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Water Quality Assessment of *Aflaj* in the Mountains of Oman

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Abstract

The research was conducted to assess the *aflaj* water quality in Al Jabal Al Akhdar, Oman. 9 *aflaj* were sampled during summer and winter seasons in 2012-2013 to evaluate for the physico-chemical characteristics of major quality parameters; and assess the suitability of *aflaj* for irrigation purposes. Samples collection, handling and processing followed the standard methods recommended by the *American Public Health Association* and analysed in quality assured laboratories using appropriate analytical methods and instrumental techniques. The quality parameters of the selected *aflaj* water indicated their suitability for irrigation as most of the quality parameters were within the permissible limits set by Omani regulations of wastewater reuse for irrigation. These selected water resources are excellent or good in quality for irrigation purposes based on the evaluation of different hazards parameters including the salinity-alkalinity hazards which indicate good to admissible water based on electrical conductivity and sodium adsorption classification; and water quality indices which reveal high or moderate classes, indicating the suitability of *aflaj* for irrigation of the majority of crops and soils. This study is a first comprehensive assessment towards providing indicators and classification indices on irrigation water quality of this fragile mountain ecosystem, which will be the basis for future planning decisions on agricultural demand management measures to protect these principal resources for agricultural production in Al Jabal Al Akhdar.

Keywords: *Aflaj*, Al Jabal Al Akhdar, hazards, irrigation water, mountains, Oman, water quality index

1. Introduction

Like other countries located in arid regions, the Sultanate of Oman suffers from rainfall scarcity and limited renewable water resources. Oman depends totally on groundwater and *aflaj* for domestic and irrigation purposes. *Aflaj* (singular *falaj*) are surface and/or underground channels fed by groundwater, springs, or streams, built to provide water to communities for domestic and/or agricultural use (Al-Marshudi, 2001; Zekri & Al-Marshudi, 2008). *Aflaj* have been constructed in Oman for thousands of years to tap concentrated lines of groundwater flow and guide them to the surface along a channel (often several kilometers long) at a lesser gradient than the water table (Al-Marshudi, 2007). On reaching ground level, the main channel splits into many smaller channels, which in turn divide to supply individual farms. *Aflaj* are managed by local people, with their own designated administrative structure, who are responsible for the overall organization of *falaj* affairs and water distribution for irrigation without government involvement in this organizational structure (Al-Marshudi, 2007; Zekri & Al-Marshudi, 2008). The *aflaj* system is mainly based on a time-share among water rights holders, but in some areas volume is used instead, especially during drought periods (Al-Ghafri et al., 2003; Zekri et al., 2014). Given the importance of *aflaj* as a unique Omani water resource, UNESCO has listed five of the *aflaj* in Oman on the World Heritage list (MRMWR, 2008a).

Most of the *aflaj* are located in the northern Oman Mountains; mountains cover 15% of the country total area. Al Jabal Al Akhdar (Green Mountain) is the largest structural domain, located in the central part of the northern Oman Mountains (Figure 1). It reaches heights between 1500 to 3000 m above sea level. Because of its altitude,

temperatures are some 10 to 12°C lower than in the coastal plains (DGMAN, 2014). In general, the temperatures drop during winter to below 0°C and rise in summer to around 22°C. Rainfall is highly variable and irregular and is the main source of fresh water in the mountain, where the mean annual rainfall is about 300 mm (DGMAN, 2014; Al-Kalbani et al., 2014; Al-Kalbani et al., 2015a). Agriculture has been the principal traditional economic sector with around 70 % of the local inhabitants practice agriculture and animal husbandry (Al-Riyami, 2006; Al-Kalbani et al., 2015b). The mountain terraces produce a variety of perennial fruits, especially pomegranates as well as roses for producing rose water, as a unique business in the area. Tourism is a growing sector in the area where the number of tourists and tourism infrastructure has increased over the last few years (Al-Balushi et al., 2011; Ministry of Tourism, 2014; Al-Kalbani et al., 2015b).

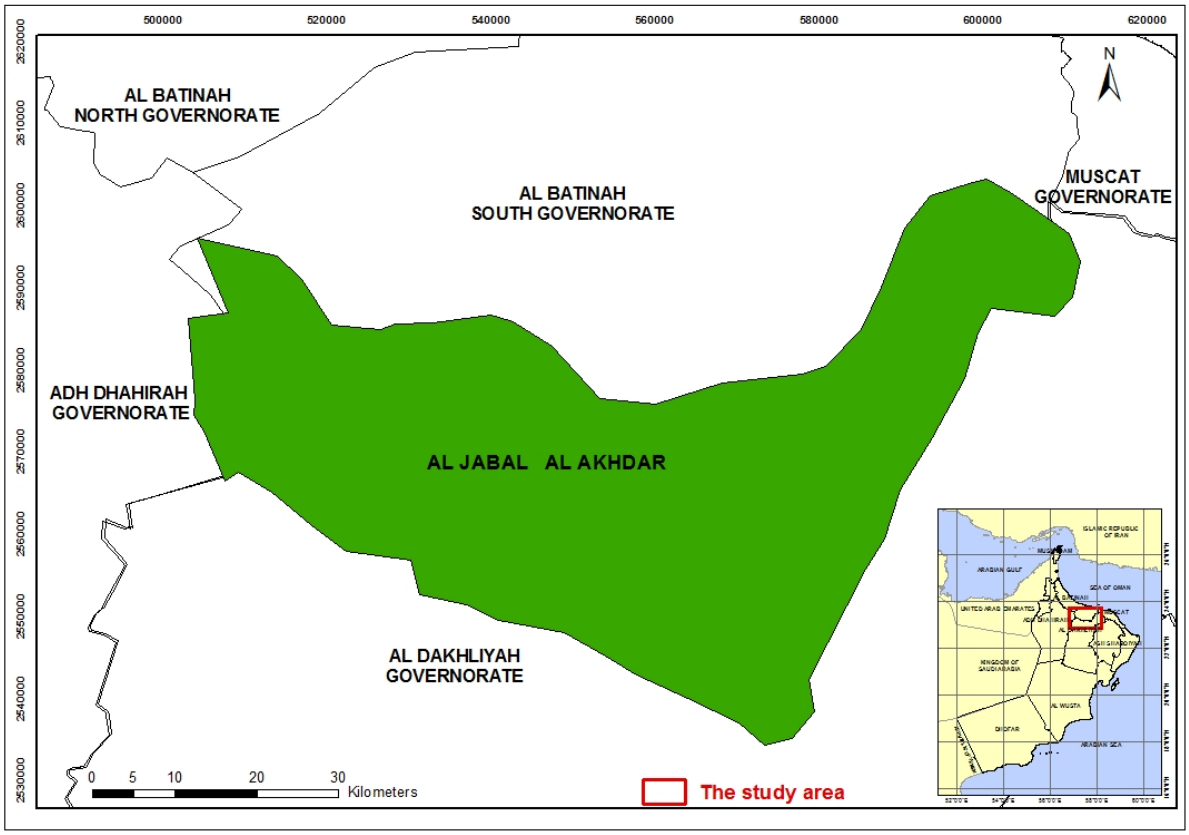

Figure 1. Location of the study area in the Sultanate of Oman map (*Source*: MECA, 2015)

Al Jabal Al Akhdar has experienced rapid socioeconomic development and urbanization in recent decades. These changes have influenced the water resources, which are the lifeline of its natural ecosystems and therefore human well-being. According to the National *Aflaj* Inventory conducted from March 1997 to June 1998, there were 72 *Aflaj* in Al Jabal Al Akhdar (MWR, 1999; MRMEWR, 2001). However, this number hasdecreased to 38 based on the recent study by Al-Kalbani et al. (2015b). Many studies have conducted on *aflaj* in Oman: their physical structure, method of construction and governance, irrigation scheduling, water right and market (e.g. Abdel Rahman & Omezzine, 1996; Norman et al., 1998; Al-Marshudi, 2007; Zekri et al., 2014). However, there is very little information assessing and classifying the water quality of *aflaj* and their suitability for irrigation and domestic purposes, especially in the mountains.

Irrigation water quality is an important tool in the assessment and sustainable management of water resources and agricultural production. The presence of excessive amounts of ions in irrigation water affects soil's physical and chemical properties, reduce soil productivity, create crop toxicity and eventually reduce yields (Kraiem et al., 2014; Nag, 2014; Varol & Davraz, 2015). Major water quality problems for irrigation are salinity, sodicity and alkalinity (Simsek & Gunduz, 2007; Sadashivaiah et al., 2008; Nazzal et al., 2014). An appropriate assessment of water for irrigation requires the determination of of physical, chemical and biological parameters that are greatly influenced

by geological formations and anthropogenic activities (Sarath Prasanth et al., 2012; Al-Khashman & Jaradat, 2014; Al-Harbi et al., 2014) and directly related to the classifying of water quality (Saber et al., 2014; Aly, 2014; Aly et al., 2014). Several quality indices can be used to assess the suitability of water for irrigation; the most commonly used are salinity hazards, percent sodium (% Na), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), soluble sodium percentage (SSP), residual sodium bicarbonate RSBC), permeability index (PI), potential salinity (PS), Kelley's index (KI) and magnesium hazard (MH) (Tatawat & Chandel, 2008; Sarath Prasanth et al., 2012; Al-Harbi et al., 2014; Nag, 2014). Water quality index (WQI) also provides a simple and concise method for assessing the water quality by integrating the water quality variables into one single number depending on several quality variables: salinity hazard, infiltration or permeability hazard, specific ion toxicity, trace element toxicity, and various miscellaneous effects to susceptible crops (Lou & Han, 2007; Simsek & Gunduz, 2007; Tatawat & Chandel, 2008; Mohammed Muthanna, 2011; Al-Bahrani et al., 2012; Adhikari et al., 2013; Aly et al., 2014).

This study interprets and classifies the hydro-chemical characteristics and WQI of *aflaj* water in Al Jabal Al Akhdar and evaluates their suitability for irrigation. Previous studies on water quality in this fragile mountainous region (e.g. Al-Haddabi, 2003; Ahmed et al., 2006; Al-Haddabi et al., 2009; Victor et al., 2009) focused only on the general physico-chemical characteristics of few *aflaj*. This paper presents a comprehensive assessment and classification of water quality of principal *aflaj* for agricultural activities in the area, using several quality parameters and classification indices.

2. Materials and Methods

2.1 Water Sampling and Analytical Methods

Nine *aflaj* were selected for water sampling (Figure 2; Table 1): these are the main *aflaj* that are most reliable for agriculture and active annually most of the time. The other *aflaj* were inactive or do not continuously flow during the whole year and are less reliable in terms of number of demand areas. At least two sampling points were identified along the channel of each *falaj*: the first at the source, and the second in a demand area (total area irrigated by the *falaj*. For longer *aflaj*, or those with many demand areas, a third sampling point was also used.

Table 1. Characteristics of the *aflaj* sampled in the study area (Data source: National *Aflaj* Inventory, March 1997-June 1998) (MWR, 1999)

Code	*Falaj* Name	Village	Type	Length (m)	*Falaj* mother well Coordinates (UTM)		Altitude (m)	No. of demand areas	Total demand area (m²)	Total annual water demand (m³/year)
					North	East				
F1	Masirat Al Jawamid	Masirat Al Jawamid	Ayni	153	2558682	554283	1420	1	21,147	41,583
F2	Masirat Ar Rawajih	Masirat Ar Rawajih	Ayni	1,979	2548880	570600	1212	4	39,208	76,802
F3	Al Azizi	Sayq	Ayni	428	2552062	564891	1942	3	118,690	234,740
F4	Qatam	Sayq	Ayni	331	2552199	564435	1914	4	2,984	5,889
F5	Al Awar	Al Ayn	Ayni	140	2551912	567800	1970	4	62,630	123,348
F6	Al Kabari	Ash Shirayjah	Ayni	1,077	2552208	568992	1941	1	272,564	539,879
F7	As Sawjrah	As Sawjrah	Ayni	22	2558641	568788	1863	2	12,541	24,723
F8	Wadi Bani Habib	Wadi Bani Habib	Ayni	833	2552346	562507	1935	9	6,512	12,839
F9	Al Khamirah Al Sufla	Sayq	Ghayli	128	2550653	565729	1864	4	9,457	18,611

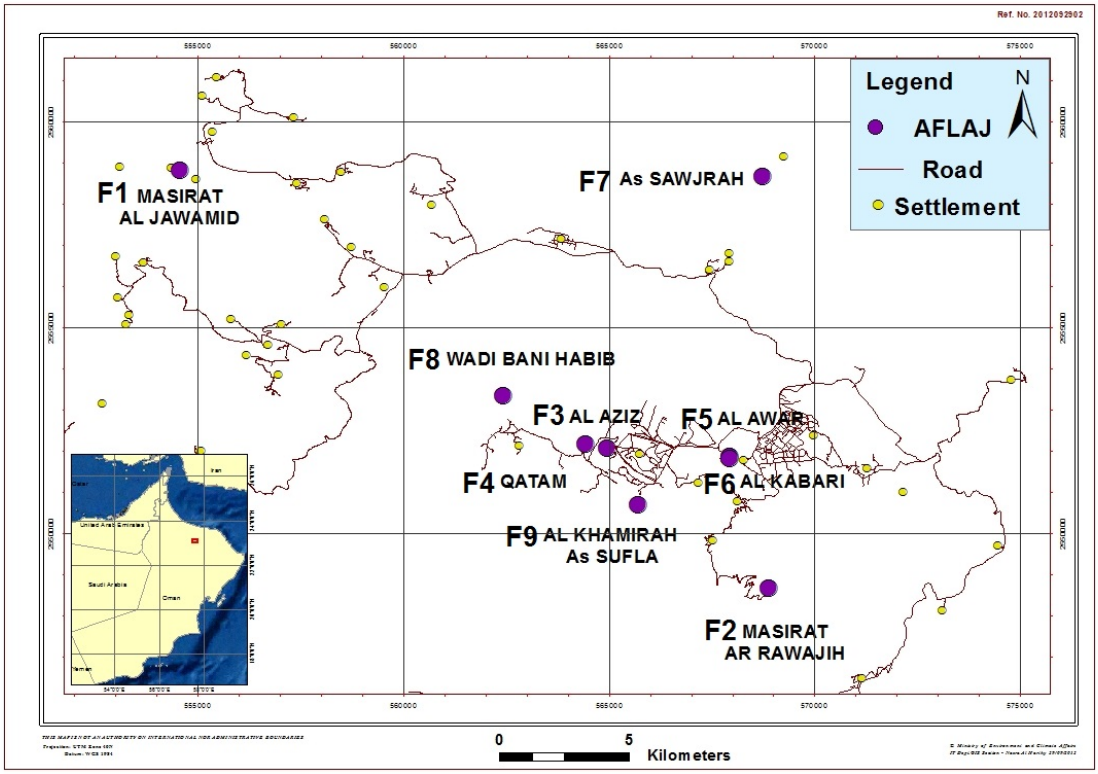

Figure 2. The location of sampled *aflaj* of the study area during summer and winter 2012-2013

Table 2. Determination of physiochemical parameters by different methods/instruments used

Parameters	Method/Instrument Used
Electrical Conductivity (EC)	Measured in the field using a battery-operated conductivity meter (SevenGo, Mettler-Toledo AG 8603 Schwerzenbach, Switzerland) and in the laboratory using the Orion Thermo 550A.
pH	Determined in the field using a pH meter (SevenGo, Mettler-Toledo GmbH, 8603 Schwerzenbach, Switzerland), and in the laboratory using a pH meter (Mettler Toledo)
Turbidity	Turbidity meter (Orion AQ 4500), Nephelometric Turbidity Units (NTU)
Total Dissolved Solids (TDS)	Gravimetric method
Alkalinity ($CaCO_3$, HCO_3 and CO_3)	Autotitration
Total Hardness (TH) (mg/l as $CaCO_3$)	Complexometric titration method using Ethylene Diamine Tetra Acetic Acid (EDTA)
Dissolved Oxygen (DO)	Measured in the field using Multi Probe System/data logger, YSI Incorporated 556 Instrument, Bramum Lane and in the laboratory using Mettler Toledo Seven Go Pro
Biochemical Oxygen Demand (BOD_5)	$BOD_5 = (D2 – D1) / P$
	D1: DO of diluted sample immediately after preparation, mg/l
	D2: DO of diluted sample after 5 days incubation at 20 ^oC, mg/l
	P: Decimal volumetric fraction of sample used
Sodium, Calcium, Magnesium, Potassium	Inductively Coupled Plasma (ICP-OES) (Perkin-Elmer Optima 3300 DV)
Fluoride, Chloride, Nitrate, Sulphate, Phosphate	Metrohm Professional Compact Ion Chromatography System 881 with Metrohm 858Professional Sample Processor
Heavy Metals	Inductively Coupled Plasma (ICP-OES) (Perkin-Elmer Optima 3300 DV)

The locations of sampled *aflaj*, mother well and points along their channels, were determined using GPS (etrex, Garmin). The sampling regime for all selected *aflaj* was 3 months in winter and 3 months in summer, taking into account that seasonal events such as rainfall and storms may influence sampling; and to obtain a reasonable range of data in each season. Sample collection, handling and processing followed the methods recommended by the *American Public Health Association* [APHA] (2005); water quality parameters were selected according to Chapmana and Kimstach (1996). Major physico-chemical and microbiological parameters were analysed in quality assured laboratories in Oman using the analytical methods and instrumental techniques shown in Table 2. The accuracy of the chemical analysis was verified by the calculation of ion-balance errors of 5% for all the sampled water resources. The respective values for all these parameters are compared with standard limits recommended by Omani standards for Un-bottled Drinking Water 8/2006 (MD, 2007) and the World Health Organization [WHO], 2011) for drinking water, and Omani regulations of Wastewater reuse for irrigation (MD, 1993). Statistical analysis was performed using descriptive statistics for all physico-chemical and microbiological parameters as well as correlation analyses using Pearson's coefficient (r) among the levels of parameters in water samples.

2.2 Hydrochemical Water Quality

Water quality indicators, including salinity hazards, percent sodium, sodium adsorption ratio, residual sodium carbonate, soluble sodium percentage, residual sodium bicarbonate, permeability index, potential salinity, Kelley's index, and magnesium hazard, were calculated for the water sampled in summer and winter from the selected *aflaj* of the study area using the equations in Table 3.

Table 3. Chemical composition indicators used for classifying irrigation water quality of the selected *aflaj* of the study (All ionic concentrations are in milliequivalents/l; meq/l)

Chemical Composition Indicator	**Equation**	**Reference**
%Na	$(Na^+ + K^+) / (Ca^{2+} + Mg^{2+} + Na^+ + K^+) * 100$	Wilcox, 1955
RSC (meq/l)	$(HCO_3^- + CO3^{2-}) - (Ca^{2+} + Mg^{2+})$	Richard, 1954
SSP (%)	(Soluble sodium concentration/total cations concentration) * 100	Todd, 2005
RSBC (meq/l)	$HCO_3^- - Ca^{2+}$	Richard, 1954
PI (%)	$Na^+ + (HCO_3^-)^{0.5} / (Ca^{2+} + Mg^{2+} + Na^+) * 100$	Doneen, 1964
PS (meq/l)	$Cl^- + 0.5\ SO_4^{2-}$	Richard, 1954
KI (Ratio)	$Na^+ / Ca^{2+} + Mg^{2+}$	Kelley, 1951
MH (%)	$Mg^{2+} / (Ca^{2+} + Mg^{2+}) * 100$	Szabolcs & Darab, 1964
Sodium Adsorption Ratio (SAR)	$\frac{[Na^+]}{\sqrt{[Ca^{2+}] + [Mg^{2+}]/2}}$	Todd, 2005

2.3 Irrigation Water Quality Index

WQI was used in this study to assess the quality of *aflaj* water and provide an overall indication for their suitability for irrigation purposes. The methodology requires that all five hazards (Appendix I) are simultaneously included in the analysis and combined to form a single WQI value, which is then assessed to determine the suitability of the irrigation water. The five hazards were grouped into five weighing coefficients, given the numbers 5, 4, 3, 2, 1, respectively, such that the most and the least important groups in irrigation water quality are given the highest (5) and lowest (1) points. For each hazard, several parameters were determined with different ranges and rating suitability. Three categories - high, medium and low - were given to the three rating suitability (3, 2, 1), respectively (Appendices I, II, III). After the total value of the index was computed, a suitability analysis was done based on the three different categories of WQI: low (< 22), medium (22-37) and high (> 37) (Simsek & Gunduz, 2007). The detailed calculation of all five hazard categories and the WQI are summarized in Appendix IV.

3. Results and Discussion

3.1 Physico-Chemical and Microbiological Parameters of Water Quality

The physico-chemical parameters of the selected *aflaj* of the study area are presented in Table 4, as mean, median, standard deviation, minimum and maximum over the summer and winter seasons of 2012-2013, and compared to the quality standards and guidelines for Omani Wastewater Reuse for irrigation and Discharge (Ministerial Decision, MD 145/1993) as there are no specific guidelines set for *aflaj* water.

Table 4. Physiochemical and microbiological characteristics of *aflaj* water quality for 22 sampling points from the study area during the two periods in 2012-2013

Variables	Mean	Median	Std. Deviation	Minimum	Maximum	Omani Standard	WHO Standard	MD 145/1993
EC (µS/cm)	564	538	159	294	896	160-1600	2000	2000
pH	8.11	8.18	0.26	7.41	8.51	6.5-9.0	6.5-9.5	6-9
Turbidity (NTU)	0.79	0.56	1.00	0.06	4.48	1 - < 5	NG	NG
TDS (mg/l)	345	329	100	172	562	120-1000	1000	1500
$CaCO_3$ (mg/l)	235	237	49	134	326	NG	NG	NG
HCO_3 (mg/l)	240	237	50	137	336	NG	NG	NG
Total Hardness (mg/l as $CaCO_3$)	272	265	58	158	376	≤ 200 - 500	500	NG
Sodium (mg/l)	19.68	16.11	11.50	7.48	48.88	≤ 200 - 400	200	200
Calcium (mg/l)	48.98	48.60	12.54	26.83	78.98	200	NG	NG
Magnesium (mg/l)	27.34	26.58	7.66	13.44	46.03	150	NG	150
Potassium (mg/l)	3.79	4.04	3.07	0.51	10.08	NG	NG	NG
Fluoride (mg/l)	0.12	0.12	0.04	0.04	0.18	1.5	1.5	1
Chloride (mg/l)	26.29	19.71	18.02	12.08	76.68	≤ 250 - 600	250	650
Nitrate (NO_3) (mg/l)	6.54	2.98	9.30	0.34	35.03	50	50	50
Sulphate (SO_4) (mg/l)	26.59	20.91	15.93	10.89	74.16	≤ 250 – 400	400	400
Phosphate (PO_4) (mg/l)	0.27	0.08	0.81	0.03	3.80	NG	NG	NG
Dissolved Oxygen (mg/l)	5.85	5.96	0.82	4.29	7.30	NG	NG	NG
BOD5 (mg/l)	1.91	1.77	0.76	0.73	3.84	NG	NG	15
Coliforms (MPN/100 ml)	133.68	155.93	82.12	3.75	> 200.50	10	10	200
E-Coli (MPN/100 ml)	7.30	2.25	10.83	0.00	37.50	0	0	NG

Omani Standard: Un-bottled Drinking Water Standard (No. 8/2006), WHO Standard: World Health Organization Drinking Water Standard, MD: Ministerial Decision (145/1993): Regulation for wastewater discharge and reuse standards, NG: No guideline is recommended.

According to the Omani regulations of wastewater reuse for irrigation water, the Electrical Conductivity (EC) of irrigation water has a maximum limit of 2000 µS/cm. The results of EC measured in all sampled *aflaj* water ranged from 341 to 793 µS/cm (mean 528.18 µS/cm) in summer, and from 246 to 999 µS/cm (mean 599.91 µS/cm) in winter. None of the *aflaj* water samples exceed the maximum limit of 2000 µS/cm specified in the Omani regulations of wastewater reuse for irrigation water. During summer, the pH values ranged from 7.37 to 8.41 and during winter they ranged from 7.44 to 8.61. These pH values are within the limits of the recommended Omani wastewater maximum quality regulations for irrigation water (pH 6-9). The measured turbidity (TR) in all selected *aflaj* during summer ranged from 0.060 to 6.67 NTU (mean 1 NTU) and from 0.050 to 2.29 NTU (mean 0.57 NTU) in winter.

Total dissolved solids (TDS) in the selected *aflaj* water ranged from 183.20 to 475.42 mg/l (mean 300.44 mg/l) in summer and 160.16 to 649.35 mg/l (mean 389.95 mg/l) in winter. These levels are well below the permissible level of TDS of 1500 mg/l in the Omani regulations of wastewater reuse for irrigation water. The total hardness (TH) measurements in the *aflaj* samples ranged from 157.43 to 348.19 mg/l; and from 159.49 to 402.84 mg/l with means of 256.86 mg/l; and 286.17 mg/l during summer and winter, respectively. Adopting Sawyer (2003) classification criteria, these water resources of the entire study area are hard to very hard as the total hardness (mg/l as $CaCO_3$) is in the range of 150-300 and more than 300 mg/l. The hardness of the water is due to the presence of alkaline earths such as calcium and magnesium, and anions such as carbonate, bicarbonate, chloride and sulphate.

According to Omani regulation of wastewater reuse, the results of cations and anions concentrations in the selected *aflaj* water studied showed no values exceeding the permissible limits and all quality values are within these standards.The mean concentration of cation (in mg/l) in the selected *aflaj* water sampled during summer and winter was in order Ca^{2+}>Mg^{2+}>Na^{+}> K^{+}. The mean concentration of anions (in mg/l) in the *aflaj* water sampled during summer and winter was in order HCO_3^->SO_4^{2-}>Cl^-> NO_3^-> CO_3^{2-}> PO_4^{3-}>F^-. None of the cation and anion concentrations in the samples exceeded the permissible limits according to the Omani regulation of wastewater reuse. Monitoring programs of phosphates particularly for cyanobacteria blooms are very important since some of the *aflaj* waters in the area are used for washing cloths by detergents containing phosphates which can be a source of pollution and contaminate these water resources and promote algal blooms growth.

Although the amount of dissolved oxygen (DO) often gives a good indication of water quality, the Omani regulations of wastewater reuse do not recommend guidelines regarding the acceptability of low levels. Generally, concentrations in unpolluted waters are usually close to, but less than 10 mg/l; concentrations below 5 mg/l may adversely affect the functioning and survival of biological communities (Chapman & Kimstach, 1996). All samples had DO concentrations less than 10 mg/l, but some samples were below 5 mg/l, taking into account changes in field water temperatures. Measurements of DO in the *aflaj* water samples during summer and winter had mean values of 7.93 and 3.77 mg/l; they ranged from 6.16 to 9.89 mg/l; and from 2.41 to 4.70 mg/l, respectively.

Omani regulations of wastewater reuse recommend 15 mg/l as a guideline values for biochemical oxygen demand (BOD_5). However, unpolluted waters typically have BOD_5 values of 2 mg/lor less whereas those receiving wastewater may have values up to 10 mg/lor more (Chapman & Kimstach, 1996). In the selected *aflaj* water samples, BOD5 concentrations were generally very low with means of 1.71 and 2.12 mg/l during summer and winter. All recorded values were below the range of BOD5 from 15 to 20 mg/l recommended in the Omani regulations of wastewater reuse for irrigation.

Most heavy metals in *aflaj* water sampled during summer and winter were below the detection levels of the ICP instrument. These include cadmium, chromium, cobalt, copper, vanadium, lithium, selenium, titanium and beryllium. In some *aflaj* water samples, concentrations of manganese, molybdenum and arsenic were just above the limit specified in the Omani standards of wastewater reuse for irrigation water. Other heavy metals were found in the *aflaj* water samples but within the safe limits for irrigation water. The chemical weathering and soil leaching are the primary natural sources that contribute in the presence of trace metals in water (Fetter, 2001; Şen, 2014).

Although all the physico-chemical parameters of *aflaj* water are within the permissible limits set by Omani standard for Un-bottled Drinking Water 8/2006 (MD, 2007) and the World Health Organization (WHO, 2011) for drinking water, most of the *aflaj* water resources studied were contaminated with coliform and *E. coli* bacteria. Of the 22 *aflaj* sampling points, 12 showed more than 200.5 total numbers of coliform bacteria in summer, and 9 in winter. Most of the *aflaj* water samples showed the presence of *E. coli* bacteria. These results indicate that *aflaj* waters are unacceptable and hazardous for drinking according to Omani standard for Un-bottled Drinking Water 8/2006 (MD, 2007) and the World Health Organization (WHO, 2011). The Omani and WHO standards allow the Most Probable Number (MPN) of 10/100 ml. In both guidelines, total *E. coli* should be 0 MPN/100 ml of a sample.

3.2 Hydro-Chemical Water Quality

Table 5 shows the mean, median, standard deviation, minimum and maximum of chemical composition indicators including percent sodium (%Na), residual sodium carbonate (RSC), soluble sodium percentage (SSP), residual sodium bicarbonate (RSBC), permeability index (PI), Kelley's index (KI), and magnesium hazard (MH) in the *aflaj* water samples in summer and winter. The selected *aflaj* of the study area have excellent or good quality; none of the water samples exceeded the limits and all were under the satisfactory category values, indicating their suitability for irrigation for the most crops and soils, based on % Na, SSP, RSC, RSBC, PI, PS and MH and their irrigation water classification criteria (Table 6).

Table 5. Descriptive statistics of chemical composition indicators for 22 sampling points of the selected *aflaj* water of the study area sampled during summer and winter 2012-2013

Chemical Composition Indicators		Mean	Median	Std. Deviation	Minimum	Maximum
%Na	Summer	11.43	10.48	4.15	6.29	23.71
	Winter	19.82	18.58	6.56	9.36	30.48
RSC (meq/l)	Summer	-1.21	-0.98	0.59	-2.72	-0.63
	Winter	-0.68	-0.62	0.73	-2.83	0.75
SSP (%)	Summer	10.60	9.53	3.76	5.85	21.63
	Winter	10.60	9.53	3.76	5.85	21.63
RSBC (meq/l)	Summer	0.90	0.94	0.54	-0.12	1.80
	Winter	1.74	1.87	0.69	0.39	3.22
PI (%)	Summer	45.77	46.81	4.02	36.30	54.39
	Winter	54.02	53.29	5.38	46.54	64.54
PS (meq/l)	Summer	0.90	0.74	0.50	0.43	2.36
	Winter	1.13	0.81	0.84	0.47	3.50
KI (Ratio)	Summer	0.12	0.11	0.05	0.06	0.28
	Winter	0.22	0.20	0.09	0.10	0.39
MH (%)	Summer	42.21	41.21	7.49	28.22	59.19
	Winter	54.00	54.47	6.42	40.49	63.74

Table 6. Classification of irrigation water based on different hazards

Parameter	Range	Water class	*Aflaj* Samples
%Na	< 20	Excellent	F1, F2, F3, F4, F5, F6, F7, F8
(After Wilcox, 1955)	20-40	Good	F9
	40-60	Permissible	
	60-80	Doubtful	
	> 80	Unsuitable	
RSC (meq/l) (After Richard, 1954)	< 1.25	Good	F1, F2, F3, F4, F5, F6, F7, F8, F9
	1.25-2.50	Doubtful	
	> 2.5	Unsuitable	
SSP (%)	0-20	Excellent	F1, F2, F3, F4, F5, F6, F7, F8
(After Todd, 2005)	20-40	Good	F9
	40-60	Permissible	
	60-80	Doubtful	
	80-100	Unsuitable	
KI (Ratio) (After Kelley, 1944)	<1	Suitable	F1, F2, F3, F4, F5, F6, F7, F8, F9
	>1	Unsuitable	
MH (%)	<50	Suitable	F1, F2, F3, F4, F5, F6, F7
(After Szabolcs & Darab, 1964)	>50	Unsuitable	F8, F9
PI (%) (After Doneen, 1964)	50-75	Suitable	F1, F2, F3, F4, F5, F6, F7, F8, F9
	25	Unsuitable	

The assessment of irrigation water quality based on the combination of salinity hazard using Electrical Conductivity (EC) and alkalinity hazard using Sodium Adsorption Ratio (SAR) is another classification for the suitability of water for irrigation. As presented in section 4.1, all the *aflaj* water have mean EC values below 700 µS/cm indicating good water quality for irrigation (Tatawat & Chandel, 2008). SAR in *aflaj* water samples ranged from 0.61 to 4.70; and from 0.53 to 2.73 with average values of 1.21 and 1.35 during summer and winter, respectively. Using the combined results of EC measurements and the SAR values, the analytical data plot on the EC-SAR diagram illustrates that most of the summer and winter water samples from the *aflaj* (Figure 3) fall in the field of C2-S1 (good: medium salinity/low sodium hazards) suitability based on the EC and SAR classification of irrigation water (Appendix V). These categories of water quality can be used for irrigation of most crops and majority of soils (Richard, 1954; Simsek & Gunduz, 2007).

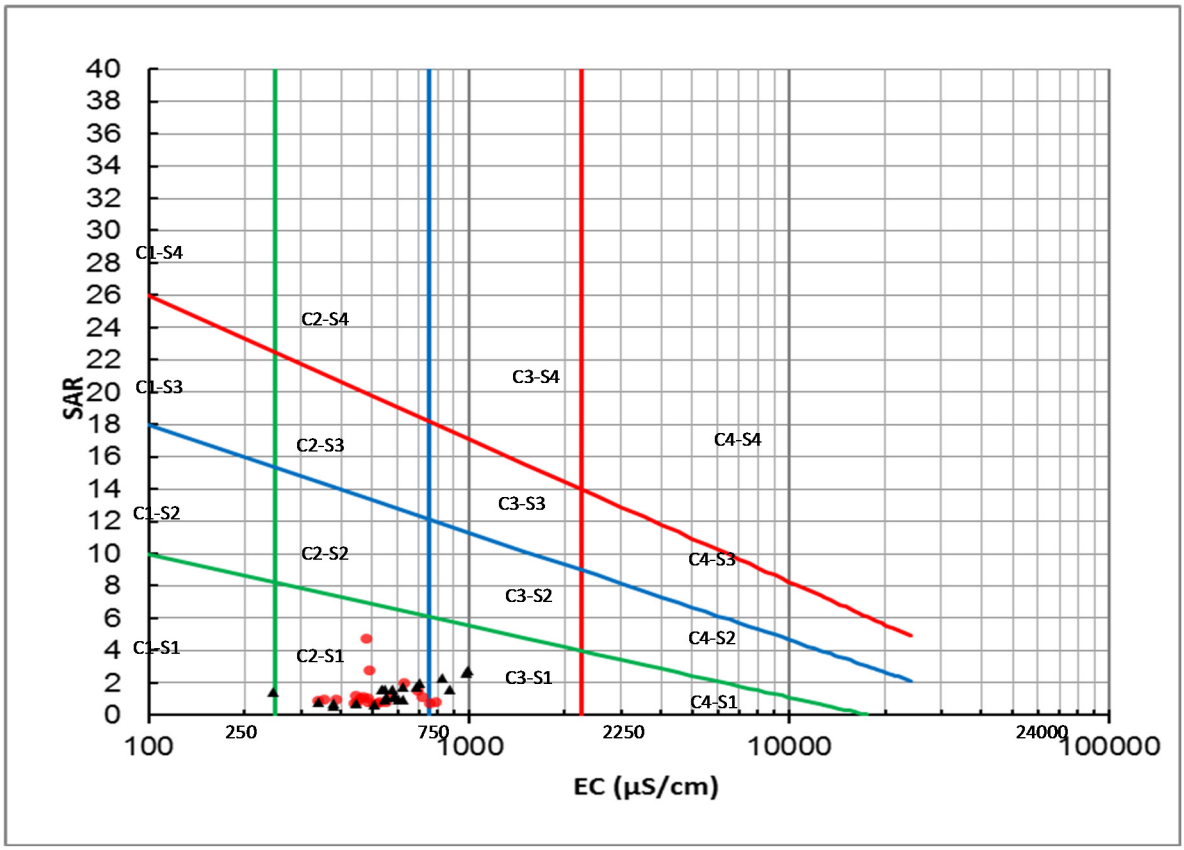

Figure 3. EC and SAR classification of *aflaj* water sampled during summer (in red circle) and winter (in black triangle) in 2012-2013

3.3 Correlation of Water Quality Parameters

Correlation analyses using Pearson's coefficient (r) among the levels of parameters in water samples indicates the existence of an association, and thus, a single parameter can act remarkably as a reliable indicator of the presence of a number of parameters (El Maghraby et al., 2013; Mohammed et al., 2014; Varol & Davraz, 2015). In the present study, statistical analysis has shown that some of the parameters correlate significantly with one another. The terms strongly, moderately and weakly correlations in this study refer to $r > 0.7$, $r = 0.5\text{-}0.7$, and $r < 0.5$, respectively.

The correlation matrix among water quality parameters of the selected *aflaj* sampling points (Table 7) showed the highest positive correlation between EC and TDS ($r = 0.978$), highly statistically significant at $p < 0.01$. Other positive strongly correlations, highly statistically significant at $p < 0.01$ include: between TDS with TH, Na^+, Mg^{2+}, Cl^-, NO_3^- and SO_4^{2-}; between EC with TH, Na^+, Mg^{2+}, K^+, Cl^-, HCO_3^-, NO_3^- and SO_4^{2-}; between HCO_3^- with TH and Ca^{2+}; between TH with Na^+, Mg^{2+} and Cl^-; between Na^+ with Mg^{2+}, Cl^-, NO_3^- and SO_4^{2-}; and between Mg^{2+} with Cl^-, NO_3^- and SO_4^{2-}. Moderately positive correlations ($p < 0.01$) were found between TDS with K^+ and HCO_3^-;

between pH with CO_3^{2-}; between HCO_3^- with Mg^{2+}; between TH with NO_3^- and SO_4^{2-} and between Na^+ with K^+. Other positively weakly correlated and statistically significant ($p < 0.01$) relationships were found between EC with Ca^{2+} and K^+; between HCO_3^- with Na^+, Cl^- and NO_3^-; between TR with Ca^{2+} and K^+; between Ca^{2+} with NO_3^-, and between Mg^{2+} with K^+.

Table 7. Correlation matrix among quality parameters for *aflaj* water of the study area sampled during summer and winter 2012-2013

	TR	TDS	EC	pH	HCO_3	CO_3	TH	Na	Ca	Mg	K	F	Cl	NO_3	SO_4
TR															
TDS	-.197														
EC	-.187	.978**													
pH	.222	-.351*	-.376*												
HCO_3	-.243	.632**	.727**	-.667**											
CO_3	.139	-.086	-.096	.681**	-.341*										
TH	-.263	.897**	.905**	-.536**	.826**	-.228									
Na	-.124	.861**	.827**	-.093	.398**	.123	.765**								
Ca	.057	.288	.436**	-.398**	.702**	-.247	.431**	.082							
Mg	-.290	.861**	.871**	-.177	.639**	.109	.853**	.813**	.272						
K	-.207	.578**	.493**	-.196	.251	-.063	.464**	.601**	-.307*	.440**					
F	-.133	.083	.092	.132	.175	.058	.167	.059	.179	.211	-.040				
Cl	-.057	.829**	.836**	-.008	.390**	.136	.705**	.909**	.296	.807**	.335*	.082			
NO_3	-.110	.725**	.764**	-.182	.432**	.038	.656**	.745**	.431**	.701**	.189	.037	.835**		
SO_4	-.031	.735**	.756**	.113	.305*	.201	.603**	.856**	.296	.744**	.316*	.107	.951**	.853**	

*significantly correlated at 0.05 level, **significantly correlated at 0.01 level.

These correlation relationships between parameters in *aflaj* water samples clearly identify the main elements that are normally found in the studied water resources. The strongest significant relationship ($r > 0.80$) between Mg^{2+} and Cl^-, and the moderately significant relationships between total hardness with Ca^{2+} ($r > 0.50$) and the strongest with Mg^{2+} ($r > 0.80$) in *aflaj* water samples, indicate that the hardness of the water was permanent in nature. The statistically significant and strong correlation ($r > 0.90$) between Cl^- and Na^+ confirms their common origin: the dissolution of the halite resulting from the action of water on salts. The concentrations of SO_4^{2-} are tightly correlated to the presence of Na^+ and Mg^{2+}, which is explained by the dissolution of evaporate minerals.

3.4 Irrigation Water Quality Index

Based on the assessment criteria of EC, infiltration hazard, sodium as SAR, chloride, boron, pH, the concentrations of bicarbonate, nitrate-nitrogen and trace elements, values of the WQI of the *aflaj* water samples in the study area were not significantly different between summer and winter ($F = 1.181$, $P = 0.283 > 0.05$). The WQI of the selected *aflaj* ranged from 35.20 to 40.31 (mean 39.57, median 39.86, standard deviation 1.05) during summer, and from 38.53 to 40.67 (mean 39.84, median 39.92, standard deviation 0.53) during winter.

These results show that the water of the selected *aflaj* was of high or medium suitability for irrigation, falling within the 3 or 2 rating categories of irrigation water classification criteria. In the selected 22 *aflaj* water sampling points during summer, 21 were classified as high in quality and only one as medium. The selected *aflaj* channel points sampled during the winter were all classified as highly suitable for irrigation based on WQI classification criteria (Figure 4).

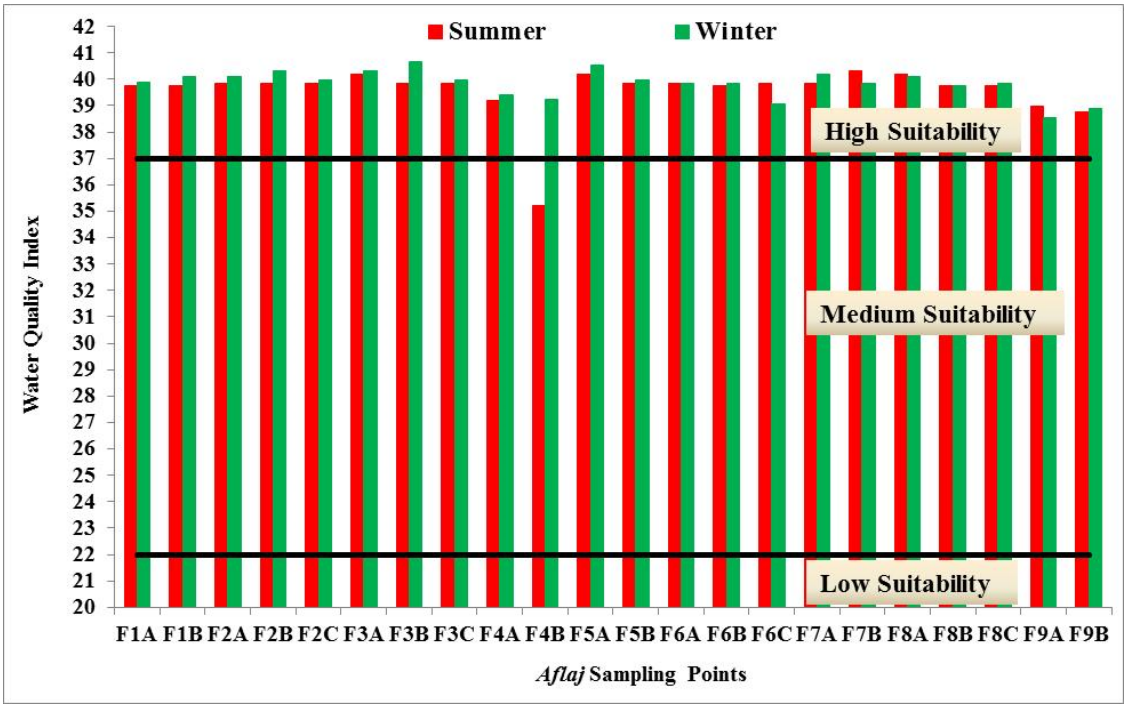

Figure 4. WQI of the selected *aflaj* water sampling points during summer and winter 2012-2013

4. Conclusions and Recommendations

Water quality assessment of the selected *aflaj* in Al Jabal Al Akhdar area indicated that quality parameters are within the permissible limits set by Omani regulations of wastewater reuse for irrigation. However, most of the *aflaj* are contaminated with *E. coli* bacteria; indicating unacceptable for drinking as per the guidelines of Omani and WHO standards. Overall, the selected *aflaj* are excellent or good in quality for irrigation purposes based on the evaluation of different hazards parameters including percent sodium, residual sodium carbonate, soluble sodium percentage, residual sodium bicarbonate, permeability index, Kelley's index, and magnesium hazard; indicating their suitability for irrigation for the majority of crops and soils. The salinity-alkalinity hazards assessment showed that the *aflaj* water are C2-S1 (Good) based on EC and SAR classification; such slightly high salinity and low sodium water can be used for irrigation on almost all types of soil with little danger of exchangeable sodium. All computed water quality indices showed that most of the *aflaj* have high suitability for irrigation and only one has moderate suitability, and no serious problems with respect to irrigation quality. To keep all *aflaj* of the study area under good water quality for domestic and irrigation purposes, the study recommends further corrective demand management measures, such as water conservation, reuse of treated wastewater effluents, reusing greywater, redesigning septic tanks and protecting *aflaj* mother well and their channels. Water quality monitoring programmes should be also carried out on a regular basis to ensure the suitability of water for domestic and agricultural uses.

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Appendices

Appendix I: Classification for irrigation WQI parameters (Simsek & Gunduz, 2007)

Hazard	Weight	Indicator	Rating		
			3	2	1
Salinity hazard	5	Electrical conductivity (μS/cm)	EC < 700	700≤EC≤3,000	EC > 3,000
Infiltration and permeability hazard	4	See Table 5			
Specific ion toxicity	3	Sodium adsorption ratio	SAR < 3.0	3.0≤SAR≤9.0	SAR > 9.0
		Boron (mg/l)	B < 0.7	0.7≤B≤3.0	B > 3.0
		Chloride (mg/l)	Cl < 140	140≤Cl≤350	Cl > 350
Trace element toxicity	2	See Table 6			
Miscellaneous effects to sensitive crops	1	Nitrate Nitrogen (mg/l)	NO_3-N < 5.0	5.0≤ NO_3-N≤30.0	NO_3-N > 30.0
		Bicarbonate (mg/l)	HCO_3< 90	90≤HCO_3≤500	HCO_3> 500
		pH	7.0≤pH≤8.0	6.5≤pH<7.0 and 8.0<pH≤8.5	pH <6.5 or pH > 8.5

Appendix II: Classification for infiltration and permeability hazard (Simsek & Gunduz, 2007)

	Sodium Adsorption Ratio (SAR)					Rating
	< 3	3-6	6-12	12-20	> 20	
Electrical	> 700	>1,200	>1,900	>2,900	>5,000	3
Conductivity	700-200	1,200-300	1,900-500	2,900-1,300	5,000-2,900	2
(µS/cm)	<200	<300	<500	<1,300	<2,900	1

Appendix III: Classification for trace element toxicity (Simsek & Gunduz, 2007)

Parameter (mg/l)	**Rating**		
	3	**2**	**1**
Aluminum (Al)	Al < 5.0	5.0 ≤ Al ≤ 20.0	Al > 20.0
Arsenic (As)	As < 0.1	0.1 ≤ As ≤ 2.0	As > 2.0
Beryllium (Be)	Be < 0.1	0.1 ≤ Be ≤ 0.5	Be > 0.5
Cadmium (Cd)	Cd < 0.01	0.01 ≤ Cd ≤ 0.05	Cd > 0.05
Chromium (Cr)	Cr < 0.1	0.1 ≤ Cr≤ 1.0	Cr > 1.0
Cobalt (Co)	Co < 0.05	0.05 ≤ Co ≤ 5.0	Co > 5.0
Copper (Cu)	Cu < 0.2	0.2 ≤ Cu ≤ 5.0	Cu > 5.0
Fluoride (F)	F < 1.0	1.0 ≤ F ≤ 15.0	F > 15.0
Iron (Fe)	Fe < 5.0	5.0 ≤ Fe ≤ 20.0	Fe > 20.0
Lead (Pb)	Pb < 5.0	5.0 ≤ Pb ≤ 10.0	Pb > 10.0
Lithium (Li)	Li < 2.5	2.5 ≤ Li ≤ 5.0	Li > 5.0
Manganese (Mn)	Mn < 0.2	0.2 ≤ Mn ≤ 10.0	Mn > 10.0
Molybdenum (Mo)	Mo < 0.01	0.01 ≤ Mo ≤ 0.05	Mo > 0.05
Nickel (Ni)	Ni < 0.2	0.2 ≤ Ni ≤ 2.0	Ni > 2.0
Selenium (Se)	Se < 0.01	0.01 ≤ Se ≤ 0.02	Se > 0.02
Vanadium (V)	V < 0.1	0.1 ≤ V ≤ 1.0	V > 1.0
Zinc (Zn)	Zn < 2.0	2.0 ≤ Zn ≤ 10.0	Zn > 10.0

Appendix IV: Summary of the five hazard categories, weighing coefficient and formula used for the calculation of each parameter group and irrigation WQI (Simsek & Gunduz, 2007)

Category	**weighing coefficient (w)**	**Formula used**	**Description**
Salinity (EC)	5	$G_1 = w_1 r_1$	w: weight value of this hazard r: rating value (Appendix I)
Infiltration & permeability hazard (EC-SAR)	4	$G_2 = w_2 r_2$	w: weight value of this hazard r: rating value (Appendix II)
Specific ion toxicity (SAR, Cl, B)	3	$G_3 = w_3/3 \sum (r_j)$	J: incremental index w: weight value (Appendix I) r: rating value of each parameter
Trace element toxicity (elements in Appendix III)	2	$G_4 = w_4/N \sum (r_k)$	k: incremental index N: total number of trace elements w: weight value of this group r: rating value of each parameter (Appendix III)
Miscellaneous effects to sensitive crops (NO_3-N, HCO_3, pH)	1	$G_5 = w_5/3 \sum (r_m)$	m: incremental index w: weight value of this group r: rating value of each parameter (Appendix I)
Irrigation Water Quality Index		$WQI = \sum (G_i)$	i: incremental index G: hazard category

Appendix V: Classification of irrigation water based on EC and SAR parameters (After Richard, 1954)

Water Class	Suitability	Water Class	Suitability
C1 – S1	Excellent	C3 – S1	Admissible
C1 – S2	Good	C3 – S2	Marginal
C1 – S3	Admissible	C3 – S3	Marginal
C1 – S4	Poor	C3 – S4	Poor
C2 – S1	Good	C4 – S1	Poor
C2 – S2	Good	C4 – S2	Poor
C2 – S3	Marginal	C4 – S3	Very Poor
C2 – S4	Poor	C4 – S4	Very Poor