Water quality for irrigation and drinking water use of Aflaj in Oman
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ABSTRACT

The Sultanate of Oman is an arid country with scarce water resources mainly consisting of groundwater. Aflaj are artificial canals constructed centuries ago to transfer horizontally the groundwater to a location at the surface. The water quality of these Aflaj is a very important factor to be considered for healthy and safe use of this water. This paper aimed to study the characteristics of the groundwater through its journey in Aflaj from source point up to its usage point. An experimental programme was adopted to investigate the water quality of Al Hammam Aflaj in Muscat, Sultanate of Oman. The results showed that some positions of the Falaj have high content of some elements, such as Ca, above the allowable values of drinking water standards. Results proved that the water of Al Hammam Falaj in general can be used with caution as a drinking water; however, some care and monitoring should be applied regularly. Results of sodium adsorption ratio (SAR) and soluble sodium percentage (SSP) equations revealed that the water Falaj can be used for irrigation for all soil types but cannot be used on soils with restricted drainage due to its relatively high salinity.

Key words | Aflaj, groundwater, water quality

INTRODUCTION

Groundwater is the primary source of water in arid regions. Many countries are using groundwater after guaranteeing its quality to provide health and safety drinking water. Oman can be considered as one of these arid regions depending mainly on groundwater as a water resource. Utilising groundwater often needs effort and requires special procedures consisting either of pumping or – as an alternative – of complex tunnel and canal systems conveying groundwater via gravity flow to the surface for anthropogenic use. Aflaj are structures including tunnels and channels built centuries ago in Oman. These structures are used to get water from the aquifers without pumping and by the gravitational force only to the surface where people can use it. Aflaj system in comparison to pumping can be considered an eco-friendly system as it saves cost, energy and CO₂ emissions. Al-Ismaily & Probert (1998) defined Aflaj as ‘the plural of Falaj’ which means a surface and/or underground channel, fed by wells or springs, built to provide a community’s water supply. The term Falaj is derived from an ancient Arabic word that means to divide (Al-Mamary 2010). Al-Marshudy (2007) mentioned that the Falaj is an irrigation system concerned not only with the transfer of water from its underground source by gravity, but also with how the water is distributed among shareholders in a fair and equitable manner. The groundwater from Aflaj was used for municipal, agriculture and drinking. Aflaj systems have provided Omani communities with domestic and agricultural water for more than 1,500–2,000 years (Al-Marshudy 2007). The Aflaj are not unique to Oman, they have also been constructed throughout the Arabian Peninsula, as well as in Iran, China, Japan, Egypt, Morocco, Spain, Mexico and even Peru (Al-Ismaily & Probert 1998).

Creating Aflaj structures was a successful and helpful idea for Omani people and increased the availability of water resources for use in Oman. There are three types of Aflaj, namely, Ghaily, Daudi and Ayni. Ghaily Falaj is usually seasonal, due to its dependence on shallow subterranean sources that disappear during dry seasons. The second type of Aflaj
is the Daudi, which employs the perennial flow of water, through the surface gravel of a wadi, i.e. valley, being diverted into a purpose-built channel. The third type is Ayni Falaj, which is fed directly from single source such as a natural spring. In reality, the third type of Aflaj is usually accompanied by high water temperatures due to groundwater flow through deeper layers. Daudi and Ayni Aflaj are characterised by sustainable water flow and Ghaily Aflaj occur only when there is rain which infiltrates, saturates the soil, and as a consequence, the Aflaj will start flowing (Al-Marshudy 1995).

The Aflaj supply water to communities, not to individual houses, and therefore complicated management systems for sharing the responsibility of water distribution and of Aflaj maintenance have developed. In 1980s, an estimation of 4,000 Aflaj systems was made and these systems delivered approximately 70% of the irrigation water in Oman but almost a quarter of them are dry and out of service nowadays (FAOUN 2009; Ghrefat et al. 2011). The cleanest water is reserved for drinking, and its communal collection point is termed a share’s, which is usually a mosque downstream where ablutions and washing occur; subsequently, the Falaj passes through the residential areas before being used for irrigation (Al-Ismaily & Probert 1998).

The aim of this paper was to investigate the water quality of Aflaj systems in Oman for drinking and irrigation purpose and to study the effect of the surrounding environment and people’s habits with water use on the quality of these Aflaj. The study was applied to one of the oldest Aflaj in Muscat governorate, Omani capital, called Al Hammam Falaj. Water samples were collected along the Falaj and laboratory tests were applied for some physiochemical parameters, namely temperature, total solids (TS), total suspended solids (TSS), total dissolved solids (TDS), pH, electrical conductivity (EC), total hardness (TH), dissolved oxygen (DO) and biochemical oxygen demand (BOD). In addition, selected cations and anions were measured. The above selected parameters and elements have a high impact on the quality of water for irrigation and drinking. For instance, selected cations are needed for calculating important coefficients for determining the suitability of water for irrigation such as soluble sodium percentage (SSP). In addition, all these above parameters have standard values for the suitability for drinking and it is necessary to compare their standards with the measured values.

**METHODS**

**The study area**

Al Hammam Falaj lies on coordinates of 23°28’13″N and 58°19’25″E. It is an Ayni type Falaj in Wilayah Bowsher, Muscat, Oman. The map of the study area is shown in Figure 1 (MRMEWR 2014). The study area has a tropical arid climate, with high rates of evapotranspiration ranging from 1,778 to 2,393 mm/year (Siebert et al. 2007). Monthly temperature average of daily maxima in summer is between 46 and 52 °C, while winter temperatures range between 15 and 23 °C. The general mean annual precipitation of Oman is about 90 mm with extremes of 500 mm in the northern mountains at the coastal area and 55 mm in the central part of Oman (Shahalam 2000). The study area is in the north with rather high rainfall. Two geomorphological zones can be recognised in the study area and the surroundings in general: mountains/piedmont upper catchment dominated by Hajar super group sedimentary rocks, and stony alluvial fans and a plain that extends through the central and lower reaches of the catchment to the coast. Groundwater occurs in an alluvium aquifer which consists of weathered limestone, mud sediments and Ophiolite gravels (Achworth 2006). Rainfall, the input to the area, tends to be higher on the hard rock mountain areas where some of the rainfall will form surface runoff. Primary runoff recharge average in this area is 7.1 Mm³/year while runoff losses average is 3.5 Mm³/year. The remainder of the rainfall will infiltrate the mountain limestone aquifer to increase its storage and hence maintain the outflow from this storage through springs. Three spring types occur: a high level spring line along the base of the limestone sequence, a piedmont-spring line along the perimeter of the Hajar limestone massif and a genetically different spring line at the northern edge of Jabal Bawshar. All three give rise to distinctive water chemistry with low EC and high calcium content. The springs are restricted to the north-facing scarp due to topographic influences and typical discharges are 5–20 l/s. Around Al Hammam Falaj, the houses of today’s 200 inhabitants, which are located on a rocky outcrop, are surrounded by 185 agricultural fields covering 1.6 ha and by 3.8 ha of palm groves.
**Experimental programme**

Eighteen water samples were collected in November 2013 as three samples for each position from six positions along the Al Hammam Falaj. One of these positions at the beginning point of the Falaj (spring source), S1, and one at the end-point of the Falaj, S6, and the other four positions in between with distance varied from 40 to 60 m, namely S2, S3, S4 and S5 as shown in Figure 1. The sampling locations were chosen to cover the inlet point of the Falaj water source and the end-point of the Falaj and other four locations in between them. This is to track the deterioration of water quality along the Falaj journey and to investigate the impacts of the surrounding environment. November was chosen because it is the lowest recharging time for the Falaj. Thus, this time will be the worst-case scenario for monitoring the water quality of the Falaj due to the shortage in water feeding, which dilutes the dissolved and suspended materials in the water of the Falaj. Temperature, EC and pH values were measured directly *in situ* using portable devices. For the other chemical parameters, the water samples were collected in 500 ml plastic bottles. These parameters include TDS, TS, TH, DO, BOD, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), bicarbonate (HCO₃), sulphate (SO₄), nitrate (NO₃), chloride.
(Cl), manganese (Mn) and iron (Fe). Samples were tested according to British Standards. In addition, long-term monitoring data for some properties of the Al Hammam Falaj were obtained from the Ministry of Regional Municipalities since 1995 (MRMEWR 2014). These data are for water temperature, EC and water discharge measurements. The above selected data are important for tracking Falaj water suitability for long-term use via knowing the variation of the water temperature and water quantity as well as the salinity of water.

RESULTS AND DISCUSSION

The spatial distributions and the temporal variations of the water discharge and EC as well as the other physicochemical analyses for Al Hammam Falaj will be presented in the following sections. Results of the collected samples are the average of three tested samples.

Long-term monitoring of water discharge, salinity and temperature

Long-term data in terms of annual averages on water discharge, salinity and temperature at the beginning point of the Al Hammam Falaj are presented in Figure 2. Results showed that the discharge rates of the Falaj decreased dramatically with time from 14.1 l/s in 1996 and reduced to 9.0 l/s in 2013. This is perhaps resulting from an increase in well pumping which dramatically caused a severe drop in water level of the groundwater which is noted recently in this area by the authorities (MRMEWR 2014). This excessive consumption led to reduce the farmed land around the Falaj area. EC measurements revealed that it was approximately consistent in their values since 1995 of around 1,300 μS/cm. This consistency is possibly due to the concord between charging the aquifer in this area and people consuming of the water. Only in 2008 and 2009, there was a significant reduction in the EC values which refers to the reduction in consuming water during this period. Figure 2 also shows that the average temperature reduced significantly with time from around 65 °C in 1995 to 48 °C in 2013.

Water characteristics

Figure 3 presents some physical characteristics of water in the Al Hammam Falaj at six locations. These characteristics include TDS, TS, TH in mg/l and temperature of the Falaj water. Temperature decreased with increasing distance from the spring source. It was 41 close to the spring and 38 at the end of the Falaj. The TDS values are in the range from 49 to 60 mg/l. TS ranged between 49 and 60 mg/l while TH is between 5.8 and 12.2 mg/l. The position S2, which is 60 m far away from the source point, showed highest values in the previous measurements. This is probably because this position is the first point after the source point and as mentioned earlier this area is dominated by Hajar super group sedimentary rocks, and stony alluvial fans which consists of weathered limestone, mud sediments and Ophiolite gravels. These materials particularly with the...
high water temperature released some dissolved and suspended particles into the water. Then with the journey of the water through Falaj these particles settled down and water temperature decrease and consequently the readings of the above-mentioned properties decreased in the succeeding tested positions.

Chemical characteristics, namely EC, pH, DO and BOD of the Al Hammam Falaj water in the six positions were presented in Figure 4. pH is a measure of the acidity or alkalinity of the water. The values of this parameter are in the range from 7.8 to 8.6. pH values are in all the studied positions greater than seven indicating the Falaj water is alkaline. Higher pH may be caused by increased bicarbonate (HCO₃⁻) which is a product of carbonate rich rock types such as those found in the study area. The pH values were found to be in the permissible range from 6.5 to 8.5 for drinking (WHO 2011). Only the location S2 with a value of 8.6 is slightly higher than the allowable values. Results showed also that EC values ranged between 1,550 and 1,700 μS/cm. These EC readings showed higher values than those presented in Figure 2 and reported by

Figure 3 | Physical characteristics of water in the Al Hammam Falaj in six positions.

Figure 4 | Chemical characteristics of water in the Al Hammam Falaj in six positions.
This is perhaps because values in Figure 2 are the average of monthly readings and it is known that the EC values change significantly with temperature alterations while values in Figure 4 were measured once in November. The different temperatures in different seasons during groundwater flow eventually influence the solubility situation during matter flow in contact with geological layers and thus affect EC values. In addition, as mentioned earlier, the recharge of water is at its lowest rate in November which means that concentrations of dissolved materials in the water will be very high at this time of year. Some researchers observed a good correlation between electric conductivity and alkalinity in dry and wet periods as water conductivity decrease in rainy seasons and increases in dry seasons (Lopes et al. 2012). Readings of DO decreased from 8.7 to 5.7 mg/l while BOD increased from 0.4 to 6.2 mg/l. This indicates a deterioration of the water quality with increasing distance from the source point. This is because the organic matter content increases due to the contact of water with surrounding environment after the source point and people’s habits of washing animals in Falaj water.

Figure 5 presents the cations, namely, Ca, Mg, Na and K found in the water of the Al Hammam Falaj in six positions. Results showed that Ca ranged from 98 to 128 mg/l while Mg ranged from 30 to 42 mg/l. K concentrations were found between 5.9 and 6.4 mg/l. Na readings were between 115 and 130 mg/l. All measurements in general showed a consistency in element concentrations along the Falaj as there is no significant difference between the first and last position. There is one exception at the location S2 which indicates a sudden change in the measurement especially for K and Na. This is perhaps because it is the first position with contact with the surrounding environment after source point. For anions of the Al Hammam Falaj water, concentrations of SO₄ increased from 215 to 237 mg/l while HCO₃ were between 215 and 220 mg/l for all positions except at S2 where there is an obvious increase in its concentrations. For Cl and NO₃, readings almost were consistent at all positions. Some heavy metals such as Fe and Mn also showed low levels and consistency in all positions as shown in Figure 6.

**Water quality of Al Hammam Falaj for human drinking**

Table 1 presents a comparison of average measurement parameters of Al Hammam Falaj water against allowable values of the World Health Organization for drinking water (WHO 2011). The comparison showed that temperature of water was not suitable for drinking directly without cooling it. High temperature of the water above 25 °C leads to bacterial activation, which affects the water quality for drinking. pH 8.2 indicated that the water was alkaline and it was close to the maximum margin of the allowable values, i.e. 8.5; however, it is still within the permissible range. EC values and Ca concentrations are slightly higher than the standard values. Perhaps increasing Ca resulted from the soil type
in this area, e.g. limestone which is rich in this element and this increase consequently increased the EC and salinity of the water. The other parameters were within the WHO standard values. The position S2 particularly showed some measurements higher than the allowable values, which make this position not suitable for collecting water for drinking. To sum up, the water of Al Hammam Falaj can be used with restriction for drinking provided that appropriate care and monitoring is applied regularly to check its water quality and suitability for human drinking. A hygienic evaluation such as \textit{Escherichia coli} count is also needed.

### Water quality of Al Hammam Falaj for irrigation

The quality of irrigation water can be evaluated using several parameters such as the total amount of dissolved salts in the water and the ratio of soluble sodium to calcium and magnesium ions. This relation is called the SAR and it is calculated as follows (Ayers & Westcot 1976):

\[
SAR = \sqrt{\frac{Na}{Ca + Mg}}
\]  

where the concentrations are reported in meq/l.

The SAR is commonly used as an index for evaluating the sodium hazard associated with an irrigation water supply. Irrigation waters having high SAR levels can lead to the build-up of high soil Na levels over time, which in turn can adversely affect soil infiltration and percolation rates due to soil dispersion. In addition, high SAR levels can lead to soil crusting, poor seedling emergence, and poor aeration (Lesch & Suarez 2009). There is another index called adjusted SAR which depends on adjusted Ca concentrations. Herein, SAR index was adopted, the SAR values ranged from 1.2 to 1.7 for all tested positions. According to SAR and EC values

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**Figure 6** | Anions and heavy metals in the water of the Al Hammam Falaj in six positions.

**Table 1** | Comparison of average measurements of Al Hammam Falaj water against World Health Organization standards (WHO 2011)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Temp (°C)</th>
<th>TH (mg/l)</th>
<th>EC (μS/cm)</th>
<th>pH</th>
<th>TDS (mg/l)</th>
<th>DO (mg/l)</th>
<th>Ca (mg/l)</th>
<th>Mg (mg/l)</th>
<th>Na (mg/l)</th>
<th>K (mg/l)</th>
<th>HCO$_3$ (mg/l)</th>
<th>SO$_4$ (mg/l)</th>
<th>NO$_3$ (mg/l)</th>
<th>Cl (mg/l)</th>
<th>Mn (mg/l)</th>
<th>Fe (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average reading</td>
<td>39.22</td>
<td>8.21</td>
<td>1,616.7</td>
<td>8.23</td>
<td>54.24</td>
<td>7.22</td>
<td>112.81</td>
<td>35.71</td>
<td>121.86</td>
<td>6.22</td>
<td>219.34</td>
<td>224.01</td>
<td>0.73</td>
<td>191.51</td>
<td>0.10</td>
<td>0.11</td>
</tr>
<tr>
<td>WHO</td>
<td>10–22</td>
<td>500</td>
<td>1,500</td>
<td>6.52–8.54</td>
<td>1,000</td>
<td>≥5</td>
<td>100</td>
<td>50</td>
<td>200</td>
<td>12</td>
<td>330</td>
<td>250</td>
<td>50</td>
<td>250</td>
<td>0.10</td>
<td>0.30</td>
</tr>
</tbody>
</table>
and following the United States Department of Agriculture (USDA) classification system for salinity (C1–C4) and sodicity hazards (S1–S4), all samples fall within the range of C3S1 classification, indicating high salinity and low sodium water, which can be used for irrigation on almost all types of soils with little danger of exchangeable sodium.

The sodium hazard can also be evaluated by using the SSP (Ayers & Westcot 1976)

\[
SSP = \left( \frac{(Na) \times 100}{Ca + Mg + Na + K} \right) \times 100
\]

Water with SSP greater than 60% may result in sodium accumulations that will cause a breakdown of the soil’s physical properties (Ayers & Westcot 1976). The measured values of SSP vary from 40 to 47.4% for all samples, i.e. they are all less than 60%. The results of Equations (1) and (2) revealed that the water Falaj is suitable for irrigation of all soil types but cannot be used on soils with restricted drainage due to its relatively high salinity.

**CONCLUSION**

Physical properties such as TDS of tested positions of Falaj water showed high levels in some positions due to contact with the earth canal and sedimentary rocks in the Falaj. Measurements of DO and BOD indicated a deterioration of the water quality with increasing distance from the source point due to the increase in the organic matter content. This increase is because of the contact of water with surrounding environment and people’s habits of washing animals in Falaj water. Falaj water temperature is not suitable for drinking directly without cooling. EC values and Ca concentrations are slightly higher than the standard values. The other tested parameters were within the WHO standards values. The water of Al Hammam Falaj in general can be used with caution for drinking providing that appropriate care and monitoring is applied regularly to check its quality and suitability for human drinking. A hygienic evaluation such as E. coli measurement is also needed. Results of SAR and SSP equations revealed that the Falaj water can be used for irrigation for all soil types; however, it cannot be used for soils with restricted drainage due to its relatively high salinity.

**REFERENCES**


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