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Article

Vulnerability Assessment of Environmental and Climate Change Impacts on Water Resources in Al Jabal Al Akhdar, Sultanate of Oman

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Abstract: Climate change and its consequences present one of the most important threats to water resources systems which are vulnerable to such changes due to their limited adaptive capacity. Water resources in arid mountain regions, such as Al Jabal Al Akhdar; northern Sultanate of Oman, are vulnerable to the potential adverse impacts of environmental and climate change. Besides climatic change, current demographic trends, economic development and related land use changes are exerting pressures and have direct impacts on increasing demands for water resources and their vulnerability. In this study, vulnerability assessment was carried out using guidelines prepared by United Nations Environment Programme (UNEP) and Peking University to evaluate four components of the water resource system: water resources stress, water development pressure, ecological health, and management capacity. The calculated vulnerability index (VI) was high, indicating that the water resources are experiencing levels of stress. Ecosystem deterioration was the dominant parameter and management capacity was the dominant category driving the vulnerability on water resources. The vulnerability assessment will support policy and decision makers in evaluating options to modify existing policies. It will also help in developing long-term strategic plans for climate change mitigation and adaptation measures and implement effective policies for sustainable water resources management, and therefore the sustenance of human wellbeing in the region.

Keywords: vulnerability index; water resources stress; development pressure; ecological health; management capacity; climate change; adaptation; mitigation; Al Jabal Al Akhdar; Oman

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1. Introduction

Freshwater resources are key ecosystem services which sustain life and all social and economic processes. Their disruption threatens the health of ecological systems, people's livelihoods and general human wellbeing. However, water resources are being degraded as a result of multiple interacting pressures [1], particularly environmental and climate changes. The Fourth and Fifth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) played a major role in framing understanding of likely impacts of climate change on human society and natural systems, making it clear that "water is in the eye of the climate management storm" [2–4]. Different possible threats resulting from anthropogenic climate change include temperature increases, shifts of climate zones, sea level rise, droughts, floods, and other extreme weather events [5]. The Earth's surface temperature has increased by about 0.5 °C during the last two decades, and a rise with similar amplitude is expected up to 2025, with direct effects on the global hydrological cycle, impacting water availability and demand [2–4]. Negative impacts on water availability and on the health of freshwater ecosystems will have negative consequences for social and ecological systems and their processes [6]. For example, with an approximately 2 °C global-mean temperature rise, around 59% of the world's population would be exposed to irrigation water shortage [7].

Besides climate change impacts, other drivers of environmental changes such as demographic trends, economic development and urbanization and related land-use changes are exerting pressures and increase demand for water resources [8]. Together, these drivers are stressing water resources far beyond the changes caused by natural global climatic changes in the recent evolutionary past. As a result of rapid population growth and economic development, and mismanagement of water resources, these drivers exert pressures on water resources, changing them both spatially and temporally and causing imbalances between supply and demand in hydrological systems [9]. The net effects can be translated into increases in the vulnerability of water resources systems. These systems are especially vulnerable to such changes because of their limited adaptive capacity, which can create major challenges for future management of water resources for human and ecosystem needs [10]. Therefore, there is a need to assess the vulnerability of water resources in order to enhance management capacity and adapt measures to cope with these changes for sustainable water resources use and management.

Vulnerability is a term commonly used to describe a weakness or flaw in a system; its susceptibility to a specific threat and harmful event. There have been many efforts to use the concept across different fields which are often location or sector specific. A variety of definitions of vulnerability have been proposed in the climate change literature, e.g., [11–18]. Common to most is the concept that vulnerability is a function of the exposure and sensitivity of a system to a climate hazard, and the ability to adapt to the effects of the hazard [15,19]. From a social point of view, vulnerability is defined as the exposure of individuals or collective groups to livelihood stress as a result of the impacts of such environmental change or climate extremes [17,20]. In this context, vulnerability can be explained by a combination of social factors and environmental risk, where risk derives from physical aspects of climate-related hazards exogenous to the social system [21–24]. Vulnerability to climate change is generally understood to be a function of a range of biophysical and socioeconomic factors. It is considered a function of wealth, technology, education, information, skills, infrastructure, access to resources, and stability and management capabilities [14,25]. The IPCC has defined vulnerability to climate change as the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes [26,27]. Vulnerability is also a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity [28,29]. It is widely seen as an integrative concept that can link the social and biophysical dimensions of environmental change [30,31].

Nevertheless, "vulnerability" means different things to different researchers. From a water resources perspective, vulnerability has been defined as "the characteristics of water resources system's weakness and flaws that make the system difficult to be functional in the face of socioeconomic and environmental change" [10] (p. 2). Thus, water resources vulnerability assessment is an investigative and analytical process to evaluate the sensitivity of a water system to potential threats and identify challenges in mitigating the risks associated with negative impacts, in order to support water resources conservation and management under climate and environmental changes [10]. It is a tool to identify potential risks, helping to analyse specific aspects that contribute to overall risk. It therefore provides useful information to the manager about which components should receive more focus, in order to improve water management capacity towards sustainability in adapting to the changing climate and environmental factors.

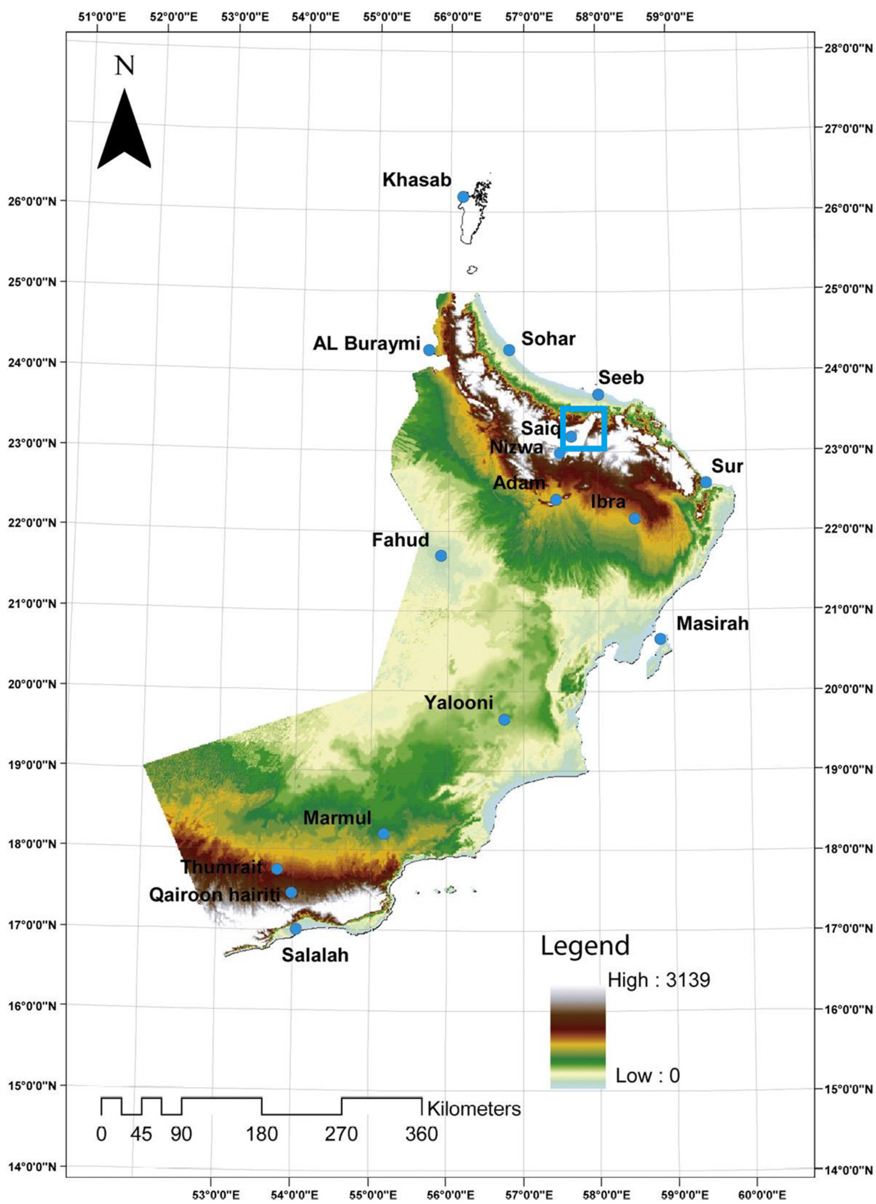
Most water-stressed arid countries are vulnerable to the potential adverse impacts of climate change; particularly increases in temperatures, less and more erratic precipitation, drought and desertification. This is especially true in arid mountain regions, particularly Al Jabal Al Akhdar where a unique set of water management practices has enabled the development and survival, over centuries, of an agro-pastoral oasis social-ecological system. This study was conducted to assess the environmental and climate change impacts on water resources of Al Jabal Al Akhdar since no vulnerability assessments have been previously conducted in Oman or in this fragile mountain ecosystem.

The overall aim of this study was to estimate the vulnerability index of water resources of Al Jabal Al Akhdar to climate and environmental changes, to establish to what extent these resources are vulnerable and identify the major risks and levels of stress it faces with regard to water stress, development pressure, ecological health and management capacity. These are essential components for computing vulnerability index and assessing water resources in the region. The results should provide decision-makers with options to evaluate the current situation, modify existing policies, and implement adaptation and mitigation measures for sustainable water resources management in the study area.

2. The Study Area

Al Jabal Al Akhdar (Green Mountain) is located in the central part of the northern western Al-Hajar Mountains of the Sultanate of Oman (Figure 1), in the highest portion of 1500 to 3000 m above sea level [32]. It is a long-established agro-pastoral oasis ecosystem which has supported communities for centuries [32]. Until the late 20th century, this social ecological system has been geographically isolated and, compared to many places, relatively closed to the outside world. Historically, water availability has connected the agro-pastoral system and dictated the bounds of agricultural development and the human development. The area is also of particular cultural significance for Omani people for its location, topography, agricultural terraces, biodiversity and climate.

Figure 1. Oman map showing the location of Al Jabal Al Akhdar (in blue rectangle).



Al Jabal Al Akhdar has a Mediterranean climate. Because of its altitude, temperatures are some 10 to 12 °C lower than in the coastal plains. In general, mean monthly temperatures drop during winter to below 0 °C and rise in summer to around 22 °C. Temperature records from Saiq Meteorology Station (the only one in the area, part of Oman's national climate monitoring network), from 1979 to 2012 show mean monthly air temperatures from February to April from 12.1 to 18.7 °C and around 25 °C during summer (July and August). Minimum temperatures ranged from −0.6 °C in January to 15.9 °C in July, and maximum temperatures from 20.3 °C in January to 33.5 °C in July [33]. Rainfall is highly variable and irregular with an annual mean of about 250–400 mm [33] and is the main source of fresh water. There are two distinct rainfall seasons: the winter season from mid-November through March, and the summer season from mid-June through mid-September. From 1979 to 2012, the average annual rainfall was 295.3 mm, with the highest monthly averages of 45.8 and 42 mm during August and July; and the lowest of 8.8 and 8.2 mm during October and November, respectively [33].

Agriculture is the main economic activity, providing the basis of livelihoods for around 70% of the inhabitants [34]. Although the sector does not contribute much to the national economy (only 3.7% of the total Oman GDP), it is the main dominant water consumer in Oman including the study area (more than 92% of the total available water) [35]. The area produces a variety of fruits, particularly pomegranates and roses (grown for the extraction of rose water), which are sold in the local markets as the major sources of income for farmers. Annual crops such as garlic, onion, maize, barley, oats and alfalfa are sometimes planted in the terraces depending on the availability of water. The area also has several endangered or vulnerable species of flora and fauna that are not found elsewhere in Oman [36].

Livestock husbandry is also an important part of the agriculture in the area, for food and income through the sale of fibre (goat and sheep hair), and provides a source of manure for the cultivation of crops. Goats are the main livestock in local communities, representing more than 80% of the total animal units [37].

Due to its relatively cool weather, especially during summer, and the construction of asphalted access road up to the mountain in 2006, followed by the construction of hotels, many tourists visit the area, mainly to see natural landscapes and agricultural terraces and to camp. There has been an increase in the number of hotels in the study area, from one in 2006 to four in 2014, plus other holiday apartments and rest houses. The number of tourists has increased by 58% from 85,000 in 2006 to 134,000 in 2013 [37].

Natural freshwater resources in Al Jabal Al Akhdar are of three types: groundwater (wells), lotic resources (natural springs and *aflaj*) and lentic resources (man-made dams) [38]. Groundwater is accessed via wells established by a government agency which supplies the water to the communities through networks or water trucks. These wells are the main local source of water for drinking and domestic purposes (municipal, commercial) in the area. *Aflaj* are surface and/or underground channels fed by groundwater or a spring, or streams, built to provide water to the farming communities. The *aflaj* water is managed and distributed to farming areas by local people with no involvement of government in their organizational structure. Dams are artificial structures which are constructed by the government to harvest rainy water. *Aflaj* and dam water are mainly used for agriculture and livestock.

Al Jabal Al Akhdar has limited and highly variable water supplies: the most significant parameters influencing freshwater availability and causing environmental stress are the amount and frequency of rainfall. According to the climate change projection for the country [39], the variability of rainfall is expected to further increase, adding more uncertainty and complication to the planning and management of water resources. Furthermore, the population of the area has grown rapidly, from less than 2000 in 1970 to over 7000 in 2010 [40]. Socioeconomic development and related land-use changes due to the expansion of infrastructure and services, construction and commercial activities and urbanization have direct impacts in terms of increasing demand for water resources [37]. The establishment of settlements has been influenced strongly by the availability of water for drinking and domestic uses; all people have access to safe and good quality drinking water [37]. Together, the anthropogenic activities and climate change have affected the availability of water resources, and if these trends continue, the area's ecosystems and residence's households will be further affected. Vulnerability assessment of the environmental and climate change impacts on water resources is therefore essential to inform sustainable water resources management in the area.

3. Methodology

The methodological guidelines for "Vulnerability Assessment of Freshwater Resources to Environmental Change", developed by United Nations Environment Programme (UNEP) and Peking University [10] were used to assess the vulnerability of water resources of Al Jabal Al Akhdar to environmental change and climate impacts. According to the guidelines, the vulnerability of water resources can be assessed from two perspectives: the main threats to water resources and their development and utilization dynamics; and the region's challenges in coping with these threats. The threats can be assessed in terms of resource stresses (RS), development pressure (DP), ecological health (EH) and management capacity (MC). Thus, the vulnerability index (VI) of the water resources can be expressed as: VI = f (RS, DP, EH, MC) [10].

Each component of VI has several parameters: RS = f [water stress (RS_s) and water variation (RS_v)]; DP = f [water exploitation (DP_s) and safe drinking water inaccessibility (DP_d)]; EH = f [water pollution (EH_p) and ecosystem deterioration (EH_e)]; MC = f [water use inefficiency (MC_e), improved sanitation inaccessibility (MC_s), and conflict management capacity (MC_g)]. In accordance with the vulnerability assessment guidelines, a number of governing equations were applied to estimate these parameters and VI (Table 1).

RS determines the water resources availability to meet the pressure of water demands for the growing population taking into consideration the rainfall variability. Therefore, it is influenced by the renewable water resources stress (RS_s) and water variation parameter resulting from long-term rainfall variability (RS_v). RS_s is expressed as per capita water resources and usually compared to the internationally agreed water poverty index of per capita water resources (1700 m^3/person/year) [10]. As Oman is part of West Asia, characterized by scarce water resources, the more appropriate and realistic value of 1000 m^3/person/year [9] was used. RS_v was estimated by the coefficient of variation (CV) of the rainfall record from 1979 to 2012, obtained from Saiq Meteorology Station. The CV was estimated by the ratio of the standard deviation of the rainfall record to the average rainfall (Table 1).

DP was estimated in terms of the overexploitation of water resources (DP_s) and the provision and accessibility of safe drinking water supply (DP_d). DP_s was estimated by the ratio of the total water demands (domestic, commercial, agriculture) to the total renewable water resources (Table 1). DP_d is defined here as the provision of adequate drinking water supplies to meet the basic needs for the society, in regard to how the water development facilities address the population needs [9]. The lack of safe water accessibility was estimated by the ratio of the percentage of population lacking accessibility to the size of the population (Table 1).

Table 1. Equations used for calculation of all categories and parameters of vulnerability index of water resources in the study area.

Category	Parameter	Equation	Description
Resource Stress (RS)	RS_s	$RS_s = (1000 - R)/1000$	R: Total renewable water resources per capita (m^3/person/year)
	RS_v	$RS_v = CV/0.3$ $CV = S/\mu$	CV: Coefficient of variation μ: Mean rainfall (mm) S: Standard deviation
Development Pressures (DP)	DP_s	$DP_s = WRs/WR$	WRs: Total water demands WR: Total renewable water resources
	DP_d	$DP_d = P_d/P$	P_d: Population without access to improved drinking water sources P: Total population of the area
Ecological Health (EH)	EH_p	$EH_p = (WW/WR)/0.1$	WW: Total untreated wastewater WR: Total renewable water resources
	EH_e	$EH_e = A_d/A$	A_d: Land area without vegetation coverage A: Total area of the country
Management Capacity (MC)	MCe	$MC_e = (WE_{wm} - WE)/WE_{wm}$	WE: GDP value produced from 1 m^3 of water WE_{wm}: Mean WE of West Asia countries
	MC_s	$MC_s = P_d/P$	P_d: Population without access to improved sanitation P: Total population of the area
	MC_g	MC_g = parameter matrix	Matrix scoring criteria (Table 2)
$VI = \sum_{i=1}^{n}\left[\left(\sum_{j=1}^{m_i} x_{ij} * w_{ij}\right) * w_i\right]$			n: number of parameter category m_i: number of parameters in ith category X_{ij}: value of jth parameter in ith category W_{ij}: Weight given to jth parameter in ith category W_i: Weight given to ith category

EH was measured in terms of the water quality/water pollution parameter (EH_p) and the ecosystem deterioration parameter (EH_e). EH_p was estimated by the ratio of the total untreated wastewater discharge in water receiving systems to the total available renewable water resources (Table 1). The amount of untreated wastewater is estimated as the difference between the generated wastewater collected by the system and amount of wastewater that received treatment. EH_e is defined in this study as the ratio of land area without vegetation coverage (*i.e.*, total land area except that covered with pastures and cultivated areas) to the total land area of Oman (309,500 km^2) (Table 1).

MC assesses the vulnerability of water resources by evaluating the current management capacity to cope with three critical issues: efficiency of water resources use; human health in relation to accessibility to adequate and safe sanitation services; and overall conflict management capacity. Thus, MC was measured with Water use inefficiency parameter (MC_e), Improved Sanitation inaccessibility parameter (MC_s), and Conflict Management Capacity Parameter (MC_g). MC_e was estimated in terms of the financial contribution to gross domestic product (GDP) of one cubic meter of water in any of the water consuming sectors compared to the world average for a selection of countries [10]. Since the agriculture sector is the major consumer of water in Oman, including the study area, it was used to indicate the financial return from the water use. Therefore, MC_e was calculated using US $40 as the mean GDP value produced from 1 m^3 of water for the countries of West Asia [9] (Table 1). MC_s was used as a typical value to measure the capacity of the management system to deal with livelihood improvement in reducing pollution levels. Improved sanitation was defined here as facilities that hygienically separate human excreta from human, animal and insect contact, including sewers, septic tanks, flush toilets, latrines and simple pits [10]. MC_s was estimated as the ratio of proportion of the population without accessibility to improved sanitation facilities to the total population of the area (Table 1). MC_g demonstrates the capacity of a water resources management system to deal with conflicts. A good management system can be assessed by its effectiveness in institutional arrangements, policy formulation, communication mechanisms, and implementation efficiency [10]. The parameter was defined here as the capacity of the area to manage competition over water utilization among different consuming sectors. MC_g was determined based on water assessment survey [37] and expert consultation [41] using conflict management capacity scoring criteria ranging from 0.0 to 0.25 (Table 2), taking into consideration the interrelation of all variables in this table. These aspects were assigned scoring criteria ranging from 0 to 1 giving weights to each parameter.

Table 2. Conflict management capacity parameter assessment matrix (Source: [10]).

Category of Capacity	Description	Scoring Criteria		
		0.0	0.125	0.25
Institutional capacity	Trans-boundary institutional arrangement for coordinated water resources management	Solid institutional arrangements	Loose institutional arrangements	No existing institutions
Agreement capacity	Writing/signed policy/ agreement for water resources management	Concrete/detailed agreement	General agreement only	No agreement
Communication capacity	Routine communication mechanism for water resources management (annual conferences, *etc.*)	Communications at policy and operational levels	Communications only at policy level or operational level	No communication mechanism
Implementation capacity	Water resources management cooperation actions	Effective implementation of basin-wide river projects/programs	With joint project/ program, but poor management	No joint project program

Because the process of determining relative weights can be biased, making it difficult to compare the final results, equal weights were assigned among the parameters in the same category, and also among different categories. According to the guidelines [10], the weight of 0.25 was assigned across all categories (RS, DP, EH, and MC). For parameters RS_s, RS_v, DP_s, DP_d, EH_p and EH_e, the weight of 0.5 was applied, and for parameters MC_e, MC_s, and MC_g, the weight of 0.33 was assigned. The total weights given to all parameters in each category should be equal to 1, and the total weights given to all categories should be also equal to 1 [10].

The vulnerability index (VI) was finally estimated based on the four categories using the equation in Table 1. VI provides an estimated value ranging from zero (non-vulnerable) to one (most vulnerable) to determine the severity of the stress being experienced by the water resources of the study area. A high VI value shows high resource stresses, development pressures and ecological health, and low management capacities.

4. Results and Discussion

4.1. Resource Stresses

4.1.1. Water Stress Parameter

The calculation of water stress for Oman, including the study area, shows a critical water stress (RS_s = 0.58) (Table 3) based on the estimated total renewable water resources per capita of 422.5 m^3/person/year [42]. The increase in population and rapid socioeconomic development in Al Jabal Al Akhdar exert pressures on water resources: domestic water consumption increased from 150,000 m^3 in 2001 to 580,000 m^3 in 2012; an annual increase of 35% per year [37]. Much of this increase may be due to the burgeoning tourist industry. For 1985, 1995, and 2005, the calculated RS_s for Oman were 0.0, 0.30, and 0.36 based on the estimated per capita renewable water resources of 1029.35, 697.76 and 635.84 m^3/person/year, respectively [9].

Table 3. Calculated Vulnerability Index with various categories and parameters for the water resources of the study area.

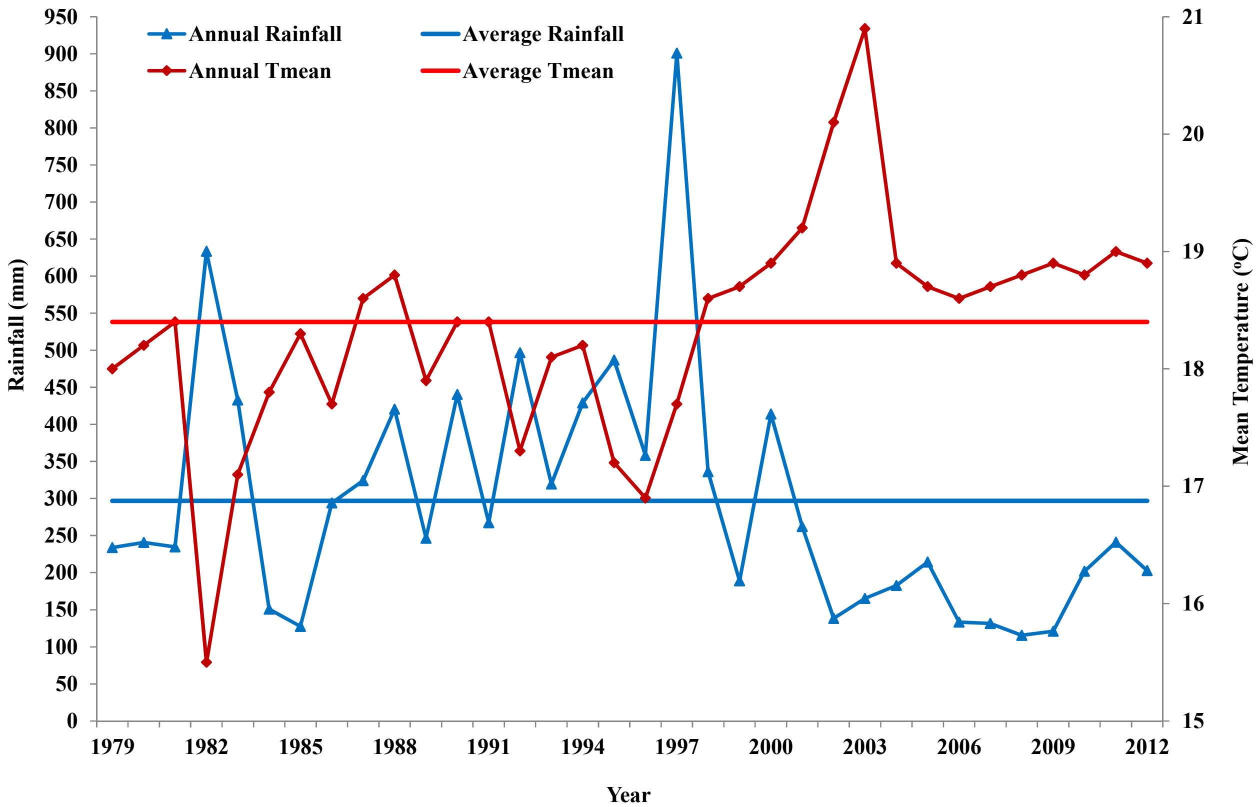
Category	Resource Stress		Development Pressure		Ecological Health		Management Capacity		
Parameter	RSs	RS_v	DP_s	DP_d	EH_p	EH_e	MC_e	MC_s	MC_g
Calculated	0.580	0.330	0.210	0.000	0.140	0.940	1.000	0.000	0.950
Weight in Category	0.50	0.50	0.50	0.50	0.50	0.50	0.33	0.33	0.33
Weighted	0.290	0.165	0.105	0.000	0.070	0.470	0.330	0.000	0.314
Component Total	0.4550		0.1050		0.5400		0.6435		
Weight for Category	0.25		0.25		0.25		0.25		
Weighted	**0.1138**		**0.0263**		**0.1350**		**0.1609**		
Overall Score	**0.436 (High)**								

Notes: Water Stress (RS_s); Water Variation (RS_v); Water Exploitation (DP_s); Safe Drinking Water Inaccessibility (DP_d); Water Pollution (EH_p); Ecosystem Deterioration (EH_e); Water Use Inefficiency (MC_e); Improved Sanitation Inaccessibility (MC_s); Conflict Management Capacity (MC_g).

4.1.2. Water Variation Parameter

Rainfall amount and availability are the dominant factors in the supply of water resources in the study area. Analysis of rainfall data records from 1979 to 2012 resulted in a water variation parameter (RS_v) of 0.33, based on the estimated CV of 0.10, indicating low rainfall variability. The methodology guidelines [9] designate a set of rainfall variation values for the coefficient of variation as CV = 0.3 or as a CV > 0.3. When CV is > 0.3, RS_v is assigned a highest value of 1, indicating large rainfall variation in time and space; a CV less than 0.3 reflects low variability. However, the study area experienced increasing temperatures over the same period (Figure 2). Minimum, mean and maximum temperatures increased at rates of 0.79, 0.27 and 0.15 °C per decade, respectively. Analysis of rainfall data showed a reduction in water availability, with a general decrease in total rainfall from 1979 to 2012 (Figure 2). Over this period, the average rainfall was 296.7 mm; the highest total was in 1997 (901 mm) and annual 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; indicating that the area is vulnerable to climate change as it is an arid mountain region. Projection of future climate in Oman using the IPCC A1B scenario shows an increase in temperature and a decrease in rainfall over the coming decades [39].

Figure 2. Trends in mean air temperature (Tmean) and annual rainfall in Saiq Meteorology Station (World Meteorological Organization (WMO) Index: 41254, Universal Transverse Mercator (UTM) coordinates Latitude: 23°04'28.33" N, Longitude: 57°38'46.63" E, Elevation: 1986 m) from 1979 to 2012 (Data source: [33]).



4.2. Water Development Pressures

4.2.1. Water Exploitation Parameter

The assessment of water development pressures indicated that the study area suffers from critical conditions in the development of water resources as determined by the water exploitation parameter (DP_s = 0.21) based on total water demands of 14 million m^3/year and the available total water resources of 66 million m^3/year [35] (Table 3), resulting in water shortages for domestic and agricultural purposes. There have been increases in the total population and socioeconomic development as well as increases in construction and commercial activities including hotels, and therefore water consumption by different sectors, causing an imbalance between supply and demand in the absence of the implementation of any conservation and management practices.

4.2.2. Safe Drinking Water Inaccessibility Parameter

The calculated safe drinking water inaccessibility parameter (DP_d) was zero since the fundamental needs of the population for water to live are met. There is sufficient infrastructure for providing drinking water throughout the study area; all people have access to safe drinking water. The government supplies drinking water to all households via groundwater wells, and a piped desalinated water project is in progress, to increase the availability of drinking water in the area.

4.3. Ecological Health

4.3.1. Water Pollution Parameter

The estimated water pollution parameter value was (EH_p = 0.14) (Table 3) based on the total untreated wastewater of 945,250 m^3/year [43] and the total available water resources of 66 million m^3/year, given that the urban water usage is 1.1 million m^3/year [35]. The analysis indicates low water pollution risks, which may be attributed to investments in wastewater treatment facilities: the government has established three wastewater treatment plants in the area with tertiary treatment levels and some sewerage systems, and all modern houses and other establishments have septic tanks. However, more investments are needed to increase the proportion of sewer networks connected with the treatment plants. Moreover, some septic tanks in old houses have unlined foundations [43], and need to be reconstructed to avoid pollution to groundwater aquifers.

4.3.2. Ecosystem Deterioration Parameter

Ecosystem deterioration due to the absence of adequate vegetation cover and modified natural landscape is a critical parameter in Oman including the study area, causing severe problems in supporting the functioning of ecosystems. EH_e was calculated as 0.94, based on the evaluation report of the land degradation and desertification in Arab Region [44] including Oman, as there is no available data on ecosystem deterioration for Al Jabal Al Akhdar. There are some indications of ecosystem deterioration in the study area due to decreased rainfall over the last three decades and therefore a decline of groundwater levels and the drying up of most *aflaj* [37]. The population growth, associated with anthropogenic activities and socioeconomic development, and overgrazing, as well as water overconsumption and expansion of land uses through sustained urbanization, have contributed directly or indirectly to the vulnerability of the water resources. The world map of the status of human-induced soil degradation [45] shows that the primary factor contributing to soil degradation in the Al-Hajar Mountains is loss of topsoil through water erosion, with 25%–50% of the area affected by a moderate degree of degradation. According to the study of desertification in the Arab Region by ACSAD (1997) as reported by [46], 89% of Oman was considered as desertified and 7.67% as vulnerable to desertification.

4.4. Management Capacity

4.4.1. Water Use Inefficiency Parameter

Based on the 2013 GDP of Oman (US$80.6 billion) [47] and the total water withdrawal of 1321 million m^3/year [42], the calculated water use inefficiency (MC_e) was zero. This is in agreement with [9] which concluded that Oman showed the greatest efficiency gains (decreasing inefficiency) in the West Asia region between 1985 and 2005 (decrease of 25.37%). This was attributed to the uptake of more modern and efficient irrigation infrastructure systems.

However, this parameter was not calculated for the study area since it is based on the country scale and cannot be estimated at a regional scale. In Al Jabal Al Akhdar, farmers still use a traditional method of irrigation by flooding, with no application of modern irrigation technology or investments in improving irrigation infrastructure systems. Based on water assessment survey [37] and personal communication [41] with the author of the UNEP report [9] on this situation, MC_e for the study area was estimated as 1, representing high water use inefficiency. This indicates unsustainable water resources management practices in the absence of a comprehensive water sector plan and strategy, leading to reduced water availability and increased vulnerability.

4.4.2. Improved Sanitation Inaccessibility Parameter

The entire population of the study area has access to sanitation facilities, such as sewer systems, septic tanks and wastewater treatment plants ($MC_s = 0$) (Table 3), indicating adequate management regarding livelihood improvement through government investment in sanitation infrastructure. The availability of this infrastructure reduces pollution levels and preserves water resources, complemented by the implementation of policies and measures which may reduce the vulnerability of water resources to environmental and climate changes. However, more investments to expand the sewerage systems, connecting all households and other establishments to the wastewater treatment plants, are needed.

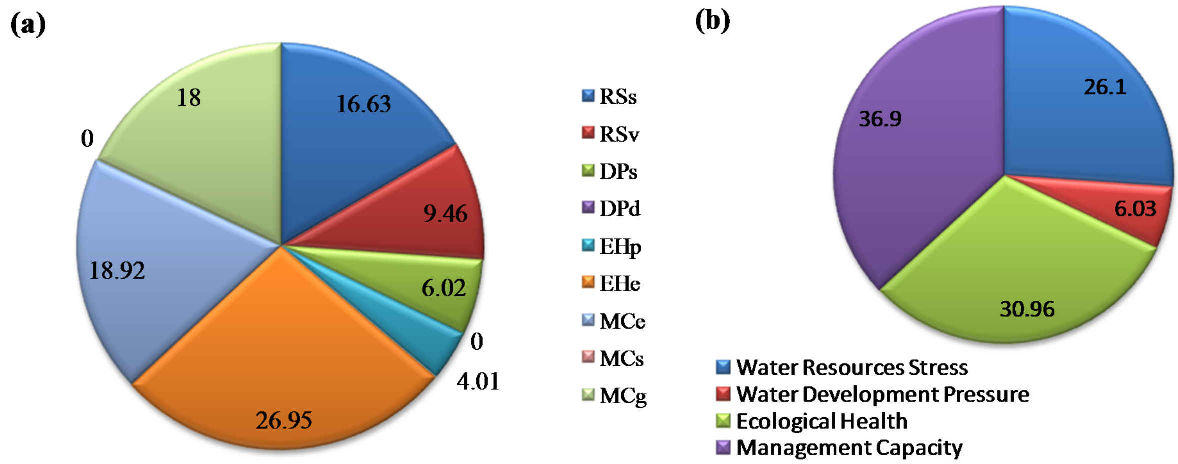
4.4.3. Conflict Management Capacity Parameter

The study area has no competition over water utilization with the neighboring regions. However, there is competition over water utilization between different sectors (agriculture and domestic). Agriculture is the dominant water consumer, with no application of conservation mechanisms and proper management capacity. There is also an increase in the domestic water consumption from groundwater wells, due to an increase in population and number of hotels and commercial activities, and there is no clear strategy for the development of the area [37]. Therefore, the assessment of MC_g showed a high vulnerability situation in regard to conflict management capacity ($MC_g = 0.95$) since this parameter takes into consideration the interrelation of different categories including institutional, agreement, communication and implementation capacity.

4.5. Vulnerability Index

Based on the available data, the calculated VI is 0.436, in the range of 0.4–0.7 which is classified as high based on the reference sheet for the interpretation of VI [10], indicating that the water resources of Al Jabal Al Akhdar are highly vulnerable and experiencing high stresses. Ecosystem deterioration is the dominant parameter, contributing 27% (Figure 3a). The area has also been experiencing a high degree of water use inefficiency, conflict management capacity and water stress representing 19%, 18% and 17%, respectively (Figure 3a), influencing the overall vulnerability on water resources. Comparison of the share of the different category groups to the final VI showed that the management capacity contributes most to the water resources vulnerability and is the dominant category (37%), followed by ecological health with 31% and water resources stress with 26% (Figure 3b).

Figure 3. (**a**) Percentage of the weighted parameters for Vulnerability Index; (**b**) Share of the percentage of the weighted categories to the final Vulnerability Index for the study area.



Notes: Water Stress (RS_s); Water Variation (RS_v); Water Exploitation (DP_s); Safe Drinking Water Inaccessibility (DP_d); Water Pollution (EH_p); Ecosystem Deterioration (EH_e); Water Use Inefficiency (MC_e); Improved Sanitation Inaccessibility (MC_s); Conflict Management Capacity (MC_g).

5. Conclusions and Recommendations

This is the first comprehensive vulnerability assessment of water resources in Al Jabal Al Akhdar, or Oman. The results have served to highlight which aspects of water management (resources stress, development pressure, ecological health, and management capacity) contribute most to the vulnerability of water resources and to understand the various risks and thus to suggest potential areas to best focus management efforts. The vulnerability assessment indicated high VI (0.436). Ecosystem deterioration is the dominant parameter contributing 27% to the vulnerability index. The water resources of the area have also been experiencing a high degree of water use inefficiency, conflict management capacity and water stress, influencing the overall vulnerability index by 19%, 18% and 17%, respectively. Management capacity is the dominant category, representing 37% of the category groups, driving the vulnerability of the water resources, which are also highly influenced by the ecological health (31%) and water resources stress (26%). These could be used as indicators for the vulnerability of water resources to environmental and climate changes in the study area. Nevertheless, it must be recognized that due to the lack of availability of local data, some of the inputs to the assessment are at national scale.

There is a clear need for policies and technical solutions to mitigate the pressures (water over consumption and inefficient use, ecosystem deterioration, climate change) which make the water resources more vulnerable. A longer term strategic development plan should be made, with a focus on management capacity to deal with the main threats of conflicts between water consuming sectors, as well as implementation of effective management practices in line with the integrated water resources management approach. Additional effort is needed to improve irrigation water use efficiency, conservation technologies, rainwater harvesting, and reuse of treated wastewater and grey water to relieve some of the agricultural pressures on water resources. There is also an urgent need for mitigation and adaptation to climate change impacts since the region is expected to face further increases in temperatures and decreases in rainfall over the coming decades.

The major contribution of ecosystem deterioration to the overall index suggests that, in order to sustain the ecological health of the area, more efforts are needed to conserve and rehabilitate vegetation cover and implement best practices for land use management and strategic development. More investments are also required to expand sewer networks along with the effective use of wastewater treatment facilities to protect freshwater from pollution. Full coordination, integration and awareness on climate change adaptation should be strongly connected to planning, policies and water management programs at all levels and across all sectors. Further research is needed to provide local, rather than national, input data particularly on the deterioration of ecosystem and vegetation cover, long-term climatic data, and socioeconomic trends, to identify the main driving forces that increase the vulnerability of the water resources, in order to define the optimal approaches for climate change adaptation, to be implemented into operational and sustainable water resources management for the green mountain.

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Author Contributions

Mohammed Al Kalbani collected and analyzed the data, and applied the methodology in collaboration with Martin Price and Asma Abahussain. He also performed all calculations and checked the results in collaboration with Mushtaque Ahmed and Timothy O'Higgins. In addition, he evaluated the data and interpretation the results with Asma Abahussain, and enhanced the writing and editing of the paper with Martin Price.

Conflicts of Interest

The authors declare no conflict of interest.

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