INTERNATIONAL JOURNAL OF WATER RESOURCES DEVELOPMENT
https://doi.org/10.1080/07900627.2019.1654440

Routledge
Taylor & Francis Group

Check for updates

Impacts of farming practices on water resources sustainability for arid lands: the case of Abu Dhabi

Ameena Kulaib Al Tenaiji[a], Nuhu Braimah[a] and Sgouris Sgouridis[b]

[a]Department of Civil and Environmental Engineering, Brunel University, Uxbridge, UK; [b]Department of Industrial and System Engineering, Khalifa University of Science Technology and Research, Abu Dhabi, UAE

ABSTRACT

The agricultural expansion in Abu Dhabi Emirate has increased the pressure on the emirate's groundwater reserves, with projections that they will be completely depleted within a few decades. This study quantitatively examines the impacts of current farming practices on the sustainability of groundwater resources. Participants from 344 farms were surveyed. The study found that 76% of the farms rely on groundwater as their main source of water, with significant occurrence of low water productivity. The findings highlight the need to develop and implement effective strategies to maintain the sustainability of groundwater and agricultural development.

ARTICLE HISTORY
Received 28 January 2019
Accepted 6 August 2019

KEYWORDS
Groundwater sustainability; agriculture policy; arid lands; Abu Dhabi farming; food security

Introduction

Since the 1950s, global agricultural production has tripled. A doubling of irrigated areas accounts for 40% of this growth, which in turn has increased the dependency on surface and groundwater resources (De Fraiture & Wichelns, 2010; FAO, 2011; Zingaro, Portoghese, & Giannoccaro, 2017). This increase in productivity was facilitated by technological improvements in drilling, pumping and irrigation (Giordano & Villholth, 2007; Shah, 2014). The agricultural expansion and farmers' management practices and cropping patterns have led to a continuous increase in the use of groundwater (Zingaro et al., 2017), which was estimated in 2010 as 43% of total irrigation water use (De Fraiture & Wichelns, 2010; Siebert et al., 2010).

In arid and semi-arid regions, there is increasing pressure from food security and environmental sustainability concerns to reduce the current depletion rate of groundwater while coping with the increase in food demand (Ouda, 2014; Patil et al., 2015). One of the key ways to respond to this pressure is to optimize water use in agriculture. Two main approaches to optimizing water use in agriculture have been assessed in the literature: improving irrigation efficiency (Al-Said, Ashfaq, Al-Barhi, Hanjra, & Khan, 2012; Playán & Mateos, 2006) and introducing cropping patterns that are based on water use (Al Said et al., 2007; Molden et al., 2010; Ommani, Chizari, Salmanzadeh, & Hosaini, 2009; Patil et al., 2015; Sakthivadivel, De Fraiture, Molden, Perry, & Kloezen, 1999; Wichelns, 2014). Therefore, understanding farming practices, including cropping

CONTACT Ameena Kulaib Al Tenaiji naakulaib@yahoo.com
Supplemental data for this article can be accessed here.

patterns and their respective water use at the farm level, is essential in the decision and policy-making processes intended to optimize agricultural water use (Al-Azwai & Ward, 2017; Jafary & Bradley, 2018).

Abu Dhabi Emirate (ADE), at 67,340 km^2, is the largest of the seven emirates in the United Arab Emirates (UAE), the country with the highest water scarcity (ESCWA, 2009) and the lowest percentage of arable land in the world (Antonelli & Tamea, 2015). Agricultural expansion and government policies concerning domestic agricultural production in ADE have exacerbated the situation (Arthur & Qaydi, 2010; EAD, 2012; Woertz, 2013). Originally, agriculture was developed for cultural reasons as a way to encourage settlement among the historically semi-nomadic tribes and enable social and economic development (Woertz, 2013). This was followed by a notable policy push for food self-sufficiency. However, these policies increase demand for groundwater, which, if current water consumption patterns continue, threatens ADE's resources with complete depletion by 2050 (EAD, 2015; Pitman, McDonnell, & Dawoud, 2009). Hence, there is an urgent need to develop and implement effective policies to regulate farming practices and irrigation water use in ADE, to improve the water productivity of the cultivated crops and manage the available water resources.

One notable obstacle in this effort is the absence of accurate data about current farming practices and their associated water consumption. This creates ambiguity and lack of clarity on what the present challenges of agricultural production are and how to sustainably mitigate them. To address it, this study has two objectives: to quantitatively examine the current farming practices and associated water consumption, and their impacts on groundwater in ADE; and to identify the most important areas that should be regulated to improve farming practices and the water productivity of crops.

Groundwater use and management practices review

The global groundwater use for agriculture is estimated as 43% of the total freshwater withdrawal (Siebert et al., 2010). In the last five decades, the area of irrigated land has more than doubled, most of which has taken place in arid and semi-arid countries (FAO, 2011). This increase was supported by innovative and improved technologies in drilling and irrigation systems (Giordano & Villholth, 2007; Shah, 2014). Worldwide, average groundwater use has increased to about 40% of total irrigated water (Shah, 2014), while it has reached 88% in the Arabian Peninsula and 90% in the Gulf Cooperation Council (GCC) countries: Saudi Arabia, UAE, Kuwait, Oman, Qatar and Bahrain (FAO, 2011). Moreover, climate change, rising average global surface temperatures and changing precipitation patterns are expected to increase the pressure on water resources and limit agricultural productivity (IPCC, 2007). Groundwater recharge may decrease by up to 70% in several areas, including arid and semi-arid regions (IPCC, 2008; UN-Water, 2012). Recent studies project that climate change will have significant impacts on GCC countries, including the UAE, jeopardizing the country's economic, environmental and social development (AGEDI, 2015b; MOCCAE, 2017).

Despite the GCC countries' limited water resources and arable land, which constrain agricultural capacity (ESCWA, 2009), their agricultural development grew rapidly during the last few decades (Arthur & Qaydi, 2010; EAD, 2012; Woertz, 2013). Subsidies were instituted to incentivize agricultural development. These subsidies included unregulated and free groundwater, and free provision of drilling and excavation services, seeds, fertilizers and fuels, as well as guaranteed price off-take support, which distorted the real cost of agricultural production (Bazza, 2005; Woertz, 2011). Inevitably, these policies led to groundwater abstraction that exceeded the annual renewable recharge, and in turn caused the depletion and deterioration of the groundwater aquifers (Woertz, 2011). In the last few years, many GCC countries have realized the negative impact of inefficient groundwater use on their groundwater reserves. For example, the Saudi government has recently decided to end wheat production and rely on imports (Mousa, 2016). Other examples include ADE's decision to phase out the cultivation of fodder crops (Rhodes grass) because of its high water use (McDonnell & Fragaszy, 2016), and its recent initiatives to restrict groundwater abstraction at the farm level (EAD, 2017). However, these initiatives have not fully addressed the issues, and achieving the desired level of regulatory compliance is still a concerning issue.

Recent research on agricultural development has shifted its focus from increasing agricultural production by expanding agricultural lands to increasing water and land productivity (De Pascale, Dalla Costa, Vallone, Barbieri, & Maggio, 2011; Molden et al., 2010; Platonov et al., 2008). Water productivity is the benefit that can be derived from a unit of water applied. It depends on several factors, such as plant genetic material, water management and farming practices, e.g. fertilizers, soil tillage and irrigation scheduling (Molden et al., 2010). Molden et al. (2010) argue that the benefit derived from a unit of water can be expressed in terms of physical mass production or value in revenue per water unit (kg/m^3, \$/m^3). These measures have been used globally in recent studies and are suggested as indicators to assess the productive use of water per crop, especially in water-scarce environments (Ali & Klein, 2014; Al-Said et al., 2012; Kijne, Barker, & Molden, 2003; Platonov et al., 2008).

Most of studies on crop yield, water use and water productivity in the GCC region have been conducted in small-scale fields, at specific conditions and seasons, for limited number of crops, such as palm trees (e.g. Al Said et al., 2007; Bhat et al., 2012; Haj-Amor, Ritzema, Hashemi, & Bouri, 2018), fodder crops (Al-Gaadi, Madugundu, & Tola, 2017; Mazahrih, Al-Wahaibi, Al-Farsi, & Ouled Belgacem, 2016; MOEW, 2010) or vegetable crops (Algharibi et al., 2013; Al-Said et al., 2012; Aly, Al-Omran, & Khasha, 2015). They have found wide variation across the studied farms, due to divergent farming practices and conditions. In ADE and the UAE, the only field studies that actually measured water use were on palm trees (Green et al., 2014) and to assess the water productivity of cucumbers and tomatoes (ADFCA, 2016). The others were based on estimates, such as water use estimates for palm trees (FAO, 2007) and Rhodes grass (MOEW, 2010; Pitman et al., 2009).

Our study targets a large number of farms and their entire portfolio of crops to examine the current farming practices and their water consumption in ADE but also the farmers' perceptions and challenges. We hope it will help the related government entities better appraise the current situation and develop targeted policies to manage it effectively. The next section specifies the area of study and the data collection and analysis methods.

Research methodology

This study covers the Emirate of Abu Dhabi. ADE is located in a semi-arid climate zone within the Arabian Peninsula, and it is characterized by low rainfall, high temperatures (reaching 50 °C in the summer) and high humidity. The average annual rainfall in the UAE varies from less than 60 mm to 160 mm, while the evaporation rate can exceed 2000 mm/y, leading to an estimated 75% loss of precipitation (AGEDI, 2015a; Murad, 2010). The scant precipitation, high temperature and rapid evaporation prevent surface water body formation (Brook, Al Houqani, Darawsha, & Achary, 2006; McDonnell, 2013) and render groundwater effectively a non-renewable resource (McDonnell, 2013; Rizk, 2008). The water abstraction rate is currently over 20 times the estimated recharge rate of 130 Mm^3/y (EAD, 2015; ERWDA, 2002), causing a decline of the water table and salinization (EAD, 2017).

As a result of the support policies discussed in the previous section, the total number of farms (and farm size) increased from 634 farms (22,377 ha) in 1971 to 24,018 farms (74,987 ha) in 2016 (SCAD, 2017). Despite the heavy subsidies and high water use, agriculture still contributes only a small fraction (around 10%) of the local food demand, with the rest dependent on food imports (AGEDI, 2015b).

Survey design

To acquire the quantitative data associated with the study objectives, a quantitative face-to-face survey was conducted with a representative proportion of the total farm population across ADE's three main regions: Abu Dhabi (AD), Al Ain (AA) and the Western Region (WR). The face-to-face survey method enabled us to get answers to the survey questions from the interviewees and to verify the acquired data through observation and further discussion with them. The survey data were gathered over the course of six months (September 2015 to March 2016) and were classified into five data groups. Table 1 shows the survey data groups and the data items included in each group. Detail of the survey questionnaire is provided in Appendix A in the online supplemental data at https://doi.org/10.1080/07900627.2019.1654440.

Stratified random sampling was used to select farms. This approach enables statistical analysis to be performed on the collected data and facilitates generalization of the output (Cochran, 1977; Israel, 2016). The sampled population consists of 24,018 farms (SCAD, 2017), and their geographical distribution is non-uniform over the three regions, so the sample size calculation was applied to each region (stratum) separately. The sample size was calculated as (Al-Subaihi, 2003; Israel, 1992):

Table 1. Survey data groups and their data items.

Data Group	Data Items
1. Farm descriptive data	Farm location, farm size, type of ownership, farm owner gender and age, farm manager
2. Farm purpose	Farm purpose (commercial or personal)
3. Water resources	Water resource types (farm well(s), government supply, small-scale groundwater desalination)
4. Farm production	Crops, cultivated area, quantity produced per season, number of harvesting cycles per year, pumping capacity, duration of irrigation per day, total water consumption per hectare per day, type of farming (open field or greenhouse), irrigation method (drip, flood or sprinkler)
5. Farmers' perceptions	Farmers' views on the drinking water tariff, water issues, knowledge of groundwater depletion and deterioration, views on government control of groundwater abstraction, views on reducing or stopping subsidies

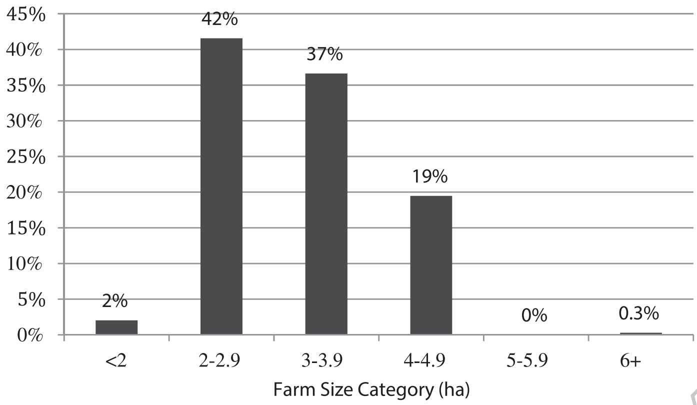

Figure 1. Percentage of farms surveyed across various farm size categories.

$$n = \frac{Z^2 p(1-p)}{e^2} / 1 + \frac{Z^2 p(1-p)}{e^2 N} \quad (1)$$

where n is the desired sample size, N the population size, p the expected value of attribute/variability in the population, e the margin of error (level of precision) and Z the standard deviation (1.96 proportion away from the mean, for a 95% confidence level). The desired minimum sample size was 285 (94, 95 and 95 farms in AD, AA and WR, respectively), but the actual data collection covered a sample size of 344 farms (115, 149 and 80 farms in AD, AA and WR, respectively). Figure 1 shows the percentage of farms surveyed across various farm size categories.

Water consumption calculation

Descriptive data analysis was used on the data collected from the farmers to determine the main characteristics of the farms' water consumption. Since the farmers did not keep records of water consumption per crop per hectare, it was not possible to obtain this information from them directly. Instead, relevant information such as pump capacities, irrigation type(s) and irrigation duration per hectare per day was gathered and used to calculate the water consumption rate in terms of the estimated water flow rate. The water flow rate (in imperial gallons per minute) was calculated as from water horsepower (Fipps, 1995) as:

$$\text{Water flow rate (igpm)} = \text{Water horsepower (hp)} \times \frac{\mu \times 3286.8}{H(\text{ft}) \times F} \quad (2)$$

where horsepower is the irrigation pump power, pump efficiency (μ) is 0.85 (Chávez, Reich, Loftis, & Miles, 2011; Fipps, 1995), H is the irrigation head in feet, and friction loss (F) was estimated at 2.26 based on the average of four representative farms, using measurements of actual flow rates and calibrating with the recorded values in Equation (2). Table B1 (Appendix B in the online supplemental data) shows the characteristics of the four farms used to calculate the average irrigation flow rate. Different irrigation systems have different average irrigation heads: 40 ft for flood, 80 ft for drip and 105 ft for sprinkler systems (Apex, 2014; Fipps, 1995).

The estimates were based on the assumption that pumps are used at high capacity for several hours per day (see the Farms' Water Sources section). This was confirmed by observations during the survey; farmers focus on pumping as much water as possible, without carefully monitoring or controlling flow rates. The flow rate for each crop per farm was determined by Eq. (2). To determine the water consumption (m^3 per day) per crop for each farm, the calculated flow rate was then multiplied by the reported irrigation duration (min/ha). The total annual water consumption per crop per farm was calculated by multiplying the water consumption per day by the crop growth duration (number of cycles and the duration of each cycle).

The growth duration for palm trees, fodder crops and turf grass is one year, but it varies in the cultivation of vegetables. Vegetables cultivated in open fields need a seven-month cultivation period from September to March. But vegetables in greenhouses (such as cucumbers) need only three to four months per cycle and can be cultivated year round (ADFSC, 2013).

Data analysis and results

The Statistical Package for the Social Sciences (SPSS) and Microsoft Excel were used to analyze the data collected from the survey and present the research findings. Descriptive data analysis presentation tools such as frequency, percentage, mean, boxplots and cross-tabulation were used to present the main characteristics of the farming practices and water consumption patterns. Statistical methods such as the chi-squared test were employed to examine the significance of the relation between the observed and expected values of the variables.

Farm demographics

Most of the farms (89.5%) have single owners (84.4% are male, and 15.6% female), with about 8.2% owned by inheritors and 2.3% by joint ownership (e.g. with spouses). Farm owners' age ranges from 30 to 70 years, with most (85%) being in their fifties or sixties. Some farms are directly managed by their owners, but most (82.5%) are managed by the farm's labourers or representatives. The rest are leased and managed by a tenant.

To understand the primary objective behind establishing a farm, the survey asked whether it was for personal use, i.e. most of the farmland is used for family leisure and consumption, or commercial, i.e. the farmland and facilities are used to generate profit. Some 81% of the farms are operated for personal purposes, and only 19% for commercial use. But when the farmers were asked whether their farms generate a profit, about 66% answered yes, much more than the proportion of commercial farms. This indicates that even though the primary purpose of most of these farms is not purely commercial, they still generate some profit through selling a portion of their produce in the market.

Farms' water sources

The survey found that 55% of the farms operate two wells, 10% operate three wells, 11% have a single well, and 24% (mostly in AD) have no wells and rely on piped water for irrigation. Most wells are between 120 and 1000 ft in depth and are operated from 2 to 24 hours per day and on average 9 hours per day. Pump capacity can be up to 25 hp in some cases. The salinity of the groundwater on the sampled farms varies from 2000 to 27,000 ppm.

Small-scale brackish desalination plants were owned by 37 farms, more than 50% of which are commercial farms. The plants range in capacity from 45 to 273 m^3 per day and are operated from 10 to 22 hours per day. Most of the respondents stated that plant brines are discharged into a decommissioned well; only a few indicated that they reuse the water for fish farming or forestry irrigation.

Farm produce and water consumption

The main crops are palm trees, seasonal vegetables and fodder crops. Palm trees are cultivated by 98% of the farms on 72.5% of the total cultivated area. Vegetables are cultivated by 69% of the farms on 14% of the cultivated area. Fodder crops are cultivated by 42% of the farms on 13.5% of the total cultivated area; these are Rhodes grass (10%), alfalfa (2.7%) and panicum (0.5%).

Despite the disproportionate land area dedicated to dates, most of the produce by weight, about 43% of total agricultural production, is vegetables. Dates follow at 30% and fodder crops at 27%. Cucumbers represent two-thirds of total vegetables and a quarter of total agricultural production. Table B2 (Appendix B in the online supplemental data) shows a summary of cultivated crops in the surveyed farms.

To estimate agricultural farm production and annual crop productivity per hectare, the reported crop yield per hectare per cycle is multiplied by the number of cycles and the total cultivated area. The crop yield rate (kg/ha) for cucumbers is by far the highest among all the cultivated crops. Palm trees have the lowest rate; fodder crops yield more than palm trees, but still much less than cucumbers. Other vegetables cultivated by open-field farming, such as marrows, eggplants, tomatoes, cabbages, sweet melons, corn, onions, peas and beans, show intermediate yields.

The analysis of average annual water consumption per hectare identified four categories. Most of the seasonal vegetables, such as onions, sweet melons, mixed vegetables (a mixture of leafy vegetables), beans, tomatoes and cabbages, fall within the highest water use ranges, 25,000–30,000 m^3/ha (Category 1) and 20,000–24,000 m^3/ha (Category 2). For the remaining vegetables such as eggplants, marrows and corn, water use ranges from 12,000 to 19,000 m^3/ha (Category 3), whereas cucumbers and peas are in the lowest water use category, from 8,000 to 10,500 m^3/ha (Category 4).

Fodder crops such as Rhodes and alfalfa and palm trees are in the second-highest category. Panicum, however, shows the lowest water use of the fodder crops (9,325 m^3/ha). This may be because demand for panicum is lower than Rhodes and alfalfa, and therefore farmers pay less attention to it.

Figure 2 is a box plot of the minimum, maximum and median of the average water consumption rate (m^3/ha) for each of the cultivated crops. The range between minimum and maximum is large for most of the crops, with the median skewed to the lower quartile. This indicates that there is a significant variation in water use across the farms. The interquartile range (representing 50% of the farms) is also large and varies from 3,806–12,686 m^3/ha in cucumbers to 14,800–44,399 m^3/ha in mixed vegetables. These

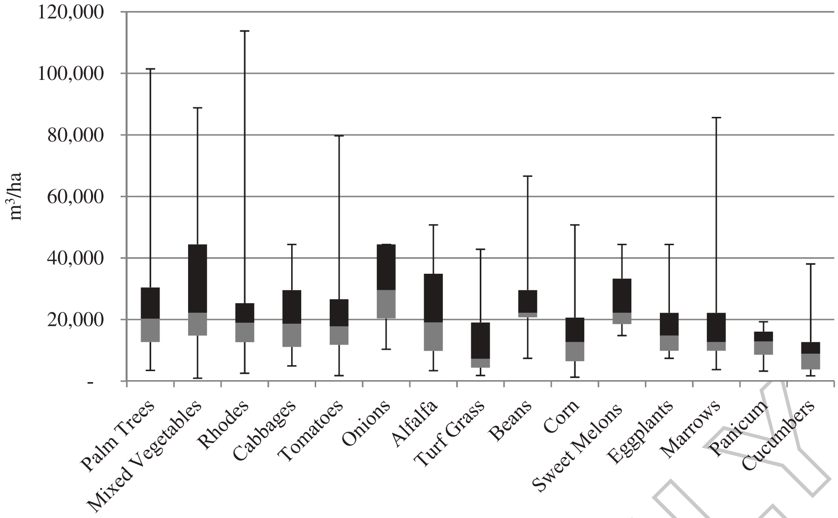

Figure 2. Box plot of average annual water consumption per cultivated crop.

variations are larger among some crops: palm trees, mixed vegetables, cabbages, tomatoes, onions and alfalfa.

The analysis of water productivity shows that the cultivation of cucumbers has by far the highest performance among all cultivated crops reported by the surveyed farms, while palm trees have one of the lowest (Figure 3). Water productivity for the same crops shows almost the same pattern in the three ADE regions (AD, AA and WE), which suggests consistent and reliable survey results. However, there is a slight increase in AD in cucumbers, and an increase in AA in tomatoes and alfalfa, whereas WR is either matching or lower than AA.

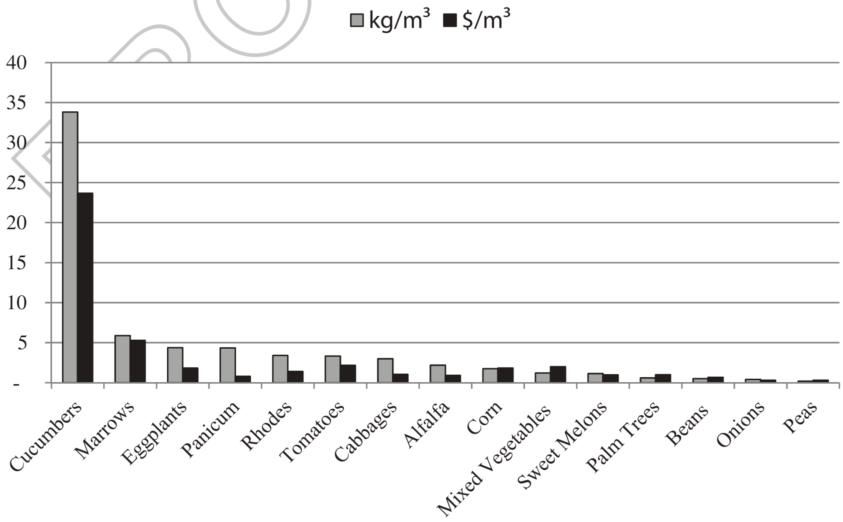

Figure 3. Physical water productivity (kg/m^3) and economic water productivity ($/m^3) per cultivated crop.

Farmers' perceptions

As discussed in the Groundwater Use section, the future development of the agricultural sector requires active policy measures to avoid negative impacts on water sustainability and the environment. For this reason, it was important to address the farmers' awareness of water-related issues in ADE in the survey.

The farmers who stated that they receive a drinking water supply (municipal water supply for drinking and household needs) were asked for their views on the drinking water tariff that had been introduced for the first time in January 2015 (Srouji, 2017). Out of 18, 8 said they agree with the introduction of this new tariff, 7 were against it, and 3 had no knowledge of it. The same group of farmers also shared their views, among four options, on the reason for the introduction of the drinking water tariff. Most (56%) selected reducing water consumption, 21.5% selected 'I don't know', 16.5% selected reducing water cost to the government, and 6% selected both reducing water consumption and sharing the cost with the government.

The farmers were also asked for their views on the government's taking action to control groundwater pumping. Most (70%) of the participants disagreed with this policy, 23% stated that they do not have productive wells, and only 7% agreed with it. Historically, farmers were free in their use of groundwater, with limited oversight that meant there was practically no restriction on the number of wells, their depth or the quantity extracted. Based on the above answers, the government needs to consider involving farmers in the development of groundwater policies, while eventually introducing proper enforcement mechanisms to regulate and control groundwater abstraction.

The farmers were also asked about their knowledge of groundwater depletion and whether they have noticed a deterioration of the quality of the groundwater. The responses to these two questions were in the form of percentages of no, yes, 'only in some wells', and 'I don't know'. About 50% of the farmers know of the groundwater depletion, and 60% perceived a deterioration in quality. When asked about their alternatives should groundwater become unsuitable for agricultural production, almost all (93%) stated that they would prefer to switch to desalination.

To assess potential influences on the farmers' answers, we checked for statistical correlation (using a chi-squared test) between farmers' responses and farm attributes, including location, size, ownership type, farm manager and whether the farm generates profit. We found a positive and significant correlation of those responses with most of the selected categories. This suggests that farmers' knowledge of groundwater issues is generally influenced by their experience. Tables B3 and B4 (Appendix B in the online supplemental data) provide more detail on these results.

Discussion

This study provides comprehensive empirical findings with respect to the area it covered (ADE). Most of the farms are used as a prestigious leisure facility for the owners and their families, rather than a primary source of income. Leisure use affects water consumption, as it implies swimming pools, family houses and non-productive landscaping on the farms. Most of the farms are heavily dependent on groundwater as the main source of supply, with a significant occurrence of high water use and low water productivity for most of the cultivated crops. This result is in line with other reports (EAD, 2017; McDonnell & Fragaszy, 2016; MOEW, 2010). As the groundwater deteriorates, almost all of the farmers (93%) would prefer to switch to small-scale brackish desalination plants. Although the occurrence of desalination plants in the surveyed farms is small (11%), the current brine discharge methods (such as discharge to the aquifer or evaporation ponds) and the absence of suitable regulatory constraints could lead to groundwater and soil contamination (McDonnell & Fragaszy, 2016) and therefore requires appropriate regulatory limits and effective oversight.

As mentioned in the Groundwater Use section, there is limited research that focuses on farming practices and their impacts on groundwater resources in ADE. Meanwhile, there is wide variation in the results of the few existing studies on ADE and on other areas of the GCC region. For these reasons, this section compares our findings to previous studies and discusses the key policy implementations.

Farms' cultivated area and production

The surveyed farms have 47% of their total area in agricultural production, consistent across the three regions (50% for AD, 43% for AA and 48% for WR) and in accordance with the 51% ratio given in the ADE 2016 report (SCAD, 2017). The percentage of crop-cultivated area out of total cultivated area is also similar to the figures in the ADE report, as shown in Figure 4, except for seasonal vegetables, which in the ADE report show a lower percentage. This is probably due to the difference in the timing of data collection between our survey and the SCAD study, which usually collects data at the end of the season.

The percentages of total dates and seasonal vegetables we obtained (30% and 43%, respectively) also confirm the corresponding percentages in the ADE 2016 report. However, the total fodder crops are 10% more than reported in the ADE report. This difference could be due to the farmers' reluctance to declare their actual production with the government so as not to endanger their subsidies, which are contingent on their not cultivating Rhodes grass on more than 10% of their land (McDonnell & Fragaszy, 2016). When this stipulation was introduced, in 2010, it drastically reduced Rhodes grass cultivation, but this started to rebound from 2012 to 2016 (SCAD, 2012, 2017) and is apparently underreported, which indicates that policy implementation and enforcement could be enhanced.

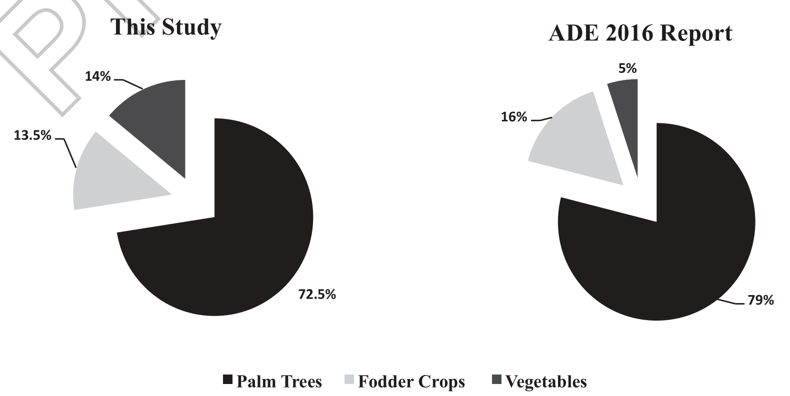

Figure 4. Comparison of percentage of crop cultivated area between this study and Abu Dhabi farm registry data in the ADE 2016 report (SCAD, 2017).

Crop yield

The average annual crop yield for palm trees in the surveyed farms is 9621 kg/ha. This rate falls within the range measured in Oman (8380–11,750 kg/ha; FAO, 2007). However, other studies show much lower rate, such as the 2700–4800 kg/ha range estimated in UAE (FAO, 2007), the 3000 kg/ha figure obtained from survey data in Oman (Al Said et al., 2007) and the 4272 kg/ha figure estimated in Oman (FAO, 2007). Rhodes grass yield inclines towards the highest productivity (50,971 kg/ha) compared to the other reviewed studies, ranging from 5000 kg/ha in Oman (Mazahrih et al., 2016) to 60,000 kg/ha in Saudi Arabia (Patil et al., 2015). Similarly, alfalfa yields, at 25,750 kg/ha, are on the higher end of the reported range from 3852 kg/ha (Al-Gaadi et al., 2017) to 35,100 kg/ha (Patil et al., 2015) in Saudi Arabia. Similarly, most of the surveyed vegetable yields fall within the range obtained from the literature (Table 2).

Water consumption

The average annual water use rate for most of the crops shows large variations across the farms, suggesting that farmers are not consistent in setting and assessing these rates. Palm trees' average water consumption in the surveyed farms is 22,745 m^3/ha, in line with prior estimates in the UAE and Oman (FAO, 2007) and Kuwait (Bhat et al., 2012), which range from 15,000 to 29,700 m^3/ha. The Food and Agriculture Organization of the United Nations (FAO) recommendation is 14,700 m^3/ha for mature trees in the UAE, while its measurement in Oman shows a range from 9320 to 16,080 m^3/ha (FAO, 2007). A somewhat lower rate was measured in Dubai (UAE), with water consumption varying seasonally from 3600 to 10,800 m^3/ha between winter and summer (Green et al., 2014). For Rhodes, the water consumption rate obtained from different studies ranges from 13,000 m^3/ha in the UAE (MOEW, 2010) to 163,294 m^3/ha measured in Saudi Arabia (Hashim et al., 2012), while the rate surveyed here (23,850 m^3/ha) is close to that estimated in another study in the UAE (20,000 m^3/ha; Pitman et al., 2009). Alfalfa water consumption varies between 5520 m^3/ha (Al-Gaadi et al., 2017) and 60,390 m^3/ha (Patil et al., 2015) in Saudi Arabia, and in this study it falls within that range (22,775 m^3/ha). Vegetable water consumption rates (m^3/ha) showed some differences from other reviewed studies (Table 3).

Table 2. Vegetable crops yield rate (kg/ha).

Crop	This study	Other studies	Location and data-collection method of other studies
Corn	15,576	10,930–11,190	Saudi Arabia, measurement and modelling[1]
		4,000	Oman, survey[2]
		4,048	Saudi Arabia, measurement[3]
Tomatoes	44,390	80,100	Oman, measurement[4]
		8,000–38,000	Oman, survey[2]
		60,000–120,000	Oman, estimation[5]
		54,900–66,500	Oman, estimation[5]
Cucumbers	160,000	24,000–38,000	Oman, survey[2]
		70,000–99,000	Saudi Arabia, measurement[6]
		91,000–150,000	Saudi Arabia, measurement[7]
Eggplants	45,238	7,000	Oman, survey[2]
		8,335	Saudi Arabia, measurement[3]
Cabbages	43,056	49,300	Oman, measurement[4]
Beans	9,778	3,007	Saudi Arabia, measurement[3]
Onions	10,125	3,000–18,000	Oman, survey[2]
Sweet melons	24,667	23,800	Oman, measurement[4]
		14,000	Oman, survey[2]

[1]Patil et al. (2015); [2]Al Said et al. (2007); [3]Hashim et al. (2012); [4]Al-Said et al. (2012); [5]Algharibi et al. (2013); [6]Aly et al. (2015); [7]Alomaran and Luki (2012)

Table 3. Vegetable crops' water consumption (m^3/ha).

Crop	This study	Other studies	Location and data-collection method of other studies
Corn	16,527	9,892–21,580	Saudi Arabia, measurement and modelling[1]
		45,260	Saudi Arabia, measurement[2]
Tomatoes	23,978	8,050	Oman, measurement[3]
		2,740–6,820	Oman, Simulation[4]
Cucumbers	10,096	1,090–3,550	Saudi Arabia, measurement[5]
		1,470–3,550	Saudi Arabia, measurement[6]
Eggplants	18,377	58,080	Saudi Arabia, measurement[2]
Cabbages	20,422	14,400	Oman, measurement[3]
Beans	26,146	30,300	Saudi Arabia, measurement[2]
Sweet melons	12,333	4,970	Oman, measurement[3]

[1]Patil et al. (2015); [2]Hashim et al. (2012); [3]Al-Said et al. (2012); [4]Algharibi et al. (2013); [5]Aly et al. (2015); [6]Alomaran and Luki (2012)

Water productivity

Our finding for palm trees' water productivity (0.59 kg/m^3) is 50% higher than the upper range of FAO (2007) estimates for the UAE (0.2–0.26 kg/m^3). Still, it is less than the minimum of FAO (2007) estimates for Oman (0.71–0.89 kg/m^3), and within the range measured in Oman (0.59–1.5 kg/m^3; Al-Mulla & Al-Gheilani, 2018). However, the economic water productivity rate obtained from this study (0.99 \$/m^3) falls within the range of the figures estimated in Oman by the latter study (0.6–1.64 \$/m^3).

The Rhodes grass water productivity range is from 0.44 kg/m^3 measured in Saudi Arabia (Patil et al., 2015) to 0.85 kg/m^3 measured in Oman (Mazahrih et al., 2016), but it is much higher in our survey (3.40 kg/m^3). Consequently, the economic water productivity is much higher in this study (1.4 \$/m^3) than that measured in Oman (0.45 \$/m^3; Al-Said et al., 2012). Alfalfa water productivity varies from 0.38 kg/m^3 (Patil et al., 2015) to 0.84 kg/m^3 (Hashim et al., 2012) in Saudi Arabia, but it is also higher in this study (2.2 kg/m^3). For panicum, the surveyed farm results are comparable to Saudi Arabia in water consumption and water productivity (kg/m^3), but higher in the yield (Hashim et al., 2012).

The water productivity (kg/m^3 and \$/m^3) for the cultivated vegetables in this study varies compared with other reviewed studies. Some crops are within, and some outside, the range reported in other studies (Tables 4 and 5).

Recommended areas for regulation

The water productivity results show that ADE is facing a challenge in creating a balance between increasing agricultural production to improve food security, maintaining social and cultural heritage, and at the same time preserving the emirate's groundwater. This calls for defining consistent strategic objectives and developing and implementing effective strategies, with their associated policies and governance processes, to improve the current farming practices and manage their water consumption.

Table 6 shows a set of proposed objectives with corresponding supporting strategies. These strategies are proposed for the government to apply in its endeavours to mitigate the negative impacts of the current farming practices on the sustainability of water resources in ADE. Policies and governance processes should be established for each of the recommended

Table 4. Vegetable crops' physical water productivity (kg/m^3).

Crop	This study	Other studies	Location and data-collection method of other studies
Corn	1.8	0.51–1.11	Saudi Arabia, measurement and modelling[1]
		0.79	Saudi Arabia, measurement[2]
Tomatoes	3	11.9	Oman, measurement[3]
		1.3–3.5	Oman, estimation[4]
		2.64	Oman, simulation[4]
Cucumbers	33.8	14.4–48.3	Abu Dhabi, measurement[7]
		27.9–64.2	Saudi Arabia, measurement[5]
		42.25–61.5	Saudi Arabia, measurement[6]
Eggplants	3.21	1.43	Saudi Arabia, measurement[2]
Cabbages	2.98	7.8	Oman, measurement[3]
Beans	0.51	1	Saudi Arabia, measurement[2]
Sweet melons	1.14	5.7	Oman, measurement[3]

[1]Patil et al. (2015); [2]Hashim et al. (2012); [3]Al-Said et al. (2012); [4]Algharibi et al. (2013); [5]Aly et al. (2015); [6]Alomaran and Luki (2012); [7]ADFCA (2016)

Table 5. Vegetable crops' economic water productivity ($/m^3).

Crop	This study	Other studies	Location and data-collection method of other studies
Tomatoes	2	0.71	Oman, measurement[1]
Cabbages	1.044	0.81	Oman, measurement[1]
Sweet melons	0.98	0.67	Oman, measurement[1]

[1]Al-Said et al. (2012)

Table 6. Proposed strategic objectives and their supporting strategies.

Proposed strategic objective	Supporting strategies
Regulate groundwater abstraction	• Restrict drilling of new wells. • Restrict groundwater use for personal and family farms. • Identify cultural heritage activities and their value, and set limits for water use in these activities. • Install meters in all wells. • Define volumetric limits for groundwater abstraction. • Apply tariffs for groundwater use. • Ban the operation of wells in areas where water table is deep. • Enforce well permit process and penalize non-compliance. • Regulate groundwater desalination and brine discharge methods.
Improve agricultural water use efficiency	• Ban cultivation of intensive-water-use crops such as Rhodes grass. • Identify list of allowed crops that have high tolerance and less water use to be cultivated in ADE. • Define water use baseline for various selected crops. • Adapt innovative agricultural farming techniques that facilitate efficient water use and high productivity (e.g. greenhouse). • Restrict open-field farming. • Improve irrigation efficiency.
Increase treated wastewater utilization	• Identify list of crops recommended by FAO for safe human use. • Define areas and regions that benefit this supply. • Build infrastructure to supply treated wastewater to selected farms.
Improve cultivation of palm trees	• Focus on high-quality palm trees with selective recommended yield to improve economic value and water productivity of crops. • Define best management practices (e.g. irrigation management, pest control, harvesting process).
Develop integrative approach for agricultural development	• Develop agricultural policies with direct link to water resources and food security policies, considering the effect of climate change on groundwater recharge rates. • Establish agricultural policy implementation governance framework that specifies decision rights and accountability of relevant stakeholders as well as the mechanisms for communication, monitoring and enforcement of developed policies. • Engage farm owners and farmers in the policy-making process. • Improve farm owners' and farmers' knowledge and awareness.

strategies to ensure the effectiveness of its development and execution. However, the details of these policies and governance processes are beyond the scope of this work. These strategic objectives are discussed in more detail below.

The first strategic objective is the regulation of groundwater abstraction. This is required to preserve the non-renewable groundwater reserve. In this regard, there have been recent efforts in the Middle East, such as in Oman, which has shown success in groundwater pumping restrictions through stringent regulations involving well permits, banning unpermitted wells, penalizing contractors caught drilling illegally, installing well metering and developing a national inventory (Shah, 2014; van der Gun, 2007). Still, achieving this objective has been challenging in Jordan, Syria and Yemen because of weak political will and enforcement capacity, lack of public acceptance and strong opposition from farmers (Shah, 2014). However, such challenges can be overcome through applying the strategies associated with the fifth proposed strategic objective.

Second, agriculture water use efficiency should be improved by focusing on reducing water use and using high-value crops to improve physical and economic water productivity. A good example is Saudi Arabia's decision to phase out the cultivation of wheat and focus on lower-water-use and high-value crops to stop the exploitation of its groundwater (Bazza, 2005; Ouda, 2014). Another example is the ADE's decision (in 2010) to phase out the cultivation of Rhodes grass and encourage farmers to use water-saving techniques such as greenhouse farming and drip irrigation (McDonnell & Fragaszy, 2016). Although there has been a drastic reduction in the cultivation of Rhodes grass, it is still cultivated by 42% of farms. A complete ban on the cultivation of Rhodes grass and other fodder crops such as alfalfa and panicum, which have high water use and low water productivity, could be pursued. This may run counter to food security objectives, though, as animal fodder would then need to be fully sourced by imports; a specific assessment should be conducted of whether storing imported fodder addresses these concerns.

Third, increase treated wastewater use as an alternative water supply to reduce the pressure on groundwater use. Given the status of water resources in the GCC countries, there is an increasing demand for the use of treated wastewater. But less than 30% of the treated wastewater is used (with the rest discharged to the sea), mostly in landscape irrigation, and a negligible percentage (7%) used in agriculture (Bazza, 2005). ADE established a pilot for using treated wastewater in 143 farms, with the anticipation of using the findings (McDonnell & Fragaszy, 2016), and is now constructing a pipeline to transport this water for wider agriculture use. However, efforts are required to encourage and promote the use of treated wastewater among farmers to assuage their scepticism.

Fourth, improve the cultivation of palm trees to increase their production capacity and water productivity while maintaining their cultural heritage value. There is a cultural heritage link to palm tree cultivation not only in ADE but in the Arab region overall, including the GCC countries (Chao & Krueger, 2007; El-Juhany, 2010). Our finding that 98% of the farms cultivate palm trees using high water consumption, with low and sometimes no productivity, suggest that focusing on the high-quality trees and removing the low-quality trees, which is perhaps 50% of them (FAO, 2007), would be a prudent policy that will dramatically reduce irrigation needs. Other recent studies also note the poor management of palm trees in the region and similarly highlight the need for measures and guideline to improve their management (El-Juhany, 2010; FAO, 2015).

Finally, an integrative approach is needed in agricultural development to enable policy makers to recognize the trade-offs among the requirements of the different sectors (e.g. agriculture, water, food security and environment), creating a balance in how water is allocated to various users, with a focus on constantly measuring and improving water use efficiency and productivity (Benson, Gain, & Rouillard, 2015; Moore, 2004). In this context, it is worth noting that the alarming messages about climate change impacts on water resources and the projected depletion of groundwater have brought increasing attention to the need to shift the strategic planning and policy-making process from a sectoral to a cross-sectoral and integrated approach, especially in water-scarce countries (Benson et al., 2015; FAO, 2014; OECD, 2010), and therefore this aspect should be seriously considered when developing the policies associated with this strategic objective.

Conclusions

Agricultural expansion in ADE has put pressure on the Emirate's groundwater reserves, potentially leading to complete depletion within a few decades. To prevent this, it is necessary to regulate the current farming practices in the emirate. In this study we quantitatively examined the current farming practices in ADE and their impacts on groundwater resources through a face-to-face survey with participants (farmers and farm owners) from 344 farms across the three regions of ADE (AD, AA and WR). The survey gathered farmers' responses regarding the farms' demographics, produce, water sources, water consumption and water use, as well as water productivity per cultivated crop. It further explored farmers' knowledge of the existing and foreseen future issues regarding water sources, as well as their perceptions of the policies currently used by the government to mitigate these issues. The survey results were discussed and analyzed and, based on that, five strategic objectives, as well as the strategies that support them, were defined to mitigate the negative impact of current farming practices on groundwater sustainability. These strategic objectives are regulation of groundwater abstraction, improving water use efficiency, increasing treated wastewater utilization, improving palm tree cultivation and establishing an integrative approach for agricultural development to ensure coordination between the relevant stakeholders and engaging farmers in the agricultural policy-making process.

This study provides a critical input to agricultural and environmental sustainability policy development in the area of farming practices and water consumption. Future research may wish to further investigate and expand the analysis in comparison to other countries of the region and confirm the practicality of the strategic objectives proposed.

Acknowledgments

The authors thank all the survey respondents (farmers and farm owners) who devoted their time to answering the detailed survey questions.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Ameena Kulaib Al Tenaiji http://orcid.org/0000-0001-6542-7062

References

ADFCA. (2016). Sustain agriculture sector in Abu Dhabi through smart irrigation system. Retrieved from Abu Dhabi Food Control Authority, https://itunews.itu.int/en/4853-Smart-irrigation-for-sustainable-agriculture-in-Abu-Dhabi.note.aspx

ADFSC. (2013). Abu Dhabi Farmers' Service: Open-field vegetable production guide. Retrieved from Abu Dhabi Farmers' Service Centre, https://www.adfsc.ae/en/SiteAssets/pages/publications/ADFSC%20Eggplant%20%20Production%20Guidelines%20.pdf?TSPD_101_R0=f4dbcd004f2d2d8cf111b58b6ba875ealR700000000000000001775eccb0ffff000000000000000000000000000005c2b2e4f006eaefe1b

AGEDI. (2015a). Executive briefing: national water-energy nexus and climate change. Retrieved from LNRCCP. CCRG/NCAR/SEI, https://www.energycommunity.org/documents/TechnicalReportUAEWaterEnergyNexus.pdf

AGEDI. (2015b). Technical report: UAE food security and climate change. Retrieved from LNRCCP. CCRG/NCAR/SEI, https://agedi.org/item/technical-report-uae-food-security-and-climate-change/

Al Said, F. A., Zekri, S., Khan, I. A. (2007). Profitability analysis of selected farms in the Batinah region of Oman. *Journal of Agricultural and Marine Sciences*, *12*, 1–12.

Al-Azwai, A. A. O., & Ward, F. A. (2017). Groundwater use and policy options for sustainable management in Southern Iraq. *International Journal of Water Resources Development*, *33*(4), 628–648. doi:10.1080/07900627.2016.1213705

Al-Gaadi, K. A., Madugundu, R., & Tola, E. (2017). Temporal dynamics of alfalfa water use efficiency under hyper arid conditions of Saudi Arabia. *Advances in Animal Biosciences*, *8*(2), 540–545. doi:10.1017/S204047001700022X

Algharibi, E., Schmitz, G., Lennartz, F., Schütze, N., Grundmann, J., & Kloss, S. (2013). *Evaluation of field and greenhouse experiments with tomatoes using the aquacrop model as a basis for improving water productivity*. *International Conference on Water Resources and Environment Research*. doi:10.5675/ICWRER_2013

Ali, M. K., & Klein, K. K. (2014). Water use efficiency and productivity of the irrigation districts in southern Alberta. *Water Resources Management*, *28*(10), 2751–2766. doi:10.1007/s11269-014-0634-y

Al-Mulla, Y., & Al-Gheilani, H. M. (2018). Increasing water productivity enhances water saving for date palm cultivation in Oman. *Journal of Agricultural and Marine Sciences*, *22*(1), 87–91. doi:10.24200/jams.vol22iss1pp87-91

Alomaran, A. M., & Luki, I. I. (2012). Effects of deficit irrigation on yield and water use of grown cucumbers in Saudi Arabia. *Transactions on Ecology and the Environment*, *168*(IV), 353–358. doi:10.24955/SI120301

Al-Said, F. A., Ashfaq, M., Al-Barhi, M., Hanjra, M. A., & Khan, I. A. (2012). Water productivity of vegetables under modern irrigation methods in Oman. *Irrigation and Drainage*, *61*(4), 477–489. doi:10.1002/ird.v61.4

Al-Subaihi, A. A. (2003). Sample size determination. *Neurosciences*, *8*(2), 79–86.

Aly, A. A., Al-Omran, A. M., & Khasha, A. A. (2015). Water management for cucumber: Greenhouse experiment in Saudi Arabia and modeling study using SALTMED model. *Journal of Soil and Water Conservation*, *70*(1), 1–11. doi:10.2489/jswc.70.1.1

Antonelli, M., & Tamea, S. (2015). Food-water security and virtual water trade in the Middle East and North Africa. *International Journal of Water Resources Development*, *31*(3), 326–342. doi:10.1080/07900627.2015.1030496

Apex, T. (2014). Which pressure is required for your sprinkler system? Retrieved from TEKNORAPEX, https://www.apexhose.com/water-distribution-blog/which-pressure-is-required-for-your-sprinkler-system

Arthur, R., & Qaydi, S. (2010). Agricultural marketing in the western region of Abu Dhabi, United Arab Emirates: attitudes and perceptions. *Agriculture and Biology Journal of North America*, *1*(4), 458–468.

Bazza, M. (2005). Policies for water management and food security under water-scarcity conditions: the case of GCC countries. *Proceedings of the 7th Gulf Water Conference* (pp. 19–23). Kuwait: Water Science and Technology Association.

Benson, D., Gain, A., & Rouillard, J. (2015). Water governance in a comparative perspective: from IWRM to a 'nexus' approach? *Water Alternatives*, *8*(1), 756–773.

Bhat, N. R., Lekha, V. S., Suleiman, M. K., Thomas, B., Ali, S. I., George, P., & Al-Mulla, L. (2012). Estimation of water requirements for young date palms under arid climatic conditions of Kuwait. *World Journal of Agricultural Sciences*, *8*(5), 448–452. doi:10.5829/idosi.wjas.2012.8.5.1674

Brook, M. C., Al Houqani, H., Darawsha, T., & Achary, M. A. A. S. (2006). Groundwater resources: development & management in the Emirate of Abu Dhabi, United Arab Emirates. In A. M. O. Mohamed (Ed.), *Arid land hydrogeology: In search of a solution to a threatened resource* (pp. 15–34). Balkema, Netherlands: Taylor and Francis.

Chao, C. T., & Krueger, R. R. (2007). The date palm (Phoenix dactylifera L.): overview of biology, uses, and cultivation. *HortScience*, *42*(5), 1077–1082. doi:10.21273/HORTSCI.42.5.1077

Chávez, J. L., Reich, D., Loftis, J. C., & Miles, D. L. (2011). Irrigation pumping plant efficiency. Retrieved from Colorado State University Extension, https://extension.colostate.edu/topic-areas/agriculture/irrigation-pumping-plant-efficiency-4-712/

Cochran, W. G. (1977). *Sampling techniques* (3rd ed.). Chichester: John Wiley & Sons. Retrieved from https://archive.org/details/Cochran1977SamplingTechniques_201703/page/n15

De Fraiture, C., & Wichelns, D. (2010). Satisfying future water demands for agriculture. *Agricultural Water Management*, *97*(4), 502–511. doi:10.1016/j.agwat.2009.08.008

De Pascale, S., Dalla Costa, L., Vallone, S., Barbieri, G., & Maggio, A. (2011). Increasing water use efficiency in vegetable crop production: from plant to irrigation systems efficiency. *HortTechnology*, *21*(3), 301–308. doi:10.21273/HORTTECH.21.3.301

EAD. (2012). Annual report 2012. Retrieved from Environment Agency-Abu Dhabi, https://www.ead.ae/Pages/Resources/Publications.aspx

EAD. (2015). Strategic plan 2016–2020. Retrieved from Environment Agency-Abu Dhabi, https://www.ead.ae/Documents/PDF-Files/EAD_STRATEGY_28%20sep%20spread%20(1).pdf

EAD. (2017). Abu Dhabi state of environment report 2017. Retrieved from Environment Agency-Abu Dhabi, https://www.ead.ae/Publications/Abu%20Dhabi%20State%20of%20Environment%20Report%202017/EAD-full-report.pdf

El-Juhany, L. I. (2010). Degradation of date palm trees and date production in Arab countries: causes and potential rehabilitation. *Australian Journal of Basic and Applied Sciences*, *4*(8), 3998–4010.

ERWDA. (2002). 2002 Abu Dhabi water resources statistics. Retrieved from https://www.yumpu.com/en/document/view/35881678/2002-abu-dhabi-water-resources-statistics

ESCWA. (2009). ESCWA water development report 3: role of desalination in addressing water scarcity. Retrieved from United Nations, https://www.unescwa.org/publications/escwa-water-development-report-3-role-desalination-addressing-water-scarcity

FAO. (2007, May 27). *Irrigation of date palm and associated crops*. Presented at the Irrigation of Date Palm and Associated Crops conference, Damascus, Syria. Retrieved from http://www.fao.org/tempref/GI/Reserved/FTP_FaoRne/morelinks/Publications/English/date-Palm-Proceedings.pdf

FAO. (2011). The state of the world's land and water resources for food and agriculture (SOLW)–managing water at risk. Retrieved from http://www.fao.org/docrep/017/i1688e/i1688e.pdf

FAO. (2014). *Water governance for agriculture and food security* (Committee on Agriculture 24th session). Rome: Food and Agriculture Organization of the United Nations.

FAO. (2015). *Proposal from the United Arab Emirates: for the designation under the GIAHS program of Al Ain and Liwa historical date palm oases*. Retrieved from: http://www.fao.org/3/a-bp822e.pdf.

Fipps, G. (1995). Calculating horsepower requirements and sizing irrigation supply pipelines. Retrieved from https://aglifesciences.tamu.edu/baen/wp-content/uploads/sites/24/2017/01/B-6011-Calculating-Horsepower-Requirements-and-Sizing-Irrigation-Supply-Pipelines.pdf

Giordano, M., & Villholth, K. G. (2007). *The agricultural groundwater revolution: Opportunities and threats to development*. Wallingford: CABI. Retrieved from https://cgspace.cgiar.org/handle/10568/36474

Green, S. R., Mc Cann, I., Clothier, B. E., Abdelfattah, M., Dakheel, A., Alyamani, W., & Pangilinan, R. (2014, August 17–22). *Water use of date palms growing in the saline desert soils of the United Arab Emirates*. Presented at the 29th International Horticultural Congress, Brisbane, Australia. Retrieved from https://www.researchgate.net/publication/267506567_Water_use_of_date_palms_growing_in_the_saline_desert_soils_of_the_United_Arab_Emiratesha

Haj-Amor, Z., Ritzema, H., Hashemi, H., & Bouri, S. (2018). Surface irrigation performance of date palms under water scarcity in arid irrigated lands. *Arabian Journal of Geosciences*, *11*(2). doi:10.1007/s12517-017-3374-5

Hashim, M. A. A., Siam, N., Al-Dosari, A., Asl-Gaadi, K. A., Patil, V. C., Tola, E. H. M., … Samdani, M. S. (2012). Determination of water requirement and crop water productivity of crops grown in the Makkah region of Saudi Arabia. *Australian Journal of Basic and Applied Science*, *9*(6), 196–206.

IPCC. (2007). *Climate change 2007: the physical science basis* (p. 333). Geneva: Author. Retrieved from https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-spm-1.pdf

IPCC. (2008). *Technical paper on climate change and water*. Geneva: Author. Retrieved from https://www.ipcc.ch/site/assets/uploads/2018/03/climate-change-water-en.pdf

Israel, G. D. (1992). Determining sample size. Retrieved from https://sites.google.com/site/estadisticayunpocomas/tama%C3%B1omuestra.pdf

Israel, G. D. (2016). Sampling the evidence of extension program impact. Retrieved from University of Florida IFAS Extension, http://edis.ifas.ufl.edu/pd005

Jafary, F., & Bradley, C. (2018). Groundwater irrigation management and the existing challenges from the farmers' perspective in central Iran. *Land*, *7*(1), 15. doi:10.3390/land7010015

Kijne, J. W., Barker, R., & Molden, D. J. (2003). *Water productivity in agriculture: Limits and opportunities for improvement*. Wallingford: CABI. Retrieved from https://books.google.ae/books?id=B1kK0yOLBAQC

Mazahrih, N., Al-Wahaibi, H., Al-Farsi, S., & Ouled Belgacem, A. (2016). Yield and water productivity of Buffel and Rhodes grasses under different irrigation water regimes using the sprinkler line-source system. *Grassland Science*, *62*(2), 112–118. doi:10.1111/grs.12120

McDonnell, R. (2013). Circulations and transformations of energy and water in Abu Dhabi's hydro-social cycle. *Geoforum*, *57*, 225–233. doi:10.1016/j.geoforum.2013.11.009

McDonnell, R., & Fragaszy, S. (2016). *Groundwater use and policies in Abu Dhabi* (IWMI Project Report No. 13). Retrieved from http://gw-mena.iwmi.org/wp-content/uploads/sites/3/2017/04/Rep.13-Groundwater-use-and-policies-in-Abu-Dhabi-Emirate.pdf

MOCCAE. (2017). National climate change plan of the United Arab Emirates: 2017–2050. Retrieved from Ministry of Climate Change and Environment, https://www.moccae.gov.ae/assets/30e58e2e/national-climate-change-plan-for-the-united-arab-emirates-2017-2050.aspx

MOEW. (2010). United Arab Emirates water conservation strategy. Retrieved from Ministry of Environment & Water, http://extwprlegs1.fao.org/docs/pdf/uae147095.pdf

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A., & Kijne, J. (2010). Improving agricultural water productivity: between optimism and caution. *Agricultural Water Management*, *97*(4), 528–535. doi:10.1016/j.agwat.2009.03.023

Moore, M. (2004). *Perceptions and interpretations of environmental flows and implications for future water resources management*. Sweden: Linkoping University.

Mousa, H. (2016). *Saudi Arabia grain and feed annual* [Global Agriculture Information Network]. Retrieved from USDA Foreign Agriculture Service, https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Grain%20and%20Feed%20Annual_Riyadh_Saudi%20Arabia_5-14-2015.pdf

Murad, A. A. (2010). An overview of conventional and non-conventional water resources in arid region: assessment and constrains of the United Arab Emirates (UAE). *Journal of Water Resource and Protection*, *2*(2), 181–190. doi:10.4236/jwarp.2010.22020

OECD. (2010). Sustainable management of water resources in agriculture. Retrieved from Organization for Economic Co-operation and Development, http://www.oecd.org/tad/sustainable-agriculture/49040929.pdf

Ommani, A. R., Chizari, M., Salmanzadeh, C., & Hosaini, J. F. A. (2009). Predicting adoption behaviour of farmers regarding on-farm sustainable water resources management (SWRM): comparison of models. *Journal of Sustainable Agriculture*, *33*(5), 595–616. doi:10.1080/10440040902997827

Ouda, O. K. M. (2014). Impacts of agricultural policy on irrigation water demand: a case study of Saudi Arabia. *International Journal of Water Resources Development*, *30*(2), 282–292. doi:10.1080/07900627.2013.876330

Patil, V. C., Al-Gaadi, K. A., Madugundu, R., Tola, E. H. M., Marey, S., Aldosari, A., … Gowda, P. H. (2015). Assessing agricultural water productivity in desert farming system of Saudi Arabia. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *8*(1), 284–297. doi:10.1109/JSTARS.2014.2320592

Pitman, K., McDonnell, R., & Dawoud, M. (2009). Abu Dhabi water resources master plan. Retrieved from Environment Agency-Abu Dhabi, https://www.scribd.com/doc/224889521/Abu-Dhabi-Water-Rosources-Master-Plan.

Platonov, A., Thenkabail, P. S., Biradar, C. M., Cai, X., Gumma, M., Dheeravath, V., … Isaev, S. (2008). Water productivity mapping (WPM) using landsat ETM+ data for the irrigated croplands of the Syrdarya river basin in Central Asia. *Sensors (Basel, Switzerland)*, *8*(12), 8156–8180. doi:10.3390/s8128156

Playán, E., & Mateos, L. (2006). Modernization and optimization of irrigation systems to increase water productivity. *Agricultural Water Management*, *80*(1–3), 100–116. doi:10.1016/j.agwat.2005.07.007

Rizk, Z. S. (2008). Inorganic chemicals in domestic water of the United Arab Emirates. *Environmental Geochemistry and Health*, *31*(1), 27–45. doi:10.1007/s10653-008-9153-1

Sakthivadivel, R., De Fraiture, C., Molden, D. J., Perry, C., & Kloezen, W. (1999). Indicators of land and water productivity in irrigated agriculture. *International Journal of Water Resources Development*, *15*(1–2), 161–179. doi:10.1080/07900629948998

SCAD. (2012). Statistical yearbook of Abu Dhabi 2012. Retrieved from Statistical Centre of Abu Dhabi, https://www.scad.gov.abudhabi/en/Pages/ThemePublication.aspx?PID=7&ThemeID=1

SCAD. (2017). Statistical yearbook of Abu Dhabi 2016. Retrieved from Statistical Centre of Abu Dhabi, https://www.scad.gov.abudhabi/en/Pages/ThemePublication.aspx?PID=7&ThemeID=1

Shah, T. (2014). *Groundwater governance and irrigated agriculture* (p. 69). Retrieved from Global Water Partnership, https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/gwp_tec_19_web.pdf

Siebert, S., Burke, J., Faures, J.-M., Frenken, K., Hoogeveen, J., Döll, P., & Portmann, F. T. (2010). Groundwater use for irrigation: a global inventory. *Hydrology and Earth System Sciences*, *14*(10), 1863–1880. doi:10.5194/hess-14-1863-2010

Srouji, H. (2017). The impact of residential water price increases and subsidy reductions on elasticity of demand in Abu Dhabi city (Master's thesis). Harvard Extension School. Retrieved from: https://dash.harvard.edu/handle/1/33826970

UN-Water. (2012). The United Nations world water development report 4: managing water under uncertainty and risk. Retrieved from UNESCO, http://www.unesco.org

van der Gun, J. A. M. (2007). Sharing groundwater information, knowledge and experience on a worldwide scale. In M. Giordano and K. Villholth (Eds.), *The agricultural ground water revolution: Opportunities and threats to development* (pp. 362–392). Wallingford, UK: CAB International.

Wichelns, D. (2014). Do estimates of water productivity enhance understanding of farm-level water management? *Water*, *6*(4), 778–795. doi:10.3390/w6040778

Woertz, E. (2011). Arab food, water, and the big landgrab that wasn't. *Brown Journal of World Affairs*, *18*(1), 119–132.

Woertz, E. (2013). *Oil for food: The global food crisis and the middle east*. Oxford: Oxford University Press. Retrieved from https://global.oup.com/academic/product/oil-for-food-9780199659487?cc=us&lang=en&

Zingaro, D., Portoghese, I., & Giannoccaro, G. (2017). Modelling crop pattern changes and water resources exploitation: a case study. *Water*, *9*(9), 685. doi:10.3390/w9090685