Sustainable *aflaj* water management in Al Jabal Al Akhdar, Sultanate of Oman

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Abstract

The *aflaj* system is a unique water resource for Omani society, culture and heritage and it is the most important for agriculture communities in Al Jabal Al Akhdar. In this paper, the Driving forces-Pressure-State-Impact-Responses (DPSIR) framework was applied as an assessment approach aiming to propose policies for sustainable *aflaj* water management in Al Jabal Al Akhdar, which has experienced rapid development over the last decades. The framework revealed that the main Driving forces are agriculture, tourism, socioeconomic development and urbanization, leading to Pressures including excessive use and mismanagement of *aflaj* for irrigation, compounded by climate change, with increasing temperatures and a decrease in rainfall. As a result, the State of the flows of the *aflaj* and their numbers has decreased, and their water quality has deteriorated and is no longer used for drinking. Consequently, this Impacts on human welfare due to the reduction in the cultivated area, and therefore losses in agricultural economic returns. Existing Responses included issuing laws and regulations, institutional development, and projects such as *aflaj* maintenance and dams construction. The DPSIR analysis concluded that the implementation of integrated *aflaj* water management through conservation practices and increased water use efficiency, in conjunction with climate change mitigation and adaptation, are a must when formulating and implementing policies to ensure the sustainability of the area's *aflaj* system and agricultural communities.
Keywords: DPSIR framework, aflaj, groundwater, agriculture communities, climate change, sustainable management, Al Jabal Al Akhdar, Oman.

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1 Introduction

Aflaj (singular falaj) are important sources of water for agricultural development in Oman. They are surface and/or underground channels fed by groundwater, a spring, or streams, built to provide water to communities for domestic and/or agricultural use. *Aflaj* have been constructed in Oman for thousands of years to tap concentrated lines of groundwater flow or surface flow and convey the water along a channel (often several kilometers long) at a lesser gradient than the water table [1]. The main channels are split into many smaller channels, which in turn divide to supply individual farms. At the time of the last National *Aflaj* Inventory (March 1997–June 1998), there were 4,112 *aflaj*, of which 3,017 were operational (live), involving a volume of 460 million m^3 per year; 99.8% goes to agricultural use [2]. Given the importance of *aflaj* as a unique Omani water resource, UNESCO has listed some *aflaj* in the World Heritage list [3].

Aflaj are managed by local people with their own designated administrative structure who are responsible for the overall organization of *falaj* affairs and the distribution of water for irrigation; there is no government involvement in this organizational structure [4]. The distribution of water by *aflaj* and the associated water markets are complicated but efficient, ensuring a fair and adequate water supply for all farmland [4, 5]. The system is mainly based on a time-share among water rights holders, but in some areas volume is used instead, especially during drought periods [5].

Most *aflaj* are located in the northern mountains of the Sultanate of Oman (Figure 1); mountains cover 15% of the country's total area. Al Jabal Al Akhdar (Green Mountain) is the largest structural domain in the northern Oman Mountains. It reaches heights between 1500 to 3000 m above sea level. Al Jabal Al Akhdar has a Mediterranean climate: temperatures are some 10 to 12°C lower than in the coastal plains; they drop during winter to below 0°C, and rise in summer to around 22°C [6]. Rainfall is highly variable and irregular and is the main source of fresh water; mean annual rainfall is about 250–400 mm [6]. According to the National *Aflaj* Inventory, there were 72 *aflaj* in Al Jabal Al Akhdar [2].

Al Jabal Al Akhdar has experienced rapid socioeconomic development and urbanization in recent decades [7]. These changes have influenced the water resources, especially the *aflaj* which are the lifeline of its agro-ecosystem and therefore human well-being. Many studies have been conducted on *aflaj* in Oman [e.g. 4, 5, 8]. However, there is very little information describing the effects of anthropogenic activities and climate change on *aflaj* water quantity and quality, especially in the mountains. In this paper, the DPSIR (Drivers-Pressures-State-Impacts-Responses) framework is applied as an assessment tool to assess the human activities and climatic factors on *aflaj* water, aiming at proposing policies towards sustainable management of the *aflaj* system of Al Jabal Al Akhdar.

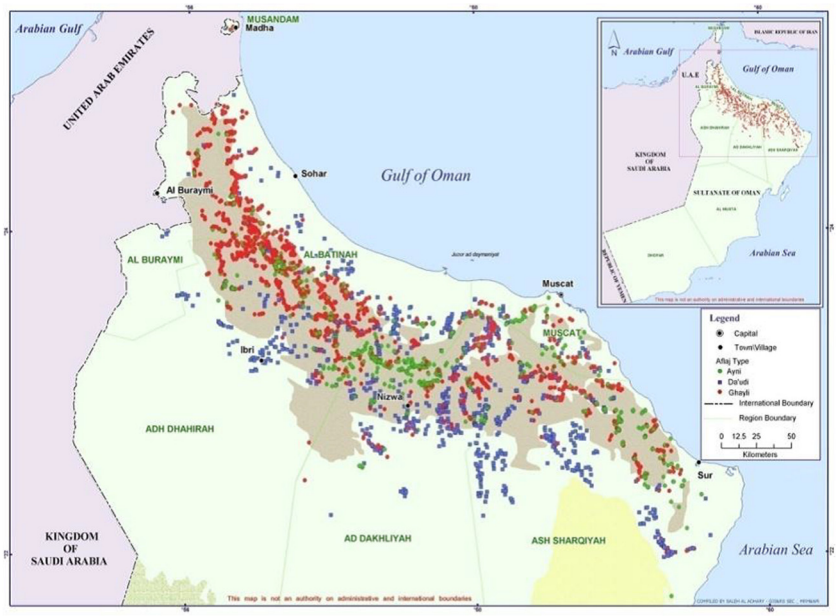

Figure 1: Distribution of *aflaj* in northern Oman Mountains (source: [2]).

2 Methodology

2.1 DPSIR analytical framework

DPSIR is a framework for describing the interactions between society and the environment, and thus it integrates the relationships between human activities and ecosystem well-being, for the purpose of structuring policy options [9, 10]. Five elements can be identified by which the framework aims to assess the Driving forces and Pressures, the State of the environment, the Impacts of these forces, and the Responses that are made. These elements are defined by several researchers [10, 11], most recently by Cooper [12] (Figure 2).

The DPSIR framework has been applied worldwide, ranging from global [13] to regional scales [14], and to a wide variety of topics including water resources [9, 15]. However, no available studies have been conducted using the framework for water assessment in arid mountain areas. The current study is the first to apply the framework to the *aflaj* system in the arid mountains of Oman.

2.2 Data collection and assessment process

The current State and changes in *aflaj* water quality were assessed; two or three sampling points were identified along the channel of each of the principal nine *aflaj*, i.e. those that are most reliable, in the area. The sampling regime was over six months during the winter and summer of 2012–2013. Sample collection,

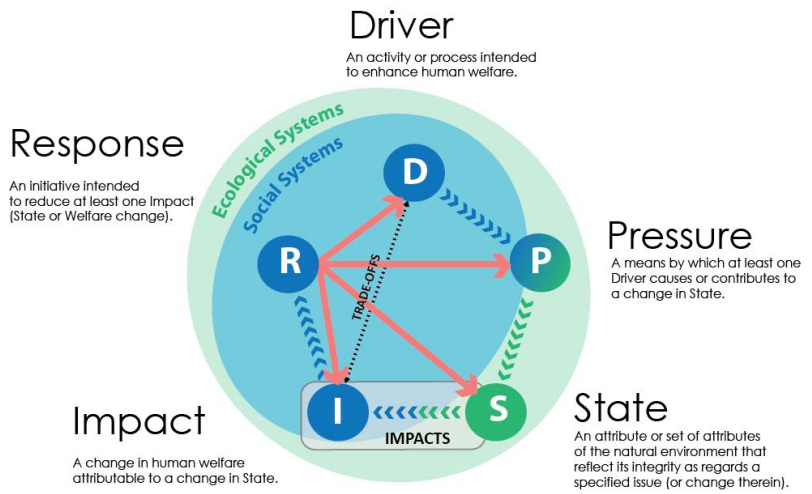

Figure 2: Definition and outline of the DPSIR framework information categories (source: [12]).

handling, processing and analysis followed standard methods [16]. The water samples were analyzed for a set of physiochemical and microbiological indicators in quality assured laboratories in Oman.

The changes in the State of *aflaj* water quantity were also assessed: farmers and local experts were asked about the current active or inactive number of *aflaj*, for comparison with the situation when the National *Aflaj* Inventory was conducted [2]. Water flow rate monitoring data in five main *aflaj* in the area were also compiled for the period 1992–2012. The effect of climatic changes on *aflaj* water was assessed by analyzing rainfall and temperature records for 1979 to 2012 for the local meteorology station. The levels of groundwater for well monitoring stations were also assessed.

The Impacts of the changes in the State of *aflaj* water on the mountain agro-system and on human welfare were analysed. In order to assess how society and government were responding to these problems, existing Responses were evaluated. Finally, policy options and actions were suggested for future sustainable management of the *aflaj* system.

3 Results and discussion

3.1 Driving forces

Driving forces affecting the changes in the State of the *aflaj* water are underlying Drivers (increase in population and socioeconomic development), and immediate Drivers (households, agriculture and tourism). There are high demands on *aflaj* water for agriculture, associated with the over-abstraction of groundwater for urban expansion. From 1970 to 2010, the population of the study area increased by 288%, from 1870 to 7028 [17]. There has also been a rapid increase in

construction and commercial activities; the number of housing units increased from 838 in 1993 to 1745 in 2010 [17]. Untreated wastewater discharge is considered one of the major challenges in the area; most of the housing units are not connected to sewer networks [18].

Agriculture is the main traditional economic sector in the area, where temperate crops (Figure 3(a)), especially pomegranate and roses, are grown. Livestock husbandry – mainly goats – is also an important part of the mountain agro-ecosystem (Figure 3(b)). It should be noted that, though agriculture consumes more than 92% of the nation's fresh water; 33% of this via *aflaj* [2], it contributes little to the overall Omani economy (about 3.7% of GDP).

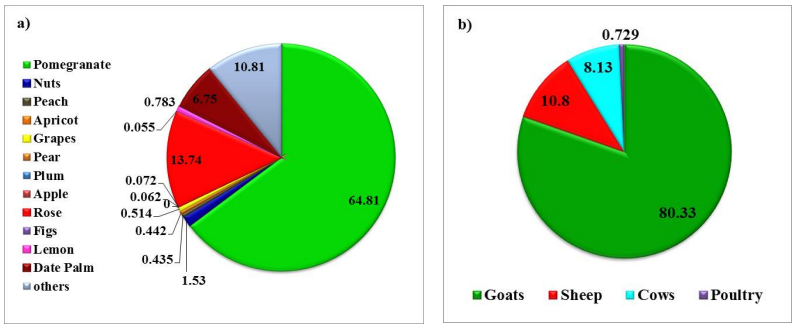

Figure 3: Trees and livestock in Al Jabal Al Akhdar. (Data source: [21].)

Due to its relatively temperate weather, many tourists visit the area mainly to enjoy the natural scenery and agricultural terraces (83% of tourists: [19]), and to camp and walk around old villages. From 2006 to 2013, the number of tourists increased from 80,000 to 134,000: an increase of 68% [20]. The number of hotels has increased from one in 2006 to four in 2014; there are also various apartments and rest houses. Overall, two-thirds of visitors come in summer (May–October); far fewer visit during winter (November–April).

3.2 Pressures

Pressures on *aflaj* are mainly associated with the immediate Drivers. Farmers use flooding for irrigation from *aflaj*; water losses from open channels are high and crops may be irrigated more than their requirements, indicating inefficiency in irrigation with no water conservation practices. Critically, groundwater extraction via wells increased from 150,000 m³ in 2001 to 580,000 m³ in 2012, an increase of 386%, or 35% a year [22].

Climate change is the major exogenous Pressure on *aflaj*. From 1979 to 2012, there have been increases in minimum, mean and maximum temperatures; the rates of increase were 0.79, 0.27 and 0.15°C per decade, respectively. There has been also a general decrease in total annual rainfall from 1979 to 2012, thus reducing *aflaj* water quantity. Over this period, the average annual rainfall was 296.7 mm; the highest total was in 1997 (901 mm), and it decreased subsequently to 202.8 mm in 2012, with a rate of -9.42 mm per decade.

These changes and trends, (described in details [7, 23]), are in accordance with the predictions of climate models for Oman; suggesting that future temperature will rise 1–2°C by 2040 and 2–3°C by 2070; rainfall will decrease, with much of northern Oman Mountains receiving up to 40 mm less in annual rainfall in coming decades [24].

3.3 State and trends

3.3.1 *Aflaj* water quantity

The analysis of the State of *aflaj* showed the deterioration in their water quantity. Of the 72 *aflaj* in the study area, only one *falaj* was inactive in 1997 [2]. It is worth noting that this was when rainfall and groundwater levels were at their highest levels in the past three decades. The current research showed that the number of the active *aflaj* has decreased to 38. With the irregular rainfall patterns, the groundwater level of aquifers has fluctuated, with markedly lower levels since a high level in 1997 or 1998, following the high rainfall in 1997 [6]. The regression analysis showed highly significant correlation ($p < 0.01$) between rainfall and groundwater levels ($r > 0.7$). The heavy reliance on groundwater has caused the lowering of groundwater levels and drying of many *aflaj*.

Moreover, fluctuations in *aflaj* water flow have occurred since 1992, as shown by water flow monitoring data for the five main *aflaj* in the area. All *aflaj* flows increased during the wet years from 1992 to 1997, but generally declined from 1998 to 2012 (Figure 4); the rate of decrease in flow rates was -8.50 l/s per year. The maximum flow rates occurred in 1997 in all *aflaj*, with the highest maximum flow of 227 l/s. The analysis of regression showed highly statistical relationships ($p < 0.01$) between rainfall and *aflaj* flow rates ($r > 0.6$); on average the rainfall has reduced by 78% and the *aflaj* flow rates decreased by 85%. The fluctuations in *aflaj* water flow create challenges for the farmers trying to irrigate their farms, especially pomegranate and rose trees, or to invest in new crops. The irrigation rotation cycle sometimes continues over longer than 15 days. This means that the trees are exposed to a severe moisture deficit, leading to low productivity, and farmers are not able to grow seasonal crops.

3.3.2 *Aflaj* water quality

Aflaj water quality assessment showed that the water is not suitable for drinking: most of the samples indicated the presence of pathogenic organisms including fecal Coliforms and *E. coli*, and therefore do not meet the Omani [25] and World Health Organization [26] standards. These findings are in agreement with research conducted in 2004–2005 [27]. For irrigation purposes, all quality indicators are within the permissible limits set by Omani regulations [28].

3.4 Impacts

As *aflaj* are the main source for irrigation, their degradation has affected agricultural production. Agriculture provides the basis of livelihoods for around 70% of the inhabitants in the area [29]. More than 66% of the people rely on selling agricultural products, as most economic activities are related to tourism [19].

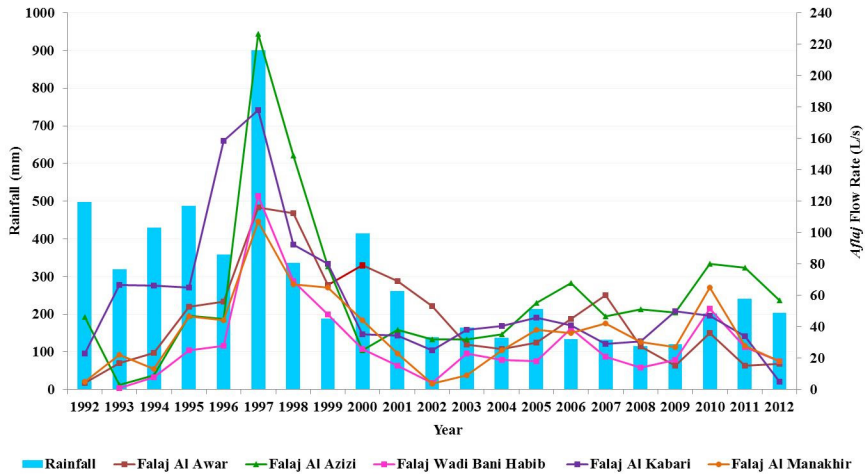

Figure 4: Annual rainfall and water flow rates for five *aflaj* in the study area from 1992 to 2012. (Data source: [6, 18].)

Pomegranates and roses are the main contributors to agricultural incomes. For example, the prices of pomegranate exceed US$2.58 per fruit of mean size 400 g [30]. Dried pomegranate peel is also commonly used in local medicine for wound healing and control of bacterial action [30]. Roses are also very important for rose water, a unique business for Oman in this area. Due to its high quality, the rose water has great potential for medicinal, culinary and celebratory purposes and is sold for US$18–23 per 750 ml.

The declining State of the *aflaj* water and thus the reduction in the cultivation area and the decreases in the total number of trees, including pomegranate and nut trees as well as rose bushes (Table 1), has resulted in considerable losses in the agricultural income. Furthermore, the deterioration of the pasture land has meant that farmers must now purchase goat meal rather than allowing goats to graze freely. The total economic costs of the loss of agriculture in Al Jabal Al Akhdar may be estimated between approximately more than US$ one million and US$ two millions from 2005 to 2013 (Table 2).

3.5 Responses

Several Responses have been taken to maintain and enhance the *aflaj* water and human well-being; these can have effects on many facets of its quantity and quality (Figure 5). Legislation and institutions have been developed. The government and *aflaj* committees have acted to maintain the *aflaj* and construct dams supporting their flows. The reconstruction of *aflaj*, using cement and blocks, helps to reduce water losses and limit pollution. Modern storage tanks are also constructed near the farming areas to store *aflaj* water for different purposes. These technological fixes decoupled Pressure from State to a certain extent, resulting in relatively more

Table 1: Decrease in number of trees from 2005 to 2013. (Data source: [21].)

Trees	*Agriculture Census Years*		*% Decrease*
	2004–2005	2012–2013	
Pomegranate	20,458	18,789	8.16
Rose	4,210	3,983	5.39
Date Palm	3,437	1,958	43.03
Peach	2,900	126	95.66
Lemon	1,646	227	86.21
Apricot	1,207	128	89.40
Grapes	1,084	149	86.25
Nuts	689	445	35.41
Figs	209	16	92.34
Pear	205	18	91.22
Apple	184	21	88.59
Plum	133	0	100
Others	16,586	3,133	81.11
Total	52,948	28,993	45.24

Table 2: Estimated costs in US$ of the loss of agriculture in Al Jabal Al Akhdar from 2005 to 2013.

Product	*Min*	*Mean*	*Max*
Pomegranate trees	648,657	972,985	1,297,314
Rose trees	65,874	75,284	84,695
Nut trees	379,322	474,153	568,984
Cost of goat meal	17,474	26,211	34,947
†Total	1,111,327	1,548,633	1,985,939
Annual cost	158,761	221,233	283,706

†Calculated based on decreased pomegranate trees: price between US$2.59–5.18 per fruit; decreased bottled rose water: price between US$18.13–23.30 for 750 ml; decreased nut trees: price between US$2.59–3.88 per 10 nuts.

efficient use of water. The government has also constructed three wastewater treatment plants and sewerage systems to prevent pollution of *aflaj* water, keeping them in good quality. Responses have been also directed to society, encouraging changes in behaviour through community participation and involvement in making decisions on digging new wells, constructing dams and maintaining *aflaj*.

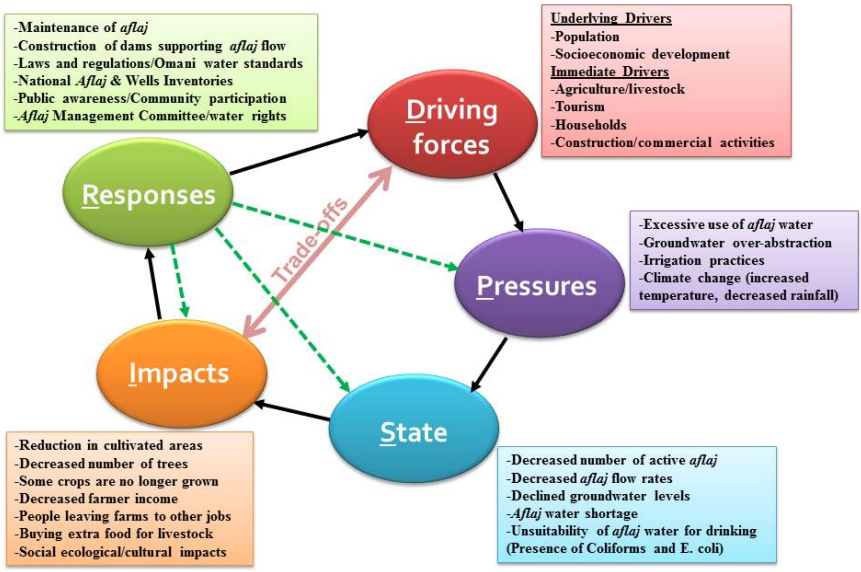

Figure 5: The DPSIR framework scheme for the *aflaj* system of Al Jabal Al Akhdar in 2012–2013.

4 Conclusions and recommendations

The application of the DPSIR framework enabled the identification of the main Drivers and Pressures on the *aflaj* system in Al Jabal Al Akhdar, and facilitated the linkage of these with the State of the water and the identified Impacts, making it possible to suggest Responses to rehabilitate and protect the system. The State of *aflaj* water is degraded, with a lower number of active *aflaj, lower* flow rates of the five principal *aflaj,* and declining groundwater levels. These are mainly due to climate change in conjunction with the anthropogenic activities: groundwater over-abstraction for domestic use and the excessive use of *aflaj* for agriculture, with no water conservation practices. The main economic Impacts include decreases in the cultivated area and number of trees, and therefore losses in agricultural returns. Several Responses have been taken to maintain the *aflaj* system; these have included promulgation of laws and regulations, and projects to maintain the State of *aflaj* water.

Although many laws, regulations and institutions have been developed for the management of water resources, including *aflaj,* in Oman, these focus on maintaining the State, rather than tackling directly the root causes (Drivers and Pressures) of water deterioration. Key suggested actions to decrease the Pressures on *aflaj* water are to increase irrigation efficiency, apply conservation techniques, harvest more rainwater, and use treated wastewater and greywater for irrigation.

To maintain *aflaj* water quality, a regular monitoring programme should be carried out to ensure the suitability of water for irrigation and domestic purposes. Improvements in sanitation and sewerage systems are also needed.

The implementation of integrated water resources management, along with the inclusion of climate change mitigation and adaptation measures in national policies, are recommended to foster the sustainable management of the *aflaj* system, and thus sustainability of agricultural communities of Al Jabal Al Akhdar. More research is needed to identify the most feasible practices, their weaknesses and strengths, to increase the agricultural economic returns and sustain the *aflaj* system and its social, ecological, and cultural heritage services.

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