farfar	Gheli	0.40	2000	0.052	800	15.00	6.00	8.00	21.00	33.00	5.00	6.00	6.00	20.00	21.00	5.00	7.00	21.00	13.38	0.26	2.16
25	Mamduk	Gheli	0.40	3000	0.024	1200	4.50	2.70	3.50	4.30	11.40	5.00	3.00	1.00	6.00	3.00	2.00	6.00	4.00	4.34	0.18	4.61
26	Museiriya	Gheli	0.40	4200	0.028	1680	5.80	0.00	0.00	28.00	30.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.91	0.18	6.66
27	Habeesa	Gheli	0.70	1200	0.053	840	8.90	0.00	0.00	0.00	15.00	7.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.38	0.04	7.43
28	Bithna (L/B)	Gheli	0.35		0.091	0	41.00	40.00	36.00	290.0	440.0	60.00	86.00	1.00	39.00	54.00	1.00	34.00	45.00	89.77	0.99	0.00
29	Bithna (R/B)	Gheli	0.30	500	0.099	150	48.00	42.00	19.00	29.00	14.00	2.00	2.00	20.00	1.00	2.00	15.00	1.00	1.00	15.08	0.15	0.91
30	Awaina	Daudi	0.45	500	0.018	225	2.20	1.30	0.70	2.00	2.00	1.00	1.00	1.00	2.00	1.00	2.00	1.00	2.00	1.48	0.08	1.69
31	Saham	Gheli	0.45	500	0.041	225	15.70	8.00	2.00	8.00	18.00	11.00	1.00	1.00	3.00	2.00	6.00	0.00	0.00	5.82	0.14	0.98
32	Farah	Gheli	0.50	2500	0.027	1250	10.00	0.00	0.00	0.00	29.00	1.00	0.00	8.00	12.00	7.00	3.00	0.00	8.00	6.00	0.22	3.13
33	Zikt	Daudi	0.55		0.040	0	4.90	5.00	6.00	7.00	8.00	8.00	9.00	8.00	0.00	0.00	0.00	0.00	0.00	4.30	0.11	0.00
	Al-Ain Area																					
34	Ain Sukhnah	Hadouri	1.20	3000	0.144	3600	30.40	35.00	45.00	50.00	48.00	46.00	50.00	80.00	0.00	0.00	0.00	0.00	0.00	29.57	0.21	4.06
35	Maziad	Daudi	0.75	2000	0.050	1500	16.00	25.00	20.00	40.00	32.00	30.00	31.00	30.00	0.00	0.00	0.00	0.00	0.00	17.23	0.34	1.61
36	Hili	Gheli	0.65	4000	0.117	2600	27.00	30.00	18.00	14.00	21.00	28.00	29.00	35.00	20.00	30.00	20.00	16.00	0.00	22.15	0.19	5.87
37	Daudi	Daudi	0.80	5000	0.168	4000	20.00	22.00	30.00	48.00	51.00	54.00	56.00	42.00	40.00	32.00	39.00	51.00	0.00	37.31	0.22	6.25
38	Al Aini	Daudi	0.80	6000	0.184	4800	11.60	116.0	49.00	56.00	49.00	44.00	45.00	43.00	43.00	40.00	41.00	45.00	46.00	48.35	0.26	6.34
39	Buraimi	Daudi	1.00	9000	0.220	9000	45.00	48.00	50.00	51.00	39.00	28.00	30.00	28.00	0.00	0.00	0.00	0.00	0.00	24.54	0.11	22.41
40	Saarrah	Daudi	0.95	6500	0.095	6175	50.00	51.00	52.00	34.00	44.00	51.00	49.00	34.00	0.00	0.00	0.00	0.00	0.00	28.08	0.30	6.11
	Maximum		1.20	10000	0.40	9000	57.7	116.0	52.0	290.0	440.0	67.0	86.0	80.0	50.0	54.0	91.0	52.0	61.0	89.77	0.99	469.44
	Minimum		0.30	500	0.02	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.08	0.00	0.00
	Sun		23.17	93600	4.16	60320	778.7	572.3	442.2	1121	1321	762.2	727.6	503.1	495.0	456.0	475.0	410.0	589.0	665.68	7.54	687.52
	Average		0.59	2836	0.10	1587	19.99	15.06	11.64	28.38	33.88	19.53	18.62	13.24	11.89	12.00	11.92	10.26	14.39	16.99	0.20	18.09

Abbreviations:

X. Area = Cross-sectional area [m^2]
A. Area = Active area of the falaj (width × length) [m^2]
Ave. Dis. = Average falaj discharge for the period 1984–1996 [l/s]

During the period 1978–1995, the total falaj discharges in U.A.E. varied between 9.0×10^6 m^3/yr in 1994 and 31.2×10^6 m^3/yr in 1982. According to their locations, the Ministry of Agriculture and Fisheries has classified the U.A.E. Falajes into five zones (Table 1; Figure 1): the Eastern Drainage Southern Area (EDSA), Western Drainage Northern Area (WDNA), Western Drainage Central Area (WDCA), East Coast Area (ECA), and Al Ain Area.

In the present time, the Ministry of Agriculture and Fisheries maintains and monitors about 40 falajes in U.A.E. The Ministry also collects water samples for chemical analyses. In the Al Ain area, the Falajes Department of the Al Ain municipality is responsible for the management and maintenance of the local falajes.

Discharge varies from one falaj to another depending on the location of the main well (wells), nature of the source aquifer, the amount of seepage from tunnel sides, and the mean annual rainfall. Some falajes dry out during periods of low rainfall while others exhibit little effect. Average discharges of U.A.E. falajes for the period 1984–1996 varied between 2.38 liter/second (l/sec) in Falaj Habeesa and 89.77 l/sec in Falaj Bithnah (L/B) (Figure 1; Table 2).

According to discharge, falajes are classified into three types locally designated as Al Gheli, Al Daudi, and Al Hadouri [6]. Al Gheli falaj carries water only in winter and its discharge is directly dependent on rainfall. Despite its limited amount, water of Al Gheli falajes is renewable and has a good quality. Because aquifers are main water source, Al Daudi falaj has a permanent discharge. Al Hadouri falaj is commonly connected to deep artesian aquifers and intercepts the groundwater as it moves upward through fissures and fractures.

A plot of the total annual discharge of U.A.E. falajes *versus* the mean annual rainfall on the Eastern Mountain Ranges (EMR) and Gravel Plains (GP), shows a direct correlation (Figure 6; Table 3). In fact, because most of U.A.E. falajes belong to the Gheli type, discharges show a pronounced response to rainfall events. In contrast, Al Daudi falajes, exhibit very little change in their discharge rates throughout the year, because large groundwater storage is the main source of water in these falajes and maintain their flow during the whole year.

Because of heavy groundwater pumping in many areas of the U.A.E., several falajes have gone dry. Discharge records of Al Ain falajes were obtained from Gibb and Partners [7], Halcrow and Partners [8], and the Ministry of Agriculture and Fisheries. These records indicated that Al Jimi, Al Mu'waji, and Al Qattarah falajes went dry in 1979, whereas Al Mu'Tarrad, Maziad, and Al Hili falajes dried out in 1981–1982 (Figure 7). Because of continuous maintenance, extension, and pumping groundwater into their channels, Al Aini and Al Daudi falajes are still active in the present.

WATER CHEMISTRY

Water samples were analyzed for major cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) and anions (CO_3^{2-}, HCO_3^-, SO_4^{2-}, and Cl^-) in the Food Control Laboratory of Al Ain Municipality. The calcium-ion (Ca^{2+}) concentration was determined complexometrically by addition of the hydroxylamine to adjust the pH value at 10 and Murexide as an indicator. Magnesium

Table 3. The Mean Annual Rainfall on the EMR and GP, and the Total Annual Falaj Discharges (10^6 m^3/yr) During the 1978–1995 Period.

Year	Rainfall (mm/yr)		Discharge	Year	Rainfall (mm/yr)		Discharge
	EMR	GP	(10^6 m^3)		EMR	GP	(10^6 m^3)
1978	94.3	73.3	18.8	1987	191.9	153.0	28.7
1979	75.6	60.4	18.2	1988	262.3	188.0	29.2
1980	160.6	137.5	17.9	1989	70.3	79.4	23.2
1981	110.8	100.2	21.1	1990	230.8	184.2	22.4
1982	339.7	283	31.2	1991	81.4	80.6	16.9
1983	353.9	225.9	26.2	1992	198.3	105.7	13.5
1984	46.1	27.2	26.3	1993	189.9	184.1	15.0
1985	32.0	30.5	18.4	1994	40.9	33.7	9.0
1986	75.9	61.3	14.0	1995	284.4	185.0	16.5

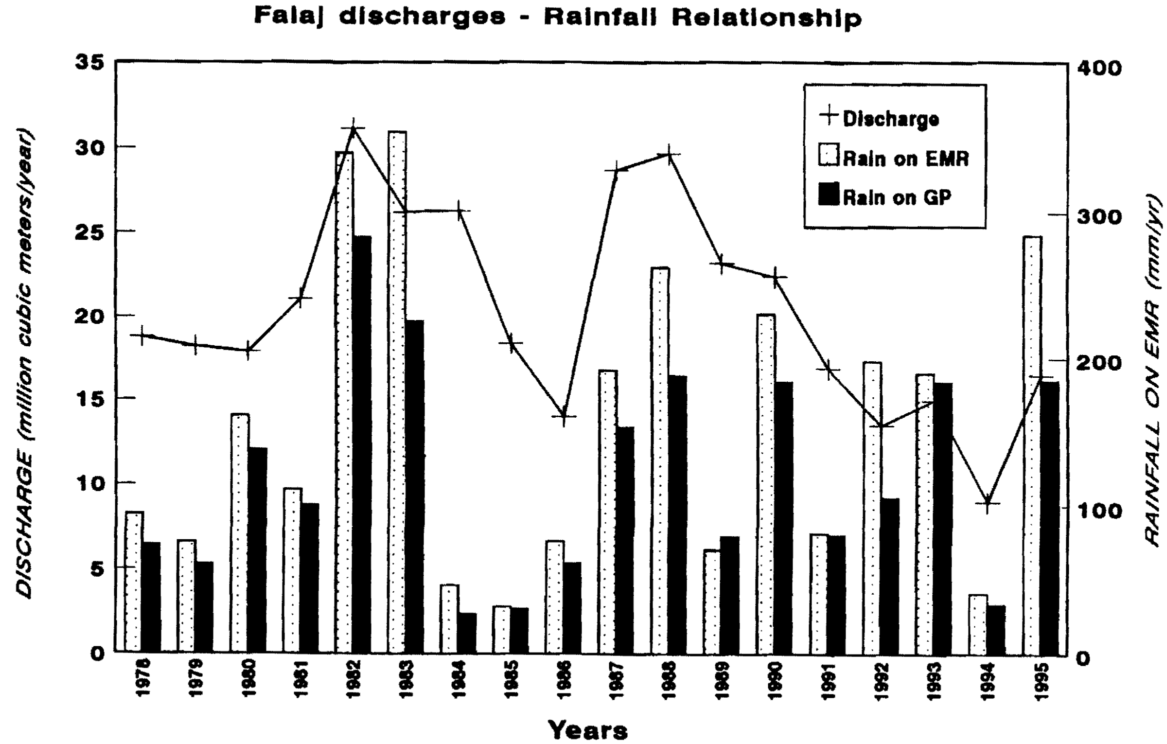

Figure 6. Total Annual Discharge (10^6 m^3/yr) of U.A.E. Falajes versus *the Mean Annual Rainfall (mm) on the Eastern Mountain Ranges and Gravel Plains.*

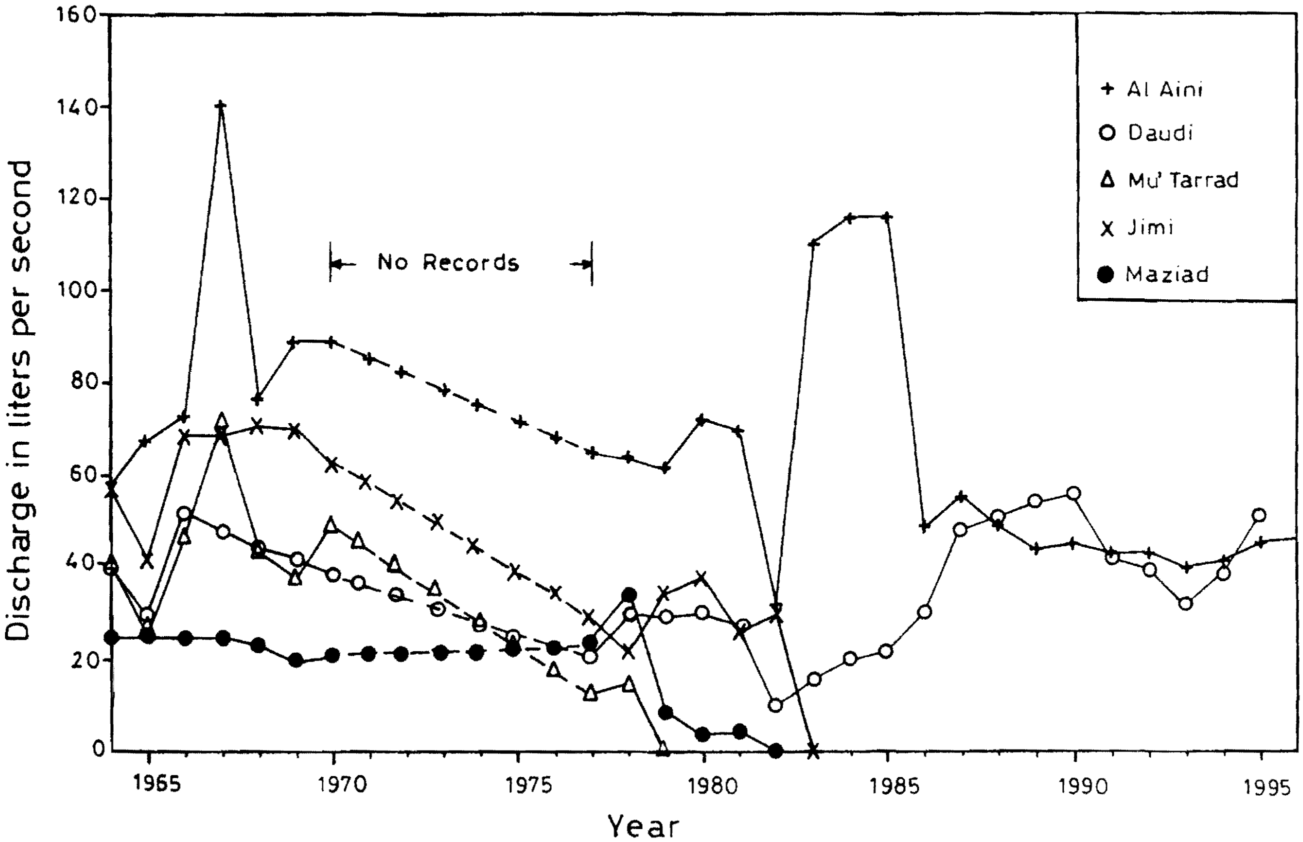

Figure 7. Hydrographs of Al Ain Falajes for the Period 1964–1996
(based on data from Gibb and Partners [7] and the Ministry of Agriculture and Fisheries).

ion (Mg^{2+}) was determined by subtraction from the total calcium and magnesium after determining both ions complexometrically using the Eriochrome black-T indicator. Sodium (Na^+) and potassium (K^+) ions were measured with a flame photometer. Samples of known concentrations of Na^+ and K^+ were used to construct standard curves, which show the relation between the contents of these ions and absorbance. Then, the absorbances of water samples with unknown concentrations of sodium and potassium ions were measured using the constructed standard curves. The bicarbonate ion (HCO_3^-) was determined volumetrically by titration against dilute sulphuric acid and the methyl orange indicator. Sulfate-ion (SO_4^{2-}) concentration was determined colorimetrically with the barium chromate method. However, SO_4^{2-} content in some samples, (marked with asterisks in Table 5 below,) was estimated by difference. Chloride-ion (Cl^-) was measured by using silver nitrate ($AgNO_3$) and potassium chromate ($KCrO_4$) as an indicator. Because no pH were provided by the lab, the pH values for all samples were obtained by calculation from the relation: $[H^+] = \log K_2 \log [CO_3^{2-}] / \log [HCO_3^-]$ [9].

Electrical Conductivity

As Table 4 shows, the EC of water samples collected from the U.A.E. falajes varied between 450 µS/cm in Falaj Asimah (Al Fujairah) and 10 940 µS/cm in Falaj Ain Sukhnah (Al Ain).

Generally, the EC values are low in water samples collected from the falajes draining ophiolite rocks, east of Al Ain and Al Fujairah areas, indicating low water salinity. In contrast, the EC values are relatively higher in water samples of the falajes draining limestone rocks in Ras Al Khaimah and west of Al Ain areas (Table 4).

The iso-EC contour map shows that the EC values of falaj waters are low near the water divide of the eastern mountains and increase further east and west, with distance from the recharge area (Figure 8) [10]. The EC of 98 groundwater samples measured by the author during late February–early March 1996 are presented on Figure 8. The iso-EC contours also shows that the groundwater salinity increases from the water divide towards the east and west.

A water sample from Falaj Ain Sukhnah in Al Ain area has an EC of 10 940 µS/cm which is an exceptionally high salinity for a falaj water. The reason is the possibility that the course of this particular falaj runs across the evaporite deposits of the Miocene Fars Formation which flank Jabal Hafit from both side. Dissolution of these evaporites might have significantly increased the salinity of the falaj water. Jabal Hafit, the main recharge area of the falaj, is mainly composed of limestones which contain some gypsum. Upon dissolution, gypsum can contribute to the high EC of the water in the falaj.

The plot of the EC (µS/cm) *versus* falaj length shows that the EC of water in open-channel falajes (Al Gheli type), which are dominant in the eastern mountain region, increase with increasing the falaj length (Figure 9(*a*)). Examples of these falajes are Falaj Asimah (Length (L) = 3 km and EC = 450 µS/cm), Falaj Fili (L = 5 km and EC = 1020 µS/cm), and Falaj Al Dhaid (L = 10 km and EC = 1180 µS/cm). The EC increase results from the high natural evaporation rates from falaj channels and interaction between water and the bedrock. The longer the channel, the larger the contact surface with the bedrock, and thus, larger amount of Total Dissolved Solids (TDS) contribution from the bedrock. Also, the longer the falaj channel, the larger the evaporation losses. This explains why old falaj channels are very narrow and rather deep to minimize the natural evaporation from falaj waters. In tunnel-type falajes (Al Daudi falajes), the EC does not correlate with the falaj length (Figure 9(*b*)) because of the variation in rock type and source of water in these falajes. Despite its short length (0.5 km), Falaj Hubhub has a high EC (2760 µS/cm). In contrast, Falaj Al Aini (6 km) is longer than Falaj Hubhub and has a much lower EC (620 µS/cm).

Major Ions

Calcium-ion (Ca^{2+}) concentrations is high in water of the falajes which drain ophiolitic rocks (6 mg/l in Falaj Asimah, Al Fujairah) and high in the falajes draining limestone rocks (601 mg/l in Falaj Ain Sukhnah, Al Ain). Magnesium-ion concentrations range from 9 mg/l in Falaj Awaina (Al Fujairah) to 150 mg/l in Falaj Ain Sukhnah (Al Ain). Water of U.A.E. falajes has high Mg^{2+} concentrations because most of these falajes run across Mg-rich ophiolitic rocks of the northern Oman mountains. As the Mg/(Ca+Mg) ratio is 0.3, the high Mg^{2+} concentration in Falaj Ain Sukhnah water can be related to the dissolution of limestone and dolomite rocks forming Jabal Hafit. Because falaj water has a short residence time compared with groundwater, sodium-ion (Na^+) contents in water of the falajes are generally low, except in falajes of Khatt South, Hubhub, Usayali, and Ain Sukhnah. These falajes belong to the Hadouri and Daudi types which may obtain part of their water from high-salinity deep formations.

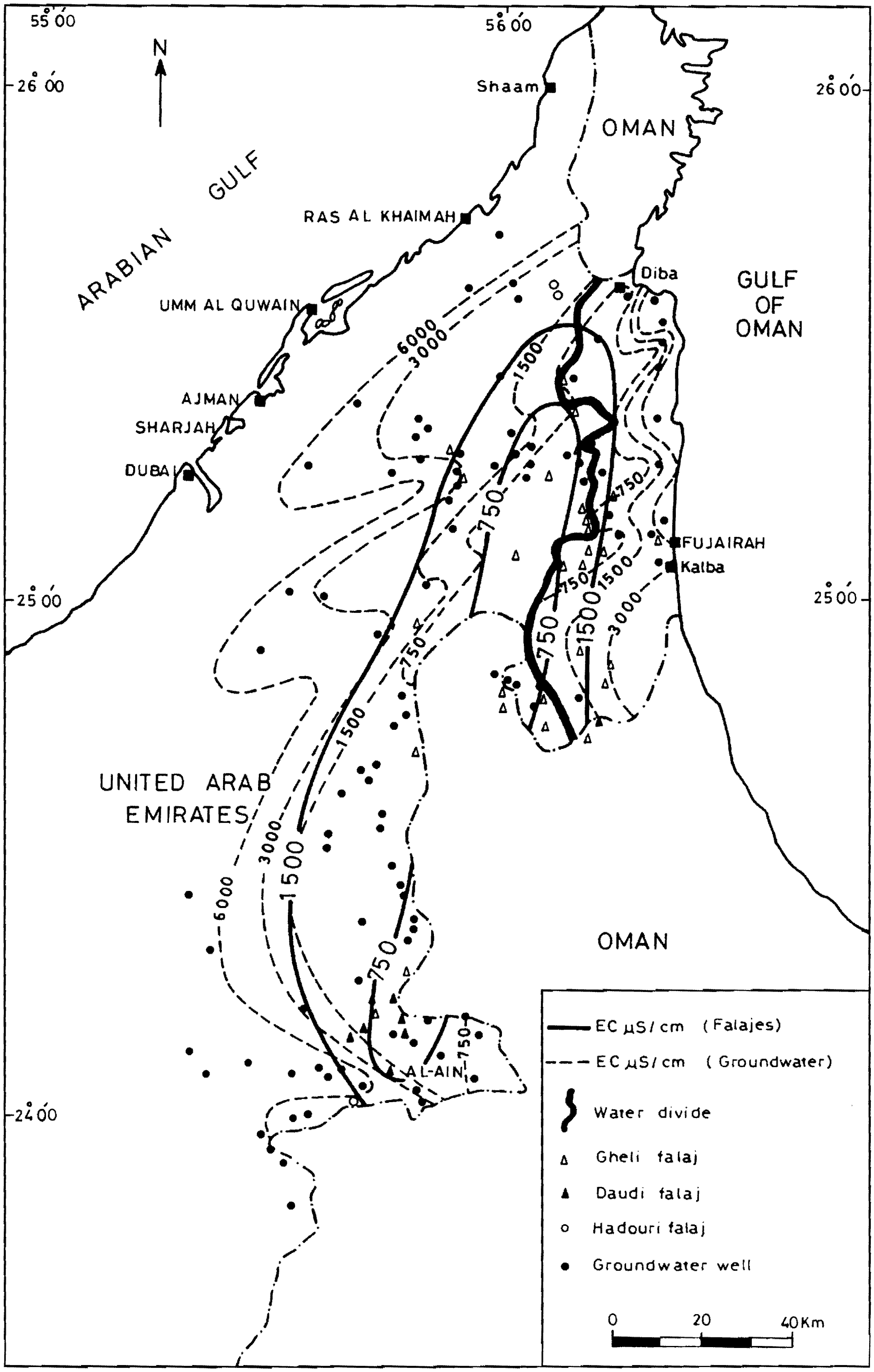

Figure 8. Iso-EC (µS/cm) Contour Map of Groundwater (Dashed Lines) and Falaj Water (Solid Lines) in U.A.E. During Early 1996.

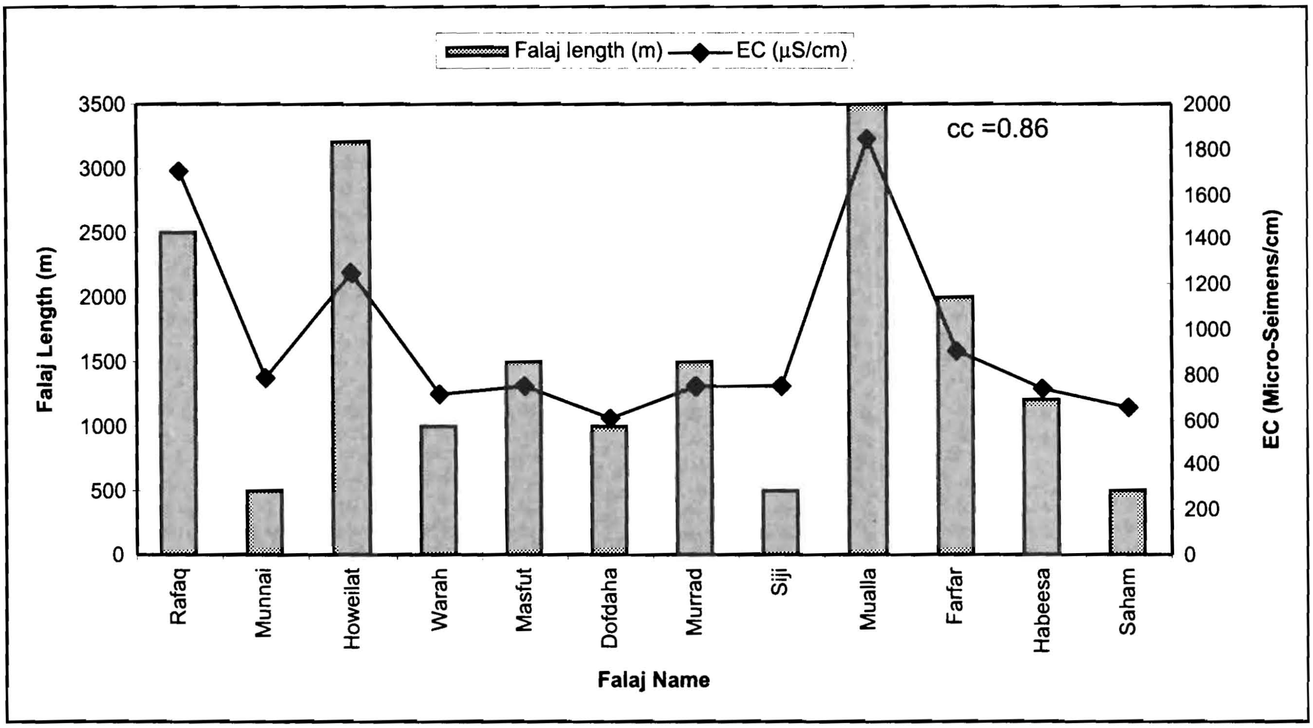

Figure 9(a). *Relationship Between Length (m) and EC (μS/cm) of Al Gheli Falajes in U.A.E.*

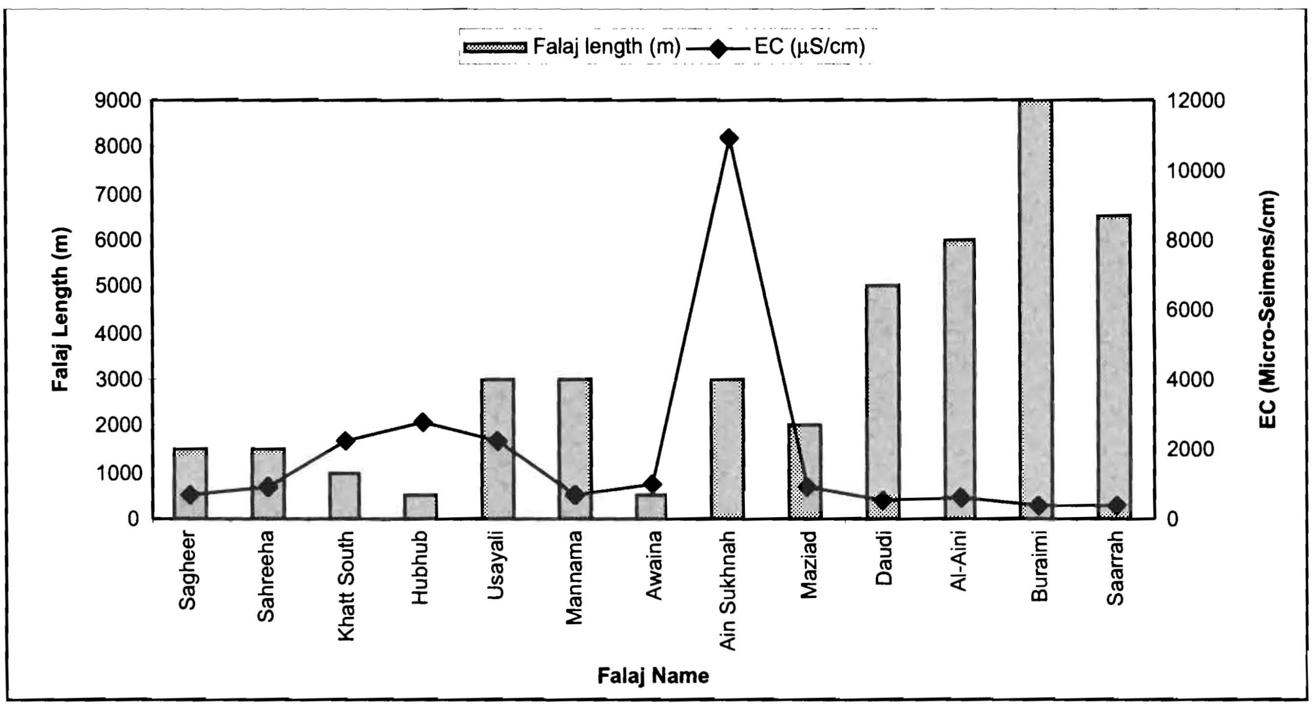

Figure 9(b). *Relationship Between Length (m) and EC (μS/cm) of Al Daudi and Al Hadouri Falajes in U.A.E.*

Table 4. Results of Chemical Analysis of Water Samples Collected from U.A.E. Falajes.
(Concentrations of ions are expressed in milliequivalent per liter. Hardness and alkalinity are expressed in milligrams per liter).

Falaj No.	Falaj Name	pH	EC	CO_3	HCO_3	SO_4	Cl	T. A.	Ca	Mg	Na	K	T. C.	Balance	SAR	Hardness	Alkalinity
	EDSA																
4	Rafaq	7.31	1700	0.15	3.06	4.09	9.40	16.70	2.75	2.48	11.40	0.13	16.76	−0.18	7.20	261.50	153.13
5	Munnai*	8.89	780	0.68	4.25	0.76	2.14	7.83	1.24	2.29	4.20	0.10	7.83	0.00	3.20	176.50	212.68
6	Howeilat*	9.08	1250	0.68	3.57	2.79	5.71	12.75	1.65	2.07	8.90	0.13	12.75	0.00	6.50	186.00	178.65
7	Warah	8.60	710	0.41	3.06	1.90	2.20	7.57	1.54	3.60	2.50	0.07	7.71	−0.92	1.56	257.00	153.13
8	Masfut	8.72	750	0.50	3.46	0.86	2.70	7.52	1.54	3.55	2.30	0.07	7.46	0.40	1.40	254.50	173.15
9	Dofdaha	9.52	610	0.31	1.04	2.60	2.18	6.13	1.03	2.89	2.20	0.07	6.19	−0.49	1.57	196.00	52.04
10	Sagheer*	9.53	700	1.00	3.68	0.56	1.76	7.00	1.34	4.56	0.87	0.23	7.00	0.00	0.50	295.00	184.16
11	Sahreeha*	10.07	900	1.12	2.65	1.53	3.70	9.00	1.34	5.35	1.95	0.36	9.00	0.00	1.00	334.50	132.61
	WDNA																
13	Khatt South*	8.16	2250	0.34	3.74	4.03	14.30	22.41	4.30	2.40	15.50	0.21	22.41	0.00	8.50	335.00	187.16
14	Hubhub*	8.12	2760	0.34	3.90	5.55	16.90	26.69	3.95	3.72	18.80	0.22	26.69	0.00	9.60	383.50	195.17
15	Usayali	8.20	2200	0.34	3.57	8.86	14.30	27.07	3.95	2.42	15.50	0.20	22.07	10.18	8.70	318.50	178.65
	WDCA																
17	Fili	8.85	1020	0.41	2.44	3.30	5.03	11.18	1.50	2.10	8.10	0.17	11.87	−2.99	6.40	180.00	122.10
18	Asimah	7.12	450	0.08	1.53	1.19	2.00	4.80	0.30	3.03	1.13	0.08	4.54	2.78	0.90	166.50	76.57
19	Murrad*	8.54	750	0.40	3.16	1.11	2.87	7.54	1.34	3.95	2.20	0.05	7.54	0.00	1.40	264.50	158.13
20	Dhaid*	8.98	1180	0.60	3.37	2.12	5.62	11.71	1.00	2.30	8.26	0.15	11.71	0.00	6.40	165.00	168.64
21	Siji*	8.97	750	0.61	3.47	2.36	1.14	7.58	1.34	4.44	1.73	0.07	7.58	0.00	1.00	289.00	173.65
22	Mualla	7.33	1840	0.20	4.49	4.90	9.50	19.09	1.29	4.59	13.04	0.23	19.15	−0.16	7.60	294.00	224.69
23	Mannama*	8.47	680	0.40	3.37	0.80	2.38	6.95	1.44	4.15	1.30	0.06	6.95	0.00	0.80	279.50	168.64
	ECA																
24	Farfar*	8.25	900	0.34	3.40	1.09	4.00	8.83	1.72	3.38	3.65	0.08	8.83	0.00	2.30	255.00	170.15
25	Mamduk*	8.69	600	0.50	3.57	0.17	1.90	6.14	1.20	2.40	2.48	0.06	6.14	0.00	1.80	180.00	178.65
26	Museiriya*	9.22		0.82	3.88	1.07	4.66	10.43	1.44	4.93	3.91	0.15	10.43	0.00	2.20	318.50	194.17
27	Habeesa	9.57	740	0.60	2.04	1.40	3.33	7.37	0.93	2.76	3.53	0.12	7.34	0.20	2.40	184.50	102.09
28	Bithna (L/B)																
29	Bithna (R/B)*	10.00	1050	0.82	2.04	2.81	4.76	10.43	1.44	4.93	3.91	0.15	10.43	0.00	2.20	318.50	102.09
30	Awaina	8.04	1030	0.20	2.14	1.82	6.04	10.20	1.65	0.70	7.80	0.06	10.21	−0.05	7.20	117.50	107.09
31	Sham*	8.20	650	0.40	4.40	0.25	1.80	6.85	1.03	4.47	1.30	0.05	6.85	0.00	0.80	275.00	220.19
32	Farah	8.63	1000	0.68	5.45	0.97	4.70	11.80	2.90	4.30	4.57	0.09	11.86	−0.25	2.40	360.00	272.73
	Al-Ain Area																
34	Ain Sukhnah	8.86	10940	0.50	3.06	12.60	103.53	119.69	30.38	12.25	80.40	1.41	124.44	−1.95	17.40	2131.50	153.13
35	Maziad	8.86	960	0.50	3.06	2.40	4.20	10.16	1.29	4.10	4.70	0.13	10.22	−0.29	2.90	269.50	153.13
36	Hili*	8.44	750	0.40	3.47	1.14	2.57	7.58	1.75	2.25	3.48	0.10	7.58	0.00	2.50	200.00	173.65
37	Daudi*	9.51	520	0.60	2.14	0.77	1.70	5.21	1.13	2.10	1.90	0.08	5.21	0.00	1.50	161.50	107.09
38	Al-Aini*	9.87	620	0.82	2.25	1.11	2.05	6.23	1.13	2.50	2.50	0.10	6.23	0.00	1.90	181.50	112.60
39	Buraimi	9.86	380	0.60	1.63	0.38	1.19	3.80	1.03	1.81	1.20	0.06	4.10	−3.80	1.10	142.00	81.57
40	Saarrah*	10.87	390	1.00	1.33	0.33	1.24	3.90	0.92	1.61	1.30	0.07	3.90	0.00	1.20	126.50	66.56

The pH was calculated from the relation $[H^+] = \text{Log } K_2 \text{ Log } [CO_3] / \text{Log } [HCO_3]$ [9]), T. A. = Total anions, and T. C. = Total cations. (*) Samples in which SO_4 was calculated by difference.

Carbonate-ion (CO_3^{2-}) concentrations in water samples collected from U.A.E. falajes ranged from 5 mg/l in Falaj Rafaq (Hatta) to 34 mg/l in Falaj Sahreeha (Hatta). Bicarbonate-ion (HCO_3^-) amounts in falajes ranged from 64 mg/l in Falaj Dofdaha (Hatta) to 336 mg/l in Falaj Farah (Al Fujairah). Sulfate-ion (SO_4^{2-}) concentrations in falajes range from 7 mg/l in Falaj Mamduk (Al Fujairah) to 605 mg/l in Falaj Ain Sukhnah (Al Ain). The high SO_4^{2-} in Ain Sukhnah water is a result of dissolution of gypsum ($CaSO_4.2H_2O$) from the evaporite deposits of the Miocene Fars Formation through which the water of the falaj moves. Chloride-ion (Cl^-) concentrations in falaj waters range from 40 mg/l in Falaj Siji (Al Fujairah) to 3687 mg/l in Falaj Ain Sukhana (Al Ain).

Figure 10 shows a trilinear plot of the chemical analysis of water samples collected from the U.A.E. falajes. The appearance of most of the samples in the upper triangle of the diamond-shaped field, points to the dominance of Na–Mg and chloride and bicarbonate water types. Water of the U.A.E. falajes is enriched in Mg^{2+} which is dissolved from Mg-rich ophiolitic and dolomitic rocks.

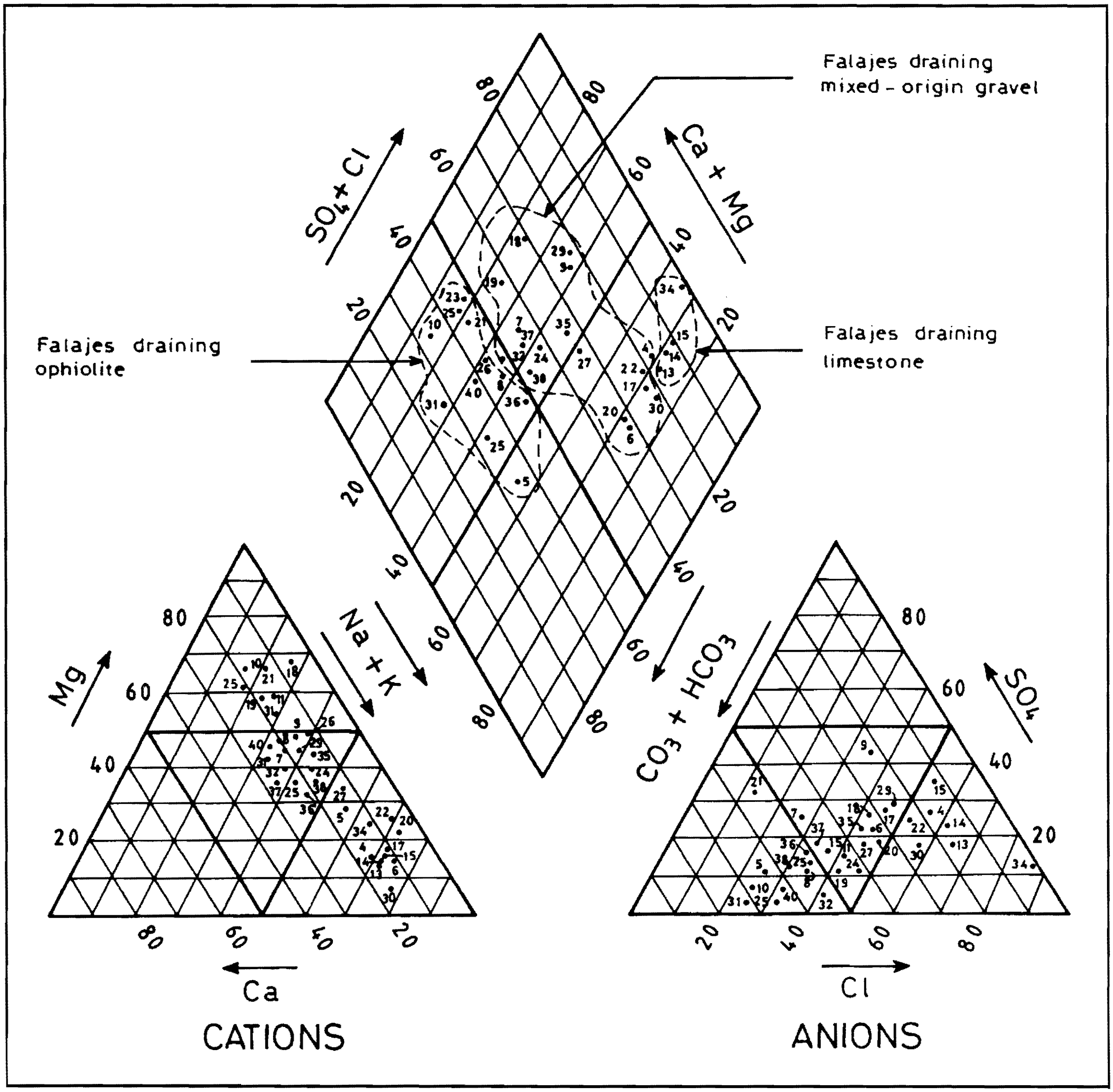

Figure 10. The Trilinear Plot of Chemical Analyses of Water Samples Collected from U.A.E. Falajes During Early 1996.

Because the water of the falajes is mainly used for irrigation purposes, values of EC and SAR were plotted on the U.S. Salinity Laboratory Staff [11] diagram. Figure 11 shows that the water of all the U.A.E. falajes, except Khatt South and Hubhub falajes, are good (vertical lines) to fair (dots) for irrigation purposes.

Hydrochemical Coefficients

The ratios Mg/Ca, Na/K, Cl/SO_4, Na/Cl, Mg/(Ca+Mg), $Ca/(Ca+SO_4)$, Cl/total anions, and HCO_3/sum anions were calculated for falaj waters (Table 5).

According to Hounslow [12], if the salinity is low and Mg is greater than Ca, this indicates probable dissolution of ferromagnesian minerals from mafic and ultramafic rocks. This is actually the case in 27 falajes out of a total of 33 listed in

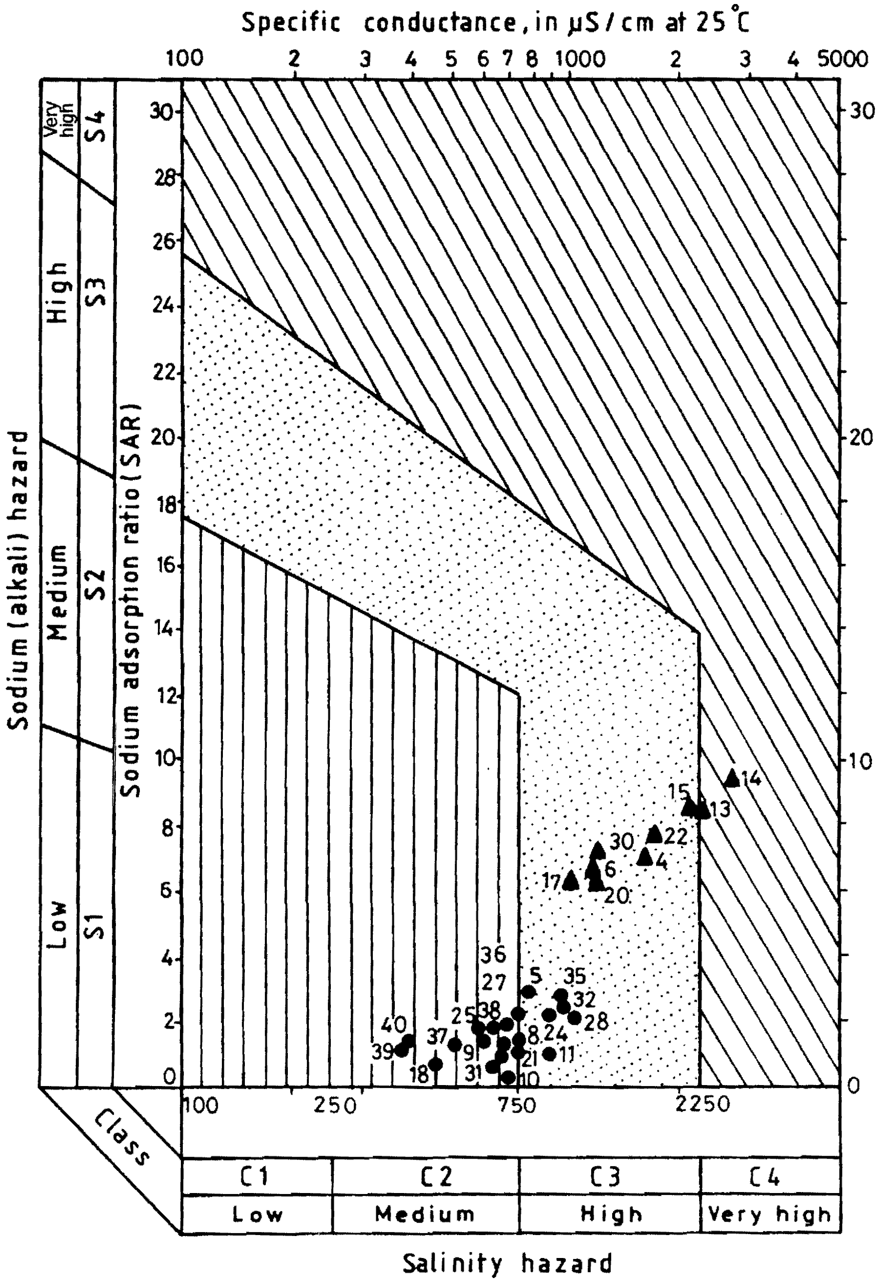

Figure 11. Classification of Irrigation Water [11]. ▥ *Good-quality,* ⁝ *fair-quality, and* ▧ *bad-quality waters.* • *Falajes draining ophiolites.* ▲ *Falajes draining limestones.*

Table 5. Waters of these falajes run across the Semail ophiolites in northern Oman mountains (Figures 4 and 12). The Ca is greater or equal to Mg in waters of the falajes draining limestone rocks, such as falajes of Khatt South, Hubhub, and Usayhli in Ras Al Khaimah and Falaj Ain Sukhnah in Al Ain.

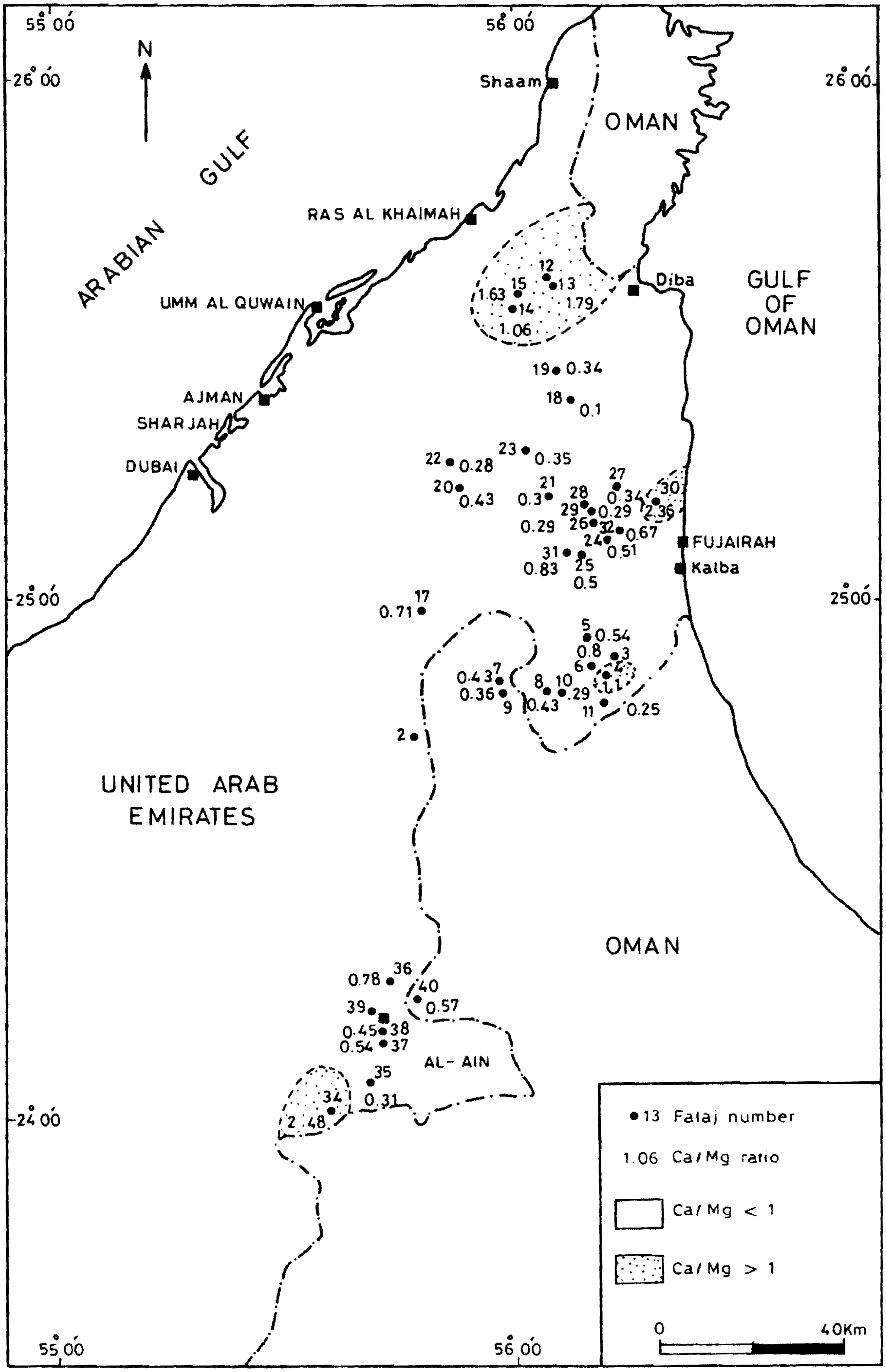

Figure 12. The Calcium/Magnesium Ratios in Water of U.A.E. Falajes.

Table 5. Calculated Hydrochemical Ratios in Water Samples Collected from U.A.E. Falajes During Early 1996.

Falaj No.	Falaj Name	pH	EC	CO_3	HCO_3	SO_4	Cl	T. A.	Ca	Mg	Na	K	T. C.	Ca/Mg	Na/K	Cl/SO_4	Na/Cl	Mg/(Ca+Mg)	$Ca/(Ca+SO_4)$	$(Ca+Mg)/SO_4$	Cl/T.A.	HCO_3/T.A.
	EDSA																					
4	Rafaq	7.31	1700	0.15	3.06	4.09	9.40	16.70	2.75	2.48	11.40	0.13	16.76	1.11	87.69	2.30	1.21	0.5	0.4	1.3	0.6	0.2
5	Munnai	8.89	780	0.68	4.25	0.76	2.14	7.83	1.24	2.29	4.20	0.10	7.83	0.54	42.00	2.82	1.96	0.6	0.6	4.6	0.3	0.3
6	Howeilat	9.08	1250	0.68	3.57	2.79	5.71	12.75	1.65	2.07	8.90	0.13	12.75	0.80	68.46	2.05	1.56	0.6	0.4	1.3	0.4	0.2
7	Warah	8.60	710	0.41	3.06	1.90	2.20	7.57	1.54	3.60	2.50	0.07	7.71	0.43	35.71	1.16	1.14	0.7	0.4	2.7	0.3	0.2
8	Masfut	8.72	750	0.50	3.46	0.86	2.70	7.52	1.54	3.55	2.30	0.07	7.46	0.43	32.86	3.14	0.85	0.7	0.6	5.9	0.4	0.2
9	Dofdaha	9.52	610	0.31	1.04	2.60	2.18	6.13	1.03	2.89	2.20	0.07	6.19	0.36	31.43	0.84	1.01	0.7	0.3	1.5	0.4	0.1
10	Sagheer	9.53	700	1.00	3.68	0.56	1.76	7.00	1.34	4.56	0.87	0.23	7.00	0.29	3.78	3.14	0.49	0.8	0.7	10.5	0.3	0.2
11	Sahreeha	10.07	900	1.12	2.65	1.53	3.70	9.00	1.34	5.35	1.95	0.36	9.00	0.25	5.42	2.42	0.53	0.8	0.5	4.4	0.4	0.2
	WDNA																					
13	Khatt South	8.16	2250	0.34	3.74	4.03	14.30	22.41	4.30	2.40	15.50	0.21	22.41	1.79	73.81	3.55	1.08	0.4	0.5	1.7	0.6	0.2
14	Hubhub	8.12	2760	0.34	3.90	5.55	16.90	26.69	3.95	3.72	18.80	0.22	26.69	1.06	85.45	3.05	1.11	0.5	0.4	1.4	0.6	0.2
15	Usayali	8.20	2200	0.34	3.57	8.86	14.30	27.07	3.95	2.42	15.50	0.20	22.07	1.63	77.50	1.61	1.08	0.4	0.3	0.7	0.5	0.2
	WDCA																					
17	Fili	8.85	1020	0.41	2.44	3.30	5.03	11.18	1.50	2.10	8.10	0.17	11.87	0.71	47.65	1.52	1.61	0.6	0.3	1.1	0.4	0.1
18	Asimah	7.12	450	0.08	1.53	1.19	2.00	4.80	0.30	3.03	1.13	0.08	4.54	0.10	14.13	1.68	0.57	0.9	0.2	2.8	0.4	0.1
19	Murrad	8.54	750	0.40	3.16	1.11	2.87	7.54	1.34	3.95	2.20	0.05	7.54	0.34	44.00	2.59	0.77	0.7	0.5	4.8	0.4	0.2
20	Dhaid	8.98	1180	0.60	3.37	2.12	5.62	11.71	1.00	2.30	8.26	0.15	11.71	0.43	55.07	2.65	1.47	0.7	0.3	1.6	0.5	0.2
21	Siji	8.97	750	0.61	3.47	2.36	1.14	7.58	1.34	4.44	1.73	0.07	7.58	0.30	24.71	0.48	1.52	0.8	0.4	2.4	0.2	0.2
22	Mualla	7.33	1840	0.20	4.49	4.90	9.50	19.09	1.29	4.59	13.04	0.23	19.15	0.28	56.70	1.94	1.37	0.8	0.2	1.2	0.5	0.3
23	Mannama	8.47	680	0.40	3.37	0.80	2.38	6.95	1.44	4.15	1.30	0.06	6.95	0.35	21.67	2.98	0.55	0.7	0.6	7.0	0.3	
	ECA																					
24	Farfar	8.25	900	0.34	3.40	1.09	4.00	8.83	1.72	3.38	3.65	0.08	8.83	0.51	45.63	3.67	0.91	0.7	0.6	4.7	0.5	0.2
25	Mamduk	8.69	600	0.50	3.57	0.17	1.90	6.14	1.20	2.40	2.48	0.06	6.14	0.50	41.33	11.18	1.31	0.7	0.9	21.2	0.3	0.2
26	Museiriya	9.22		0.82	3.88	1.07	4.66	10.43	1.44	4.93	3.91	0.15	10.43	0.29	26.07	4.36	0.84	0.8	0.6	6.0	0.4	0.2
27	Habeesa	9.57	740	0.60	2.04	1.40	3.33	7.37	0.93	2.76	3.53	0.12	7.34	0.34	29.42	2.38	1.06	0.7	0.4	2.6	0.5	0.1
28	Bithna (L/B)																					
29	Bithna (R/B)	10.00	1050	0.82	2.04	2.81	4.76	10.43	1.44	4.93	3.91	0.15	10.43	0.29	26.07	1.69	0.82	0.8	0.3	2.3	0.5	0.1
30	Awaina	8.04	1030	0.20	2.14	1.82	6.04	10.20	1.65	0.70	7.80	0.06	10.21	2.36	130.00	3.32	1.29	0.3	0.5	1.3	0.6	0.1
31	Sham	8.20	650	0.40	4.40	0.25	1.80	6.85	1.03	4.47	1.30	0.05	6.85	0.23	26.00	7.20	0.72	0.8	0.8	22.0	0.3	0.3
32	Farah	8.63	1000	0.68	5.45	0.97	4.70	11.80	2.90	4.30	4.57	0.09	11.86	0.67	50.78	4.85	0.97	0.6	0.7	7.4	0.4	0.3
	Al-Ain Area																					
34	Ain Sukhnah	8.86	10940	0.50	3.06	12.60	103.53	119.69	30.38	12.25	80.40	1.41	124.44	2.48	57.02	8.22	0.78	0.3	0.7	3.4	0.9	0.2
35	Maziad	8.86	960	0.50	3.06	2.40	4.20	10.16	1.29	4.10	4.70	0.13	10.22	0.31	36.15	1.75	1.12	0.8	0.3	2.2	0.4	0.2
36	Hili	8.44	750	0.40	3.47	1.14	2.57	7.58	1.75	2.25	3.48	0.10	7.58	0.78	34.80	2.25	1.35	0.6	0.6	3.5	0.3	0.2
37	Daudi	9.51	520	0.60	2.14	0.77	1.70	5.21	1.13	2.10	1.90	0.08	5.21	0.54	23.75	2.21	1.12	0.7	0.6	4.2	0.3	0.1
38	Al-Aini	9.87	620	0.82	2.25	1.11	2.05	6.23	1.13	2.50	2.50	0.10	6.23	0.45	25.00	1.85	1.22	0.7	0.5	3.3	0.3	0.1
39	Buraimi	9.86	380	0.60	1.63	0.38	1.19	3.80	1.03	1.81	1.20	0.06	4.10	0.57	20.00	3.13	1.01	0.6	0.7	7.5	0.3	0.1
40	Saarrah	10.87	390	1.00	1.33	0.33	1.24	3.90	0.92	1.61	1.30	0.07	3.90	0.57	18.57	3.76	1.05	0.6	0.7	7.7	0.3	0.1

Sodium is greater than chloride in 21 falaj, indicating a sodium source other than halite, such as albite (plagioclase) or natural softening according to the following equation [12]:

$$Ca^{2+} + 2\ Na\text{-}clay \rightarrow 2\ Na^{+} + Ca\text{-}clay$$

The chloride is greater than sodium in waters of 13 falaj, indicating reverse softening or

$$2\ Na^{+} + Ca\text{-}clay \rightarrow Ca^{2+} + 2\ Na\text{-}clay.$$

According to Hounslow [12], the Mg/(Ca+Mg) ratio = 0.5 indicates a probable origin by dolomite weathering. This is the case in Falaj Hubhub (Ras Al Khaimah). The Mg/(Ca+Mg) ratio is <0.5 in the falajes of Khatt North, Usayali, and Ain Sukhnah, indicating weathering of limestone and dolomite which constitute the aquifer feeding these falajes. The Mg/(Ca+Mg) ratio is >0.5 in 27 falajes out of 33, indicating the dissolution of Mg-rich rocks which are the main constituent of the ultramafic rocks of the Semail ophiolites. These conditions also favor the precipitation of calcite ($CaCO_3$) and possibly huntite ($Mg_3Ca(CO_3)_4$) which can be altered later to magnesite ($MgCO_3$) [13].

The ratio of Cl/sum anions is less than 0.8 in all falajes, indicating rock weathering. Only one falaj (Falaj Ain Sukhnah) has a Cl/sum anions ratio >0.8. Since this falaj belongs to the Hadouri-type falajes, the high Cl/sum anions ratio may explain the high EC (10 940 µS/cm) where saline water is intercepted by the falaj as it moves under pressure from deep horizons in the Eocene limestone aquifer in this area. In fact, this area is now being explored for its hydrothermal water (temperature ≈50°C) [14].

CONCLUSIONS

Despite their limited amount, falaj waters are a renewable resource which originated as rainfall. During the 1978–1995 period, the total falaj discharge in U.A.E. varied between 9.0×10^6 m^3/yr in 1994 and 31.2×10^6 m^3/yr in 1982, which represents 2.8 to 9.7% of the total water use in the country. Except for a few cases, the discharge of U.A.E. falajes is directly related to the antecedent rainfall on the eastern mountains and the gravel plains.

Water of all U.A.E. falajes has exceptionally high Mg^{2+} concentrations because most of these falajes run across Mg-rich ophiolitic rocks of the northern Oman mountains. The high Mg^{2+} concentration in water of Falaj Ain Sukhnah (Al Ain) is related to the dissolution of dolomitic rocks from Jabal Hafit. The EC of falaj waters in U.A.E. are variable, ranging from 450 µS/cm in Falaj Asimah (Al Fujairah) to 10 940 µS/cm in Falaj Ain Sukhnah (Al Ain). The iso-EC map shows that the EC of water in the U.A.E. falajes is minimum near the water divide of the northern Oman mountains and increases to the east and west. In Al Gheli falajes, the EC increases with increasing falaj length, but in Al Daudi and Al Hadouri falajes, EC is generally low irrespective of the length of the falaj.

A plot of the EC *versus* SAR on the U.S. Salinity Laboratory Diagram shows that the water of the U.A.E. falajes are good to very poor for irrigation purposes. Because of their relatively high salinity and SAR, waters of Khatt South and Hubhub falajes, Ras Al Khaimah area, can threaten salt-intolerant crops, such as citrus and other sensitive fruits.

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