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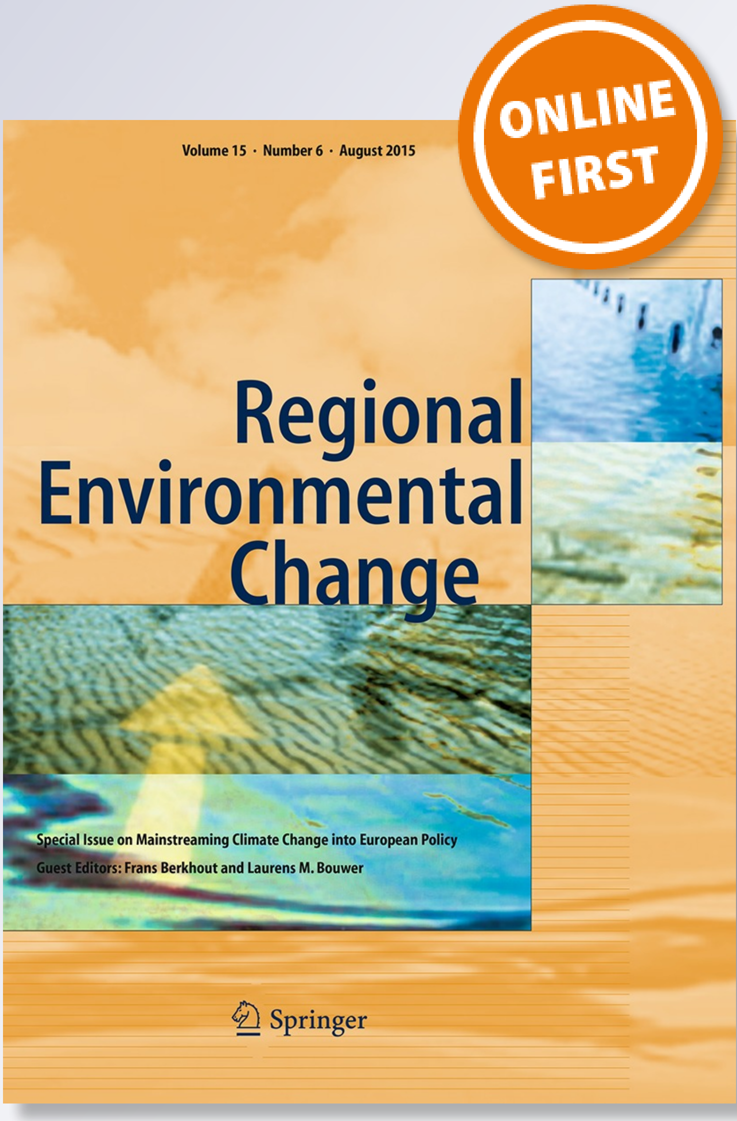

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ORIGINAL ARTICLE

Integrated environmental assessment to explore water resources management in Al Jabal Al Akhdar, Sultanate of Oman

Mohammed Saif Al-Kalbani[1] · **Martin Francis Price**[1] · **Timothy O'Higgins**[2] · **Mushtaque Ahmed**[3] · **Asma Abahussain**[4]

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Abstract Al Jabal Al Akhdar, an arid mountain region in northern Oman, has experienced rapid development over the last decades, resulting in the deterioration of water resources. This paper applies the driving force–pressure–state–impact–response (DPSIR) framework as an integrated environmental assessment tool to illustrate the cause-and-effect relationships for sustainable management of water resources in the area. The research aimed to examine social and ecological aspects of mountain water to explore optimal approaches for sustainable use and management. The water resources are affected by increasing drivers of population growth and socio-economic development, through agriculture, tourism, and urbanization, exerting pressures through overconsumption of water, coupled with the exogenous pressure of climate change. The decreased rainfall and increased water demand have resulted in the degradation of water quantity and quality. The declining state of the water resources and reduced area of cultivation have resulted in considerable losses in agricultural income. The Omani government has adopted some responses, including water development projects, acting to reduce pressures as well as to improve the state of water resources. The DPSIR analysis indicates that trade-offs should be made between economic development and the continued supply of water for the agro-ecological system; choices could be in the prioritization of drivers. A dependence on desalinated water will introduce a reliance on a non-renewable external energy supply and is unlikely to ensure water supply at the multi-century timescale of the social–ecological system. In addition, tourism is predominantly based around the disappearing agro-ecosystems which in turn are dependent on the supply of water. Therefore, efforts should be directed towards improving water-use efficiency through installing modern irrigation technology, water conservation methods, use of greywater and treated wastewater, and rainwater harvesting as well as integrated water resources management, and climate change mitigation and adaptation measures.

Keywords DPSIR framework · Integrated environmental assessment · Groundwater · *Aflaj* · Dams · Social–ecological system · Climate change · Trade-offs · Al Jabal Al Akhdar · Oman

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✉ Mohammed Saif Al-Kalbani
Kmohd2020@yahoo.com;
Mohammed.Al-kalbani@perth.uhi.ac.uk

1 Centre for Mountain Studies, Perth College, University of the Highlands and Islands, Perth, UK

2 Scottish Association for Marine Sciences, University of the Highlands and Islands, Scottish Marine Institute, Dunstaffnage, Argyll, UK

3 Department of Soils, Water and Agricultural Engineering, College of Agricultural and Marine Sciences, Sultan Qaboos University, Muscat, Sultanate of Oman

4 Department of Natural Resources and Environment, College of Graduate Studies, Arabian Gulf University, Manama, Kingdom of Bahrain

Introduction

Dryland regions worldwide face unprecedented environmental challenges, especially in developing countries, whose ecosystems are under the greatest threat of degradation and depletion (Agyemang et al. 2007). Every ecosystem provides essential services and goods, contributing to the satisfaction of human needs and well-being,

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and delivers support functions and benefits (MEA 2005). Recent studies have emphasized the importance of human–environment interactions through the relationships that exist between people and ecosystems (Luck et al. 2009; Rounsevell et al. 2010): the welfare of societies depends directly and indirectly on changes in ecosystems and their services (Carpenter et al. 2009).

Water resources are a key ecosystem component, sustaining life and all social and economic processes. When the state of water resources changes, the resulting changes in ecosystem services may impact the welfare of individuals and communities (Moss 2000; Kallioras et al. 2006; Atkins et al. 2011). Water resources, particularly in arid and semi-arid regions, are being degraded as a result of multiple drivers of environmental change due to various anthropogenic activities. Rising population, economic development, and urbanization represent key environmental and social challenges in many parts of the world (FAO et al. 2011; Victor 2012). Drivers of environmental change exert pressures on water resources, changing the spatial and temporal patterns of water supply and causing not only imbalances between supply and demand in hydrological systems but also deterioration of water quality, threatening ecological systems, livelihoods, and general human well-being (Pinto et al. 2013). In particular, mountain regions may be regarded as 'water towers' (Meybeck et al. 2001; Viviroli et al. 2007, 2011; Messerli 2009; Gautam et al. 2010): changes in the status of their water resources affect not only mountain dwellers, but also the livelihoods and welfare of a considerable proportion of humanity (Körner and Ohsawa 2005; Price 2006). Consequently, tools to assess the ecological status and trends in environmental degradation and depletion of natural resources, including water resources, and the consequences for human well-being in these regions have become essential for the long-term management of natural resources and sustenance of livelihoods (Kohsaka 2010; Pinto et al. 2013).

A key step in the assessment of human-driven environmental problems is to understand pressures from human activities and impacts on social processes, through the adoption of appropriate environmental assessment tools (Walmsley 2002). The driver–pressure–state–impact–response framework (hereafter DPSIR), developed in the late 1990s by the Organization for Economic Co-operation and Development (OECD 2003), is one such tool. It has been widely used for integrating quantitative and qualitative ecosystem/socio-economic interactions and supporting sustainable management by providing policy-relevant information (Borja et al. 2006; Marques et al. 2009; Mattas et al. 2014; O'Higgins et al. 2014). Despite the potential capabilities of this framework for the assessment of environmental problems, its adoption is still at an early stage in many developing countries, such as the Sultanate of Oman.

This paper is the first DPSIR analysis of the water resources of Oman's mountains. The DPSIR is used to examine social and ecological aspects of water resources management in Al Jabal Al Akhdar, an arid mountain region of Oman, with the aim of exploring the causal relationships between DPSIR components and identifying management priorities for the area, with a particular focus on water quantity and quality. Driving forces and pressures affecting the state of water quantity and quality and their impacts on humans are assessed. Based on the analysis, the paper characterizes and identifies some potential measures (responses) towards development and sustainable management of water resources in the region.

Methodology

The study area

Al Jabal Al Akhdar (the Green Mountain) is a semi-arid mountainous area (altitude 1000–3075 m above mean sea level) located in the northern mountains of the Sultanate of Oman (Fig. 1). The area of Al Jabal Al Akhdar is not exactly identified or formally designated; there are no formal administrative boundaries for this area, and for the neighbouring regions located within the northern Oman Mountains as a whole. Niyabat Al Jabal Al Akhdar, the study area (Fig. 1) is the administrative area (404 km^2) designated by the government and where the settlements are located. The long-established agro-pastoral oasis ecosystem in the study area has supported communities for centuries. Until the late twentieth century, this social–ecological system was geographically isolated and relatively closed to the outside world. Historically, water availability connected the agro-pastoral system directly with human well-being and dictated the bounds of agricultural practices and human development (Al-Kalbani et al. 2014).

The study area has a pleasant climate, with temperatures lower by 10–12 °C than the surrounding lowland plains (DGMAN 2014). Air temperatures range from below 0 °C in January to over 33 °C in July, and there is a distinct seasonal rainfall pattern, with a dry season from mid-November through March, and a rainy season from mid-June through mid-September (DGMAN 2014). In recent decades, there has been a long-term decline in rainfall (Al-Kalbani et al. 2014).

Niyabat Al Jabal Al Akhdar has limited and highly variable water supplies; water is critical to the survival of the agro-ecosystems and the communities they support. The natural freshwater resources are of three types: groundwater, *aflaj*, and *wadis*. The groundwater aquifers are solely exploited to supply drinking water to all households living in the settlements in the area, via 11

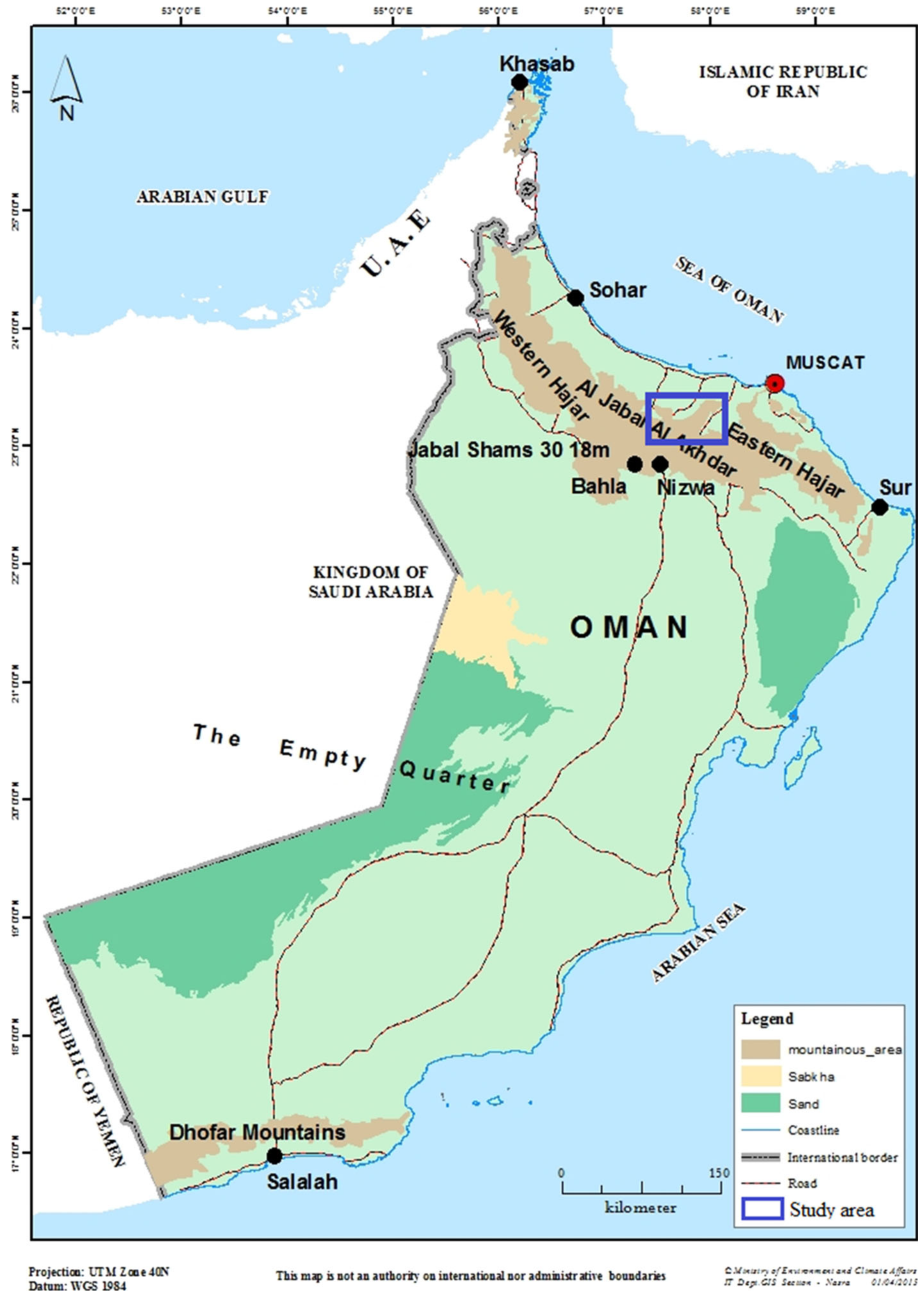

Fig. 1 Map of Oman showing the location of the study area (*Source*: MECA 2015)

wells established by the Omani government in the last 30 years (PAEW 2014). For settlements not connected to the water distribution networks, water trucks provide people with a certain amount of water free of charge. *Aflaj* (singular *falaj*) are surface and/or underground channels fed by groundwater or springs, or built to provide water to communities for domestic and/or agricultural use (Al-Marshudi 2001; MRMWR 2008). *Wadis* are valleys or ephemeral riverbeds that have intermittent stream flow, mainly after rainfall (MRMWR 2008). The water in the *wadis* was traditionally captured by small man-made reservoirs built by local communities in the *wadi* channels. By 2014, the Omani government had constructed 50 storage dams in the area with a total capacity of 152,580 m^3 (MRMWR 2014). Water from *aflaj* and *wadis* (dams) is mainly used for agriculture and livestock.

The establishment of settlements has been influenced strongly by the availability of water for drinking, domestic, and agricultural purposes. The Omani government is the main provider of water to the people living in the area, as well as to other business (commercial and tourism sectors) and public sector installations. Although groundwater is currently the only local source of drinking water in the area, the government is now working on a project to bring desalinated water from the coastal region to the mountain to meet the ever-growing needs. To protect the groundwater aquifers, the government has constructed three wastewater treatment plants in the area.

Agriculture is the economic foundation for Niyabat Al Jabal Al Akhdar. Agricultural terraces are used for growing perennial fruits, especially pomegranate, as well as roses (for rosewater) (MAF 2014). Date palms are grown at lower altitudes, and annual crops such as garlic, onion, maize, barley, oats, and alfalfa are also planted on the terraces depending on the availability of water. Goats are the main livestock; more than 60 % of the farmers keep up to 40 animals (Zaibet et al. 2004; Al-Kalbani 2015). The cool climate and verdant hillsides have made Al Jabal Al Akhdar a place of special significance for the Omani people and an attractive area for tourism (Ramanathan et al. 2010; Al-Balushi et al. 2011).

DPSIR analytical framework

Under the DPSIR framework, five elements are distinguished with respect to a given environmental problem, the driving forces and pressures on an area, the state of its environment, the impacts these forces have, and the responses that are implemented (Gabrielson and Bosch 2003). The DPSIR method is used to structure and examine causal linkages and assess trade-offs for a specific environmental problem. The framework originated in the social sciences (Rapport and Friend 1979) as a tool for structuring multidisciplinary information and demonstrating causal links between science and policy in economic, social, and natural systems (Walmsley 2002; Lundberg 2005; Ness et al. 2010). The framework has been applied to a wide variety of environmental topics, such as marine environments (Al-Mazaini 2009), coastal areas (Abahussain and Al-Sabaq 2010), marine ecology (Gari et al. 2015), integrated coastal management (Bowen and Riley 2003), offshore wind power generation (Elliot 2002), agriculture (Smaling and Dixon 2006), climate change (Holman et al. 2008), biodiversity (Kuldna et al. 2009), sustainable development (Carr et al. 2007), and water management (Kagalou et al. 2012; Mattas et al. 2014; Azarnivand and Chitsaz 2015). Some applications have been made in mountain regions (Bunce et al. 2004; Odermatt 2004; Fagarazzi 2005; Wei et al. 2007; Biswas et al. 2012), but rarely in arid mountain regions (Essayas 2010; Bait Said 2011; Al-Baraami 2012). This analysis adopts the recent, rigorous definitions of the DPSIR information categories developed by Cooper (2013) (Fig. 2).

Data collection and sampling

Data were gathered using a number of techniques. Primary data were gathered using two complementary assessment methods: (1) water resources quantity and quality analysis; (2) a questionnaire survey of three target stakeholder groups (households, farmers, and government officials/experts). Sampling locations for water quality and quantity analysis, as well as for distribution of surveys, were selected using cluster analysis based on human population number and growth rate, altitude, agricultural area, total number of trees, and total animal units. Each criterion was classified into three classes, high, medium, or low; 14 sampling locations associated with individual settlements were selected.

The current state, recent changes, and trends of water resources were assessed by analysing water quantity data and fieldwork sampling of the quality of different water bodies (wells, *aflaj*, dams). For each sampling site, the water resources and bodies were identified according to their location and potential usage by local people. Water samples were collected from 17 dams and nine *aflaj* in both summer and winter 2012–2013. Sample collection, handling, processing, and analysis followed the standard methods recommended by the American Public Health Association (APHA 2005); water quality parameters were selected according to Chapman and Kimstach (1996). A set of physical, chemical, and microbiological quality indicators was identified for the water assessment and determined in quality-assured laboratories, using analytical methods and instrumental techniques (Table 1).

Secondary data—such as meteorological data, *aflaj* flow rate data, and groundwater levels—were gathered from many grey literature sources. Domestic and hotel water consumption data were obtained from relevant local ministries and other official unpublished sources. Historical data on the number of active and inactive *aflaj* were obtained from the National *Aflaj* Inventory (MWR 1999). Data on current numbers of active *aflaj* were obtained by surveys with local farmers during the field work in 2012. Water balance data for the large-scale water catchment including the study area were obtained from studies completed in 2000 (NWRMP 2000) and 2012 (Mott MacDonald 2013).

Results

Drivers

Population and socio-economic development were identified as the main underlying drivers. The population in the area has tripled in the last three decades, from less than 2000 in 1970 to over 7000 in 2010 (NCSI 2012). Population growth and rapid socio-economic development have resulted in urban expansion: the number of households in the study area has grown along with population, and the number of housing units has doubled since 1993 (NCSI

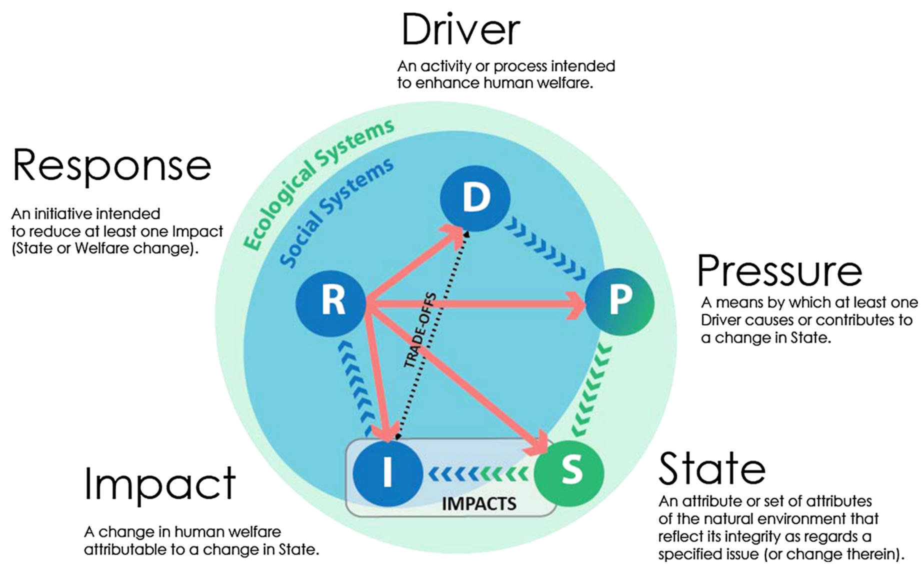

Fig. 2 Definition and outline of the DPSIR information categories (*Source*: Cooper 2013)

Table 1 Determination of physiochemical parameters by different methods

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)	Autotitration
Total hardness (TH) (mg/l)	Ethylene Diamine Tetra Acetic Acid (EDTA) complexometric titration method
Sodium, calcium, magnesium potassium	Inductively coupled plasma (ICP-OES) (PerkinElmer Optima 3300 DV)
Fluoride, chloride, nitrate, sulphate, phosphate	Metrohm Professional Compact Ion Chromatography System 881 with Metrohm 858 Professional Sample Processor
Heavy metals	Inductively coupled plasma (ICP-OES) (PerkinElmer Optima 3300 DV)
Coliform bacteria	IDEXX Quanti-Tray (51-Well Quanti-Tray) quantification methods (Most Probable Number; MPN)
Escherichia coli (*E. coli*)	Spectroline Model (EA-160/FE), ultraviolet light (365 nm)

2012). The most important bases of the traditional economy are agriculture and livestock. The other source of income is cash brought in by villagers working outside Al Jabal Al Akhdar (Al-Balushi et al. 2011), as most young people now either work in the government sector in the area or have taken jobs in the government and private sectors in Muscat or other regions of Oman and come home at weekends. No data on the number of people from the study area employed in different sectors are available.

Most people have left their old houses in small villages, which are now abandoned, and moved to larger modern houses in a newly developed housing area, where most of the governmental offices and facilities are located. A key factor was the completion of an asphalted road in 2006, establishing the first high-quality transport link to the study area. There has also been an increase in construction, including road networks, schools, a hospital, mosques, government offices, municipal services, a petrol station, government wells for water supply, and storage dams. There are plans to establish an industrial area for light industries (Supreme Committee for Town Planning 2011).

Traditionally, agriculture has been the principal economic sector and the main immediate driver of demand for water resources. Around 70 % of the local inhabitants practice agriculture; seasonal numbers are higher, as members of farming families work during the growing and harvesting seasons (Al-Riyami 2006). The cultivation of pomegranates and the extraction of rosewater are the main activities, requiring irrigation with water from dams and *aflaj*. Livestock husbandry is also important; and between

2005 and 2013, the animal units of goats, sheep, and cows increased by 33.3, 47.7, and 36.0 %, respectively (MAF 2006, 2014). Livestock are commonly cited as being the major contributor to rangeland deterioration, as evidenced by reduced plant cover and the dominance of inedible plant species associated with reduced rainfall, human activities, and overgrazing by livestock (Robinson et al. 2009). However, although agriculture is the dominant consumer of water in Al Jabal Al Akhdar, this economic sector contributes little to the overall Omani economy (about 3.7 % of GDP) (Al-Kalbani 2015).

Tourism is a developing sector: the number of visitors increased 58 % since the completion of the asphalted road, from 85,000 in 2006 to 134,000 in 2013 (Fig. 3). Of these, 67 % arrive between May and October, with July and August being the busiest months due to the relatively cool climate. At times during this critical period, high demand for water from groundwater wells results in a water shutdown, not only to the households, but to other establishments including hotels. There has been an increase in the number of hotels, from one in 2006 to four in 2014; more are planned. The traditional agricultural practices also play a role in attracting tourists to visit the area: 83 % visit mainly to see the natural scenery and agricultural terraces (Al-Balushi et al. 2011). Water for domestic use and tourism is therefore the second major immediate driver of the use of water resources in the area.

Pressures

The pressures associated with the immediate drivers mainly include water abstraction and consumption; climate introduces an exogenous pressure, as levels of rainfall are decreasing (Al-Kalbani et al. 2014). In the wider region including the study area, agriculture accounts for 92 % of water consumed, with the remainder being for domestic use (Mott MacDonald 2013). Irrigation for agriculture is by flooding of agricultural terraces with water from dams and *aflaj*. Although no modern irrigation monitoring systems have been installed in the area, it is clear that water losses from open channels and flooding are high, indicating inefficiency in irrigation.

The water abstracted from the area's groundwater wells for domestic consumption increased from 150,000 m^3 in 2001 to 580,000 m^3 in 2012, an average annual increase of 26 % (Fig. 4). Based on the survey data, some households use drinking water to irrigate their gardens and for livestock. Much of this increase in domestic consumption may be due to the burgeoning tourist industry. The groundwater wells supply drinking water to all villages and all other establishments, including hotels. Based on the water tariffs paid by the hotels and the number of hotel visitors, the average daily water consumption per hotel visitor is between 641 and 1300 l, five to 10 times the average per capita daily water consumption in Muscat, the capital of Oman.

The increasing levels of water abstraction and consumption occur in tandem with the exogenous climatic pressures. The study area experienced increasing temperatures from 1979 to 2012: minimum, mean, and maximum temperatures increased at rates of 0.79, 0.27, and 0.15 °C per decade, respectively. The annual average rainfall over this period was 296.7 mm. The highest total was in 1997 (901 mm), and rainfall decreased subsequently to 202.8 mm in 2012, with an overall decrease in total rainfall at a rate of −9.42 mm per decade (described in detail by Al-Kalbani 2015; Al-Kalbani et al. 2015). These trends are in accordance with the predictions of climate models which suggest that temperatures will rise 1–2 °C for the entire country by 2040 and 2–3 °C by 2070 and that rainfall will decrease, with much of the Hajar Mountains receiving up

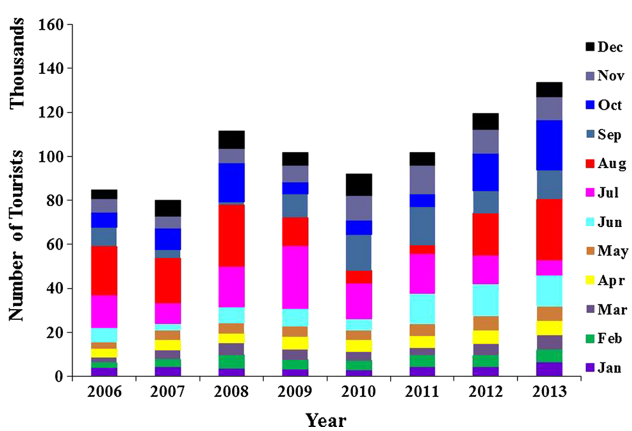

Fig. 3 Number of tourists visiting the study area from 2006 to 2013 (*Data source*: Ministry of Tourism 2014)

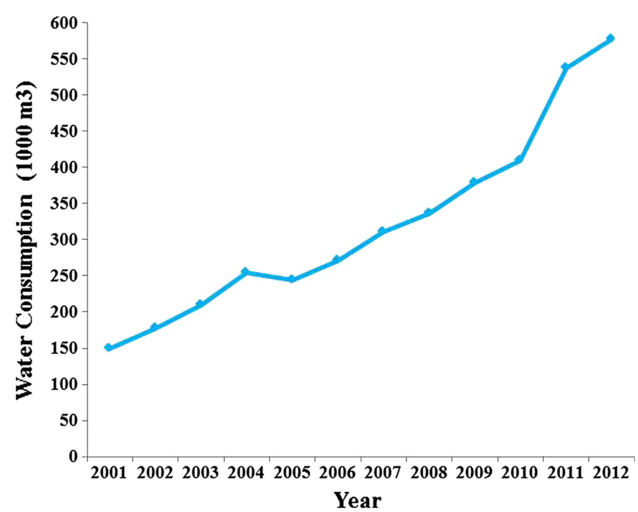

Fig. 4 Total annual water consumption from the main groundwater wells supplying water for drinking and domestic purposes in the study area (*Data source*: PAEW 2014)

to 40 mm less annual rainfall in coming decades (Al-Charaabi and Al-Yahyai 2013; Al-Kalbani et al. 2015).

State

Water quantity

Average rainfall in the area has decreased by 58 % between 1997–2000 and 2009–2012. Groundwater levels in the aquifers of the study area have fluctuated, with markedly lower levels since an historical high following the high rainfall in 1997 (Fig. 5). The 44 % decrease in groundwater levels since 1997 is significantly correlated ($p < 0.01$, $r > 0.7$) to the decrease in rainfall. Declining rainfall and groundwater has resulted in decreased availability of water in aquifers, *aflaj*, and dams, and therefore decreased water supply for drinking, domestic, and agricultural purposes.

For *aflaj*, water flow rates are influenced by the regional rainfall and the availability of water in their mother wells. The National *Aflaj* Inventory conducted from March 1997 to June 1998 identified 72 *aflaj* in the Al Jabal Al Akhdar area, of which only one was inactive (dry) (MWR 1999; MRMEWR 2001). Fieldwork in 2012 showed that the number of the active *aflaj* had decreased to 38.

The major trend in *aflaj* flow rates has been a decrease of 85 % since 1997. This is significantly correlated ($p < 0.01$, $r > 0.6$) with the decrease in rainfall. However, average annual flow rates of *aflaj* in the area have fluctuated considerably, as shown by data for the average flow rates of the main *aflaj* (Fig. 6). These data show that flows in all *aflaj* increased during the wet years from 1992 to 1997, but generally declined until the beginning of this century, since when flows have fluctuated at levels comparable to those before 1995. Water for irrigation is supplied by dams which are constructed to entrain *wadis*. While there are no official data on the amount of water stored in these dams, water levels are critically dependent on rainfall.

Water balance data are not available specifically for the study area, which is located in North Halfayn Water Assessment Unit Area (WAUA), one of the five subunits of the Andam-Halfayn Water Assessment Area (WAA). The only available water balance studies were completed in 2000 and 2012 for each WAUA in the Andam-Halfayn WAA. Even though these water balances are not defined for a particular area or a fixed period, they represent the best estimates of average long-term inputs and outputs using all available data. In Oman as a whole, the water balance study completed in 2012 indicated that 12 of the country's 28 WAA had a deficit in the water balance, compared with eight in 2000. Areas with a high deficit are those with high demands, primarily agricultural. The average water demand in 2012 was about 1872 million m^3/year, which exceeds the available water resources, leading to a total deficit of −316 million m^3/year. For North Halfayn WAUA, including Al Jabal Al Akhdar, the average annual rainfall used for the 2000 water balance study was 210 million m^3/year; for the 2012 study, 184 million m^3/year was used. For the 2012 study, the total water flow components in North Halfayn WAUA were 66.89 million m^3/year, and the total water outflow was 76.58 million m^3/year, indicating an imbalance between supply and demand: a deficit of −9.69 million m^3/year (Mott MacDonald 2013). In summary, as shown by a recent assessment of the vulnerability of water resources to environmental and climate changes, the study area experiences water stress and suffers from critical conditions in

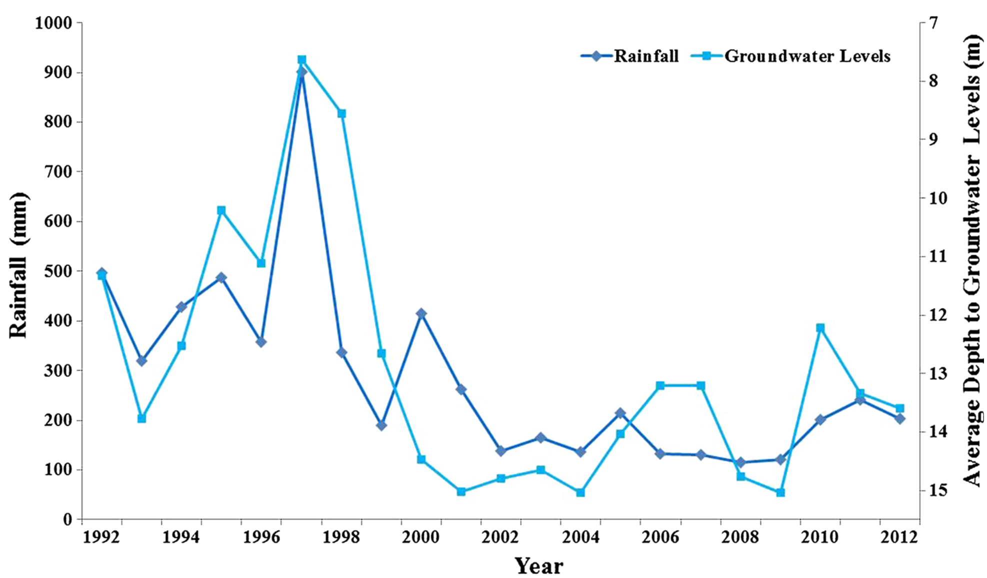

Fig. 5 Annual rainfall and average depths to groundwater level for well monitoring stations from 1992 to 2012 (*Data source; rainfall*: DGMAN 2014; *Ground water levels*: MRMWR 2014)

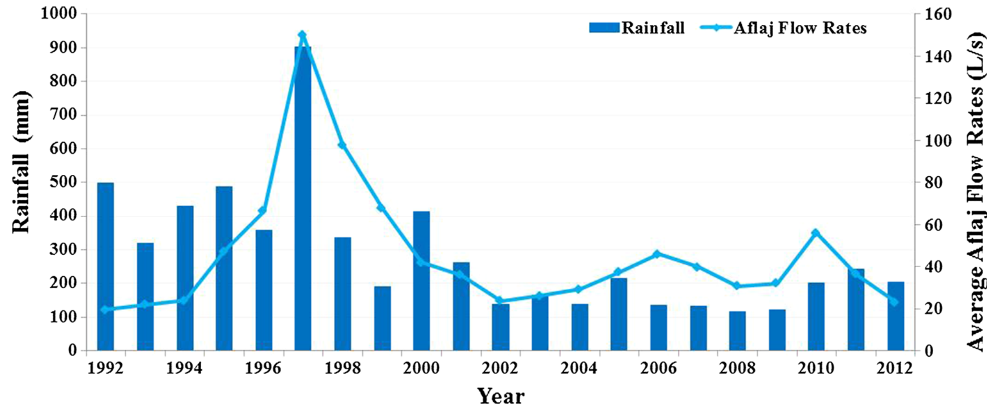

Fig. 6 Annual rainfall and average water flow rates for the main *aflaj* in the study area from 1992 to 2012 (*Data Source*: DGMAN 2014; MRMWR 2014)

the development of water resources (Al-Kalbani et al. 2014).

Water quality

Analysis of groundwater samples from wells revealed that all physical, chemical, and microbiological quality indicators (Table 2) were within the permissible limits set by Omani standard (8/2006) for Un-bottled Drinking Water (MD 2007) and the World Health Organization (WHO 2011); these indicators were not significantly different between summer and winter. However, nitrate concentrations in a number of groundwater wells were elevated. One sample at Hayl Al Yaman well, collected during winter, had a concentration of 101.45 mg/l, exceeding the acceptable level of 50 mg/l according to Omani and WHO standards for drinking water. A number of other wells also showed relatively high nitrate concentrations; the highest levels generally occurred during winter, but not exceeding the allowable limit. These measurements suggest that, in some locations, there may be nitrate pollution into the groundwater aquifers from the seepage of wastewater due to unlined septic tanks and inadequate sewerage systems.

Analysis of the quality of irrigation water in the selected dams and *aflaj* indicated that all physical, chemical, and microbiological quality indicators (Tables 3, 4) were

Table 2 Mean, median, standard deviation, minimum, and maximum of groundwater quality variables for 11 samples from the study area in 2012–2013

Variables	Mean	Median	SD	Minimum	Maximum	Omani standard	WHO standard
Turbidity (NTU)	3.27	0.19	7.38	0.05	20.45	1–<5	NG
TDS (mg/l)	492.22	398.12	198.19	277.44	949.66	120–1000	1000
EC (µS/cm)	786.42	649.95	284.04	431.20	1401.00	160–1600	2000
pH	8.00	7.98	0.24	7.68	8.35	6.5–9.0	6.5–9.5
$CaCO_3$ (mg/l)	273.36	261.53	66.92	176.38	379.60	NG	NG
HCO_3 (mg/l)	297.21	284.85	71.92	189.79	410.95	NG	NG
Total hardness (mg/l)	346.94	327.55	112.22	206.75	566.73	≤200–500	500
Sodium (Na) (mg/l)	36.77	26.19	28.98	12.51	97.77	≤200–400	200
Calcium (Ca) (mg/l)	77.08	66.76	34.19	35.32	145.60	200	NG
Magnesium (Mg) (mg/l)	31.85	30.06	7.81	22.14	44.42	150	NG
Potassium (K) (mg/l)	2.98	1.70	2.81	0.56	8.21	NG	NG
Fluoride (F) (mg/l)	0.26	0.24	0.14	0.11	0.46	1.5	1.5
Chloride (Cl) (mg/l)	51.91	28.99	46.58	17.44	165.14	≤250–600	250
Nitrate (NO_3) (mg/l)	18.49	9.36	23.49	0.73	72.77	50	50
Sulphate (SO_4) (mg/l)	56.64	42.04	35.57	19.06	114.10	≤250–400	400
Phosphate (PO_4) (mg/l)	0.16	0.06	0.27	0.02	0.93	NG	NG
Coliforms (MPN/100 ml)	6.65	0.00	18.22	0.00	61.30	10	10
E. coli (MPN/100 ml)	0.00	0.00	0.00	0.00	0.00	0	0

Omani standard, Un-Bottled Drinking Water Standard (No. 8/2006); WHO Standard, World Health Organization Standard for Drinking Water (WHO 2011); NG, no guideline is recommended

Table 3 Mean, median, standard deviation, minimum, and maximum of dams' water quality variables for 17 samples from the study area in 2012–2013

Variables	Mean	Median	SD	Minimum	Maximum	MD 145/1993
Turbidity (NTU)	21.51	11.97	25.68	0.46	90.15	NG
TDS (mg/l)	238.48	219.18	108.52	120.32	556.54	1500
EC (μS/cm)	385.49	350.70	177.32	191.95	887.00	2000
pH	7.74	7.76	0.39	7.15	8.30	6–9
$CaCO_3$ (mg/l)	162.71	158.30	59.29	77.33	276.71	NG
HCO_3 (mg/l)	172.32	164.83	66.35	79.79	290.64	NG
Total hardness (mg/l)	186.12	175.71	70.56	102.69	365.08	NG
Sodium (Na) (mg/l)	10.14	5.48	13.77	2.46	52.85	200
Calcium (Ca) (mg/l)	49.98	44.30	19.19	26.88	87.67	NG
Magnesium (mg/l)	9.95	5.71	11.01	2.70	42.83	150
Potassium (K) (mg/l)	3.36	2.18	3.18	1.09	11.59	NG
Fluoride (F) (mg/l)	0.10	0.11	0.06	0.02	0.22	1
Chloride (Cl) (mg/l)	14.69	8.74	18.48	3.25	74.15	650
Nitrate (NO_3) (mg/l)	3.85	0.64	7.40	0.01	27.86	50
Sulphate (SO_4) (mg/l)	15.65	9.74	17.62	4.28	71.39	400
Phosphate (PO_4) (mg/l)	0.20	0.11	0.27	0.03	1.07	NG
Coliforms (MPN/100 ml)	123.84	>200.500	91.75	5.55	>200.500	200
E. coli (MPN/100 ml)	6.50	2.50	10.23	0.00	35.50	NG

MD 145/1993, Ministerial Decision for Regulation of Wastewater Reuse and Discharge; NG, no guideline is recommended

Table 4 Mean, median, standard deviation, minimum, and maximum of *aflaj* water quality variables for 22 sampling points from the study area in 2012–2013

Variables	Mean	Median	SD	Minimum	Maximum	MD 145/1993
Turbidity (NTU)	0.79	0.56	1.00	0.06	4.48	NG
TDS (mg/l)	345.19	328.80	100.26	171.68	562.39	1500
EC (μS/cm)	564.05	537.58	159.10	293.50	896.00	2000
pH	8.11	8.18	0.26	7.41	8.51	6–9
$CaCO_3$ (mg/l)	235.44	236.71	49.15	134.30	325.61	NG
HCO_3 (mg/l)	240.01	236.93	49.98	136.50	335.96	NG
Total hardness (mg/l)	271.51	265.27	58.17	158.46	375.52	NG
Sodium (Na) (mg/l)	19.68	16.11	11.50	7.48	48.88	200
Calcium (Ca) (mg/l)	48.98	48.60	12.54	26.83	78.98	NG
Magnesium (Mg) (mg/l)	27.34	26.58	7.66	13.44	46.03	150
Potassium (K) (mg/l)	3.79	4.04	3.07	0.51	10.08	NG
Fluoride (F) (mg/l)	0.12	0.12	0.04	0.04	0.18	1
Chloride (Cl) (mg/l)	26.29	19.71	18.02	12.08	76.68	650
Nitrate (NO_3) (mg/l)	6.54	2.98	9.30	0.34	35.03	50
Sulphate (SO_4) (mg/l)	26.59	20.91	15.93	10.89	74.16	400
Phosphate (PO_4) (mg/l)	0.27	0.08	0.81	0.03	3.80	NG
Coliforms (MPN/100 ml)	133.68	155.93	82.12	3.75	>200.500	200
E. coli (MPN/100 ml)	7.30	2.25	10.83	0.00	37.50	NG

MD 145/1993, Ministerial Decision for Regulation of Wastewater Reuse and Discharge; NG, no guideline is recommended

within the permissible limits set by Omani regulations of wastewater reuse for irrigation (MD 1993). Most of the heavy metals in summer and winter water samples from dams and *aflaj* were below the detection levels; other metals were present but within the safe limits for irrigation water and did not exceed the recommended quality limits of Omani regulations. Microbiological analysis revealed that, while faecal coliform counts in some samples were above the Omani standard (200 MPN/ 100 ml) for irrigation of type A crops (vegetables likely to be eaten raw; fruit likely to be eaten raw and within 2 weeks of any irrigation), all samples were within the permissible limits to irrigate type B crops (vegetables to be cooked for processing; fruit if no irrigation within 2 weeks of cropping; fodder, cereal, and seed crops) (MD 1993). *E. coli* bacteria were present in most samples, but the regulation does not set a standard for these. Thus, dam and *aflaj* water resources are not fit for drinking, due to the presence of high levels of faecal coliform and *E. coli*, which exceeded the maximum allowable levels of Omani and WHO drinking water standards. These findings are in agreement with studies conducted by Victor and Al-Ujaili (1998, 1999), Ahmed et al. (2006) and Victor et al. (2009).

Impacts

The declining state of the water resources has resulted in several environmental, social, and economic impacts, affecting ecosystem services and human welfare. As described above, domestic drinking water in the area is derived from groundwater which has declined by 44 % in recent years (Fig. 5), resulting in periodic water shortages for domestic supply. These shortages lead to an increased demand for bottled water at times of scarcity: this is the main direct economic impact on households. According to the household respondents, the annual cost per household of buying bottled water is US$ 124–US$ 1088 (average US$ 390): about 14 % of a farmer's average annual income (of US$ 2708). As the number of households in the area is 867 (NCSI 2012), the total annual cost in the area may be estimated as US$ 108,000–US$ 944,000 (average of US$ 337,000). Additional water is also supplied to certain locations by truck, for example when any kind of construction is ongoing, when water supply networks are shut down or when dams are empty. Households are charged US$ 7.77–15.55 per 300 gallons for this additional water, depending on their distance from the groundwater aquifer.

As noted above, agriculture remains the main economic activity for most people in the area, and this is totally dependent on water from *aflaj*. The decline in the state of *aflaj* water is detailed in Fig. 6. The average *aflaj* flow rates in the region from 2009 to 2012 decreased by 59 % in comparison with the average flow rates from 1997 to 2000. Since *aflaj* are the only source of water for irrigation, these declining flow rates have meant that a decreasing area can be irrigated for agriculture. Based on data from the Agriculture Censuses, these impacts can be clearly seen: the cultivated area decreased by 27 % from 1,155,275 m^2 in 2004–2005 to 840,200 m^2 in 2012–2013 (MAF 2006, 2014). If this trend were to continue, by 2050 less than 10 % of the agricultural area at the beginning of this century would remain. Local change in cultivated area of agricultural terraces between 1995 and 2014 is illustrated visually in Fig. 7. This reduction in agricultural area has had an economic impact. The total number of trees almost halved from 2004–2005 to 2012–2013. Plums are no longer grown; numbers of peach, pear, and fig trees decreased by more than 90 %; apricot, apple, and lemon trees and grape vines by more than 80 %; and nut trees by 35 % (Table 5).

More than 66 % of the population of the study area relies on selling agricultural products, mainly pomegranates and rose water, to tourists who visit the area during the harvesting season (Al-Balushi et al. 2011). Pomegranate and roses are the most economically important trees in the area, representing the majority of trees grown—currently 65 and 14 %, respectively (MAF 2014)—and provide high economic returns. Pomegranates are highly sought after in the local market; tourists often pay more than US$ 2.59 per 400 g fruit (Opara et al. 2009). Al-Riyami (2006) has estimated that one acre (4200 m^2) of pomegranate trees can bring an income of 9880 OMR (US$ 25,583) in an agricultural season. Specific cultural activities depend on these crops and farming activities, and the resulting benefits are not measured directly through these economic estimates. For example, pomegranates are not only eaten fresh but used for juice; dried pomegranate, particularly the peel, is commonly used for wound healing and control of bacteria (Opara et al. 2009). Rose cultivation and distillation are also culturally important; rosewater is used for medicinal, culinary, and celebratory purposes. Farmers use the available *aflaj* and dam water mainly to irrigate these two species preferentially because of the shortage of water.

Farmers also keep animals, especially mountain goats, which are adapted to local conditions and have very high productivity for meat and milk (Mahgoub et al. 2009); these comprise more than 80 % of the total animal units (MAF 2014). Traditionally, farmers take their goats in the early morning into the grazing area, where woodland, shrubs, and grasses are available, and return with them to the village at midday. Currently, with reduced rainfall, shortage of water, and the deterioration of rangelands, most of the goats are kept in corrals and no longer graze the open range, because herders believe that their animals will not find sufficient food. So goats are fed fodder crops. However, as there is limited availability of these crops in the area, herders must buy this fodder from the local markets at an additional economic cost. The change agricultural practices have also resulted in a social loss, as the traditional herding lifestyle has disappeared.

Table 6 provides estimates of the economic losses to agriculture, due to the reduction in crop area and decreases in the number of trees, based on the 2005 and 2013 agricultural censuses, interviews with stakeholders, and the costs of buying goat meal. The economic impacts from the water shortages can thus be divided into two types. First, the extra costs incurred through reduced groundwater levels and the necessity to purchase bottled water:

Fig. 7 Agricultural terraces of Al Jabal Al Akhdar, **a** summer 1995 (*Source*: Al-Moharbi 1995) and **b** summer 2014 (*Source*: Al-Kalbani 2015)

Table 5 Decrease in number of trees from 2005 to 2013 (*Data source*: MAF 2006, 2014)

Trees	Agriculture census years		% decrease
	2004–2005	2012–2013	
Pomegranate	20,458	18,789	8.16
Rose	4210	3983	5.39
Date palm	3437	1958	43.03
Peach	2900	126	95.66
Lemon	1646	227	86.21
Apricot	1207	128	89.40
Grapes	1084	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

For Agriculture Census 2012-2013, the data are estimated based on primary results obtained from the database of the Ministry of Agriculture and Fisheries; these are used for the purpose of this study, but not officially published and should not be cited elsewhere

approximately $300,000 annually as detailed above. Second, the costs to agriculture detailed in Table 6, which result chiefly from the decreased availability of irrigation water from *aflaj*. The combined average annual costs of water shortages to households and farmers might be estimated around US$5 million.

Table 6 Estimated total losses in agriculture from 2005 to 2013, cost of goat meal and the estimated total annual cost from buying bottled water in the study area (values in US$)

Item	Min	Mean	Max
Agriculture losses			
Loss in pomegranate trees	1,306,471	1,565,880	1,823,134
Loss in rose trees	291,277	285,728	280,240
Loss in nut trees	476,837	514,089	550,770
Total agriculture losses[a]	2,074,585	2,365,697	2,654,144
Annual agriculture losses	259,323	295,712	331,768
Annual cost of goat meal[b]	3,512,000	3,947,488	4,382,976
Annual cost of bottled water[c]	107,827	336,960	943,487
Total annual costs (US$)	3,879,150	4,580,160	5,658,231

[a] Calculated based on the decrease in the number of pomegranate, rose, and nut trees (Agricultural Censuses 2005–2013), and the estimated decrease in the prices of fruits and bottled rosewater between 2005 and 2013, including the external expenses (e.g. fertilizers, pesticides, labour work, and rose extraction's materials) and the number of farmers and rosewater extractors in the area. Consumer Price Index (CPI) for Oman was used to estimate the change in prices between 2005 and 2013 (The World Bank 2015)

[b] Calculated based on the number of goats in the area (14,048) and the cost of feeding one goat (US$250–312) per year

[c] Calculated based on the number of households in the area of 867 (NCSI 2012), and the minimum, mean, and maximum total annual cost for buying bottled water of 124, 390, and 1088 US$, respectively, per household (questionnaire survey)

Considering that the benefits created by a single hotel in the study area are about US$ 390,000 annually (NCSI 2014), and that there are currently four hotels, the benefits generated by the tourism industry are likely of similar magnitude to the losses to households and to agriculture caused by reduced amounts of water. However, tourism is mainly based around the disappearing agro-ecosystems, which in turn are dependent on the supply of water. If tourism and agriculture are to coexist, there is a clear need to address the issue of water shortages.

Responses

Figure 8 summarizes the major aspects of the DPSIR for water resources in the study area; responses may act towards any element of the DPSI. The major responses have been in the form of development measures, such as digging wells, establishing water distribution networks, maintenance of *aflaj*, and construction of dams, and a scheme to provide desalinated water. All of these rely on the considerable income generated through national oil and gas resources.

Responses acting on pressures

The number of government wells increased from one well in 1984 to 11 in 2014 (MRMWR 2014); these are only available sources for drinking and other domestic purposes to all households and other establishments including hotels. The construction of wells increases the pressure (the rate of abstraction of groundwater) and reduces the state (the amount of groundwater in the area). Actions have been also taken to maintain traditional *aflaj* irrigation systems by reconstructing their channels using cement and blocks, and covering their mother wells, altering the relationship between driver and pressure. This helps to reduce water losses and limit pollution along the channels from the mother well to the farming areas, where different sizes of modern water storage tanks have been constructed to store *aflaj* water for irrigation. The maintenance of *aflaj* and the construction of modern distribution networks result in the relatively more efficient use of water, decreasing the pressure (rate of water abstraction) per unit of water abstracted; these are technological fixes which decouple pressure from state to a certain extent. The government has also constructed three wastewater treatment plants and sewer systems to prevent pollution of water resources and keep them in good quality and suitable for agriculture and drinking and other domestic purposes.

Response acting on state

The number of storage dams constructed by the government increased from 26 in 1994 to 50 in 2014 (MRMWR 2014). This response acts directly on the state by increasing the absolute amount of available water in the system. The current major response taken by the government is the construction of a scheme to pipe desalinated water from the coast up to the study area, at a total cost of approximately US$75 million. This will also act directly to address the state (quantity of water resources) by bringing new water to

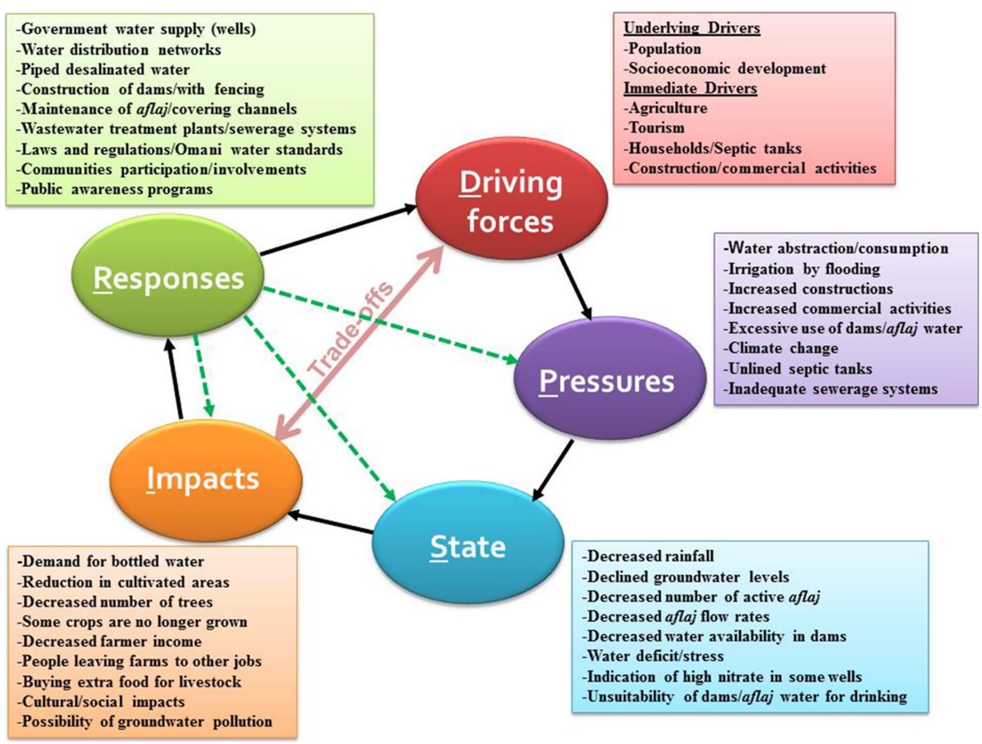

Fig. 8 DPSIR framework scheme for water resources of the study area in 2012–2013

the area. However, this measure introduces reliance for water on an external supply, with high costs of producing desalinated water by reverse osmosis and transporting it over a distance of around 155 km and from sea level to an altitude of about 2500 m.

Response acting within the social system

In addition to the physical measures and the development of infrastructure, responses have been directed towards the social part of the system, to encourage changes in behaviour through community participation and involvement. These include public awareness programmes and campaigns on water issues using various media—such as leaflets, brochures, newspaper articles, radio, and TV broadcasts—to heighten awareness of the need for, and benefits of, reducing water consumption, linked to water conservation and management. Communities have been also involved in making decisions on digging new wells, establishing water distribution networks, constructing dams, and maintaining *aflaj*. Local people are called to meetings related to water issues and invited to attend symposia, conferences, and agricultural extension activities organized by different government organizations.

Discussion

Population growth, agriculture, and tourism are the major driving forces exerting pressures on the water systems of Al Jabal Al Akhdar. The rapid recent socio-economic development, combined with the pressure of an increasingly dry climate, have greatly altered water-use practices and reduced the quality and quantity of water. The remarkable agricultural terraces, coupled with the relatively cool climate and the recently improved transport links, attract increasing numbers of visitors, but their arrival threatens the social–ecological system of this agro-pastoral oasis which is a key element of the attraction. The government has recognized need for improved water management and directed responses at reducing pressures on water resources as well as improving their state. The analysis also recognizes the exogenous pressure of a changing climate and in turn can be used in designing proportional response measures directed at the appropriate elements of the social–ecological system.

Our analysis of changes in welfare (impacts) through reduced agricultural area and domestic supply, though based on imperfect data, indicates that the absolute magnitude of the economic costs is around US$5 million annually, and that they are likely offset by the economic benefits generated by tourism. However, if the decline in agriculture continues along current trends, further annual losses will be incurred. This decline in agriculture may also undermine the tourism industry which is dependent on it. Therefore, there is a clear need to improve water management, balancing the needs of agriculture, tourism, and households.

Given that the rapid local development in the area, which is placing increasing pressure on water resources, is taking place alongside measures to improve water quality and quantity, it is not possible to provide objective metrics for the relative success of specific measures to manage water resources or to compare them to other such measures. All elements of the social–ecological system are in a constant state of flux, and specific improvements in management and their results cannot be isolated from increasing pressures and the state changes they cause. Nevertheless, from the perspective of sustainability, certain initiatives may be seen to be more successful than others. The construction of wells, a response directed at state, improves the efficiency of water abstraction, alleviating the problems of current water availability, but places increasing pressure on the resource and does not address the problem of water deficit.

The major investment in increasing the amount of water in the area is the construction of a pipeline to carry desalinated water up to the region. The cost of desalinated water transported from the coast, based on a similar project in Sana'a (Yemen), is in the order of US$ 3.6/m^3 (ESCWA 2009). Based on the current rates of water use, the cost to meet the total demand for water (domestic and bottled) with desalinated water would be around US$ 2 million annually, approximately double the existing cost of domestic and bottled water. Comparing the US$ 75 million cost of constructing the pipeline combined with the high cost of desalinated water with the average annual economic return from the four hotels in Al Jabal Al Akhdar (~US$ 1.2 million), it is clear that significant further economic development in the region will be required to justify the cost of the pipeline desalinated water project. Over the long term, the use of desalinated water means that the region's socio-economic development will depend on a continued supply of energy for water. This energy is currently anticipated to come from fossil fuels. The future viability of Al Jabal Al Akhdar will therefore be vulnerable to fluctuations in the price of global energy markets, and this solution to local water shortage will also exacerbate the exogenous pressure of changing climate at global as well as local scales. While the nation is currently fortunate to have access to these significant sources of wealth through oil rents, policies to ensure the long-term viability of Al Jabal Al Akhdar cannot rely indefinitely on these sources of revenue.

Desalinated water cannot be used for agriculture because it is very expensive. Though increased domestic water supply from a desalinated source may alleviate some of the pressure on the existing groundwater resources, this will not obviate the need for continued careful management of water supply and use for agriculture, domestic use, and tourism, particularly if the current trend of diminishing annual rainfall continues.

Responses directed at pressures (*aflaj* maintenance, modern distribution networks) at least need to ensure that the resource which is available is used more efficiently. Given that further development is planned for the region, there is further potential for improvement in such measures. Very few policies tackle the driving forces, which are the root causes of changes in water resources in the area. The advantage of considering trade-offs between agricultural and tourist drivers is that there is potential to balance development around the limiting resource to adapt to any potential future declines in water availability driven by climate.

Conclusions

Al Jabal Al Akhdar is challenged by increasing drivers and pressures on water resources associated with economic development as well as the exogenous pressure imposed by a changing climate. Though many strategies have been employed to improve the management of water resources, the continued survival of the agro-pastoral oasis system is still under threat.

Water is precious in the area as in many regions of Middle East and North Africa (MENA), and our analysis indicates that there is a trade-off to be made regarding the rate and scale of economic development and the continued supply of water for agriculture. Explicit recognition of this trade-off may help to prioritize drivers. The scale of investment to supply desalinated water suggests that economic development has already been implicitly favoured over the continuation of the traditional agricultural practices.

However, since the burgeoning tourism industry is focused around the agro-pastoral systems and the ecosystem services they provide, further measures to ensure the continuity of the agricultural activities are required. Balancing use between the agricultural and tourism sectors could be achieved by implementing a pricing system for tourist establishments that not only reflects the actual costs of drinking water management efforts but also incorporates the dependence of the tourism sector on agriculture, subsidizing infrastructure, and management practices to foster the more efficient use of water for irrigation. Such a policy should be supported by strong regulations to encourage proactive implementation of sustainable water management practices.

Efforts should also be directed towards improving water-use efficiency through the expansion of water distribution networks, installation of modern irrigation systems, water conservation techniques, use of greywater and treated wastewater, rainwater harvesting, changing traditional agricultural practices, more investments to expand sewerage systems and increase the capacity of wastewater treatment plants, regular water quality monitoring programmes, better coordination between government agencies, strengthening community participation, and involvement in management process and decisions, as well as integrated water resources management along with climate change mitigation and adaptation measures.

Many mountains across the MENA region face similar challenges in terms of adaptation to altering climatic conditions as well as continuing sustainable human development. This system's approach to analysis has proved useful for approaching the problem of water resources in this study. Consequently, there is potential for further specific and comparative international studies of water resources management in similar semi-arid mountain regions (for example in Lebanon, Morocco, Saudi Arabia, Syria, Tunisia, and Yemen) to improve our understanding and develop best practices for sustainable development in these regions.

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