The Food–Water Dilemma of Agriculture in Arid Regions: Assessing Abu Dhabi Water Options for Domestic Agriculture

By

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Abstract

Agriculture is by far the largest water user, both worldwide and in arid regions such as the Abu Dhabi Emirate (ADE). ADE is the largest region in the United Arab Emirates (UAE). It is characterised by negligible surface water and groundwater recharge resources with limited recharge capacity. Moreover, growing agricultural expansion in ADE through heavy subsidies and ambitious field planning is increasing the pressure on this non-renewable groundwater, as demonstrated by the constant decline of the water table and deterioration of groundwater quality. Despite the government push to achieve food self-sufficiency, current domestic agricultural production is only able to contribute a small fraction of the Emirate's food needs and the majority is still imported. In recent years, the ADE government has expressed concerns over the significant impacts of high water use on groundwater, which is predicted to be completely depleted in a few decades' time. However, only limited anecdotal data exists on groundwater usage and associated farming practices, making it difficult for the government to devise suitable strategies and policies needed to address the agricultural water use challenges in the region. This project will investigate the current farming practices, their impacts on groundwater, and how they are influenced by existing agricultural policies, with the aim of developing an appropriate framework for ensuring sustainable management and regulation of agricultural production and its water use.

The research employed a mixed-methods approach that was initiated by a comprehensive review of relevant extant literature and data synthesis of the available secondary data. This was followed by a large face-to face survey with farmers to understand their current practices. Later, semi-structured interviews were conducted with experts from relevant entities regarding their roles and policies used for the regulation and management of agricultural water.

The study's key findings provide a comprehensive empirical data set, the first in the region that has the essential inputs for policy development and future agricultural strategy. The findings show that agriculture in ADE uses 71% of the groundwater for over 76% of the farms; 80% goes to irrigate palm trees, which is more heritage driven than commercial. Palm tree cultivation yields produce an excessive 441% self-sufficiency, of which the majority are used as animal feed. This production is poorly managed, as it consumes a high water quantity (22,745 m^3/ha) with low water productivity (0.6 kg/m^3 and \$1/m^3). The study demonstrates that a change in palm tree cultivation practices, such as self-sufficiency ratio, water use, yield rate, etc., would help to sustain a suitable groundwater abstraction rate

while meeting the local market needs at the same time. The cultivation of vegetable crops via open-field farming also reveals low production performance due to its less reliable supply, accounting for only 27% of the self-sufficiency target. Such crops consume a considerable amount of water (16,527 m^3/ha to 30,422 m^3/ha) and yield low water productivity (0.2 kg/m^3 and \$0.3/m^3 to 5.9 kg/m^3 and \$5.3/m^3). Cucumbers, cultivated in greenhouses, are the only vegetable with a low water use (10,096 m^3/ha) and high water productivity performance (33.8 kg/m^3 and \$23.7/m^3). Limiting open-field farming and focusing on cultivation technology such as greenhouses will help to reduce the total water consumption by more than 95%.

The study further shows that the current regulation and management of agricultural water use policies and practices are highly fragmented, and that there is a lack of an integrated approach for dealing holistically with agriculture, water and food security issues. Therefore, an Agriculture-Water Policy Framework (AWPF) has been developed, based on the key study findings and best practice from the literature, to provide guidance for the decision-making process. The AWPF consists of seven primary steps that are interlinked in an iterative sequential process. These steps involve a systematic and integrated approach with a feedback loop to offer guidelines for making decisions relating to the development, analysis and implementation of sustainable agricultural water use, strategies and policies.

Acknowledgements

This research is a significant achievement in my career that has extended to more than 27 years of working in water- and power-related projects. During my work on this research, I have met many interesting individuals who have provided valuable contributions to this work. Without mentioning all their names, I hereby wish to thank them for their great support.

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Last but not least, I would like to express my gratitude to my family, especially my father, who has always been my model for how to manage life's difficulties by focusing on success and achievements. Also thanks to my sisters for their support and encouragement to motivate me to finish my work successfully.

Dedication

To my late cousin, Ahmed Abdulrahman Al Tenaiji, who devoted his life to help the less fortunate and was always on my side to support me. Unfortunately, he lost his life during his volunteer work in Afghanistan in January 2017. I dedicate this thesis to his soul.

Declaration and Copyright

I declare that the work in this thesis was carried out in accordance with the regulations of Brunel University. The work is entirely my own except where indicated by special reference in the text. Any views expressed in the thesis are those of the author and in no way represent those of Brunel University. No part of the thesis has been presented to any other university for any degree.

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Abbreviations and Acronyms

Abu Dhabi Emirate	ADE
Abu Dhabi Farmer Service Centre	ADFSC
Abu Dhabi Food Control Authority	ADFCA
Abu Dhabi Global Environmental Data Initiative	AGEDI
Abu Dhabi Municipality	ADM
Abu Dhabi National Oil Company	ADNOC
Abu Dhabi Region	AD
Abu Dhabi Sewage Service Company	ADSSC
Abu Dhabi Water and Electricity Authority	ADWEA
Abu Dhabi Water and Electricity Company	ADWEC
Agriculture-Water Policy Framework	AWPF
Al Ain Municipality	AAM
Al Ain Region	AA
Department of Municipal Affairs and Transport	DMAT
Environmental Agency-Abu Dhabi	EAD
European Union	EU
Executive Affair Authority	EAA
Executive Council	EC
External Renewable Water Resources	ERWR
Food and Agriculture Organization of the United Nations	FAO
General Secretariat of the Executive Council	GSEC
Gulf Cooperation Council	GCC
Integrated Water Resources Management	IWRM
International Centre of Bio-saline Agriculture	ICBA
International Panel on Climate Change	IPCC
International Renewable Water Resources	IRWR
Millennium Development Goals	MGDs
Ministry of Climate Change and Environment	MOCCAE
Organization for Economic Co-operation and Development	OECD
Permanent Committee for Water and Agriculture Strategies	PCWAS
Regulation and Supervision Bureau	RSB
Statistical Centre of Abu Dhabi	SCAD
Statistical Package for the Social Sciences	SPSS
Subject Matter Experts	SMEs
Total Renewable Water Resources	TRWR
United Arab Emirates	UAE
United Nations Development Programme	UNDP
United Nations Environment Programme	UNEP
United Nations Water	UN-Water
Urban Planning Council	UPC
Water Framework Directive	WFD
Western Region	WR
Western Region Municipality	WRM

Chapter 1. Introduction

1.1 Background

Abu Dhabi Emirate (ADE) is one of the seven emirates of the United Arab Emirates (UAE), which is among the most water-scarce countries in the world (ESCWA, 2009). The UAE is located at the southern part of the Arabian Peninsula, covering about 82,880 km^2, bounded by the Gulf of Oman in the east and the Arabian Gulf in the west and sharing borders with Oman to the east and Saudi Arabia to the south (Figure 1.1).

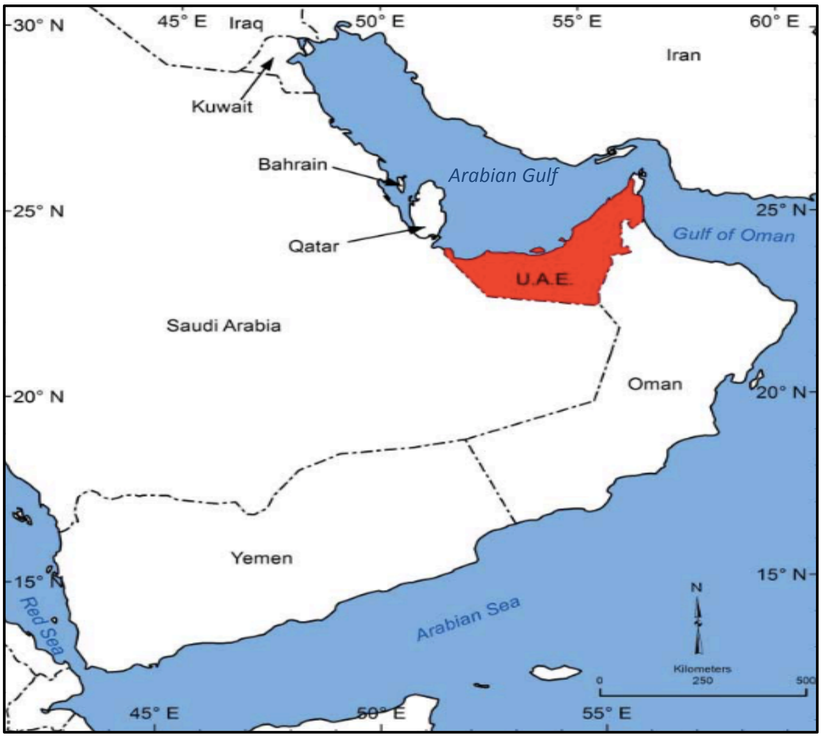

Figure 1.1 Location of the United Arab Emirates (Abdelfattah and Pain, 2012).

ADE is an important part of the country as a capital, because it covers more than 80% of both the country's land and agricultural area. The population in ADE was estimated at 3 million in 2018 (a third of the total UAE population); it has increased more than 100-fold since 1960 (SCAD, 2015), with a forecasted annual growth rate of 3.4% (HAAD, 2016). Growth in population and urbanization in ADE have led to a boost in water demand.

While municipal and commercial water demand is met through the provision of desalination plants, agricultural irrigation has relied almost exclusively on groundwater resources. This has led to an excessive water abstraction rate that exceeds more than 20 times the estimated recharge rate (Brook *et al.*, 2006; Pitman, McDonnell and Dawoud, 2009; MOEW, 2010; McDonnell and Fragaszy, 2016) of 130 Mm^3/year (ERWDA, 2002), causing a decline in the water table and an increase in its salinity (EAD, 2017). As mentioned by the Environmental Agency–Abu Dhabi (EAD), at the current abstraction rate, the groundwater is expected to be completely depleted within the next 32 years (EAD, 2015b).

The growing groundwater dependency of agriculture is not particular to ADE alone; it is a worldwide trend. Since the 1950s, agricultural production has tripled and 40% of this growth has come from irrigated areas (which have doubled), showing an increasing dependency on groundwater resources (De Fraiture and Wichelns, 2010; FAO, 2011c; Zingaro, Portoghese and Giannoccaro, 2017). The increase in agricultural productivity and expansion is driven by technological improvements in drilling, pumping and irrigation methods (Giordano and Villholth, 2007; Shah, 2014). This has led to a continuous rise in groundwater use, estimated in 2010 as 43% of the total irrigated water use (De Fraiture and Wichelns, 2010; Siebert *et al.*, 2010). The demand increase primarily depends on agricultural expansion, which in turn depends on farmers' decisions and their cropping patterns (Sharaiha and Ziadat, 2008).

In ADE, agricultural expansion and government-led objectives to increase domestic agricultural produce in the interest of food self-sufficiency (Arthur and Qaydi, 2010; EAD, 2012b; Woertz, 2013) have exacerbated the situation. This expansion has been demonstrated in the vast increase in the number of farms, from 634 in 1971 (SCAD, 2010) to 24,018 in 2016, covering 74,986 hectares (ha; SCAD, 2017a), where the majority of farms own a minimum of two wells. The domestic agricultural contribution is very small and it is only focused on some limited vegetable crops and the date palm. This unsustainable reliance on groundwater resources poses serious threats to the country's agricultural production targets that are required to address the needs of the increasing population. In the last few years, some essential projects have been launched in ADE to sustain water use and preserve the groundwater reservoir, but most importantly to establish an accurate and complete database on groundwater (abstraction rate, quality change, etc.). These projects include installing well meters, piloting treated wastewater use for agricultural production, reforming subsidies to enable the phasing out of the cultivation of high water use crops (such as Rhodes grass) and developing guidelines for crop water use (McDonnell and Fragaszy, 2016; EAD, 2017). However, these projects are yet to provide answers or address the issues they were set up to tackle. As indicated by various government reports (Pitman, McDonnell and Dawoud, 2009; MOEW, 2010; Government of Abu Dhabi, 2015), the absence of measured and accurate agricultural water use data is creating ambiguity and lack of transparency on what are the real challenges and the best way to address them. Only limited anecdotal data exists on groundwater usage and farming practices in relation to the reasons for the unsustainable state of affairs and how to solve these issues.

This study aims to develop an in-depth understanding of the current farming practices and their impacts on groundwater resources. It also seeks to assess how agricultural water use is managed and regulated across different relevant entities. Furthermore, it will build up an integrated agriculture and water policy framework to enable decision- and policy-makers to make informed decisions based on the synergy between sustainable agricultural water use and food security requirements.

1.2 Problem Definition

As emphasized in the previous section, one of the main problems in ADE is the necessity of water resources, agricultural expansion and increasingly unsustainable groundwater pressure to meet the fast-growing demand for food and water. The following sections provide further details on each of these issues, in addition to pointing out the critical need for a shift in the current management strategies to deal with them.

1.2.1 Critical Water Resources Issues

The UAE is located in a semi-arid climate zone within the Arabian Peninsula that is characterized by low rainfall and high temperature and humidity. The rainfall is erratic and irregular in time and space, with an annual average varying from less than 60 mm towards the western and southern parts of the country, to 160 mm that occurs towards the mountainous areas in the north and east (AGEDI, 2015a). Temperatures can be as high as 46–50 degrees Centigrade, especially in summer, when they are accompanied by high evaporation rates that can exceed 2,000 mm/year and lead to a loss of 75% of precipitation through evaporation (Murad, 2010). With the low precipitation rate, high temperature and evaporation, surface water is almost non-existent, thus making a negligible contribution to the country's water supply resources (Brook *et al.*, 2006; McDonnell, 2013), particularly with groundwater receiving minimal recharge that renders it a non-renewable resource (Rizk, 2008; McDonnell, 2013).

The UAE has the world's highest water consumption per capita of 353 litres per person per day (Ministry of Environment and Water, 2014), which is triple the global average water consumption (EAD, 2012a), despite the dire water scarcity it is currently facing. The Regulation and Supervision Bureau (RSB) found that there is an additional 73% loss of water for landscaping and vegetation in villas which is not collected through the sewage system (RSB, 2014). This goes to increase the UAE's carbon footprint, which is already known to be very high, estimated as twice the United States' carbon emissions per capita (Kazim, 2010). The rapid increase in demand has created stress and lays a burden on the government to build the necessary capacity and infrastructure to meet the required demand. This pressure has been shown in groundwater in particular, which has been exploited over the years. Historically, there was a high dependency on groundwater not only for the agricultural sector but also for domestic use. As the groundwater depleted in quantity and deteriorated in quality, gradually it was replaced by desalination and treated wastewater options (Murad, 2010; Dawoud and Sallam, 2012).

Currently, the government realizes the significance of high water use, especially groundwater use. About a decade ago, it issued reports explaining that groundwater was expected to be completely depleted by 2050, if the current farming practices continue (Pitman, McDonnell and Dawoud, 2009). It also highlighted the significant data gap, especially with regard to farmers' abstraction rates and water use. Accordingly, as mentioned in the previous section, a number of essential initiatives were launched to help develop a complete and accurate database as well as preserve the groundwater reserves for future generations. Despite these efforts, the groundwater data are scattered, with a lack of accuracy and completeness, and there is no system in place to monitor the abstraction and water use rate (EAD, 2017). Farmers still have no plan or guideline to follow in their water use for agricultural irrigation.

1.2.2 Unsustainable Agricultural Water Usage and Food Security

With the current heavy subsidies and investments that the government has put in place, agricultural production is still only meeting a small fraction of the country's self-sufficiency target for only a few selected crops (AGEDI, 2015b). Consequently, about 90% of food is imported to meet the needs of the increasing population. Agriculture also makes a negligible contribution to the country's GDP (Department of Economic Development, 2010). One of the reasons for this low contribution is the fact that farming is not a source of income for the majority of owners of farms, which are used mostly as family vacation resorts (Gallacher and Hill, 2008) wherein landscaping is more important and requires more water use (McDonnell and Fragaszy, 2016).

Agricultural expansion is linked more to social and cultural heritage than to food security. This is explained by the vast number of palm trees (about 6 million) that are cultivated but have limited value. It is estimated that the capacity of 71% of the trees has a production rate four times less than the government's estimated average rate, where only 35% of the total produced enters the market (Government of Abu Dhabi, 2016). Even though the date palm is the only crop that meets a high percentage of the self-sufficiency target, there is a huge amount of waste, not only in the quantity produced but also in the water use in general. This especially refers to water use for non-bearing and low yield rate trees. Rhodes grass is the second most cultivated crop and it consumes the highest amount of water (Pitman, McDonnell and Dawoud, 2009; Bollaci *et al.*, 2010; EAD and ADFCA, 2012). Therefore, in 2010, the government decided to phase it out, which led to a 90% drop, but its cultivation started to increase again in 2013. This could result from a lack of policy enforcement and monitoring mechanisms.

1.2.3 Agricultural Water Management

In the last four decades, agriculture-related policies were developed without considering the impact of farming practices on groundwater sources (McDonnell and Fragaszy, 2016). Such policy deficiencies are evident in the sharp increase in the number of farms (which jumped by more than 37 times since 1971) without any additional mechanism in place for dealing with consequences for groundwater resources (Pitman, McDonnell and Dawoud, 2009). Another example is the generous subsidies that were provided to farmers to encourage them to increase cultivated areas (Woertz, 2013) and the government's plan to increase agricultural production to meet food self-sufficiency (EAD, 2017). All these policies have moulded past and current farming practices and cropping patterns, which have subsequently created increasing pressure on the groundwater. Although in recent years the government has developed a number of policies and regulations aiming to preserve groundwater and reduce water use in agriculture, such as drilling regulation, irrigation methods and shifting from high to low water use crops, the implementations and enforcements have been quite challenging (McDonnell and Fragaszy, 2016).

Agriculture and water along with other sectors are managed by different entities that report directly to the Executive Council (EC) of ADE. There are fragmentations in the roles and duties of these entities, which affect integration, coordination and information flow between them. Therefore, the EC developed a Permanent Committee for Water and Agriculture Strategies (PCWAS) to fill this gap and ensure in-depth studies for any related policies and strategies (El Masri, 2010). Furthermore, the EC has assigned a number of team leaders with different levels of expertise to conduct workshops and facilitate communications between entities (drawn from the author's anecdotal information). In spite of these committees, there are still policy issues and fragmentation of effort between the entities, as well as a lack of data on how to ensure strict compliance.

1.3 Research Aim and Objectives

This research was triggered by a number of different critical observations, as explained in the previous section. The crucial point of these observations is the increasing consumption of groundwater to meet the challenges of the country's current and future food self-sufficiency targets. As already demonstrated, ADE's main challenge is to create a balance between increasing agricultural production to support food security policy, maintaining social and cultural heritage, and at the same time preserving the groundwater.

The main aim of this research is therefore to develop a deep understanding of groundwater use in agriculture and its impacts on water resources in ADE, which will go towards developing a policy framework, to enhance sustainable water use in food production. In pursuit of this aim, the following key objectives were established:

1. Develop an in-depth understanding of water usage in ADE through critical mapping of water consumption patterns across various sectors.
2. Establish enhanced knowledge and understanding of groundwater development, usage and associated sustainability issues.
3. Critically investigate agricultural development and its contribution to food self-sufficiency and the local market.
4. Develop a comprehensive understanding of current farming practices and their impact on water resources sustainability.
5. Critically determine how water use in agriculture is regulated and managed.
6. Develop a systematic and integrated agriculture-water policy framework to aid the relevant policy- and decision-makers in ADE.

1.4 Research Questions

To brief, the two main questions answered in this research are:

- How does the growing demand for water for agriculture affect groundwater use and food production in Abu Dhabi?
- To what extent should groundwater be used for domestic agricultural food production under sustainable agricultural water use development and food security goals?

1.5 Brief Overview of Research Methodology

The problems identified in Section 1.2 are complex and comprise numerous areas, including human behaviour (farmers, entities, individuals and experts), fees and time. Therefore, mixed methods involving both quantitative and qualitative approaches were used to conduct the study. Chapter 3 will indicate the justifications and application process of the methods used, but a summary of the main steps is explained below.

There is extensive literature in the food–water context. This review covers the global and regional food–water context, as well as agricultural and groundwater dilemmas, and points out the relevant initiatives to meet the food and water challenges. Next, the available secondary data are synthesized to assess the historical trends and the status of groundwater and agricultural development. The review and the assessment helped to develop a farmer survey to collect quantitative data, followed by the fourth step, gathering qualitative data to develop semi-structured interviews with selected subject matter experts (SMEs) from the associated entities. Finally, based on the key findings and the background research, an agriculture-water policy framework was developed to enable the decision-making process to sustain agricultural development in ADE.

1.6 Significance of the Study and Main Achievements

Through its main findings, this study has achieved the following:

- Developed an updated review on the food–water context, agriculture and groundwater issues, and international initiatives developed to overcome these issues. It offers deep insights for interested future researchers and industry practitioners.
- Established an in-depth knowledge of groundwater and agricultural developments and their impact on water resources and food security in ADE, through synthesizing the largely fragmented secondary data. The results provide detailed information not only for scholars, but also for relevant government entities.
- Developed a deep understanding of current farming practices and their impact on water resources and food security, which forms a vital information source in the policy-making process.
- Explored farmers' perception of ADE's water issues and relevant policies. These results provide unique and valuable information for developing policies and educational programmes for farming practices at local and national levels.
- Developed deep insight into current agricultural water use regulation and management in ADE. The findings provide assessments of the responsible entities' level of involvement, their knowledge and understanding of the current agricultural water issues, and gaps in the existing structure and policy development and implementation processes.

- Developed an innovative Agriculture-Water Policy Framework (AWPF) that provides systematic guidelines to help decision- and policy-makers in developing a sustainable agricultural water strategy. This framework can be used in ADE as well as in UAE and other Gulf Cooperation Council (GCC) countries to enable sustainable agricultural development.

1.7 Thesis Structure

Figure 1.1 shows the thesis structure, how the chapters relate to each other and their order of development. Following this chapter:

Chapter 2 reviews the literature in the food and water context at the global and regional levels. It contains food and water security links, agriculture and groundwater dilemmas and agricultural development in GCC countries. It also demonstrates relevant international initiatives to meet current and future food and water challenges.

Chapter 3 explains the methodology used in this research, justifies the selection of methods and outlines how it is implemented to meet the research objectives. It also demonstrates the data collection procedures, sample selections, and data analysis.

Chapter 4 reviews historical and current trends in ADE in water use, groundwater and agricultural development. It also assesses the contribution of domestic agricultural production to food security and food self-sufficiency.

Chapter 5 reports the data collected from the farmers' perceptions survey, and discusses the findings of the survey questionnaire in order to understand current farming practices in ADE and their impact on groundwater. Further, the findings validate farmers' awareness of water-related policies.

Chapter 6 provides the basis for relevant entities' and organizations' views on the critical water issues, as well as how water use policies are developed and implemented, and identifies barriers to successful policy implementation.

Chapter 7 describes the proposed Agriculture-Water Policy Framework, including its objectives and the framework structure, and discusses its implementation in ADE. The discussion includes running and assessing a number of relevant policy scenarios for food and water security.

Chapter 8 summarizes the key findings and draws conclusions on the contribution to knowledge, recommendations for policy and decision makers, research limitations and recommendations for further research.

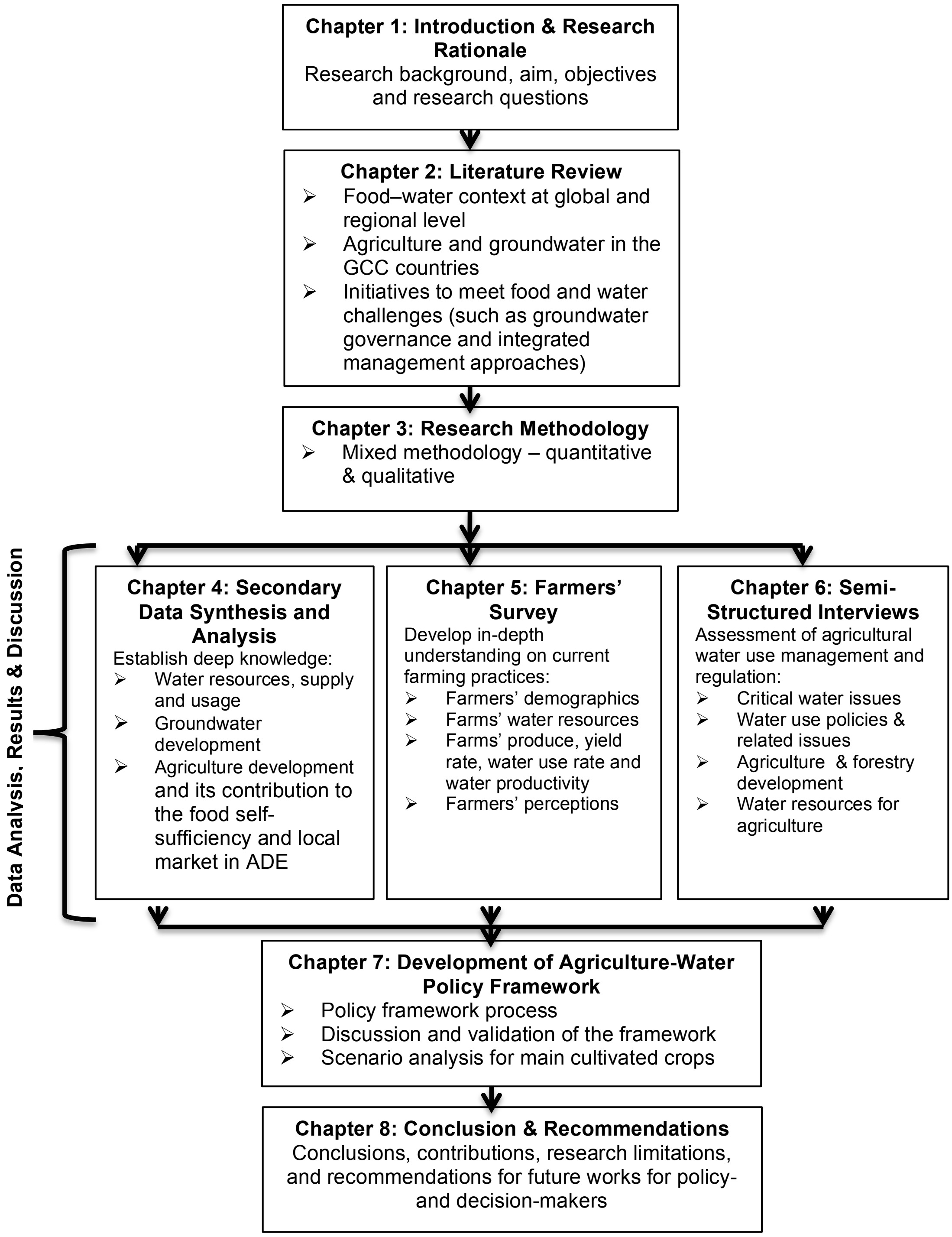

Figure 1.2 Flow diagram showing the thesis structure.

Chapter 2. The Food and Water Context

2.1 Introduction

This chapter describes the background to this work relating to four main issues that were found relevant to addressing the research objectives: 1) food and water security, 2) agriculture and groundwater dilemmas, 3) agriculture and groundwater in the GCC countries, and 4) initiatives to meet food and water challenges.

2.2 Food and Water Security

This section reviews food and water security by first describing the concept of food security and self-sufficiency, and how they are differentiated from each other. It also provides a review of the relation between food security and water security, the effect of climate change on food security, water scarcity, its severity and global distribution.

2.2.1 Food Security and Food Self-Sufficiency

Food security is defined by the Food and Agriculture Organization of the United Nations (FAO) as "[the condition in which] all people, at all times, have physical, social and economic access to sufficient, safe, and nutritious food which meets their dietary needs and food preferences for an active and healthy life" (FAO, 2015b, p. 3). The FAO's definition points out four dimensions of food security: availability, access of appropriate quality (physical and economic), utilization through adequate diet, and stability to ensure access of all individuals all the time.

The FAO's food self-sufficiency definition assesses the degree to which a country's domestic food production meets its food needs (Clapp, 2015); in other words, the ratio of the food consumed to that produced domestically per capita per day (calories, volume or monetary value). Since the origin of the food produced is not an element of the food security concept, food security does not mean self-sufficiency. High self-sufficiency does not necessarily lead to food security, since even large food-exporting countries import some of their food needs.

Countries around the world vary in their food self-sufficiency ratios: some, such as India, with a high ratio still have poverty (Schmidhuber and Tubiello, 2007), while others, including Singapore, Hong Kong, UAE and other GCC countries, with a low ratio are able to secure their food needs using their financial resources (Clapp, 2017). This puts them at risk of increasing food prices, geopolitical instability and vulnerability, as they are relying on international trade (Belesky *et al.*, 2014; Gilmont, 2015). Global trade plays an important role in food security, has surged during the last decade and is expected to continue increasing among importers and exporters.

Self-sufficiency in the UAE is very low due to its limited water resources, arable land and harsh climate, and around 90% of its food is secured by imports (AGEDI, 2016a), especially cereal, vegetables, meat and dairy products. Economic health, political stability, strong diplomatic relations and an open trade policy enable the country to secure its food needs (Fiscbach, 2018). However, increasing food prices during 2007–2008 triggered the need for a more robust, strategic and sustainable framework to protect fast-growing future needs.

2.2.2 Food Security and Water Security Link

Arable land and freshwater availability are the main two factors that limit the evolution of food production. At a net global scale, according to the FAO, these resources are sufficiently available to produce the required food for the growing population if sustainable practices are ensured (Belesky *et al.*, 2014).

Water is an essential input in each of the four dimensions through all the steps in the food cycle, from production (crop cultivation, fisheries and aquaculture, and livestock) to processing, transformation and preparation (Webb and Iskandarani, 1998; FAO, 2015b; HLPE, 2015). Therefore, at a global scale to ensure food cycle production processes, water also needs to be accessed at the same time as each of those aspects at the required quality, quantity and stability. However, the relationship between food security and water security is not straightforward, as water has multiple functions and is required in different quantities for various food cycles to address food security. It is also a key input in most human livelihood and wellbeing needs. United Nations Water (UN-Water, 2015) provides a comprehensive definition of water security: "The capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" (UN-Water, 2015, p. 8). This definition clearly demonstrates the competition for water in different important sectors, which creates more stress on water and the complexity to deal with this stress. This stress and complexity worsen with the growth of population and demand.

The FAO has forecast that the global population will reach between 9 and 10 billion by 2050 (an additional 80 million every year), which is a 40% increase compared with the 2005 population (FAO, 2015b; UN-Water, 2015; Mujtaba, Srinivasan and Elbashir, 2017). Along with this population increase, economic growth, urbanization and industrialization have resulted in production and consumption increases in different resources. This in turn has provoked increasing demand for water resources. According to the FAO (2015), most of the population growth is forecast to be in developing countries with low incomes and in rural areas, where increases in urbanization and development will restrict the availability of water of sufficient quantity and quality, especially for agriculture (FAO, 2015b).

The demand for food will also increase accordingly (by 60–100%) by 2050 compared with 2005, but this increase is much higher than the population growth proportion (UNDP, 2006; FAO, 2012a; HLPE, 2015). In the UAE, food demand growth is currently predicted to be 12% per year (Fiscbach, 2018), in a situation in which its total (national and non-national) population increased more than threefold from 2000 to 2011. This is one of the highest growth rates in the world (AGEDI, 2016a). The high increase in food demand caused by the increase in population, as explained by FAO (2012a), is also caused by increases in income, changes in lifestyle and a diet that has shifted towards animal-based food (FAO, 2009) and requires much more water compared to other crops such as rice (UNDP, 2006). UNDP (2006) estimates that to produce 1 kg of rice requires 2,000–5,000 litres of water, whereas to produce 1 kg of meat requires 11,000–15,000 litres of water in industrial farming.

2.2.3 Climate Change Impact on Food Security

Climate change refers to changes in the atmospheric gases (greenhouse gases: carbon dioxide, methane, nitrous oxide and others) that cause average weather change that lasts for long periods. By 2005, carbon dioxide concentration had increased by more than 35% compared to pre-industrial times, primarily due to fossil fuel combustion and land use change (IPCC, 2007). This drives global climatic change. Agriculture contributes to 10–12% of greenhouse gases such as methane and nitrous oxide (FAO, 2011c) and 25% if combined with livestock and forestry (IPCC, 2014; Sadik, El-Solh and Saab, 2014).

According to the International Panel on Climate Change (IPCC), these changes are attributed to natural variability or to direct or indirect human activities (IPCC, 2007). These changes contribute to an increase of surface and air temperature, melting of glaciers and rising of average sea level. The IPCC projection of average global surface temperature rise, precipitation changes and fluctuations of extreme events will have a great impact on agricultural productivity, stability and the ability of individuals to utilize and have access to food (Schmidhuber and Tubiello, 2007). Therefore, there is a common understanding that climate change is a major threat to food and water security (Pandya-Lorch, Rosegrant and Pinstrup-Andersen, 2001; Schmidhuber and Tubiello, 2007; Kang, Khan and Ma, 2009; IPCC, 2013; Belesky *et al.*, 2014).

The rate of evaporation and evapotranspiration is expected to increase, which will lead to an increase in demand for water and limit the productivity of agriculture (UNDP, 2006; IPCC, 2007; IAASTD, 2009; FAO, 2011a). Rainfall is expected to become more intense in some areas (higher-latitude tropics) and subsequently create floods that sweep away crops where runoffs will be decreased, which will reduce the recharge to groundwater aquifers. In contrast, it is expected to decrease in other areas such as the arid and semi-arid latitudes, which will become drier with a severe reduction in groundwater recharge (IPCC, 2008; FAO, 2011a).

The IPCC highlighted the expected increasing pressure on global water resource vulnerability in terms of availability and variability. Its study demonstrated the impact of increasing river flows and flooding in the next two to three decades as a result of accelerated melting of snow and glaciers (IPCC, 2008). This will influence groundwater recharge and agricultural stability. The IPCC concludes that groundwater recharge will decrease by up to 70% in most areas, and possibly even more in arid and semi-arid regions (IPCC, 2008; UN-Water, 2012). The negative impact on groundwater resources and the decrease of precipitation are expected to be severe in countries such as China, Sub-Saharan Africa and South Asia (IPCC, 2008). This will affect the rain-fed production of grains such as rice, wheat and corn in these countries, which is expected to drop in China by 20–30% in the next 20–80 years (IPCC, 2008; UN-Water, 2012). The United Nations Development Programme (UNDP) in 2006 forecast that climate change will induce food insecurity and water scarcity by 2080 (UNDP, 2006). Thus, adaptation to and mitigation of climate change, particularly with regard to agriculture and food, are essential (UNDP, 2006; FAO, 2015b).

In 2000, the UN officially issued eight Millennium Development Goals (MDGs) to be achieved by 2015, and these were agreed by world leaders. The first goal (eliminate poverty) is directly relevant to food security and the seventh (environmental sustainability) is relevant to agriculture and water management (Lomazzi, Borisch and Laaser, 2014; Wichelns, 2015). As the world realized the negative impact of climate change, it also realized that achievement of MDGs had failed in areas that are highly vulnerable to climate change, therefore it makes more sense to consider climate change impact while working on achieving the MDGs (Kreft *et al.*, 2010). In 2015, world leaders, at the World Government Summit, adapted 17 Sustainable Development Goals (SDGs) in order to build on the MDGs issued 15 years before (World Bank and UN, 2016). The SDGs are focused on poverty and inequality (SDGs 1 and 10), health, education and gender (SDGs 3, 4 and 5), food, water and energy (SDGs 2, 6 and 7), growth, employment and innovation (SDGs 8 and 9), sustainable consumption and human settlements (SDGs 11 and 12), climate, ocean and biodiversity (SDGs 13, 14 and 15), peace and justice (SDG 16) and global partnership to achieve these goals (SDG 17; World Bank and UN, 2016). Under the UN, there is a global commitment to achieve the SDGs, aligned with adaptation to and mitigation of climate change, including in water-scarce countries, the number of which is forecast to grow with climate change.

Climate change is also known to have significant impacts on GCC countries, including UAE. Studies (AGEDI, 2015a; MOCCAE, 2017) have predicted there will be an increase in temperature, storm surges and sea level rises in UAE, which will have severe negative impacts on the marine ecosystem and water resources. This will create a risk to the country's economic, environmental and social development. Therefore, UAE, which is among the most water-scarce countries in the world, shows a strong commitment through its national climate change plan for 2017–2050 and the sustainable environmental Vision 2021 (MOCCAE, 2017; UAE Government, 2018). The main objectives of these plans are managing greenhouse gases, building a green economy and using innovative solutions for economic diversification and sustainable development.

2.2.4 Water Scarcity

Water scarcity is defined based on the balance between freshwater availability and water use (UNDP, 2006; World Bank, 2007; FAO, 2012a). FAO (2012a) showed that water scarcity occurs when fresh water demand exceeds water supply. It varies from one region to another, depending on climatic conditions and water usage patterns. Three types of water scarcity are currently recognized: physical scarcity, which means not enough physical freshwater is available; economic scarcity, which translates into the inability to develop the required infrastructure (FAO, 2011c, 2012a); and institutional capability, which is the inability of the institutions and legislations to secure equitable of water supply to users (HLPE, 2015; FAO, 2011c).

Threshold values for water scarcity levels have been defined based on the rate of population that can live with a unit of water, which is estimated for the household, energy, agricultural and industrial sectors, and environmental need (Falkenmark and Widstrand, 1992; Rijsberman, 2006; UNDP, 2006; UN-Water, 2012). These levels fall between less than 500 m^3/capita/year (absolute water scarcity) and more than 1,700 m^3/capita/year (occasional or local water stress). Water scarcity is also measured by assessing the annual renewable water resources available per person at a country or regional level (FAO, 2003; Rijsberman, 2006). A renewable water resource receives considerable fresh annual recharge and a non-renewable resource receives negligible or no recharge, such as a deep aquifer. Total renewable water resources (TRWR), as described by the FAO, consist of international renewable water resources (IRWR) and external renewable water resources (ERWR). IRWR receive water flow and precipitation within the country or region and ERWR receive water flow from upstream in the neighbouring country (FAO, 2003; Mancosu *et al.*, 2015).

Figure 2.1 shows the global predicted change in m^3/capita per year (IRWR) from 2010 to 2050. It was developed by simulating predicted population growth, freshwater availability and abstraction rate per region (HLPE, 2015). As population increases, global IRWR are forecast to decline by 25% by 2050, where they vary from 2% in Europe and Central Asia to 52% in Sub-Saharan Africa (constructed by using information from HLPE, 2015). As a result, the number of countries that face water scarcity will likely increase from 30 to 50 by 2050, with most being developing countries (Fischer *et al.*, 2012). Figure 2.1 shows that the Middle Eastern and North African regions are those with the lowest IRWR and the second highest rate of reduction (after Sub-Saharan Africa) by 2050.

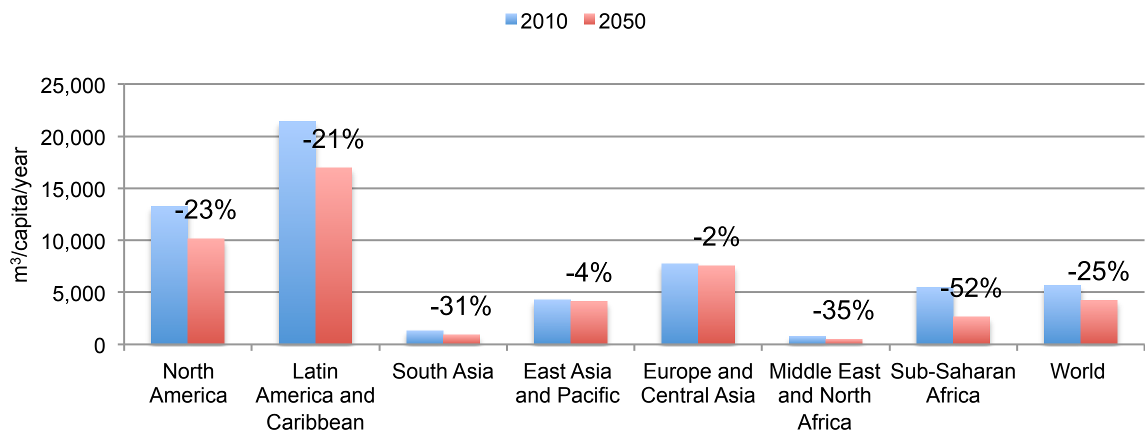

Figure 2.1 Global internal renewable water resources in 2010 and 2050.

Figure 2.2, developed from data obtained from ESCWA (2009), shows that Middle Eastern countries have the lowest per capita renewable freshwater compared to the average world rate. The GCC has the lowest in the region, where Kuwait, Qatar and UAE are the lowest, at 10, 40 and 50 m^3/capita/year, respectively (ESCWA, 2009), which is far below the UN's absolute water scarcity threshold (<500 m^3/capita/year), making these countries the poorest in renewable freshwater available worldwide.

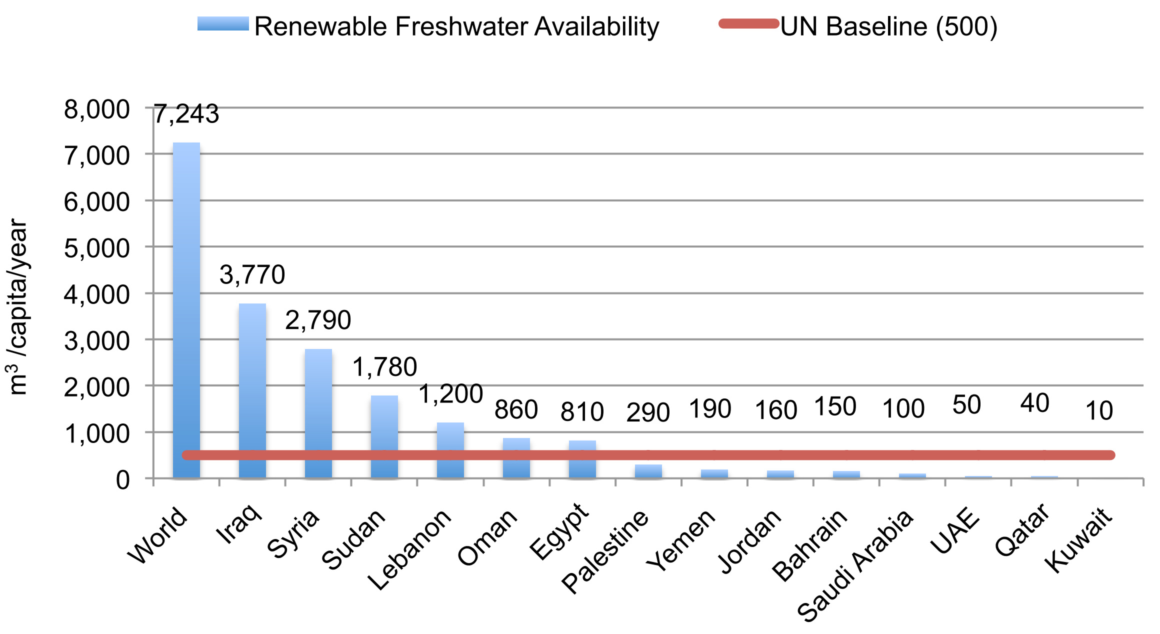

Figure 2.2 Renewable freshwater resources in world compared to UN baseline (adapted from ESCWA, 2009).

The UAE is the country with the third lowest renewable freshwater resources (after Kuwait and Qatar, as shown in Figure 2.2). Its semi-arid climate with low precipitation rate and high temperature and evaporation means that surface water almost does not exist and groundwater receives minimum freshwater recharge (Murad, 2010). This leads to surface water making a negligible contribution to the country's water supply resources (Brook *et al.*, 2006; McDonnell, 2013) and non-renewable groundwater resources (Rizk, 2008; McDonnell, 2013).

In the GCC countries (including UAE), freshwater resources are under increasing pressure, since total water withdrawal is exceeding the renewable freshwater reserve (HLPE, 2015). The increase in withdrawal has led to excessive exploitation of the renewable groundwater, where most is consumed by the agricultural sector. The level of water required per capita per day is mainly used to grow food (70 times the domestic need) and only a small portion is required for domestic use (Gleick, 2000; Rijsberman, 2006; FAO, 2012a). This indicates that water scarcity is more heavily affected by food production than domestic water use (Seckler, 1998; Yang *et al.*, 2003).

2.3 Agriculture and Groundwater Dilemmas

Historically, agriculture was reliant on rainwater, but as rainfall can be variable or insufficient when needed, irrigation from surface water and groundwater sources is used to support agricultural production. Global rain-fed cultivated land is 80% of the total cultivated land, producing 60% of total crop production, with the remaining 20% being irrigated land that produces 40% of total crop production (FAO, 2011c). However, even though irrigated agriculture possesses a smaller percentage of the total land cultivated compared with rain-fed cultivated land, it still uses 70% of total global (groundwater and surface water) freshwater withdrawals (Covalla *et al.*, 2001; Siebert *et al.*, 2010; UN-Water, 2012). Global groundwater use for agriculture is estimated to be 43% of the total freshwater withdrawal (Siebert *et al.*, 2010).

According to the FAO (2011c), land cultivation increased by 12% from 1961 to 2009, whereas agricultural production increased three times during the same period. All the increase in the cultivated area is attributed to the large increase in irrigated land, which has more than doubled and most is taking place in arid and semi-arid countries (FAO, 2011c).

Over the last 50 years, agriculture's dependency on groundwater has rapidly increased worldwide. This rapid growth spurred drilling and irrigation innovations (Giordano and Villholth, 2007; Shah, 2014). Groundwater has become an important water resource for agriculture in various countries, especially developing countries in Asia (such as India, Bangladesh, north China and Pakistan), where it is critical for food security (Giordano and Villholth, 2007). This resource has provided major support to reduce poverty (smallholder farming: increasing income through crop diversification and intensification) in those countries (Shah, 2014), where groundwater use increased to almost two-thirds (57%) of the total irrigated water (FAO, 2011c). Figure 2.3, based on information from Siebert and colleagues (2010), shows how Asia takes the largest share of global total irrigated groundwater use (73%) across the five continents. Since 1960, groundwater use in agriculture has also witnessed rapid growth, with a lower percentage share in less arid and more developed countries located in Europe, America and Oceania, such as Spain, Canada, the USA and Australia (Siebert *et al.*, 2010; UN-Water, 2012; Shah, 2014).

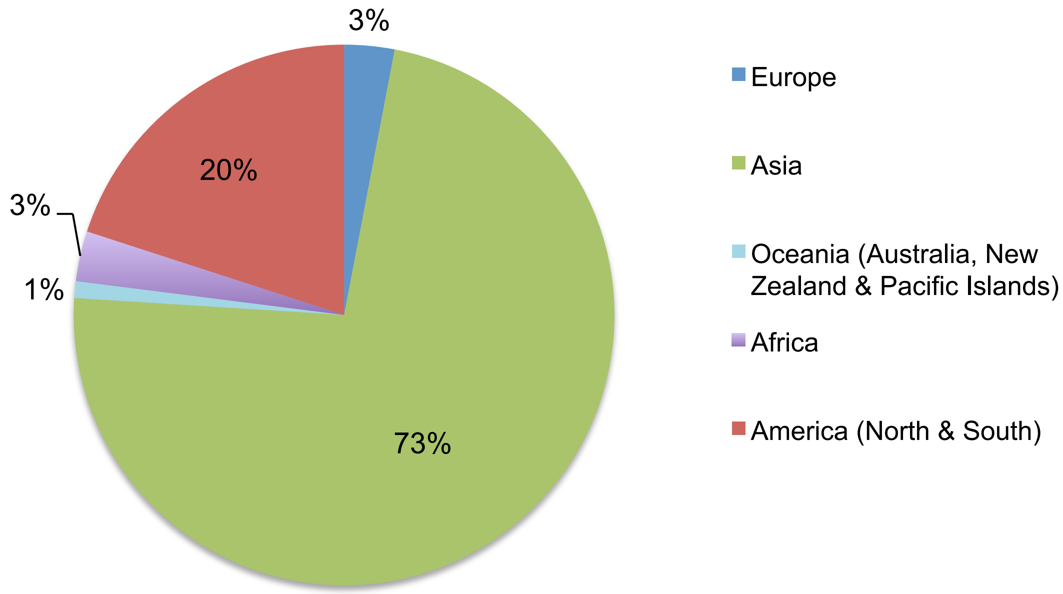

Figure 2.3 Global share of groundwater irrigation.

The continuous pumping of groundwater leads to changes in the characteristics and dynamics of aquifers: decline in the water table, rate of productivity and water quality (FAO, 2011c; UN-Water, 2012). The increase in irrigation also causes groundwater contamination through leaching of fertilizers and pesticides, soil salinization, subsistence of land and potential for overdrawing or exploitation of groundwater (Smith *et al.*, 2016). The main aquifers that are located in the largest food-producing regions are already showing evidence of groundwater degradation. These are in the USA (Ogallala), India (Punjab) and the North China plain (FAO, 2011c). Given the importance of groundwater for agricultural production in these regions, its degradation threatens current and, certainly with more severity, future food security at a global level. As global food demand is predicted to double by 2050, it is estimated that global agricultural water demand will increase by 19%, of which 5% is water withdrawal (UN-Water, 2012). Most of this increase will occur in countries that are already struggling with water scarcity, as in the Middle East (FAO, 2009, 2015b; UN-Water, 2012).

In the Middle East (Arabian Peninsula, Caucasus, Islamic Republic of Iran and Near East), overall irrigation groundwater use is 54% of total irrigation use, while it reaches 88% in the Arabian Peninsula (GCC countries and Yemen; Siebert *et al.*, 2010). In the GCC countries this percentage is more than 90% (FAO, 2011b). The rate of abstraction in this region has exceeded the annual renewable freshwater recharge, which has caused the groundwater to be depleted and contaminated by irrigation leaching or deeper brackish water (Siebert *et al.*, 2010; Sadik, El-Solh and Saab, 2014). Some aquifers have already been overdrawn and salinized, as in Qatar, UAE and Oman (Bazza, 2005).

2.4 Agriculture and Groundwater in the GCC Countries

2.4.1 Background

During the last few decades, the GCC countries have experienced rapid growth in oil revenue. This led to substantial growth in population, especially the urban population, which jumped from 5 million in 1960 to 47 million in 2012 (Saif, Mezher and Arafat, 2014; AlRashed, 2017). The population growth is driven by both indigenous organic growth and expatriate workers who immigrate to the Gulf countries (Mahmoud, 2016; UNDP, 2016) due to favourable socio-economic conditions. The fast economic development, with average growth of 5.2% of gross domestic product (GDP) per year, is driven to a large extent by fossil fuel exports, which have led to one of the world highest income levels per capita (Saif, Mezher and Arafat, 2014). Population growth and affluence have also influenced lifestyle and food consumption patterns. Food demand increased significantly, where food retail sales value increased by roughly 68% from 2013 to 2017 (Farrelly & Mitchell, 2014). The demand for water has also increased across all sectors, but mostly in agriculture, which exceeded the average of 80% mainly for irrigation (60% in Kuwait, 67% in UAE, 71% in Bahrain, 74% in Qatar, 90% in Saudi Arabia and 93% in Oman; AlRashed, 2017).

Despite intensive agricultural water use, about 80% of the food in the GCC countries is imported. Food imports are forecast to double by 2020 compared to 2010 (Farrelly & Mitchell, 2014). The limited arable land and water resources in this region constrain the countries' ability to expand their agriculture. Their productivity is not adequate to produce enough food to meet domestic demand. The area of arable land is far lower than that of the four main food producers: 2% and 2.8% in Saudi and the UAE, respectively, whereas it is 38.9%, 35.3%, 87.5% and 21.5% in the USA, UK, India and China, respectively (Farrelly & Mitchell, 2014). However, agricultural development is growing rapidly, which has led to the exploitation of surface and groundwater resources in excess of their natural recharge rates, causing aquifers to be depleted and dried out, as explained in the previous section.

Municipal water use has also increased dramatically, leading to desalination becoming an alternative to groundwater for all the GCC countries. Desalination developments started in the mid-1950s and reached significance in the 1980s (Saif, Mezher and Arafat, 2014; Mahmoud, 2016). Despite the high cost and negative environmental impact of desalination, its use continues to grow. The GCC stands to become the desalination world leader, with more than 50% (>30 Mm^3/day cumulative installed capacity) of the world's desalination capacity (Saif, Mezher and Arafat, 2014). The use of desalination for agricultural production is not yet commercially feasible due to its high cost, but it is being considered in a number of countries, such as Spain and Australia (Beltrán and Koo-Oshima, 2004).

2.4.2 Agricultural Development and Self-Sufficiency Ambition

Agricultural development in the GCC has more social and cultural value than economic value, where its share of GDP is very limited (Bazza, 2005; Kotilaine, 2010). The GDP share of agriculture in the GCC varies from 0.4% to 5%, which is significantly lower than other relatively water-rich countries such as Egypt and Turkey (10–15%) or India and China (15–20%; Kotilaine, 2010).

The GCC countries started the evolution to become food self-sufficient in the mid-1960s and early 1970s (Bazza, 2005; Kotilaine, 2010). They developed different policies to expand their agricultural sector, which needed continuous expansion of the water supply to meet its needs. Subsidies were developed to provide incentives for agricultural development. The form of these subsidies is by non-regulated and free groundwater; the provision of free services such as drilling, excavating, seeds, fertilizers, energy and fuel; as well as price support, which distorts the real cost of agricultural production (Bazza, 2005; Woertz, 2011). Subsequently, the irrigated area has increased accordingly, at a rate of 5% per year to the 1990s, then slowing down to 1.5% thereafter (Bazza, 2005), where in the span of three decades (1965–1995) irrigation expansion has more than doubled in the majority of these countries (Amery, 2015).

In the 1980s, a wheat cultivation project in Saudi Arabia demonstrated a practical example of the ambition for self-sufficiency. The production of wheat met most of the country's needs and also played a major role in world exports. However, by the 1990s, Saudi Arabia had decided to gradually reduce production (by 12.5% per year) to stop the exploitation of its fossil groundwater (Allan, 1997; Bazza, 2005). As a result, it reduced the relevant subsidies and restricted well drilling and groundwater abstraction (ESCWA, 2009). As the Saudi government realized the drastic impact on its scarce water reserve, it decided to end wheat production by 2016 and rely on wheat imports instead (Woertz, 2011; Mousa, 2016). It started to encourage farmers to use water-saving techniques such as greenhouses and drip irrigation to produce fruits and vegetables (Mousa, 2016). Consequently, the wheat cultivation area has decreased from 450,330 ha, producing 2.4 million tonnes in 2008 (Mousa, 2014), to 102,613 ha, producing 660,145 tonnes in 2013 (Fiaz, Noor and Aldosri, 2016).

Despite the high groundwater use in the GCC, self-sufficiency remains limited (Sadik, El-Solh and Saab, 2014). In these water-scarce conditions, with limited arable land and a harsh climate, achieving self-sufficiency is not only difficult to balance with the increasing population, but is also not economically viable, either in the GCC or in the whole of the Middle East and Arab region (Keulertz and Woertz, 2015). Table 2.1 shows the change (mostly decrease) in self-sufficiency percentage from 2003 to 2013 in cereals (wheat, millet, barley, sorghum and maize), fruits and vegetables across the six GCC countries. This information was collected from Bazza (2005) and FAOSTAT (2013).

Table 2.1 GCC countries' food self-sufficiency rate (%) in 2003 and 2013.

Country	2003			2013		
	Cereals	Fruits	Vegetables	Cereals	Fruits	Vegetables
Saudi Arabia	19.44	66.3	82.91	5.3	61.1	75.7
Oman	1.34	73.05	69.46	5.9	40	76.2
UAE	0	68.75	54.23	0.2	18.7	17.3
Bahrain	0	22.12	9.16	0	5.9	9.9
Qatar	7.72	44.01	36.07	0.3	1.1	12.5
Kuwait	0.59	13.47	58.2	0.2	9.9	36.8

** Note: Self-sufficiency ratio for 2003 obtained from Bazza (2005) and for 2013 calculated by using production and domestic supply data from FAOSTAT Statistics Database (2013).*

In total, the change in production shows an increase of 9% in cereals, and decreases of 48% and 19% in fruit and vegetable production, respectively (FAOSTAT, 2013, 2016). The only food item produced with a high self-sufficiency rate is dates, with more than 100% in Saudi Arabia and the UAE (including 8–10% exported) and 97.5% and 81% in Oman and Kuwait, respectively. The lowest rates are shown in Bahrain and Qatar (25% and 40%, respectively). The production of dates from 2013 to 2016 decreased by 12% in Saudi Arabia and 7% in Bahrain and Qatar, while it increased by 182%, 30% and 21% in the UAE, Oman and Kuwait, respectively (FAOSTAT, 2016).

2.4.3 Virtual Water Trade

Virtual water refers to water used in the production of a commodity (Antonelli and Sartori, 2015), therefore it can be defined as the water embedded within the production of any product (Allan, 2003; Horlemann and Neubert, 2006). Exchange of traded agricultural produce implies a virtual water trade (Horlemann and Neubert, 2006; Antonelli and Sartori, 2015). It can be estimated as the volume of water (m^3) used or required to produce a unit of food (kg or tonne; Obuobie, Gachanja and Dörr, 2005), where food can be crops or animals (e.g. the amount of water required to produce 1 kg of wheat or beef). This value varies depending on the location, duration of production, method of measurement and time of production, which is influenced by climatic change (Antonelli and Sartori, 2015). However, this value can also be the quantity of potential water saving where the commodity produced is consumed (Hoekstra, 2003; Antonelli and Sartori, 2015).

If food is traded from an area of low virtual water value, such as a humid region, to an area of high virtual water value, such as an arid or semi-arid region, there would definitely be an opportunity for water saving and better water allocation (Obuobie, Gachanja and Dörr, 2005). This would help to reduce the pressure on non-renewable groundwater and allow the importing country to utilize its limited water resources for more economically efficient means of production and to reduce the environmental impacts. At the global level, the trade of virtual water through agriculture was 987 km^3 from 1997 to 2001, which saved 455 km^3 (8%) of water per year (Horlemann and Neubert, 2006). The GCC countries are the major net importers of virtual water, with the UAE and Saudi Arabia being among the highest (Saif, Mezher and Arafat, 2014; Mahmoud, 2016).

Virtual water trading is vulnerable to food price increases, such as the food price spikes that occurred in 2007, 2008 and 2010 (FAO, 2015b; Keulertz and Woertz, 2015; Pirani and Arafat, 2016). This drove the GCC countries to look for alternative options to secure their nations' food supply.

Among the options taken are leasing or buying of farmland, targeting countries with good climates, suitable agricultural land and enough freshwater availability in Africa (Sudan, Uganda, Madagascar, Ethiopia, Somalia, etc.), Asia (the Philippines, Indonesia, Pakistan, Vietnam, Thailand, Cambodia and Burma) and America (Brazil and Argentina). Currently UAE and Saudi Arabia have purchased or leased (including deals still in process) 3 M ha and 1 M ha of farmland, respectively (Seo and Rodriguez, 2012). However, this kind of arrangement can put countries (investors) under risk of losing access to the land and of investing hugely in land with no guarantee of full control (Seo and Rodriguez, 2012). The terror attack on a Saudi farm in Ethiopia in 2012 is an example of a risk that these countries can be subject to, which has induced them to seek similar arrangements in politically stable countries (USA and Australia), such as the purchase of 4,000 ha of land in Arizona (USA) to cultivate alfalfa hay and ship it to a large dairy manufacturer located in Saudi Arabia (Mahmoud, 2016; Postel, 2017). The latter arrangement is debatable, since Arizona is also a desert that faces droughts and relies on non-replenished ancient groundwater. Increasing the risk to groundwater in another region does not meet global water use efficiency, where it is highly suggested that the virtual water trade along with efficient water allocation should be considered at local, national and international levels (Hoekstra and Chapagain, 2008; Antonelli and Sartori, 2015).

2.5 Initiatives to Meet Food and Water Challenges

This section presents national and international initiatives to meet food security objectives focusing on water scarcity and environmental impact. It includes sustainable agriculture, productivity improvement, alternative agricultural water resources, groundwater governance, and integrated management approaches and frameworks.

2.5.1 Sustainable Agriculture

Sustainable agriculture can be defined as meeting current food and fibre needs, making efficient use of natural resources at an economic and environmental cost (Cohen *et al.*, 1991; Crosson, 1993; FAO, 2014a). This cost should be socially acceptable without putting future generations' food demand at risk (Crosson, 1993; Lichtfouse *et al.*, 2009; FAO, 2014a). The social cost is all costs required for agricultural production, which includes the supply of water, energy, land, knowledge and capacity building, and related management. Crosson (1993) explains that the sustainable agriculture concept should be considered at an international level (similar to the virtual water trade), because in some regions the agricultural production cost is too high to be economically sustainable, while it is low in other regions, which makes food trading from low-cost to high-cost regions a sustainable option. In this sense, agricultural sustainability can be measured by the ability of the global agricultural system to be flexible in trading its food production or resources to meet the increasing future food demand at acceptable total costs (FAO, 2014a; HLPE, 2016).

To achieve sustainability in agriculture, multiple objectives are required, starting with maintaining production while sustaining and conserving the ecosystem (natural resources such as soil, water, energy, land and air), as well as minimizing the negative impact on the environment and enhancing profitability in a socially acceptable manner. There are many interactions and trade-offs that should be realized and assessed. Therefore a holistic vision and dynamic strategy have been suggested by the FAO to create a balance between these interactions within the environmental, economic and social dimensions (FAO, 2014a, 2015b).

The literature reveals several techniques and practices. Some require simple changes such as cropping management through reduction of chemicals and pollution via fertilizers and pest control (Lichtfouse *et al.*, 2009) and conserving tillage, which aims to conserve the soil with permanent cover, and crop rotation, which enhances soil nutrients and holding capacity, reduces soil erosion and creates a sink of atmospheric carbon dioxide without reducing yield levels (Kassie *et al.*, 2009; FAO, 2014a). Other techniques require fundamental change at a farm level, such as integrating agricultural practices with animal production, pest management methods, water resources and soil management, considering decreasing negative externalities (Lichtfouse *et al.*, 2009; Godfray *et al.*, 2010). These changes will require altering practices with different and innovative technologies such as precision agriculture, where different technologies are used to apply, monitor and control the use of water, pest control and fertilizers that are required by plants in a timely manner (Godfray *et al.*, 2010).

2.5.2 Productivity Improvement

In the past, agricultural research focused on increasing agricultural production in order to meet growing demand. It shows that agricultural production has increased mainly by expanding irrigated agricultural lands with the fast development of irrigation technologies (Pereira, Oweis and Zairi, 2002; FAO, 2011c; Fischer *et al.*, 2012). However, this focus has diverted to water and land productivity (De Pascale *et al.*, 2011), which are traditionally the primary limiting factors for agricultural productivity. In water-scarce regions, water is more likely to be the limiting factor, therefore agricultural productivity is strongly linked to water productivity (Pereira, Oweis and Zairi, 2002; Molden *et al.*, 2003; Ali and Talukder, 2008).

Water productivity is expressed based on the benefits that can be derived from a unit of water applied (Molden *et al.*, 2003; Playán and Mateos, 2006). It depends on several factors, for instance plant genetic material, water management and farming practices (e.g. fertilizers, soil tillage, irrigation schedule). According to Molden et al. (2010), the benefit can be physical mass production or value in money per water unit (kg/m^3 and US \$/m^3). Physical productivity (kg/m^3) is defined as the ratio between crop yield in kg per ha (kg/ha) to the cubic meterage of water used per ha (m^3/ha), whereas economic productivity (US \$/m^3) is valued in US dollars gained per unit of water (Platonov *et al.*, 2008; Molden *et al.*, 2010). The water applied is the water flow to the plant via irrigation or rainfall, including the water lost through plant transpiration and evapotranspiration and leaching into the soil. When farmers face a shortage of water, they intend to increase the crop production (mass) per unit of applied water through different strategies, such as deficit irrigation and/or water conservation practices.

At a farm level, water productivity can be improved by understanding the relation between evapotranspiration and crop yield in its different growth stages (Molden *et al.*, 2003; Geerts and Raes, 2009) and how crop yields respond to water (Molden *et al.*, 2003). This knowledge will help farmers better select irrigation methods and manage irrigation scheduling during stress and the critical growth stage, which will increase crop yield. To advance water productivity, studies show that using innovative technologies helps to increase crop yield, as observed in many countries through efficient irrigation systems (FAO, 2015b). It was also observed that the use of drip irrigation in the Middle East increased productivity from 40–50% to 60–70% (Perry, 1999; Playán and Mateos, 2006). A smart irrigation system was recently tested at the Abu Dhabi Food Control Authority (ADFCA) research centre for two crops (cucumber and tomato) planted in greenhouses (plastic houses with controlled temperature and humidity) using an automatic drip irrigation system connected to soil moisture sensors. Based on the data collected on soil water content, irrigation timing and duration scheduled, the result of this study shows a growth in crop yield and a significant reduction in irrigation requirements compared to FAO estimated crop water requirement (Al Hammadi, 2014).

Greenhouses as an alternative to traditional open field farming are suggested in arid regions (Sharan, Jethava and Shamante, 2005; Fiaz, Noor and Aldosri, 2016). This technique has been adapted in the UAE (particularly in ADE), Saudi Arabia and Qatar, where it has proven to improve crop productivity and reduce water use in irrigation (Vraneski and Allan, 2001; Sharan, Jethava and Shamante, 2005; FAO, 2013; Al Qaydi, 2016; Fiaz, Noor and Aldosri, 2016; Ouled Belgacem, 2017). Farming in greenhouses can use soil or soilless (hydroponic) systems, which have been increasingly promoted by ADFCA and EAD in order to improve crop productivity and reduce water use (EAD, 2012b). Recently, the ADE government introduced greenhouse soilless farming (2 units of 400,000 m^2) in a closed system combined with aquaculture (aquaponic system). This project succeeded in producing 200 tonnes of tilapia and 300,000 heads of lettuce per year with 60–70% of water circulated (Al Qaydi, 2016).

The use of improved technologies in the UAE is also shown by different tissue culture methods to improve palm tree genetics, which help to speed up multiplication to produce the required fruit quality and growth rate (FAO, 2015a). Therefore, according to the FAO (2015a), the increase in the role of technology and the learning curve during the last 50 years has not only improved crop productivity and optimization of water use, pest control and nutrients, but has also helped farmers to diversify their cropping pattern and increase their income (FAO, 2015a).

2.5.3 Alternative Water Resources for Agriculture

2.5.3.1 Desalination

Most of the desalination plants built in the GCC countries are for seawater purification. For inland areas away from the coastline, brackish groundwater desalination plants are also built, but with a smaller proportion. The desalination process remains costly because it is energy intensive, despite the cost decreasing by almost 90% since the 1970s (Mohammed Qadir *et al.*, 2007). Although there is some potential for more technological development and use of different sources of energy, such as nuclear, solar and wind energy, a high reduction in cost is not expected any time soon (Sgouridis *et al.*, 2013). The major drawbacks of desalination are high capital and maintenance costs (Wade, 1999; Dawoud, 2005; ESCWA, 2009; Sommariva, 2010), intensive energy use (mainly natural gas; Wade, 1999; Sommariva, 2010), risk of oil spills and red tides (McDonnell and Fragaszy, 2016), high carbon emissions if powered by fossil fuels (ESCWA, 2009) and increase in the temperature and salinity of the Arabian Gulf due to desalination brine discharge (AGEDI, 2016b).

Brackish groundwater desalination has a lower cost than seawater desalination, but the use of desalination for irrigation remains expensive. It has been used at a small scale to produce a high crop value using innovative technology (in greenhouses) in southeast Spain, for example, where the government shares the capital and operational costs with farmers (Beltrán and Koo-Oshima, 2004; Mohammed Qadir *et al.*, 2007). In ADE, small-scale brackish desalination is also an option for some commercial farms, which receive heavy subsidies for the water and energy costs required for greenhouse farming (McDonnell and Fragaszy, 2016). Furthermore, the total seawater desalination supplied in ADE that is used in agriculture is estimated at 21%, although there have been no measures or studies of its water productivity.

2.5.3.2 Treated Wastewater

Universally, it is estimated that 20 million ha of agricultural land is irrigated with wastewater (FAO, 2012a) in different forms: treated, diluted, partly treated or untreated (Jimenez and Asano, 2004; Mohammed Qadir *et al.*, 2007; Srinivasan and Reddy, 2009; Mateo-Sagasta and Burke, 2012). Mohammed Qadir *et al.* (2007) highlighted in their study that crop yields and economic returns from untreated or partially treated wastewater irrigation are higher than those from freshwater or groundwater irrigation. However, there are major environmental and health risks that should be considered (Srinivasan and Reddy, 2009; Qadir *et al.*, 2010). Accordingly, the World Health Organization (WHO) along with the FAO has developed wastewater use guidelines to ensure safe use (WHO, 2006). These international organizations realize the need for this type of water, especially in water-scarce countries, because of its high nutrients and low cost, but it should be subject to a high degree of control to secure safe use. Therefore, they have suggested a strong institutional set-up, policy frameworks and enforcement mechanisms.

Given the status of water resources in the GCC countries, there is a growing use of treated wastewater in these countries. The main uses are for landscaping, public parks and gardens. However, it is still only utilized by less than 30%, with the remaining percentage disposed of in the sea (Saif, Mezher and Arafat, 2014) and a negligible percentage, only 7%, used for agriculture (Bazza, 2005).

2.5.3.3 Marginal Quality Groundwater

Most water-scarce countries have saline and hyper-saline aquifers or high alkali water (sodic water). It is common practice in many of these countries (South Asia, USA and Spain) to use saline and sodic water to grow salt-tolerant crops (Mateo-Sagasta and Burke, 2012). Crops' tolerance of salinity differs significantly, therefore when using saline water it is vital to pay attention to crop selection as well as appropriate soil, land and irrigation system management, in order to prevent any risks and improve the efficiency of water use (Manzoor Qadir *et al.*, 2007).

For the last 20 years, the International Centre for Bio-saline Agriculture (ICBA) has been studying the feasibility of marginal water use in agriculture in the Middle East (Egypt, Morocco, Jordan, Oman, Yemen and UAE), Central Asia (Kyrgyzstan and Uzbekistan) and Africa. It has demonstrated success in the cultivation of halophytes such as quinoa and salicornia using high-salinity water in dry and harsh environments under appropriate farming practices (Al Wafi and Begmuratov, 2017). The ICBA is also studying the use of high-saline water for inland aquaculture (fish farming) in these regions by way of high saline and desalination brine discharge. In the UAE, the ICBA is also participating in promoting halophyte cultivation and aquaculture in coordination with MOCCAE (ICBA, 2015, 2016; Al Wafi and Begmuratov, 2017).

2.5.4 Groundwater Governance

Groundwater governance is challenging everywhere and there is still much to be done in order to have full control (Shah, 2014). There are various cases in different countries that provide lessons on different approaches to dealing with some of the challenges, such as groundwater regulations, groundwater replenishment and improving the knowledge gap. These are explained in the following subsections.

2.5.4.1 Groundwater Regulation

Regulating the abstraction of groundwater is usually challenging because of weak political will, public acceptance and enforcement capacity (Rogers and Hall, 2003; Shah, 2014). This is a typical scenario in developing countries such as those in South and West Asia. In the last three to five decades, countries such as India, China and Jordan have introduced groundwater quota systems, well metering, volumetric pricing, energy pricing and penalties, which remain unenforced because of strong opposition from farmers (Wang *et al.*, 2007; Shah, 2014).

Oman, on the other hand, has been successful with groundwater pumping restrictions through stringent regulations involving administering permits to register wells, closing unpermitted wells, penalizing contractors culpable of illegal drilling, installing well metering and developing a national inventory (Van der Gun, 2007; Shah, 2014). In other Middle Eastern and GCC countries (such as Jordan, Syria and Yemen), there have been recent efforts to preserve non-renewable groundwater, but so far no evidence of success has been seen.

In ADE, a well inventory project was launched in 2016 to install well meters in order to monitor the groundwater abstraction rate and set limits for different locations. In the same year, a developing crop calculator project was launched to obtain the optimum crop water requirement to provide farmers with guidelines on the quantity of irrigation water required (McDonnell and Fragaszy, 2016). To date there has been no report on the findings or the progress of this project.

However, in developed countries, groundwater abstraction regulation is commonly used (typically including volumetric charges and fixed fees) in order to protect and preserve aquifers (OECD, 2010). In the USA, for example, the decline in groundwater level in the Ogallala aquifer pushed the government to restrict the drilling of new wells and to ask farmers to submit data on the volume abstracted every year, in order to generate statistical data on the rate of abstraction and increase farmers' awareness of the rate of aquifer depletion. The US government managed to reduce groundwater abstraction by 1,850 m^3 by introducing further water-saving technologies and converting farming from irrigation to rain-fed cropping (Gollehon and Winston, 2013).

2.5.4.2 Groundwater Replenishment

Traditionally, dams, barrages and weirs were constructed to allow runoff water to recharge aquifers artificially in order to replenish and reserve groundwater (Asano, 1985). Recently and in the absence of runoff, treated wastewater and desalination water have been used for the same purpose (Spandre, 2009). Artificial groundwater recharge is also used widely in most developed countries, such as Germany, the Netherlands, Sweden, Switzerland and the USA. These countries replenish groundwater by 15–25% even though they are not heavily dependent on groundwater, except for the USA (Qureshi *et al.*, 2010). The same technique is used in ADE, but involves injecting desalination water into surficial aquifers, considered as the country's strategic emergency plan (Sathish and Mohamed, 2018). Other GCC countries, for instance Oman, Kuwait and Qatar, have realized the need for such a technique and have established pilot projects to study this approach (Al-Katheeri, 2008).

2.5.4.3 Groundwater Knowledge Gap

One of the major challenges in managing and controlling groundwater is the absence of complete and accurate relevant information. This information can be about the aquifer system (location, lithology, dimensions, capacity and vulnerability) and groundwater conditions (discharge, recharge, water level, water quality, etc.). Such information is vital to formulate the foundation to improve groundwater management and enhance the ability to diagnose the extent of groundwater and understand the current and future issues (Smith *et al.*, 2016). The information collected can further be used to help develop long-term groundwater monitoring, land zoning and modelling. This will enable understanding of the nature of aquifers and their vulnerability, which will support the technical capability to build intervention planning programmes.

In ADE, groundwater information is limited and not robust enough to help with accurate assessment of current and future reserves (Pitman, McDonnell and Dawoud, 2009; MOEW, 2010; McDonnell and Fragaszy, 2016). This is also the case in many other countries. Therefore, in 2011 the FAO, in coordination with four other international agencies – United Nations Educational, Scientific and Cultural Organization International Hydrological Programme (UNESCO IHP), International Association of Hydrologists (IAH), World Bank (WB) and Global Environment Facility (GEF) – initiated the Groundwater Governance Programme to help governments at a global level to sustain groundwater and prevent water crises (FAO, 2014b). The programme's objective is to build a global shared vision using existing knowledge and experience and to develop guidelines to help policy-makers manage their groundwater.

2.5.5 Integrated Management Approaches and Frameworks

The recent trend of increasing stress on water and the overexploitation of many major water bodies, degradation of soil fertility and the expected increasing demand for the next 50 years, altogether have pushed for an increasing need to change the way these resources are managed. As explained in Section 2.2.3, the alarming messages about climate change impacts coupled with projected extreme water scarcity, especially in developing countries, have urged researchers and international institutions (such as the FAO and the Organization for Economic Co-operation and Development, OECD) to develop studies and propose recommendations that could help these countries cope with scarcity.

Therefore, in the last few decades, there has been concerted attention on the need to develop an integrated and holistic approach or a nexus to manage different sectors, including water, land, energy, climate change, food security and environment (World Bank, 2007; Bazilian *et al.*, 2011; Hoff, 2011; World Economic Forum, 2011; ICIMOD, 2012; Bizikova *et al.*, 2013). The most vital commonality between these resources is their sensitivity to climate, expressed via their adverse impacts on climate change and vice versa, which results in an increase of pressure on them (Eriksson *et al.*, 2009; Shrestha and Aryal, 2011; Rasul and Sharma, 2015). This sensitivity is at stake in arid and semi-arid regions of developing countries where these resources are limited, scarce and dwindling, while demand is spiking (Rockström *et al.*, 2009; Rasul and Sharma, 2015). Therefore, it is a top priority in these regions to sustain the use of these resources without impacting each other and at the same time to minimize climate and environmental impacts (FAO, 2014a). In order to achieve this, it has been suggested that strategic planning, policy-making and decision-making should shift from a sectoral to a cross-sectoral and integrated approach (World Bank, 2008; FAO, 2014a, 2015b; Sadik, El-Solh and Saab, 2014; HLPE, 2015). This will enable policy- and decision-makers to recognize the trade-offs between the different sectors and utilize resources such as water in a more effective way, creating a balance in how water is allocated to different sectors with a greater focus on improving water use efficiency and productivity (Moore, 2004; Benson, Gain and Rouillard, 2015).

The literature (OSTROM, 1990; Ruttan & Hayami, 1984; FAO, 2012a) shows that improving efficiency can be a technology issue, but mainly that policy and institutional changes are more challenging and require reform to face the rapid developments in these countries. It also shows that there is no single solution that can fit every country and suggests that policies be adapted to fit specific local conditions within a given timeframe (FAO, 2012a).

A holistic and common conceptual framework to administer both agriculture and water is suggested as a better way, instead of managing each sector in a silo (Adger and Jordan, 2009; FAO, 2012a; OECD 2010). This will enable the increasing scarcity, growing demand and interrelation between the two sectors to be managed while ensuring policy coherence, sharing knowledge and information (IFAD, 2015) and allowing experts from different sectors to work together (FAO, 2014b). The FAO and OECD further emphasize the need to empower responsible institutions with clear roles and responsibilities, as well as enforcement mechanisms (OECD, 2010; FAO, 2012a).

Currently in developing countries especially, the sectors of water and agriculture are administered separately, which can be a barrier to sustainable and efficient water use (World Bank, 2005; Binswanger-Mkhize, Meinzen-Dick and Ringler, 2012). Similarly, in UAE and particularly ADE, these sectors are planned and managed in isolation, where policies and strategies are developed separately by fragmented efforts from different entities. This is realized by the government, which recently put effort into facilitating coordination between the relevant entities (McDonnell and Fragaszy, 2016). However, there is no formalized framework with a specific policy to translate the integration concept into practice.

In general, there is a growing number of agricultural frameworks developed at global level that provide general guidelines (Pearson, Gotsch and Bahri, 2004; OECD, 2010; Bizikova *et al.*, 2013; FAO, 2014a; Global Water Partnership, 2017; IFREMER, 2017) and at a local level that are based on specific issues identified in a specific country (Sharifi and Rodriguez, 2002; Greiner, 2004; Ferreyra, de Loë and Kreutzwiser, 2008; Bansouleh, 2009; Hargrove *et al.*, 2013). The following subsections present relevant examples of three global frameworks followed by three national/local frameworks. These frameworks provide measures and insights for a better decision- and policy-making process to ensure sustainable development for agriculture under water and climate change uncertainty.

2.5.5.1 Integrated Water Resources Management (IWRM)

Integrated Water Resources Management (IWRM) was recommended in 1992 at the International Conference on Water and the Environment in Dublin and enacted in 2003 at the World Water Forum in Kyoto (HLPE, 2015). As shown in Figure 2.4, IWRM promotes integrated management for water resources by bringing together policy-makers, planners, users and all relevant stakeholders to develop a framework with a focus on demand management and sustainable use of groundwater (World Bank, 2005; HLPE, 2015). The FAO and the UN are applying IWRM principles to their programmes in managing agricultural sectors (FAO, 2014a). These principles are mainly integration, optimal governance, participation, resource use and sustainable development (Benson, Gain and Rouillard, 2015).

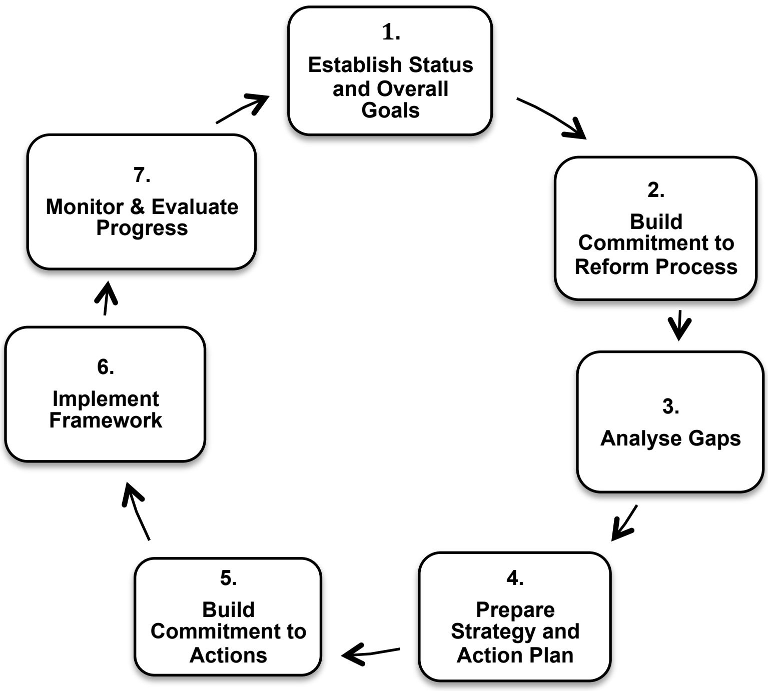

Figure 2.4 The IWRM planning cycle (adapted from Global Water Partnership, 2017).

In developed countries, the attempt to integrate water policies was initiated in the 1930s to manage flooding, preserve water quality and protect fisheries, for example in the UK (Lorenzoni, Benson and Cook, 2015), which established multipurpose authorities under the Water Act 1973. In the UK and other European Union (EU) member states, this management framework was reconstructed to be managed by a centralized body in the late 1980s and early 1990s. It then proceeded to focus more on an integrated approach that currently reflects the IWRM principles (Benson, Gain and Rouillard, 2015). The same principles are used in the USA and Australia, where they were developed further (as adaptive water management) to focus on developing policies based on a continuous systematic feedback process (Berkes, Colding and Folke, 2003; Olsson, Folke and Berkes, 2004; Allen *et al.*, 2011).

In developing countries, although there has been increasing recognition of IWRM, they still face challenges in its adoption, with no significant evidence of successful implementation (Van Koppen and Shah, 2007). In ADE, the government anticipated IWRM as a potential sustainable approach (McDonnell and Fragaszy, 2016) to manage the relevant sectors, although there is no formal framework developed yet.

2.5.5.2 Water Framework Directive (WFD) and Common Agriculture Policy (CAP)

The Water Framework Directive (WFD) and the Common Agriculture Policy (CAP) are frameworks developed by the European Commission that legally bind all EU members. WFD objectives are to sustain and protect all water bodies, including groundwater (European Commission, 2012). Similar to IWRM, WFD provides integrated management for all water resource planning and brings all stakeholders into the decision-making process in order to maintain sustainable and economic development. Its management cycle is shown in Figure 2.5 and consists of three main processes: development of management plans, review of their effectiveness and implementation of management plan measures (IFREMER, 2017).

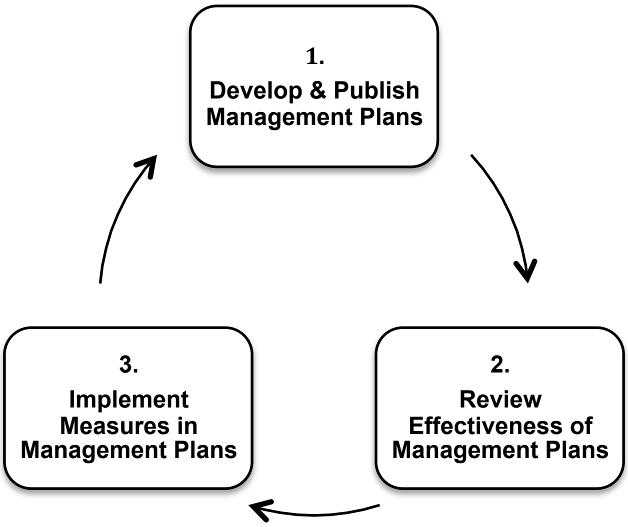

Figure 2.5 WFD management cycle (adapted from IFREMER, 2017).

CAP's main objectives are to ensure viable food production, maintain sustainable development of natural resources under climate change adaptation and balance territorial development (Basch *et al.*, 2011). As the main focus of CAP is farmers, its measures are developed to directly link farmers' performance to allowable payments. These two frameworks (WFD and CAP) focus mainly on connecting agriculture policy and water policy to facilitate the development of water use in irrigated agriculture, and to ensure the development of sustainable agriculture and sustainable water use policies. Recently, the EU has been working on further development to strengthen the policy for climate change adaptation and enhance the integration of both CAP and WFD objectives to increase synergy and reduce conflicts (Basch *et al.*, 2011).

2.5.5.3 Agriculture Policy Analysis Framework (APAF)

An agriculture policy framework is a concept used to develop clear thinking for decision-makers and to reduce conflict between policies and misunderstanding among policy-makers. It also permits linkage and integration between different policies and identifies trade-offs and conflicts (Monke and Pearson, 1989; Ellis, 1992). It is a theoretical framework that consists of four main components: objectives, strategies, policies and constraints (Monke and Pearson, 1989; Pearson, Gotsch and Bahri, 2003, 2004). As shown in Figure 2.6, the framework components interlink with each other in a clockwise circle.

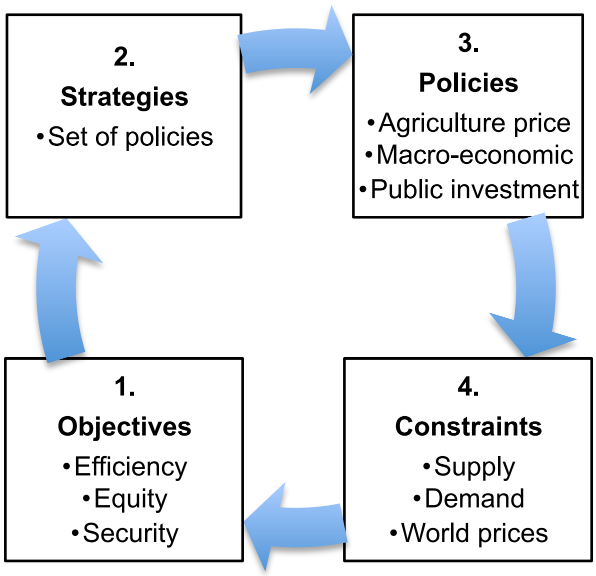

Figure 2.6 Agricultural policy framework diagram (Pearson, Gotsch and Bahri, 2004).

Most governments base their agriculture on three fundamental objectives: efficiency (allocation of resources); equity (distribution of income; Ellis, 1992; OECD, 2010); and security, for example food security (Monke and Pearson, 1989). There are many other objectives that policy-makers target, which should be within these three main objectives. Currently, there is an increasing trend, especially in developed countries, to link these objectives with water and climate change (OECD, 2010). Usually, trade-offs arise between objectives; therefore, weight and value should be assigned to the objectives, which are subject to the policy-makers' judgement.

Based on the defined objectives, long-term strategies consisting of a set of policies are to be developed. Agricultural policy consists of three main categories. The first category is agricultural price policies, which target specific agricultural produce. This policy enables the transfer from or to three groups: producers, consumers and government budget (subsidies, trade law and taxes). One or two of these groups will benefit and the other one will lose out.

For example, in areas of heavy government subsidies such as the UAE, beneficial parties are producers and consumers and the government is losing out. The second category is macro-economic price policies that affect all commodities simultaneously, as well as the country's economy. These are mainly fiscal and monetary, foreign exchange and factor price policies such as interest rate, wage, land use and natural resource policies (Pearson, Gotsch and Bahri, 2003; Norton, 2004). The third category is public investment policies, involving allocation of capital investments to a certain public location.

As explained by Pearson, Gotsch and Bahri (2004), usually there are three basic constraints that limit the achievement of agricultural policies: supply, demand and world prices. The supply is the agricultural production that is required to meet the demand. The ability of the government to achieve agricultural production can be limited by the availability of the resources (such as land, water, energy, finance, etc.), technologies and management capabilities required. The demand is based on the population, income and lifestyle and commodity prices. World prices affect the ability to import to meet demand and to export marketable domestic production. The constraints and limits in these components lead to policy trade-offs and in some cases the development of policies tailored to overcome these limitations. For example, if technology and knowledge form a constraint, policies can be instruments to accelerate technology development and capacity building (Ellis, 1992).

An example of the application of the agriculture policy framework is shown in Figure 2.7, which is implemented on rice strategy in Indonesia. This figure shows the four components of the framework: objectives, strategies, policies and constraints. According to Pearson, Gotsch and Bari (2004), the policy analysis provides quantitative and empirical data on the advantages and disadvantages of each strategy for the country's economy (rural income, employment, rice price stability and government subsidies). It also spells out and assesses the policies used, the constraints and assesses how far the defined objectives have been met (Pearson, Gotsch and Bari, 2003; 2004).

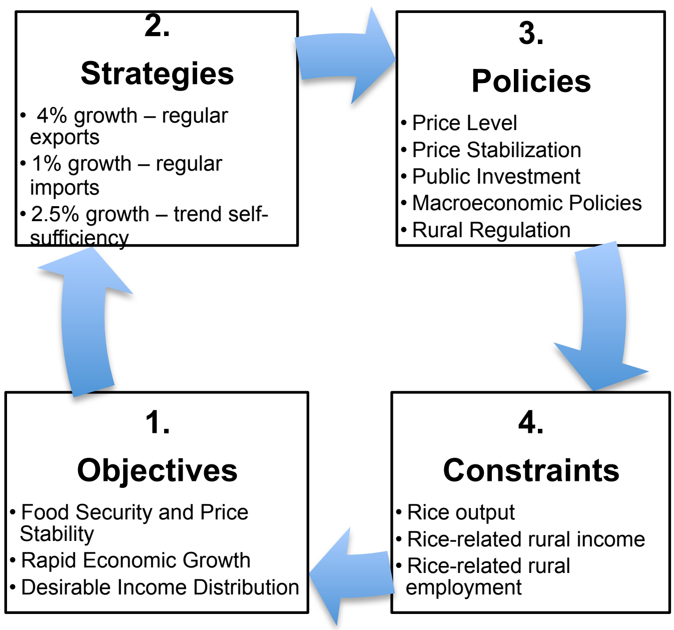

Figure 2.7 Rice policy in Indonesia (Pearson, Gotsch and Bahri, 2004).

Such policy analysis application does not exist in ADE, although ADFCA highlighted the need for agriculture-water policy analysis in its policy document issued in 2012 (ADFCA, 2012). To date there is no information on how agricultural policies are developed and implemented, or analytical reports on policy achievements and outcomes.

2.5.5.4 Conceptual Framework for the Analysis of IWRM in Agricultural Areas

In Ontario (Canada), IWRM emerged during the 1980s in order to improve the integration between various actors and stakeholders within environmental governance (Margerum, 1997), aiming to protect surface and groundwater resources. The implementation of IWRM principles improved institutional integration for water and agriculture planning and management, but it lacked flexible and meaningful social and political linkages in agricultural areas at a local level (Lowndes and Skelcher, 1998; Ferreyra, de Loë and Kreutzwiser, 2008). Therefore, Ferreyra, de Loë and Kreutzwiser (2008) developed a conceptual framework for the analysis of IWRM in an agricultural area in Ontario to identify its strengths and weaknesses, as well as enhance creative and flexible integration among various social levels within an agricultural area (Figure 2.8).

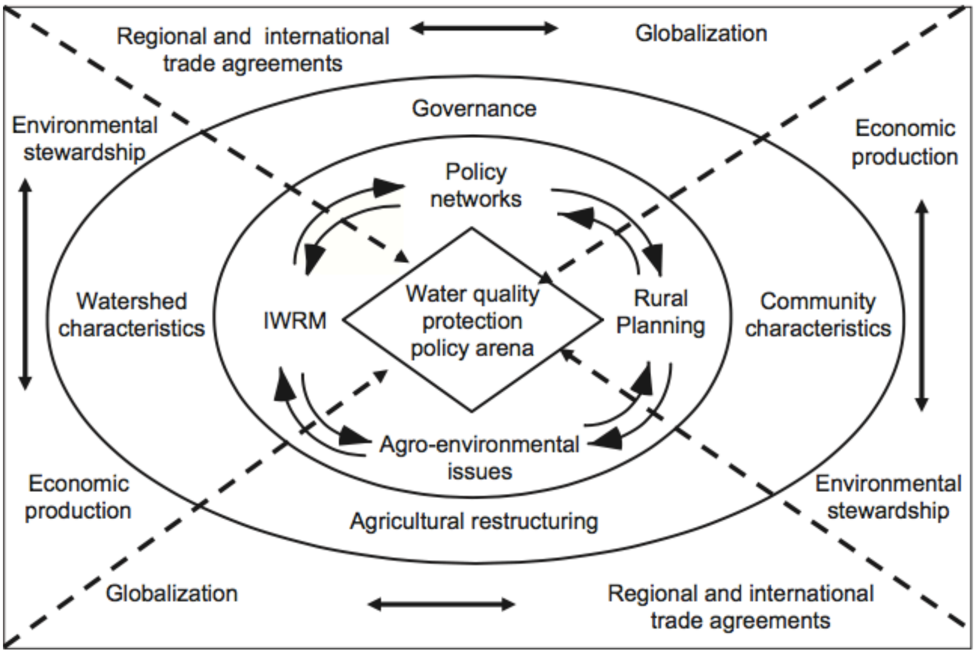

Figure 2.8 Conceptual framework for the analysis of integrated water resources management in an agricultural area (Ferreyra, de Loë and Kreutzwiser, 2008).

Figure 2.8 illustrates the agricultural policy network relevant to the water quality policy arena, connected to ecological, political, economic and social levels within agro-environmental management strategies. Ferreyra, de Loë and Kreutzwiser (2008) explain further the need for in-depth study and simulation of the relation between water and other related sectors such as population, food, energy and environment in order to determine future food security. The framework also lacks direct linkages between farming activities and their impacts on water resources.

2.5.5.5 Conceptual Framework for Coupling Human and Natural Dimensions of Water Resource Sustainability

In the Middle Rio Grande region (Texas, USA), the conceptual framework for coupling human and natural dimensions of water resource sustainability was developed in order to enhance systematic understanding of the pressure on water resources and the predicted response (Figure 2.9). The framework focuses on groundwater capacity and flexibility to recover (resilience and transformability) by linking components obtained from various resources such as research, modelling, education, system complexity, outreach and stakeholders (Hargrove *et al.*, 2013). It is suggested that this framework can provide a new approach to ensure sustainability through improving strategies and decision outcomes to protect fragile water resources under climate change and increasing demand.

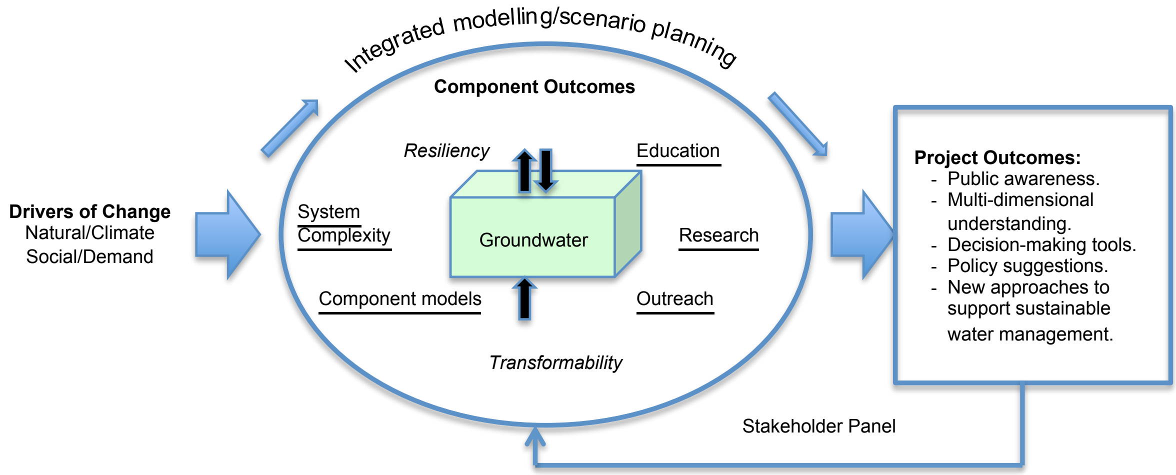

Figure 2.9 Conceptual framework for coupling human and natural dimensions of water resource sustainability (Hargrove *et al.*, 2013).

2.5.5.6 Conceptual Framework of Planning Support System for Agriculture

The conceptual framework of a planning support system for agriculture was developed by Bansouleh (2009) in order to cope with increasing water scarcity and food demand in Borkhar and Meymeh district in Esfahan province in Iran. This framework was developed based on the main decision-making framework principles established and applied in Spain by Sharifi and Rodriguez (2002). These principles are assessment of the current status to identify the problem, formulate the required objectives, conduct policy analysis of possible solutions and actions, and then choose selected preferred policies (Sharifi and Rodriguez, 2002).

As shown in Figure 2.10, Bansouleh's framework focuses on three main areas. The first is to understand the current pattern of available resources and how they are utilized and allocated, in order to identify gaps and explore opportunities for further development under land resource analysis. The second is to assess the impacts of the formulated policies on farmers and other objectives from various stakeholders under policy impact assessment. Finally, policy analysis is conducted that should aim to select the most favourable policy taking into account the perspectives of various stakeholders and the consequences of objective development (Bansouleh, 2009).

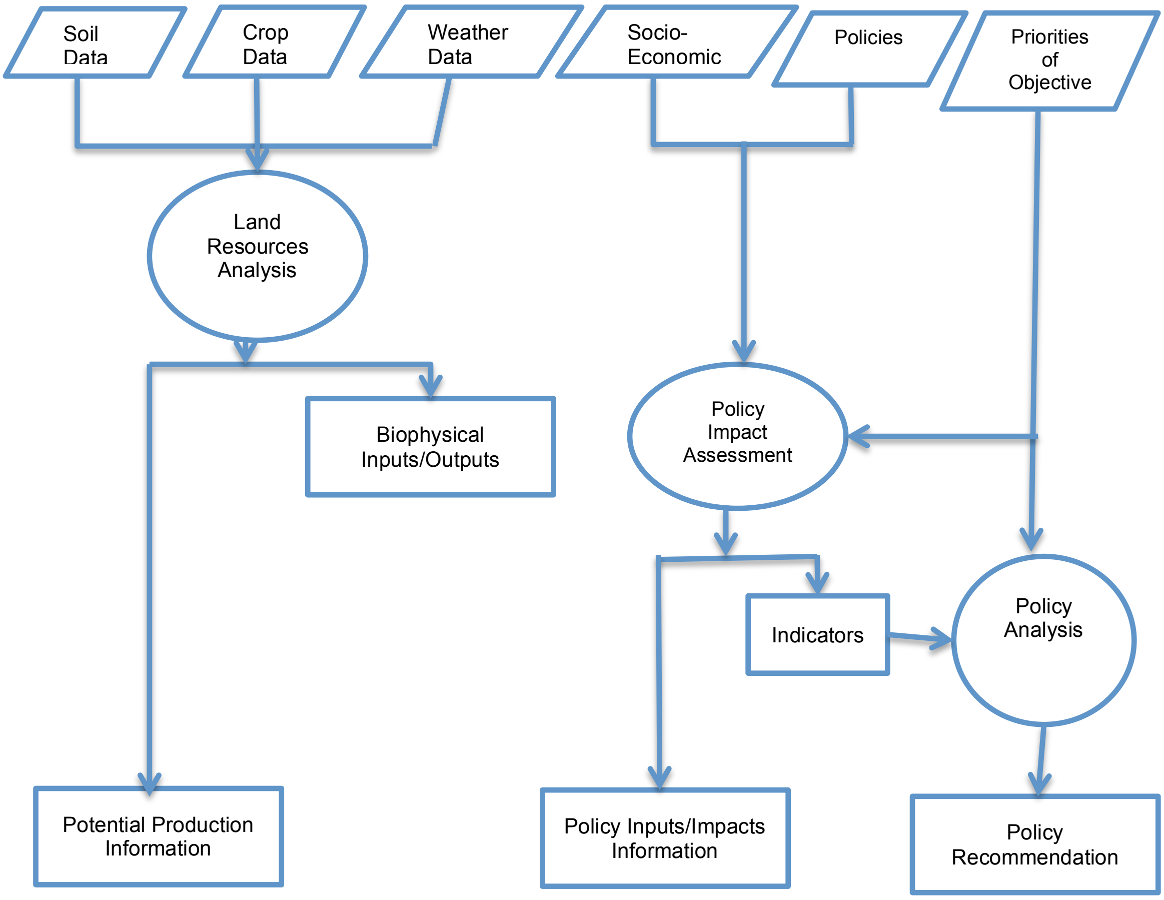

Figure 2.10 Conceptual framework for planning support system for agriculture in Iran (Bansouleh, 2009).

This framework, although, developed for site specific in Iran that considers local conditions, data required and socio-economic settings, but it demonstrates a practical example of a systematic sequential process that can be used as a reference to help develop ADE framework. This is also applicable for the conceptual framework developed for Ontario in Canada and the one developed for Middle Rio Grande region in Texas presented in the previous Sections 2.5.5.4 and 2.5.5.5.

2.6 Chapter Summary

The literature review presented in this chapter shows an increasing pressure on food security while resources, especially groundwater, are depleting and deteriorating. In addition, climate change is predicted to have a negative impact, especially in arid and semi-arid regions. Increases in water scarcity and food insecurity are also predicted as inevitable consequences. Countries such as the UAE and GCC are aiming to increase food self-sufficiency, hence their groundwater dependency has improved and become the main water supply for agriculture, and is critical for food security.

This chapter also examined the implementation of a number of global policy initiatives, such as sustainable agriculture, productivity improvements, looking for alternative water resources and strengthening groundwater governance, as common good practices to meet food and water challenges, and integrated frameworks that demonstrated improved management of water and agriculture towards ensuring sustainable development. It also highlighted ADE's several attempts to implement and test these initiatives (such as subsidizing modern irrigation systems, phasing out high water use crops, promoting greenhouse farming, licensing groundwater drilling, etc.). However, these efforts remain disconnected and fragmented across different entities, with no integrated policy framework. Therefore, the objective of this thesis is to assess and quantify the current agricultural water usage, and explore how it is regulated and managed in ADE. This, along with the insights and guidelines from the selected frameworks reviewed in this chapter, will be used to develop the Agriculture-Water Policy Framework (AWPF) for ADE as a solution to ensure sustainable agricultural water development.

The next chapter outlines the research design roadmap and provides detail on the selected methods used to gather primary and secondary data in order to achieve the thesis objectives.

Chapter 3. Research Methodology

3.1 Introduction

The research methodology adopted involves the collection of secondary and primary data. The secondary data were collected from the literature review and the gathering of existing reports generated by various associated entities. The primary data were compiled based on the design and implementation of appropriate research methods.

This chapter describes the research methodology adopted in order to capture the data required to meet the study's aims and objectives. It starts by providing a detailed description of the research design and methods, and the development of the farmers' perception survey (quantitative) and semi-structured interview (qualitative). It also includes a description of the development of the Agriculture-Water Policy Framework, data analysis techniques and ethical approval.

3.2 Research Design and Methods

In order to clearly map out the research design methods and stages, the "Research Onion" framework developed by Saunders, Lewis and Thornhill (2003) was found useful as a guideline (Saunders, Lewis and Thornhill, 2003, 2012). By examining Saunders' framework stages within the context of the research focus and objectives, a design was developed that was appropriate to illustrate the research philosophy, approach, strategy, time horizons, choices and data collection methods, as illustrated in Table 3.1.

Table 3.1 Summary of selected research design methods.

Onion Layers	Research Design	Quantitative	Qualitative
1	Research Philosophy (Knowledge Claims)		
	Ontological Positions	Objectivism	Constructivism
	Epistemological Positions	Positivism/Post-positivism	Interpretivism
2	Research Approach	Deduction	Induction
3	Research Strategy	Survey	Semi-structured Interview
4	Time Horizons	Cross-sectional	
5	Choices	Mixed Method – Concurrent Embedded	
6	Data Collection Methods	Questionnaire	Interview

The criteria for the selection of the research design and related procedures are largely influenced by the research questions, the nature of the problem and the available resources (Gill and Johnson, 2002; Creswell, 2003; Saunders and Lewis, 2009). Therefore, the initial step of this research was to provide a background to the selected study area (ADE) and identify the current gaps in water- and agriculture-associated areas. This was conducted by reviewing the national and international literature available. The literature review was extended to understand current practices worldwide and uncover practical suggestions to provide solution(s) for the best water use in agriculture while maintaining food security.

Six objectives were developed to answer the research questions shown in Section 1.3. The first three objectives are focused on mapping water use across different sectors and its major issues, understanding groundwater development and identifying the main drivers for agricultural development and its impact on natural resources. This was done through an exhaustive review, synthesis and analysis of fragmented quantitative and qualitative data obtained from associated government offices. Secondary data were used to verify water use under different water and agriculture policies, and to identify different variables that influence the misuse of water across different sectors. This area along with the initial literature review process led to the identification of gaps in the data/knowledge that was required to answer the research questions. These gaps are summarized as follows:

- Missing, inconsistent or inaccurate data on groundwater abstraction and consumption.
- Lack of records on water use policies and their development and implementation.
- Unclear justifications for any water- and agriculture-associated policies, strategies or decisions.
- Lack of knowledge on how associated entities are integrated with each other as well as with end users.
- Absence of records on farming practices and how farmers perceive current and future government policies and strategies.

As a result of the multiplicity of variables – quantitative and qualitative in nature – that comprise the research objectives, and the different types of data sources needed to achieve these objectives, it became very obvious at an early stage of the research that it required both quantitative and qualitative data. This suggests the need to adapt the mixed-methods design approach determined by Tashakorri and Teddlie (1998) and Creswell (2003). This involved the use of quantitative data to empirically assess the relation between different variables, which can be analysed statistically, and the use of qualitative data to understand different individuals' or groups' positions on a particular problem (Denzin and Lincoln, 2005; Creswell, 2014).

Using the "Research Onion" framework as a guide to develop the researcher's philosophical positions, it is necessary to consider the research topic, objectives and questions. As this researcher wishes to develop an in-depth understanding of the current farming practices and explore how agricultural water use is managed and regulated, the researcher's positions from the ontological orientation involve both objectivism and constructivism (Table 3.1). Objectivism is a perception obtained by the researcher of any external human influence that is demonstrated in quantitative data, while constructivism is built up by the influence of social actors, and is explained by qualitative data (Creswell, 2003; Bryman, 2012; Saunders, Lewis and Thornhill, 2012). The positions selected from the epistemological orientation are also both positivism and interpretivism. Positivism came from the objectivist perspective (Crotty, 1998a; Bryman, 2004) and focuses on the quantitative data that are used to analyse a real situation. This application has its strengths, as it enables the researcher to provide a quantifiable data analysis interpretation (representative sample or explanation) that can be generated to the full population size. Interpretivism aims to gain understanding and insights on existing phenomena and how they are explained (Saunders, Lewis and Thornhill, 2012). The application of this position is through qualitative data focusing on answering specific question(s) via the emergence of perceptions and ideas in order to gain in-depth understanding (Crotty, 1998b; Creswell, 2009).

The research approaches selected are the deductive and inductive approaches. The deductive approach used focuses on descriptive analysis, correlation and comparison of the quantitative data (Saunders, Lewis and Thornhill, 2003, 2012), whereas the inductive approach focuses on drawing out various themes (through content analysis) from the qualitative data (Easterby-Smith, Thorpe and Jackson, 2008).

The research strategy to collect the quantitative and qualitative data is selected based on the form of the research questions, as well as whether the research requires control over behavioural events and whether or not it focuses on contemporary events. The commonly used strategies that are associated with deductive/quantitative and inductive/qualitative approaches are experiment, survey, interviews, archival research, case study and ethnography (Bryman, 2004). Experiments were discounted, since they require more extensive time and cost to conduct (Creswell, 2003) than this research could afford. Archival analysis, case studies and ethnography were found not suitable because they require exposure to data and material that are not available and/or considered confidential by the publishers and the relevant entities. This approach was also discounted, leaving survey and interviews as the appropriate options for this research.

A quantitative research strategy that involves the use of a survey (survey questionnaire) was used on a representative proportion of the farm population in ADE, where the data can be empirically analysed and findings can be generalized to the whole population (Bryman, 2012). In terms of time horizons, these may be longitudinal, where the data collection occurs over a considerably long time, or cross-sectional, where the data collection takes place within a particular period (Creswell, 2003; Saunders, Lewis and Thornhill, 2012). In this research, longitudinal surveys were eliminated as unsuitable due to the time and resource constraints within the research timeline, leaving the cross-sectional survey as the most appropriate.

The qualitative research strategy used interviews (structured interviews) with selected experts from agriculture- and water-associated entities to gain in-depth qualitative insights into how agriculture and its water use are managed and regulated. The method used to conduct the two data collection methods (quantitative and qualitative) was concurrent embedded, where they are not necessarily sequential and each method answers different research questions (Saunders, Lewis and Thornhill, 2009).

These two methods do not only complement each other, they also enable the researcher to get answers to the research questions and provide deep interpretations to explain a complex social situation, because they provide different findings and interpretations from different points of view (Tashakkori and Teddlie, 1998). All relevant objectives noted in Section 1.3 that require numerical data collection were addressed by the quantitative approach, whereas all the other areas that require descriptive and insightful responses were handled by the qualitative approach. The findings of these two approaches enabled the development of a solution “Policy Framework” that provides a guideline to better optimizing and allocating water use in agriculture.

3.3 Farmer Perception Survey

The aim of the farmer perception survey is to understand farmers’ current farming and water management practices, and assess their awareness of issues related to current water policies, crop selection and how much they cooperate to help in the implementation of these policies. Moreover, the survey seeks to gain understanding of famers’ current main challenges and their anticipated plans to deal with them.

3.3.1 Questionnaire Design

The survey questionnaire was mainly designed to elicit quantitative data from the selected farms from the three different regions of ADE: Abu Dhabi (AD), Al Ain (AA) and the western region (WR). It consisted of five sections and ran over a total of six pages (**Appendix A**). The first section of the questionnaire focused on demographic information about the farms and their owners. The second section sought information on different water resource connections, and the quantity and quality of water supplied to the farms. The third section focused on the main purpose of the farm and its management. The fourth was on farm productivity, marketing of produce and future plans. The fifth (and final) section concentrated on farmers' awareness of water-related issues and their perceptions of current and future related policies. Questions on such policies covered the drinking water tariff that was introduced at the beginning of 2015, government control of groundwater abstraction and other related issues, and the reduction or stopping of agricultural subsidies.

The questionnaire was written in both English and Arabic in order to facilitate easy comprehension by the respondents, as their mother tongue is Arabic. Each questionnaire took around 45–60 minutes to complete, but this varied from one person to another, depending on the respondent's time availability and their level of understanding of the questions.

A pilot questionnaire was first administered by conducting a face-to-face survey with six selected farm owners in September 2016. The purpose of the pilot survey was to check on the readiness of the respondents when completing the questionnaire and whether it contained unclear and/or sensitive questions, as well as to test the effectiveness of this data collection method. Four of the farms selected for the pilot are located in the AD region and two in the AA region. The majority of farms are owned by a single male owner within the age range of 40–69 years. Most of the farms have their main purpose as either commercial or personal. Three of them have desalination plants with a capacity of 46–227 m^3/day (10,000–50,000 gallons/day).

The pilot study helped to identify some sensitive questions and terminology, especially relating to farm profits and government subsidies, that were uncomfortable or off-putting to those completing the questionnaire. This led to a number of amendments to the questionnaire, including rewording some of the questions, converting some open-ended questions to closed-ended questions, and adding a few more questions in some sections.

3.3.2 Survey Protocol

Early in the survey design process, it became clear that there was a high risk of not getting enough responses, as most farmers or farm owners are unfamiliar with what the survey entails. In addition, most farm owners are not available at their farms and they delegate the full responsibility of managing the farm to one of their workers, who is usually a migrant from Egypt or South Asia. Therefore, the help of local individuals was sought in administering the questionnaire and introducing us to the farmers.

The survey was conducted through different methods – as a mixed-mode survey (Dillman, Smyth and Christian, 2008) – in order to overcome the difficulties of meeting farm owners in person and also increase responses. Face-to-face meetings with respondents were considered a suitable primary method for administering the questionnaire (Doyle, 2005); however, other appropriate methods were also used in order to cover the whole sample area (consisting of all three regions). Such methods included telephone surveys (used to collect data from 10 farms) and emails (used in one case only). Responses to the survey questions were mainly recorded on the questionnaire during the meetings with farm owners or their representatives generally conducted at their farm sites, which helped to provide a better idea of farm practices.

3.3.3 Observations and Challenges

It was observed that farm owners are not available most of the time because they rely on their labourers and tend to protect their privacy. Therefore, it was not easy to have access to the farm owners unless you knew them in person or through a mutual friend. However, the interactions with farmers were managed through different individuals leveraging personal networks and references. Thus, during the majority of farm visits, the researcher was accompanied by an individual with a wide range of networks and long experience in the region. On some occasions where farmers became suspicious and did not welcome strangers, mainly in WR, the researcher for safety reasons had to stay in the car and send the escort to complete the survey with the farmers inside their farms.

While conducting the surveys it was noted that some farms are deserted and it seemed as though farm owners are giving less attention to maintaining and managing their farms. Some of these farms are cultivated mostly with palm trees but with no attendance; consequently, they were not included in the survey.

During administration of the survey, some of the farmers were a little reluctant to answer some questions. This issue was resolved by briefing the respondents about the fact that the survey had been approved through the university's rigorous ethical approval process to satisfy all ethical requirements, for example participating had a negligible level of risk. They were also informed of the researcher's responsibilities to ensure the confidentiality of the survey data for educational purposes.

To ensure that the farmers participating in the survey had enough and accurate information about the farm, they were questioned on the length of their work experience and their knowledge of the farm. Accordingly, some of the farmers were replaced with others who had more experience on the farm.

3.3.4 Sampling Technique

Statistically, there are two main sampling techniques: probability (random sampling; Cochran, 1977; Israel, 2016) and non-probability (non-random sampling; Bailey, 1994; Cochran, 2007). These techniques are further divided into various types of sampling, as shown in Table 3.2.

Table 3.2 Examples of sampling techniques.

Sampling Technique	Sampling Type	Description	Reference
Probability			
	Stratified sampling	The population is divided into groups or "strata" based on common characteristics, and then each stratum is randomly sampled.	Cochran, 1977; Israel, 2016
	Simple random sampling	Each unit in the population has an equal chance of random selection. This technique is more applicable to small populations, but is out of the scope of this research.	
	Systematic sampling	The selection is based on equal and defined intervals.	
	Cluster sampling	The population is divided into clusters that are characterized by homogeneity between them and heterogeneity within each. This technique is applicable to dispersed and very large populations with no available frame list.	
Non-Probability			
	Purposive sampling	The researcher uses their judgment and expertise to select required samples that are suitable for specific objectives.	Bailey, 1994; Cochran, 2007
	Haphazard sampling	The researcher selects samples that are convenient or accessible, but this can produce highly unrepresentative samples.	
	Quota sampling	The researcher pre-identifies the type and size of sample for each category; this technique makes the selection biased towards a certain type and number of unit.	
	Snowball sampling	The first or a few samples selected are linked to a larger network to cover the remaining selection of sample size.	

The selection of any of these sampling types is dependent on the target population (research sample; Bryman, 2004; Saunders, Lewis and Thornhill, 2012). The target population for this study is the farmers/farm owners in ADE across the three regions, which will enable knowledge to be built of "what" is the current practice and "how" it impacts the groundwater resources. Stratified sampling was found most appropriate for the target population of 24,018 farms, which is geographically distributed into the three regions (15% in AD, 49% in AA and 35% in WR). These three strata have common attributes and characteristics, therefore stratified random sampling was used for each region separately.

The sample size for each region was calculated independently, as shown in the sample size calculation (Section 3.3.6).

3.3.5 Sampling Procedure

Since there was no accessible contact information on the active farms, farm samples were selected randomly by first visiting the three regions periodically. During each visit a reconnaissance walk was undertaken on farms to observe and select active farms for the survey. On most occasions, local individuals who are known through past experience or industry or personal contacts were relied on for information on the location of potential farms to include in the survey.

3.3.6 Sample Size

The target sample size for the farmers' survey was determined by the method suggested by Israel (1992) and Al-Subaihi (2003), which calculates the required size statistically using Equation 3.1:

$$n = \frac{Z^2 p(1-p)}{e^2} \Big/ 1 + \frac{Z^2 p(1-p)}{e^2 N} \qquad \text{Eq 3.1}$$

where n=sample size needed, N=population size, p=expected value of attribute/variability in the population, e=margin of error (level of precision) and Z=degree of standard deviation (proportion of 1.96 away from the mean for a 95% confidence level).

The sample size was calculated based on the farm population distribution across the three geographical regions in ADE (Figure 3.1), using Equation 3.1 for a confidence interval of 95% and an expected value of attribute of 50% (0.5 of the variability in the population).

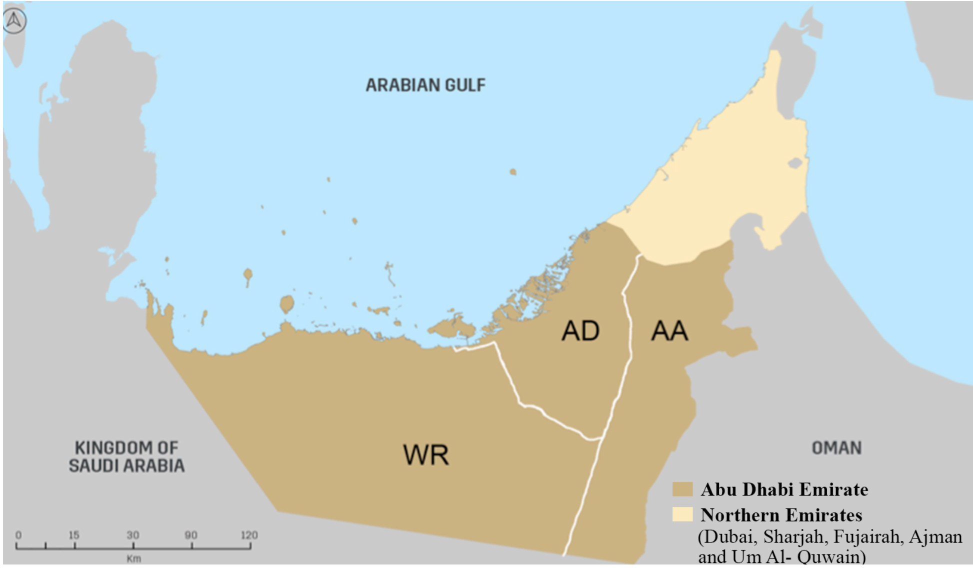

Figure 3.1 ADE location map and its three regions (adapted from EAD, 2017).

Table 3.3 shows the farm population, the calculated sample size and the actual collected farm size per region and in total. The total actual sample size collected amounts to 344 farms, comprising 33.4% (115 farms) from AD, 43.3% (149 farms) from AA and 23.3% (80 farms) from WR.

Table 3.3 Calculated and actual collected sample sizes per region.

Region	Total Number of Farms	Calculated Sample Size	Actual Collected Sample Size	% of Collected Sample Size
AD	3,605	94	115	33.4%
AA	11,921	95	149	43.3%
WR	8,492	95	80	23.3%
Total	24,018	284	344	

The minimum sample size calculated was 285, determined based on Equation 3.1, which gives the minimum statistically valid sample required to represent the target population. The actual sample collected (344) exceeded the minimum size required, which was made possible by the fact that the researcher had to visit participants in person and also make use of their network.

As shown in Table 3.3, the actual sample sizes collected from AD and AA were more than their calculated sample sizes, whereas the actual sample was almost 16% less than the calculated sample for WR. The reason was that most of the farms in WR are situated in remote areas and isolated from the road infrastructure, which makes it difficult to reach them. In addition, some of the farmers in this region were reluctant to fully cooperate with the survey because they felt the information sought from them was quite sensitive. This led to more than 40 non-respondents.

The farms in ADE are divided into six farm size categories, from <2 to >6 ha, with a total population of 24,018 farms (Table 3.4). Most of the farms fall within the <2, 2–2.9, 3–3.9 and 4–4.9 ha farm size categories. As shown in Table 3.4, the majority of the collected sample across the six farm size categories also follow the same pattern, except for categories <2 and >5 ha. Most of the farms that are less than 2 ha were usually abandoned (deserted), where the farm owner has larger farms in different locations, and farms that are greater than 5 ha were mostly owned by high-profile individuals who would be careful of their privacy in providing us with permission to access their farms.

Table 3.4 Total actual collected sample size per farm size category.

Region	Number of Farms/Farm Size Category (ha)						
	<2	2–2.9	3–3.9	4–4.9	5–5.9	>6	Total
Total Abu Dhabi Emirates	4,490	6,450	9,774	2,661	172	471	24,018
Total of actual collected sample size	7	143	126	67	0	1	344

3.4 Semi-Structured Interview

In addition to the current secondary data issues that are explained in Section 3.2, there is a lack of records on how water use is managed and how related policies are developed. Moreover, there is a big information gap in how the associated entities are integrating with each other while developing and implementing such policies. Therefore, the semi-structured interview is a suitable methodology to explore and clarify this area and support some of the research questions.

The semi-structured interview provides flexibility and allows in-depth discussion and detailed communication of an issue (Miles and Gilbert, 2005). This helps to provide rich information, identify issues of importance to the interviewees and understand the meaning attributed to their experiences.

The main objectives of the semi-structured interview were the following:

- Assess the participants' views on the most critical water issues and their suggestions for improvements (this would assess the level of awareness or area of focus of each of the entities).
- Explore and document the existing water use policies for agriculture/forestry.
- Understand how these policies are developed and implemented by related stakeholder organizations.
- Identify issues and obstacles/barriers to successful policy implementation.
- Provide insight into the most recent developments in agriculture and forestry from each entity.

- Provide the entities' view into the use of desalination and/or groundwater for agriculture and forestry.

In addition to the above objectives, related background information, factual material and data were also collected wherever possible to capitalize on the expert's knowledge and experience. Such information is used where it is needed throughout the thesis, including in this chapter.

3.4.1 Interview Questionnaire Design

The interview questionnaire consisted of two parts: main questions and entity-specific questions. The questionnaire was developed as a guideline to help start and control the interview, as suggested by Miles and Gilbert (2005). The main questions were used as a guideline to get the interviewees to elaborate on their views in four areas (**Appendix B**):

- Critical water issues
- Policy development
- Agriculture and forestry development
- Water resources for agriculture/forestry

These are mostly open-ended questions that allow the participants to elaborate and provide further insights. The specific questions were tailored to particular entities and were only used to obtain factual or statistical data or documents. Therefore, closed-ended questions were more suitable to be used in this part of the questionnaire.

3.4.2 The Interview Protocol

The interviews were done over 11 months from October 2016 to August 2017. Each interview was arranged in advance through email or telephone requests, with an agreed date and time at the interviewee's office. The interviewees had an opportunity to choose between English and Arabic; English was the main language used in the interviews, whereas Arabic was only used if requested or for any necessary interpretation.

The interview started by providing a brief on the objectives of the research and the expected duration of the interview, which varied from one to two hours. The interviewee's rights were explained and their consent was obtained. In order to break the ice and create rapport with the interviewees, the discussion were initiated by asking general questions, as suggested by Taylor, Bogdan and DeVault (1998). Those questions covered the interviewee's job title and responsibilities, and the organization's main roles.

Although the list of questions within different focus areas was developed as a guideline for the discussion, it was modified or altered as needed or based upon the participant's interest and how comfortable they were to proceed. Sometimes during the interview probing was used to obtain more clarification on the questions or stimulate the interviewee to talk more about the subject or the issue at hand. The probing also helped to obtain empirical data and documents that were needed for the research.

Some of the interviews were tape recorded with prior consent from the interviewees (21 out of 36). This provided a great advantage in capturing the interview data more effectively and allowing the researcher to focus on the conversation with the interviewee. At the end of the interview, the researcher thanked the respondent and indicated the next step of the data collection process, including making follow-ups on relevant documents.

3.4.3 General Observations and Challenges

In general, the participants showed a positive attitude and enthusiasm to initiate discussions on the topic, as they did consider it pertinent. Most of the selected interviewees expressed their strong opinion on the importance of the subject of the research and how it could provide potential solution(s) to the sector(s). As a result, most of the interviewees were happy to provide more information and insights voluntarily, which added value to the author's understanding of the issue. It was also observed that few interviewees were likely to have their own ulterior motive (or agenda) during the course of the discussions. Further, few appeared sceptical about answering the questions because of their lack of knowledge of the study area or it being a sensitive subject to them, either of which might have create some limitations in the interview discussions.

3.4.4 Sampling Technique

The semi-structured interview is focused on selected subject matter experts (SMEs) from different entities associated with water and agriculture. From the 14 entities, 36 experts were selected. A purposive sampling technique (Cochran, 1977; Miles and Gilbert, 2005) was used to select the SMEs via intentional selection of individuals who hold key roles, and have the willingness and the capacity to give the maximum variation. The SMEs selected are mainly senior managers and advisors with sound knowledge and long experience in different fields of water and agriculture management. They also have a level of interaction with individuals from the higher authorities and decision- and policy-makers in ADE.

3.5 Development of an Agriculture-Water Policy Framework

As discussed in Section 2.5.5, several relevant global and local frameworks were selected and reviewed. The main focus of these approaches is cross-sectoral integration, which enables comprehensive analysis to help policy-makers have a clear understanding and develop suitable policies. The management planning cycle (Section 2.5.5) of each of these frameworks was built based on a set of high-level principles such as integration of knowledge and stakeholders, setting objectives, management planning, monitoring and providing feedback. In this research, the insights of these principles along with the findings obtained from the research objectives were used to develop the ADE AWPF management planning cycle. ADE AWPF consists of seven main steps interlinked in a sequential process to ensure a systematic approach for the agricultural development decision- and policy-making process. It also includes suggested policy scenarios for the main crops produced (palm date and vegetables) to assess the impact on water resources.

In order to provide assurance for scholars and practitioners (such as decision- and policy-makers), the developed framework is further validated. The research validation process is to check, investigate and ensure the rigour and reliability of the study findings (Miles and Huberman, 1994). There are numerous validation techniques in the literature, depending on the research question and strategies used, but the most common and widely mentioned techniques are triangulation and member check (Miles and Huberman, 1994; Denzin and Lincoln, 2005; Creswell and Poth, 2017). Triangulation is conducted by using several methods and sources of data findings in order to determine the credibility of the findings (Creswell and Poth, 2017). The member checks technique checks and confirms the researcher's interpretation by the participants who were studied (Denzin and Lincoln, 2005). The latter validation technique (member check) was found most suitable in this research to check if the framework is reasonable and provide practical solutions/guidelines for the ADE government to facilitate and ensure sustainable agricultural development.

3.6 Data Analysis Technique

3.6.1 Data Analysis Technique for the Survey Data

Statistical Package for the Social Sciences (SPSS) and Microsoft Excel were used to analyse the data collected from the survey. The analysis involved using descriptive data on the main characteristics of the respondent farmers and their farming practices, where different statistical techniques were used such as frequencies, percentages, mean, boxplot, cross-tabulation and related graphs. Statistical techniques were also used to examine the relation between variables, such as the Chi-square and Pearson tests. The Chi-square test assesses the significance of the relationship between two nominal variables. Non-statistical data analysis such as interpretive and discussion approaches was also used.

3.6.2 Data Analysis Technique for the Interview Data

The transcriptions of the 36 interviews conducted were done immediately after the completion of the interviews. Following the development of the interview transcripts, multiple reviews of each transcript were done to ascertain similarities or conflicting patterns of views among the responses. Following this, inductive content analysis was undertaken, which helped to create codes, themes and categories from each of the sentences/segments mentioned in the interview by using manifest coding (Hsieh and Shannon, 2005) as well as a latent coding approach (Elo and Kyngäs, 2008; Siegel, 2008).

As suggested by Renner and Taylor-Powell (2003) and Lichtman (2012), this process of coding and theme development was repeated multiple times in order to enhance the level of analysis. Each group of meaningful segments or “words” was identified line by line in every transcript to create a code, then similar words and phrases were grouped under common headings and subheadings. Some of the subheadings (subcodes) were combined with other main headings when appropriate; for example, “technologies with less water use” and “hydroponic system” were both combined under “innovative technology”.

Following Ose (2016) and Amozurrutia and Servos (2010), Microsoft Word and Excel were used as software tools to help sort and structure the qualitative interview data and further develop codes and themes.

3.7 Ethical Approval

Since the data collection process through the survey and the semi-structured interview required human contact, ethical approval was obtained from the College of Engineering, Design and Physical Sciences Research Ethics Committee, Brunel University, London (**Appendix C**). All participants were briefed on the objectives of the study and guaranteed confidentiality of any personal and sensitive information. They were also assured that they have the right to participate or pull out at any time if they wish. Accordingly, consent was obtained from all respondents.

3.8 Chapter Summary

This chapter conducted an overview of the research methodology adopted, which combines quantitative and qualitative data methods. It started with a broad literature review followed by the secondary data analysis to explore the historical development of water's association with agriculture. It pointed out the existing issues and challenges. To develop an in-depth understanding of these problems and the factors that exacerbate them, a farmer perception survey was conducted, and then semi-structured interviews with selected experts from water- and agriculture-associated entities and authorities took place. This later helped to explore the main focus of these sectors on managing the development of and implementing the relevant policies. The findings of both methods (including a literature review of selected relevant frameworks) were used as an input to help develop the Agriculture-Water Use Policy Framework for ADE.

The next chapter demonstrates in detail the synthesis and data analysis of the largely fragmented secondary data collated on water resources, groundwater, agricultural development and its contribution to food self-sufficiency in ADE.

Chapter 4. The Food–Water Context in ADE

4.1 Introduction

In the most water-scarce countries, including the UAE, which have a low percentage of arable land and high growth rates in urbanization and population, there is a need to develop a suitable short- and long-term plan with careful attention to allocating different water resources to different sectors. In order to develop these plans to meet future water demands, it is essential to assess the current situation across various sectors of water demand, water supply and water usage from the three main sources of water: groundwater, desalination water and treated wastewater. It is also important to study the growth trend and the main factors and drivers behind it. Accurate, consistent, quantitative and comprehensive data are required to assess the impact of policy decisions on other sectors.

Acquiring such quality data for groundwater is a challenge in ADE. The number of wells, abstraction rate, salinity changes and water use per farm are not available because they are usually not measured. These data and figures are primarily estimated by the Environmental Agency–Abu Dhabi (EAD). Most of the resources are scattered over different reports and articles, but the majority of recent groundwater and agricultural data presented in the annual reports issued by the Statistical Centre of Abu Dhabi (SCAD) were originally obtained from EAD and the Abu Dhabi Food Control Authority (ADFCA).

This chapter synthesizes related information to help draw a complete picture of the development of water usage in the agricultural sector. Primarily it presents an assessment of the supply pattern of water resources and their usage across different sectors. This is followed by relevant background on groundwater development, abstraction and its impact on quantity and quality. The next section explores agricultural development and the magnitude of land use. Lastly, the chapter describes agricultural production's contribution to food self-sufficiency and local market demand.

4.2 Water Resources

In ADE, surface water makes an insignificant contribution to the country's water supply (Brook *et al.*, 2006; McDonnell, 2013), with groundwater receiving minimal recharge which makes it a finite resource (Rizk, 2008; McDonnell, 2013). Figure 4.1 shows the water production contribution from each of the three resources (groundwater, desalination and treated wastewater) for 2001, 2003, 2005 and 2007–2016. In 2011, EAD decided to stop supplying groundwater data until it managed to deliver measured data. Thus, SCAD used EAD's 2011 groundwater withdrawal data (2218 Mm^3) for 2012–2016.

Though the groundwater supply share decreased during the last decade, it still represents the main water resource if compared to desalination and treated wastewater. From 2001 to 2016, the share of groundwater supply decreased from 72% to 63% (Figure 4.1). The share of desalination supply increased from 23% to 32%, whereas that of treated wastewater almost stayed the same (5%) during the last 15 years. (Figure 4.1 was created based on information from Shahid et al., 2013; Brook et al., 2006; SCAD 2012, 2013, 2015, 2016; ADWEC, 2016b; EAD, 2017).

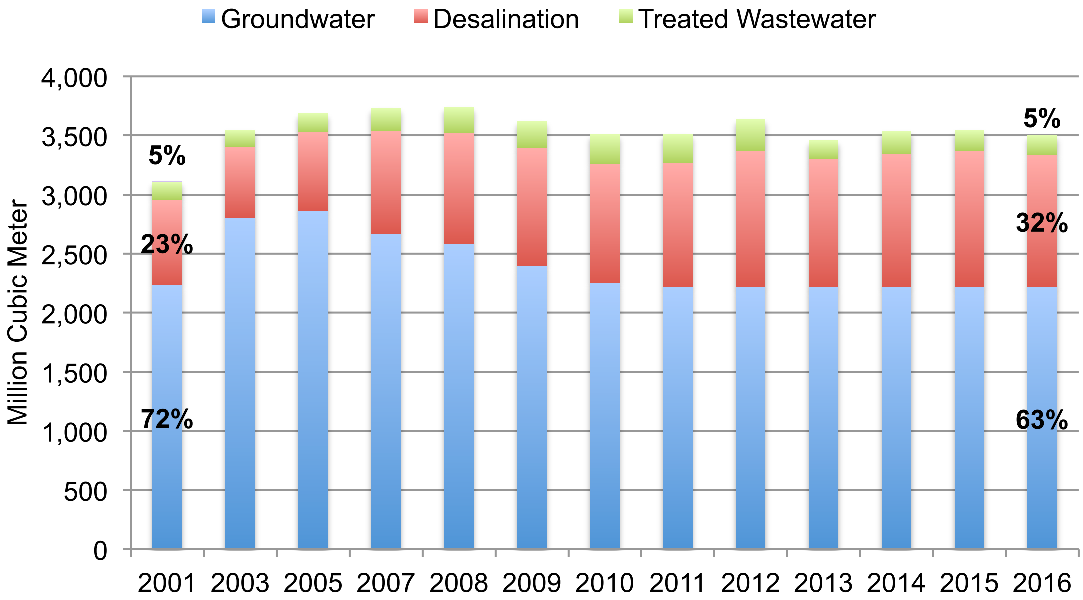

Figure 4.1 Water resources production share in Abu Dhabi Emirate.

From 2001 to 2005, government policies were introduced to encourage agricultural development that led to increases in the cultivation of palm trees, fodder crops and seasonal vegetables (Woertz, 2013). This was also followed by increases in the drilling of wells and groundwater abstraction rates, which led to a growth in the total groundwater supply, as shown in Figure 4.1. As water demand increased and groundwater depleted and deteriorated, desalination and treated wastewater were used to replace the shortage in the groundwater supply. The desalination sector in ADE uses mainly seawater as a feed. There are nine plants that produce more than 900 Mm^3/year (ADWEC, 2016b). There are also a few plants with small-scale brackish water desalination, at 8 Mm^3/year, primarily owned and operated by oil production companies (McDonnell and Fragaszy, 2016) and private farmers (Ali Al-Alwai, 2014). The first desalination plant constructed in ADE was in the 1970s with a capacity of 250 m^3/day (Ali Al-Alwai, 2014), which gradually increased to reach 2.6 Mm^3/day in 2015 (ADWEC, 2016b). Abu Dhabi Water and Electricity Company (ADWEC) records in 2016 show an increase of more than 160% in annual water production every decade (Figure 4.2).

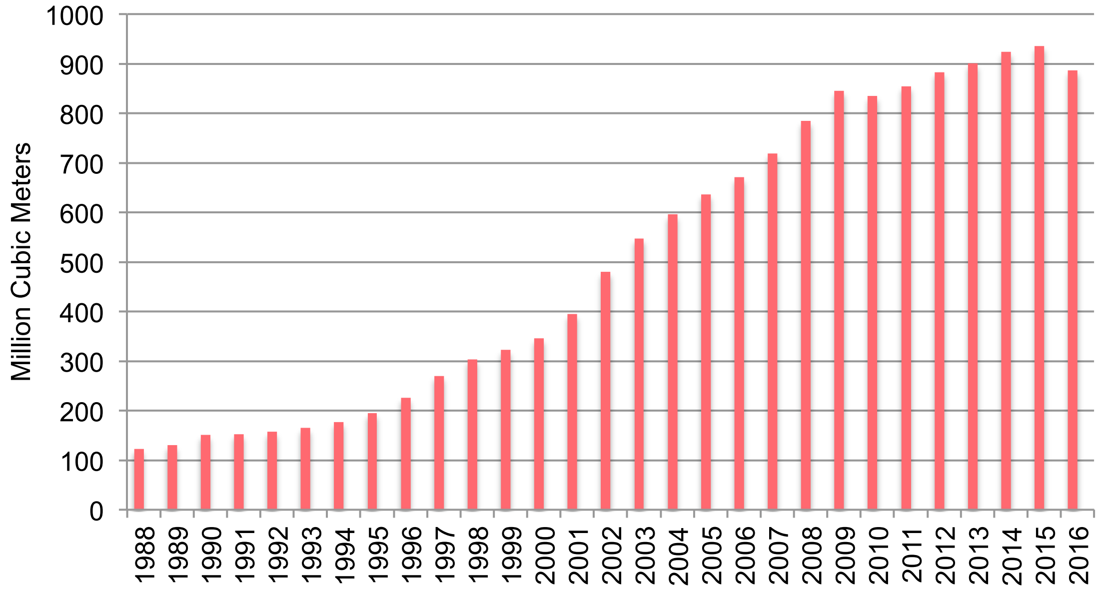

Figure 4.2 Desalination output (1988–2016) in Abu Dhabi (ADWEC, 2016b).

As noted in Section 2.5.3.1, the major drawbacks of desalination are high cost, high energy use, risk of feed water pollution and negative environmental impact. Furthermore, in the UAE, the operational link between power generation and desalination, based on a co-generational set-up where desalinated water is a by-product of electricity production, creates a strong tie between power and water production. This leads to inflexibility and inefficiency in the water production system because of the different seasonal variations in the water and power demand profiles (Lin *et al.*, 2011).

The ADE government has taken a number of actions to meet these challenges, including the development of nuclear power plants (project currently under construction), different solar energy plants and demonstration plants for renewable energy desalination (RSB, 2013). Renewable desalination has been studied by a number of researchers, who have shown that it is technically and economically feasible due to the high ambient temperature and solar radiation in Abu Dhabi (Howari, Sadooni and Goodell, 2008; Sgouridis *et al.*, 2016).

4.3 Mapping Water Use across Various Sectors

Table 4.1 shows a detailed distribution of usage of the three water resources across all sectors. Groundwater is exclusively used for irrigation (estimated by EAD) of agriculture, forestry, livestock and amenities at 71%, 28%, 1% and 0.3%, respectively (EAD, 2017; SCAD, 2017b).

Table 4.1 Water resource usage across various sectors (SCAD, 2017b; EAD, 2017).

Sector	Groundwater		Desalination		Treated Wastewater		Total	
	Mm^3	%	Mm^3	%	Mm^3	%	Mm^3	%
Irrigation	2218	100%	230	21%	167	100%	2614	75%
Agriculture	1574	71%	230	21%	4	2%	1808	52%
Forestry	617	28%	0	0%	0	0%	617	18%
Livestock	21	1%	0	0%	0	0%	21	1%
Amenities	6	0.3%	0	0%	163	98%	169	5%
Domestic	0	0%	472	42%	0	0%	472	13%
Government	0	0%	122	11%	0	0%	122	3%
Commercial	0	0%	261	23%	0	0%	261	7%
Industry	0	0%	30	3%	0	0%	30	1%
Other	0	0%	2	0.2%	0	0%	4	0%
Grand total	2218		1116		167		3503	100%
%	63%		32%		5%			100%

Notes: Groundwater total annual withdrawal and usage across various sectors was estimated by EAD for 2016 (EAD, 2017), whereas desalination and wastewater data were measured as total annual production and usage by ADWEC and ADDC (SCAD, 2017b).

Desalinated water is the only source for domestic use at a supply of 472 Mm^3, which is 42% of the total desalination used. It also supplies 23% for commercial, 21% for agriculture, 11% for government buildings, 3% for industries and 0.2% for others (SCAD, 2017b).

Only 27% of the total desalinated water supplied is collected and treated, whereas 73% is lost via irrigation and other water-loss activities, such as uncollected car washing at household connections, as explained by RSB (2014). Therefore, the total treated wastewater is only one-third of the total desalinated water supplied (332 Mm^3), where 167 Mm^3 is used for irrigation, mainly amenities, and the remainder is discharged to the sea (SCAD, 2017b; EAD, 2017). Amenity and forestry also use a considerable amount of desalination (366 Mm^3 and 91 Mm^3 for amenity and forestry, respectively; Pitman, McDonnell and Dawoud, 2009), but this is not indicated in SCAD annual reports.

With economic and urban development and population growth, the volume of treated wastewater more than doubled from 2003 to 2016 where it is largely used for amenity, forestry and landscaping in parks, roadsides and golf courses. Currently, improving the utilization of treated wastewater is one of the major government initiatives. This is shown in the recent use of treated wastewater in agriculture (1%), as demonstrated by a pilot in 143 farms in the AD region. In this pilot, ADFCA provides irrigation water supply to selected farms by a direct connection from a major treated wastewater plant (Al Mafraq treatment plant) located within close distance (20 to 40 km) from these farms and produces enhanced treatment of sewage effluent. The findings and results of the pilot will be used to inform future policies and provide practical incentives for other farmers (McDonnell and Fragaszy, 2016).

In summary, water use for irrigation is the largest in ADE (Figure 4.3). It is about 75% (52% for agriculture, 18% for forestry and 5% for amenities) of the total water produced. Agricultural irrigation relies heavily (71% of total groundwater supplied) on groundwater, but as it is depleted, desalination is supplied to meet increasing agricultural demand.

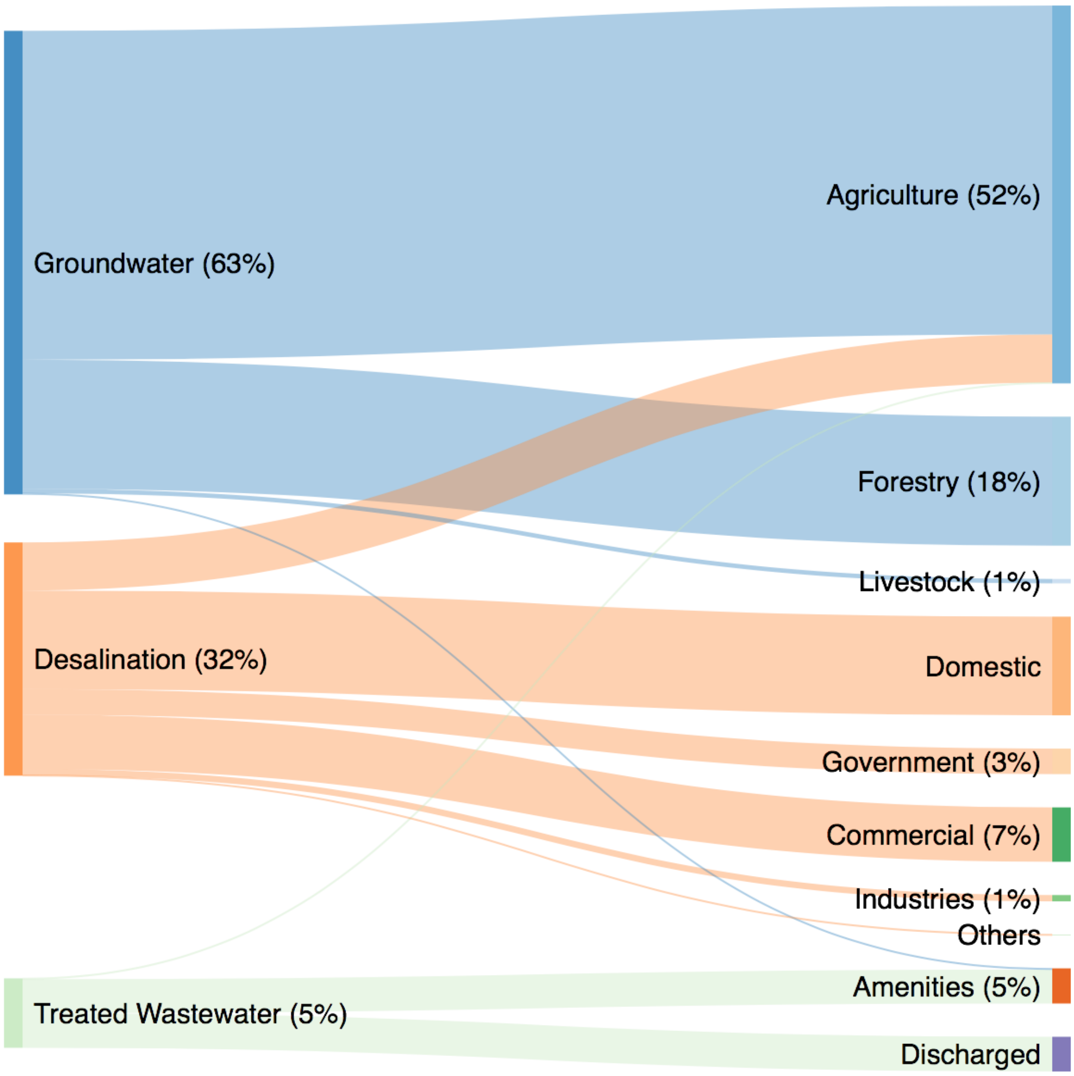

Figure 4.3 Mapping water use in ADE.

In 2016, the government established a treated wastewater committee to focus on developing a practical plan to improve treated wastewater utilization in order to reduce the dependency on desalination and groundwater. It also took the initiative to promote water savings in government and commercial offices. These initiatives have shown clear success, which is reflected in the decrease in water use in some of the sectors. The analysis of desalinated water use across the sectors from 2012 to 2015 (Figure 4.4) shows a slight decrease in domestic use and about a 50% decrease in water use in government buildings. This decrease might result from the removal of all water subsidies from government buildings (Interview with RSB expert, 2016). However, this analysis shows that there is some increase in desalinated water use in the commercial sector and a high increase in agriculture.

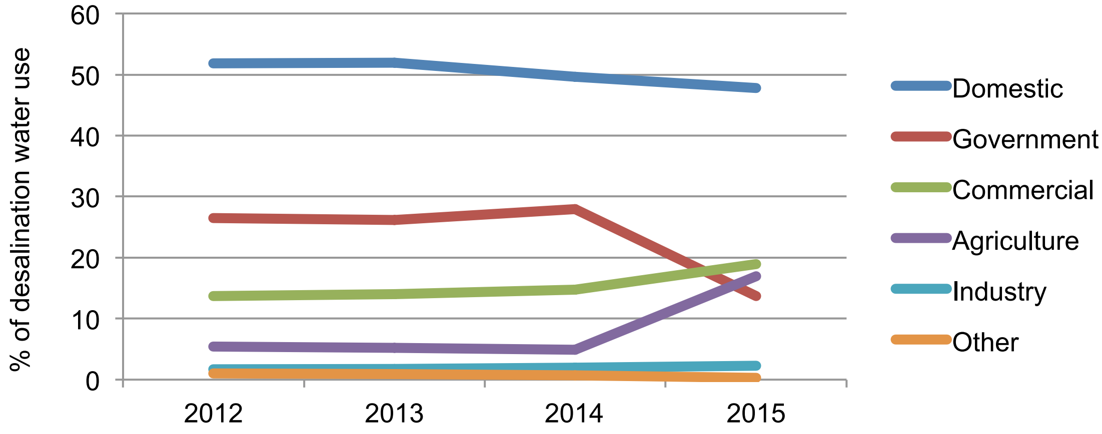

Figure 4.4 Desalinated water use from 2012 to 2015 (SCAD, 2016).

The trend in irrigation water use from groundwater, desalination and treated wastewater from 2007 to 2016 shows a gradual decrease in groundwater usage (16%) and an increase in desalination and treated wastewater (Table 4.2). From 2007 to 2016, desalination and treated wastewater increased more than 17 times and 1.45 times, respectively.

Table 4.2 Irrigation water use from 2007 to 2016 (SCAD, 2010, 2011b, 2013, 2016; EAD, 2017).

Year	Groundwater	Desalination	Treated Wastewater	Total
2007	2669	13.15	117.18	2799.13
2008	2585.54	26.46	132.9	2744.9
2009	2400	26.98	147.7	2574.67
2010	2251	34.92	126.3	2412.12
2011	2217.90	30.77	133.5	2382.17
2012	2217.90	57.2	138.8	2413.9
2015	2217.90	196.18	170.8	2584.88
2016	2217.90	230	169	2616.90

Figure 4.5 demonstrates the entities responsible for irrigation water supply sources (based on the interview with experts from ADWEA and ADFCA). It shows that groundwater wells are owned and operated by four groups: farms (75,000), DMAT (300), EAD (4000) and ADFCA (500).

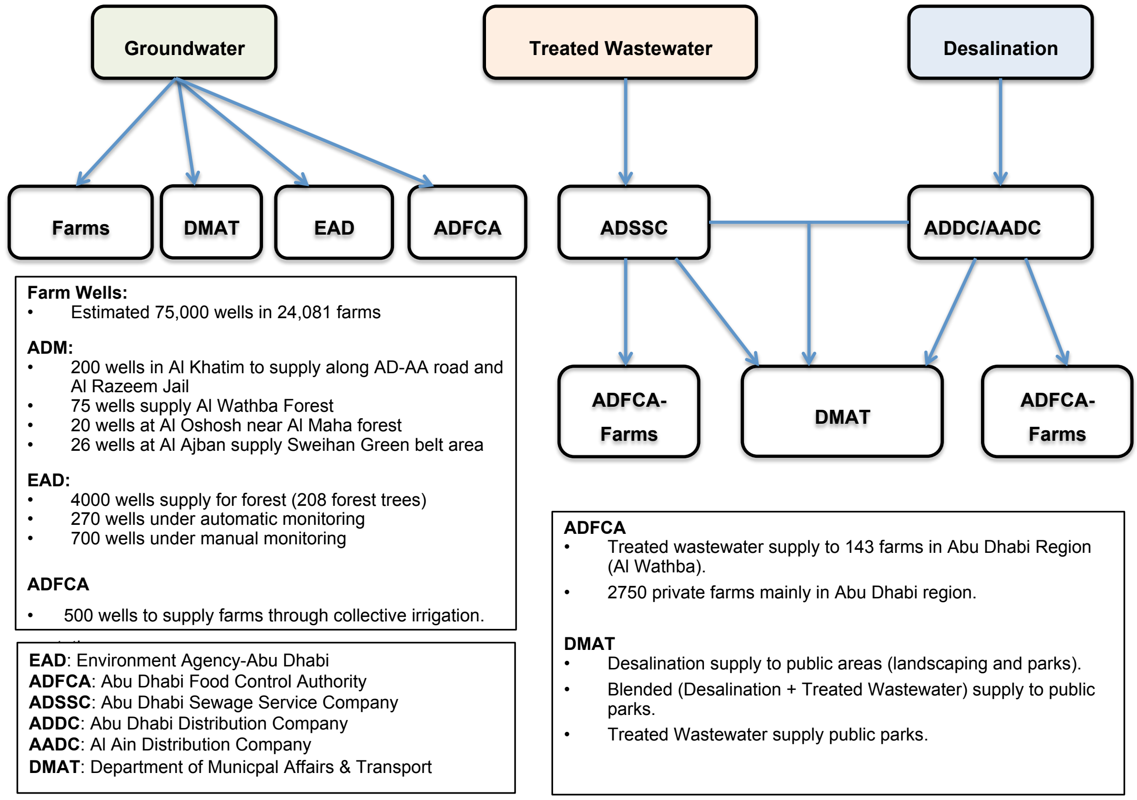

Figure 4.5 Irrigation water supply networks in ADE.

The treated wastewater is pumped from Abu Dhabi Sewage Service Company's (ADSSC) wastewater treatment plants to ADFCA and DMAT stations. It is also mixed with desalinated water coming from Abu Dhabi and Al Ain distribution companies (ADDC/AADC) to be used for landscaping and public parks via DMAT. The desalination is also directly supplied from distribution companies to ADFCA and DMAT stations. All water supplied to ADFCA is collected and distributed to selected farms through ADFCA's collected irrigation network. Further details are provided in Section 4.6.4.2.

4.4 Groundwater

In the 1960s, groundwater quality and quantity in ADE were suitable for potable water demand. Since that time, the demand for groundwater has increased more than 10-fold, which has led to water table decline and groundwater salinity increase (EAD, 2015a). During the same period, ADE government policies were initiated for desert greening (to convert large areas to forest), increasing agriculture (boosting local supply) and landscaping, and since then the water use rate has increased (Pitman, McDonnell and Dawoud, 2009). This policy encouraged exploration of the groundwater, especially in AA, south of WR (Liwa) and the area between them, which has encouraged an increase in agricultural coverage to the deserts (Government of Abu Dhabi, 2013). A recent report from EAD shows the decline of the groundwater level as the freshwater becomes brackish in these areas (EAD, 2017).

Historically, the responsibility for groundwater drilling, operation and maintenance (management) in the Emirate was with the Abu Dhabi National Oil Company (ADNOC) through the National Drilling Company (Interview with SME from EAD, 2016). In 2000, the ADE government transferred the responsibility for groundwater management to EAD, which started to compile relevant data. In 2005, EAD established a groundwater central database. The following year, EAD started to regulate drilling of wells under Law No. 6, 2006 (EAD, 2012b). However, it is evident that actual information (such as number of wells per farm, depth, salinity and abstraction rate) is not available, especially on the private wells owned and operated by farm owners. Therefore, most of the data only come from EAD's rough estimations, which are based on pump capacity (horsepower) and estimated duration of daily well operation (Interview with SME from EAD, 2016). The absence of such data creates a challenge to control groundwater use and assess the magnitude and actual impact on current and future groundwater reserves.

EAD is currently working on a well inventory project to meter all wells in order to monitor the abstraction rate, salinity and water table levels accurately and precisely (EAD, 2017). Eventually, this will help to develop a mechanism to control groundwater abstraction in the future (Interview with SME from EAD, 2016). In 2016, EAD also amended Law No. 6 in order to gain more authority to manage and control drilling and abstraction (EC, 2016). The latter law also states that ownership of the groundwater is only with the Abu Dhabi government.

4.4.1 Groundwater Aquifers

In ADE there are three main aquifers: the western gravel aquifer, the sand dune aquifer and the Sabkha aquifer (flat salt along the coastline). The whole Emirate is predominantly underlain by quaternary gravel and sand aquifers (McDonnell and Fragaszy, 2016), as shown in the ADE hydrogeology map in Figure 4.6. The gravel aquifer is located in the east (AA) adjacent to the Oman Mountain and covers 15,177 km^2, with a 120–530 m hydraulic head and 800–5,700 ppm salinity. The sand dune aquifer consists of a linear dune and a star sand dune, where dunes grow upwards according to different wind directions and create a star shape (EAD, 2011), and covers the middle area between the western gravel aquifer and the coastal area in the west. This aquifer covers 68,376 km^2 with a 50–120 m hydraulic head and 5,000–15,000 ppm salinity. The star sand dune, which is located in the south and central part of the Emirate at Liwa crescent (south of WR), covers 8,194 km^2 with 800–2,000 ppm salinity water, where most of the recharge occurred 6,000–9,000 years ago (Brook *et* *al.*, 2006). The coastal aquifer is located along the coastal line in the west and covers 22,760 km^2 with a 0–50 m hydraulic head and salinity greater than 15,000 ppm (Elmahdy and Mohamed, 2015). At the coastal line, hyper-saline groundwater occurs as high as 200,000 ppm due to slow movement with a high residence time that exceed 15 years, which allows more dissolution of salt from the Sabkha coastline (Brook *et al.*, 2006).

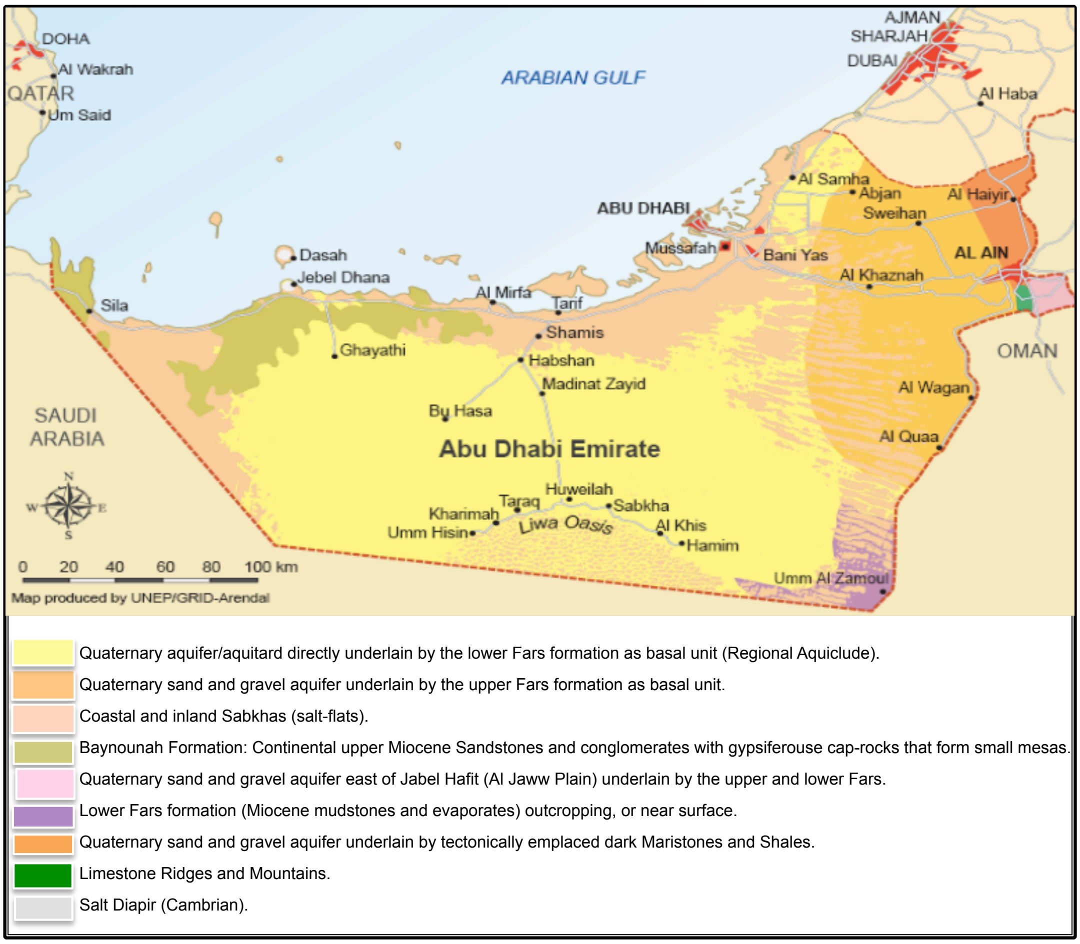

Figure 4.6 Hydrogeology map of Abu Dhabi Emirate (adapted from McDonnell and Fragaszy, 2016).

The gravel aquifer is the only one that receives recharge during precipitation and run-off from the Oman Mountains. Both the gravel and the star dune aquifers are considered to be the only natural freshwater available in the Emirate (Figure 4.7), estimated at 3% of the total groundwater reserve (Pitman, McDonnell and Dawoud, 2009; EAD, 2011, 2017). Table 4.3 illustrates the percentage share of fresh, brackish and saline groundwater reserves.

Table 4.3 Percentage shares of water resources (Pitman, McDonnell and Dawoud, 2009).

Water Type	Reserve (Mm^3)	% Share
Fresh groundwater	16,420	3
Brackish groundwater	114,000	23
Saline groundwater	506,200	80
Total	636,620	100

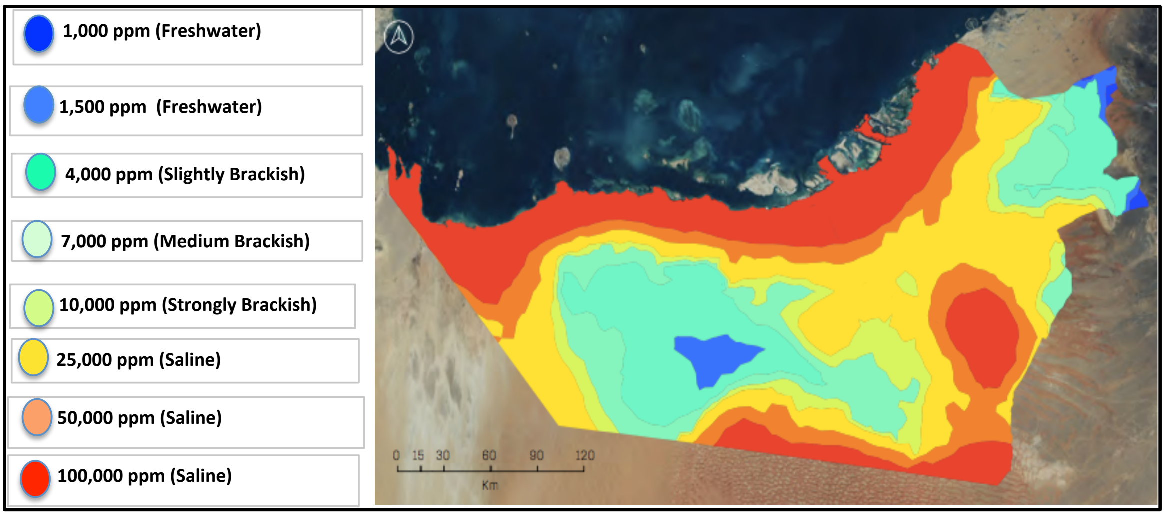

Figure 4.7 Groundwater salinity distribution (EAD, 2017).

4.4.2 Groundwater Abstraction

In the 1960s, groundwater abstraction was estimated at 200 Mm^3/year, as stated by Dawoud *et al.* (2005), where 163 Mm^3/year was used in agriculture, less than 1 Mm^3/year in forestry and around 36 Mm^3 was for domestic use (Dawoud *et al.*, 2005). Groundwater abstraction jumped to 2,233 Mm^3 in 2001 (Shahid *et al.*, 2013) and 2,862 Mm^3 in 2005 (SCAD, 2012), which shows a more than 10-fold increase in 45 years. From 2005 to 2011, the rate decreased to 23%. This decrease can be justified by depletion and deterioration of the quality of the groundwater from over-abstraction.

According to EAD (2011), the rate of groundwater abstraction varies from 12 m^3/hour in AD and WR to 150 m^3/hour in AA region (EAD, 2011). These groundwater abstraction levels exceed the renewable freshwater recharge, which is estimated at 4% of total water use (ERWDA, 2002; Dawoud *et al.*, 2005). With less than 100–120 mm per year rainfall, it is not enough to replace the volume of groundwater abstracted. Therefore, the groundwater table has declined significantly, from 1.5 m to 5 m (Pitman, McDonnell and Dawoud, 2009; EAD,

2017) and groundwater quality, especially fresh water in AA and Liwa Crescent, has been replaced by brackish and saline water (Dawoud *et al.*, 2005; EAD, 2017). With the current abstraction pattern, it is expected that the groundwater will be exhausted in the next three to four decades.

Furthermore, intensive agricultural irrigation has contaminated the groundwater with concentrated chemicals (such as boron, fluoride and nitrate) and fertilizers to exceed the WHO guidelines (Bollaci *et al.*, 2010; Ali Al-Alwai, 2014). This has impacted the groundwater so that it is unusable for human consumption, as found in Liwa Crescent (Pitman, McDonnell and Dawoud, 2009), and harmful not only for human use, but also for agriculture and livestock, where it was tested positive for traces of heavy metals (such as chromium) by Ali Al-Alwai (2014) in his study in Sweihan (northeast of ADE).

The unsuitability of groundwater quality is a factor leading farmers to install brackish water desalination plants (reverse osmosis), especially those who are planning to establish commercial agricultural production. Although this is a positive way to increase crop yields and market value, the desalination brine that usually will be discharged into an old well will contribute to further degradation of the groundwater quality (Bollaci *et al.*, 2010; Ali Al-Alwai, 2014). The absence of a regulatory framework could lead to further pollution of the groundwater as well as increasing soil salinity.

4.5 Agricultural Development

4.5.1 Background and Main Drivers

As noted in Section 2.4.2, the main driver for agricultural development in the UAE and other GCC countries is food self-sufficiency, despite the fact that the whole region does not have sufficient renewable freshwater. Sheik Zayed, the late president and founder of the UAE, initially promoted agricultural development in the 1950s and 1960s in Al Ain. This region has available freshwater through oases and the aflaj (a manmade canal) as well as more rainfall. Also, it was traditionally involved in agriculture (Woertz, 2013). To increase Emirati citizen settlement, facilitate social development and develop a permanent income, additional agricultural policies were implemented. Those policies focused on encouraging citizens to farm by providing subsidies such as free agricultural land and supporting services. Such services are land levelling, drilling of wells, fertilizers, seeds, pesticides, a 50% reduction for most production input, interest-free loans for equipment, guaranteed take of farm products at high prices by the government (Shihab, 2001; Pitman, McDonnell and Dawoud, 2009) and, most importantly, a free water supply (Woertz, 2013).

These policies have encouraged the development of agriculture and increased its output, which in turn increased its GDP share from 0.7% in 1975 to 3.6% in 1998 (Gallacher and Hill, 2008). However, as groundwater deteriorated, agricultural productivity decreased, which led to a decline in its GDP share. From 2000 to 2008, there was a sharp drop (63%) in agriculture's percentage GDP share (World Bank, 2005), which was less than 1% in 2014 (Department of Economic Development, 2010).

Woertz (2013) pointed out the historical development of the agricultural sector in the country, which can be summarized as follows:

- From 1965 to 1979, there were 800,000 trees planted in the UAE.
- During the 1970s, the main infrastructure such as alflaj, borehole drilling, etc. was developed.
- In the 1970s, afforestation and landscaping became one of the priorities as a cultural and social link, and started to compete with the agricultural sector for the water supply.
- In the 1980s, actual agricultural production and marketing were established and implemented. The use of electrical submersible pumps replaced the older diesel pumps and allowed for an increased abstraction rate.
- In 1983, the UAE government developed a model farm to provide practical education on different agricultural practices for farmers.
- In 1992, the International Center for Bio-saline Agriculture (ICBA) was established in Dubai, where it was granted land and subsidies. The main focus of ICBA is to develop research on desert crops that tolerate a dry climate and saline water.
- From 1994 to 2003, the cultivated areas more than tripled.
- In 2003, three-quarters (178,500 ha) of the cultivated areas in the country were planted, mainly with palm trees, followed by fodder crops and then vegetables. All of these are water-intensive crops.

During the last few years, the ADE government has realized the impact of the high water use pattern on groundwater, which is predicted to be completely depleted within the next three to four decades. Therefore, in 2010, it started to put in place practical measures to phase out fodder crops (mainly Rhodes grass) in order to save around 60% of the irrigation water. It is also working on developing a mechanism to control and limit groundwater abstraction at a farm level (McDonnell and Fragaszy, 2016).

4.5.2 Soil Suitability for Agriculture

An extensive field survey was completed in ADE at a scale of 1:100,000 using an Indian remote sensing satellite and USDR for soil classifications, in addition to the high number of observation boreholes/sites with a depth from 2 m to 10 m from which samples were taken and analysed. This was complemented with physical field measurements also undertaken to assess the physical infiltration rate, permeability and penetration resistance (Shahid *et al.*, 2013; Abdelfattah and Kumar, 2014).

The soil in the Emirate is mostly sandy, loamy with particles coarse to fine in size, poor in nutrient capacity, containing percentages of gypsum, carbonate and silica (Shahid *et al.*, 2013). Sandy soil has less ability to hold irrigated water. Therefore, it needs to be carefully managed to improve its agricultural production capacity. In 2009, ICBA identified five different soil categories in ADE based on their physical, chemical and mineralogical characteristics, such as depth, particle size, soil moisture and temperature, mineralogical composition and water content (Pitman, McDonnell and Dawoud, 2009; Abdelfattah, 2013; Abdelfattah and Kumar, 2014).

According to Shahid et al. (2013) and Abdelfattah and Kumar (2014), the soil is categorized as follows (Table 4.4):

- Highly suitable soil characterized by permeable soil at the surface, deep drainage with capacity to drain excess irrigation water, root zone salinity <4 dS/m and low soluble salts and neutral pH level. This type of soil only covers 2,000 ha and mostly occurs in the south of Madinat Zayed in WR.
- Moderately suitable soil that has moderate limitations, which can be rectified by suitable irrigation management. It covers 309,000 ha and occurs mostly in the central part of WR at Madinat Zayed and Liwa Crescent and east of Jabal Hafit in AA.
- Marginally suitable soil has severe limitations that can be corrected by proper management strategies. It covers 1,550,000 ha from the northeast to the northwest coastal plain.
- Currently unsuitable soil has more salt content, with a shallow zone root and steep gradient. It covers 1,753,000 ha in the southern part of the Emirate and along the western coastal Sabkha.
- Permanently unsuitable soil with severe limitations that cannot be corrected is very shallow, on a very steep gradient with poor drainage. It covers 2,108,000 ha and mostly occurs in the southwest of WR.

The current soil suitability of the irrigated area (Table 4.4) indicates that there is a high percentage of irrigated agriculture located within land with currently and permanently unsuitable soil that covers 38% and 22%, respectively (EAD, 2011).

Table 4.4 Soil suitability in ADE (EAD, 2011; Abdelfattah and Kumar, 2014).

Soil Type	% Available Area	Mostly Occurring	% of Irrigated Agriculture Size	% of Forestry Size
Highly suitable	0.04% (2,000 ha)	Central WR	0	2
Moderately suitable	5.4% (309,000 ha)	Central WR, Liwa and east of AA	4	3
Marginally suitable	27% (1,550,000 ha)	Northeast to northwest coastal plan	32	44
Currently unsuitable	31% (1,753,000)	South WR and western coastline (Sabkha)	38	15
Permanently unsuitable	37% (2,108,000 ha)	Southwest of WR	22	28
Not mapped			4	6

Figure 4.8 provides the geographical distribution of farms across ADE's three regions and soil suitability distribution map. It shows that most of the farms are located in marginally suitable, currently and permanently unsuitable soil areas, whereas there are no farms located in highly suitable soil and a small percentage only located in moderately suitable soil. It is expected that given this recent comprehensive knowledge of soil suitability, the distribution of the irrigated areas should consider the location of the five soil suitability types, with more restrictions in areas characterized by permanently unsuitable soil.

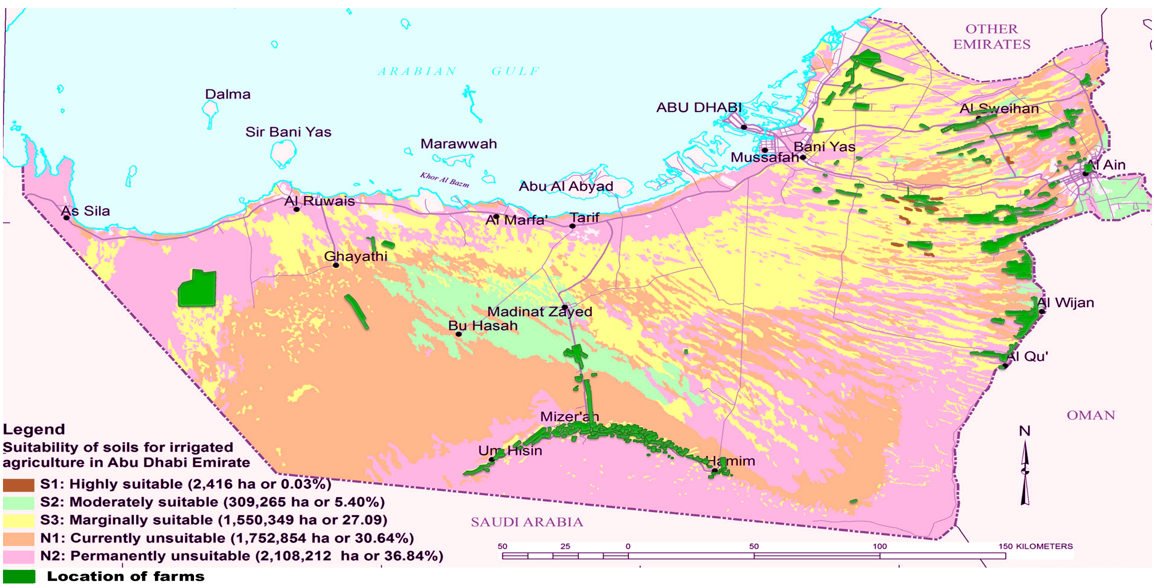

Figure 4.8 Distribution of soil suitability and farms in ADE

(adapted from Bollaci et al., 2010; EAD, 2011; Abdelfattah and Kumar, 2014).

4.5.3 Farm Distribution

The ADE government provides farms of an average of 2–3 ha for its citizens distributed in the three regions, AD, AA and WR (Figure 3.1), in addition to the free services mentioned earlier, which include drilling of between two and three wells on each farm (Pitman, McDonnell and Dawoud, 2009). Figure 4.9 illustrates the historical trend in the number of farms and the total farm area from 1971 to 2015, which shows a high increase from 1971 to 2000 and then a decrease, until it remained the same in 2014, 2015 and 2016 (Pitman, McDonnell and Dawoud, 2009; SCAD, 2010, 2011b, 2012, 2013, 2016, 2017b).

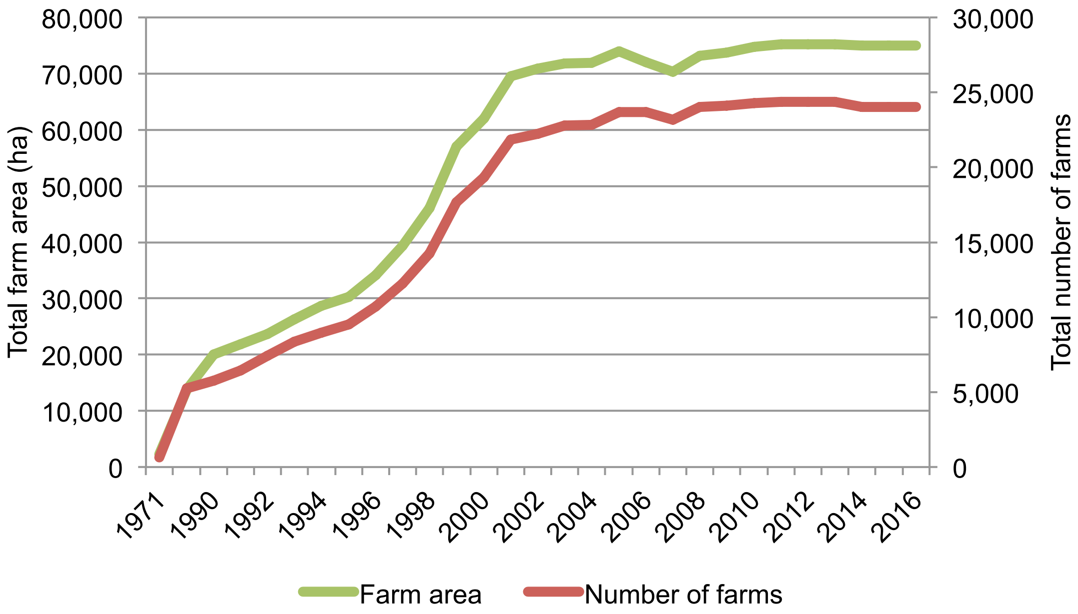

Figure 4.9 Historical growth of number of farms and farm areas, 1971–2016.

In 2016, the number of farms in Abu Dhabi was 24,018, with a total area of 74,986.8 ha, representing 1% of the total area of the Emirate (SCAD, 2016). The farms' distribution was as follows: 15% in AD with a total area of 8,968 ha, 50% in AA with a total area of 45,250 ha, and 35% in WR with a total area of 20,769 ha. As explained in Section 3.3.2.5, farm size is categorized from <2 to >6 ha.

The distribution of number and size of farms across these six categories is shown in Figures 4.10 and 4.11. These demonstrate that in AD, 80% of farms are situated within 2–2.9 ha, followed by 16% within the <2 ha farm size category and only a small percentage in the remaining categories. In AA, 78% of farms fall within 3–3.9 ha, followed by 10% within 2–2.9 ha, 5% within <2 ha, 3% within >6 ha, 2% within 4–4.9 ha and 1% within 5–5.9 ha. In WR, 38% of farms are within <2 ha, 28% within 2–2.9 ha and 4–4.9 ha, 5% within 3–3.9 ha and 1% within the >6 ha farm size category.

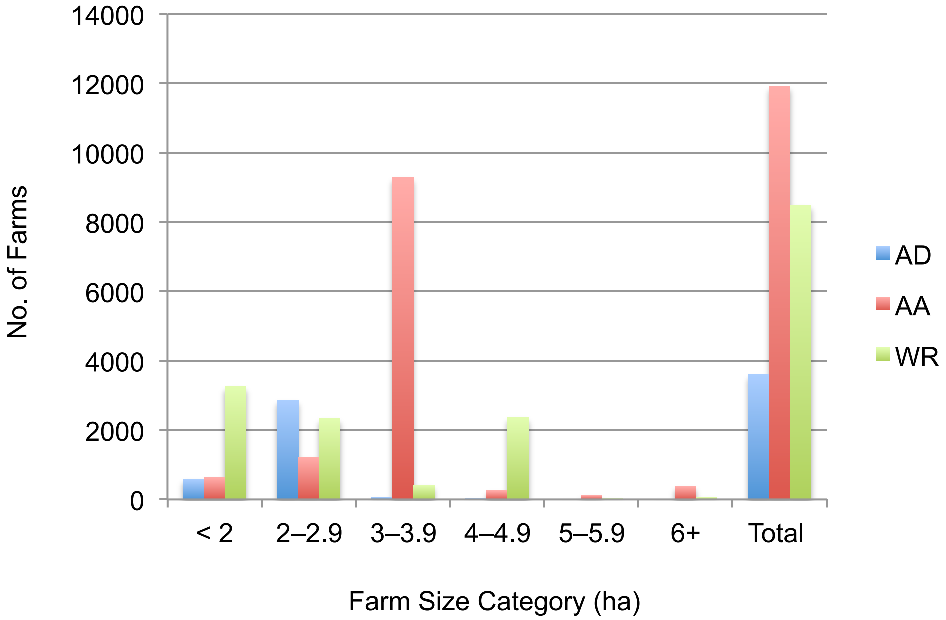

Figure 4.10 Distribution of farms per farm size category across Abu Dhabi’s three regions.

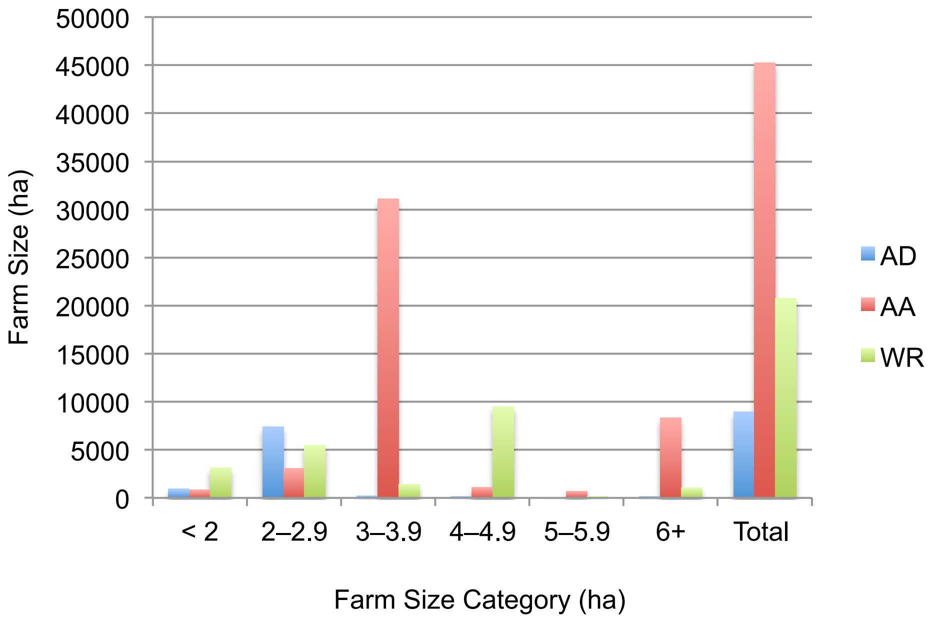

Figure 4.11 Distribution of farm size per farm size category across Abu Dhabi’s three regions.

4.5.4 Water Resources Used in the Agricultural Sector

There are three main water supplies to agriculture: farm wells, a collective irrigation network and small-scale brackish desalination plants. In the following subsections, detailed descriptions are provided of these three means of supply.

4.5.4.1 Farm Wells

As demonstrated in Section 4.4, the majority of wells are owned and operated by farm owners in the three different regions. Unfortunately, the information available on farm wells per region is only from 2005 to 2011 in the SCAD Statistical Yearbook, whereas the more recent SCAD reports do not have any updated data. According to the SCAD report (2012), there are 71,165 wells, 47% of which are located in AA, 40% in WR and only 13% in AD. Table 4.5 shows an increase in the number of working and non-working wells, plus a change in average groundwater withdrawal in ADE's three regions from 2005 to 2011.

Table 4.5 Working wells and non-working wells across ADE's regions (SCAD, 2010, 2011b, 2012).

Region	2005	2007	2008	2009	2010	2011	%
Abu Dhabi Region							
Working wells	4,240	3,880	3,780	2,980	8,500	9,050	13
Non-working wells	2,130	1,540	1,160	1,100	1,500	1,615	
Average groundwater withdrawal	158	135	123	101	78	77	
Al Ain Region							
Working wells	41,240	40,870	39,820	35,460	32,000	33,500	47
Non-working wells	2,130	19,600	18,760	16,350	11,000	11,150	
Average groundwater withdrawal	1,570	1,499	1,455	1,287	1,261	1,251	
Western Region							
Working wells	28,980	26,540	25,656	16,855	27,700	28,615	40
Non-working wells	16,670	15,130	14,920	13,880	9,300	9,430	
Average groundwater withdrawal	1,134	1,035	1,008	1,013	912	889	
Total							
Working wells	74,870	71,290	69,250	65,290	68,200	71,165	
Non-working wells	41,050	36,270	34,840	31,336	21,800	22,195	
Average groundwater withdrawal	2,848.09	2,668.45	2,585.19	2,400	2,251	2,218	

Table 4.5 shows that there was a small increase (4%) in the total number of working wells in the ADE overall from 2009 to 2010; however, this increase was much larger in AD and WR, at 185% and 64%, respectively. This increase may be related to the ADFSC programme

(focusing on WR and AD in 2010) to increase the domestic agricultural contribution to the local market (McDonnell and Fragaszy, 2016). The table also shows that in general there was a decrease of 5% in the total number of wells and 19% in annual well abstraction from 2005 to 2011 and that about a third of the total number of wells are defunct, although the proportion of abandoned wells varies from one region to another.

4.5.4.2 Collective Irrigation Network

ADFCA operates and manages irrigation supply systems (the collective irrigation network) to support farms that have no or little groundwater or have highly saline groundwater. There are 29 collective irrigation stations: 14, 12 and 3 in AD, AA and WR, respectively. There are 98 reservoirs located at these stations, with a total capacity of 395,273 m^3 supplied by 78% desalination, 17% groundwater and 5% treated wastewater (Table 4.6). The stations supply the selected farms directly based on time schedule rather than volume of water (McDonnell and Fragaszy, 2016). The number of farms that receive supplies through the collective irrigation programme across the three regions is only 6,051, whereas the remaining farms (73% of the total) rely on their own local private wells. This information was obtained from the semi-structured interview at ADFCA (2016).

Table 4.6 Summary of the collective irrigation system in ADE.

Region	Number of Stations	Number of Reservoirs	Total Reservoir Capacity (m^3)	Volume of Water Supplied (m^3/Day)				Number of Farms Benefiting
				Desalination	Groundwater	Treated Wastewater	Total	
AD	14	18	195,455	120,264	5,455	11,000	136,719	3,031
AA	12	77	193,000	35,327	24,588	0	59,915	2,572
WR	3	3	6,818	10,958	7,045	0	18,003	448
Total	29	98	395,273	166,549	37,088	11,000	214,637	6,051

Table 4.6 and Figures 4.12 and 4.13 show that 50% of the farms that benefit from the ADFCA irrigation system are located in AD, where most of them receive a desalination supply, 689 receive groundwater and 143 receive treated wastewater (Section 4.3). In AA, there are 2572 benefiting farms, of which 1,487 receive a mix of 90% desalination and 10% groundwater and 1,085 farms receive groundwater. From 448 farms in WR, 214 receive desalination and 234 receive a mix of desalination and groundwater.

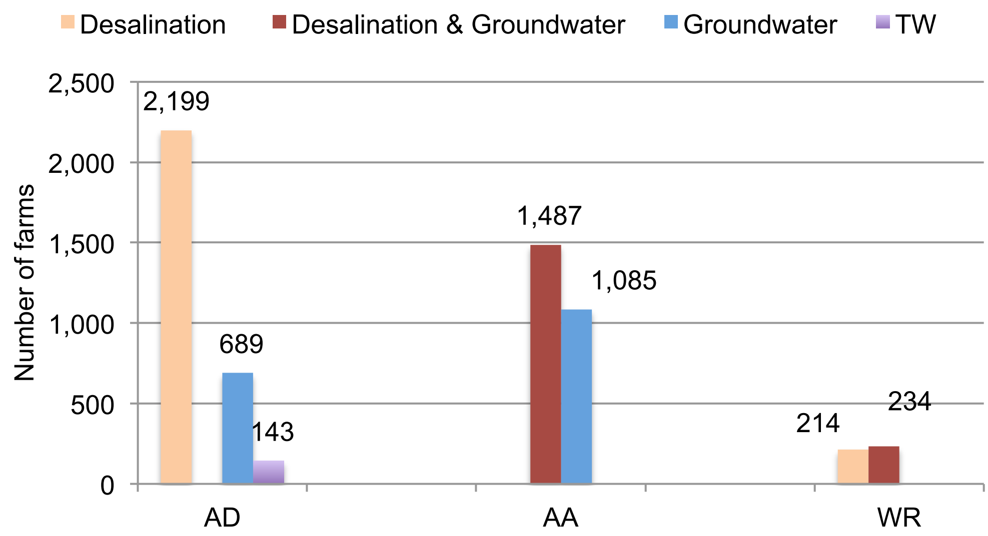

Figure 4.12 Number of farms benefiting from ADFCA's collective network

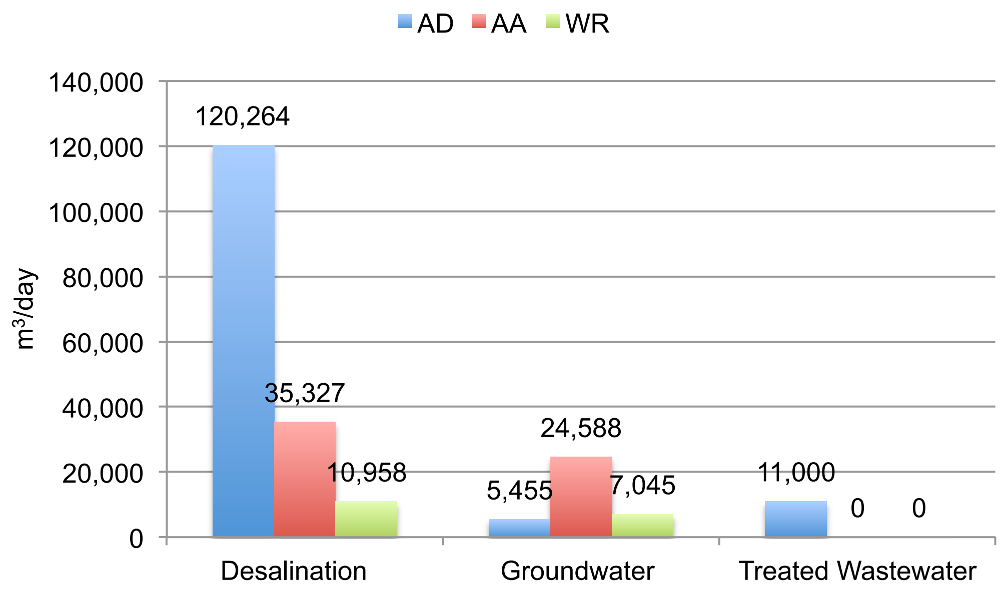

Figure 4.13 Total water supplied by the collective irrigation network

The average volume of water supply varies in different regions and locations. It ranges from 8 to 77 m^3/farm/day in AD, from 5.5 to 69 m^3/farm/day in AA and from 34 to 52 m^3/farm/day in WR.

4.5.4.3 Brackish Water Desalination

Due to the deterioration of groundwater quality, small-scale reverse osmosis desalination systems for brackish groundwater are installed in some farms to improve the water quality for agricultural production, especially of vegetables and fruits. These plants are owned and operated by farm owners, with capacities varying from 114 to 341 m^3 per day, and are not subject to any regulatory or environmental assessment (Pitman, McDonnell and Dawoud, 2009).

There is no record of the number of plants, their capacities and the method(s) of brine disposal on top of the negative impact on the environment. However, it is indicated in some government reports that the method of discharge is either injected into an old well or dumped in the desert, both methods that can lead to groundwater pollution (Pitman, McDonnell and Dawoud, 2009; McDonnell and Fragaszy, 2016).

4.5.5 Agricultural Production and Land Use

Most of the farms are covered 36% and 40% by forest trees and fruit trees, respectively. The forest trees are mainly current fallows and 6% windbreaks, and more than 98% of the fruit trees are palm (see Figure 4.14 and Table 4.7). Of the farmland, 13% is considered a potential area as it is usually empty, 6% is covered by fodder (mainly Rhodes grass), 3% by vegetable crops and 1.7% by buildings (SCAD, 2016).

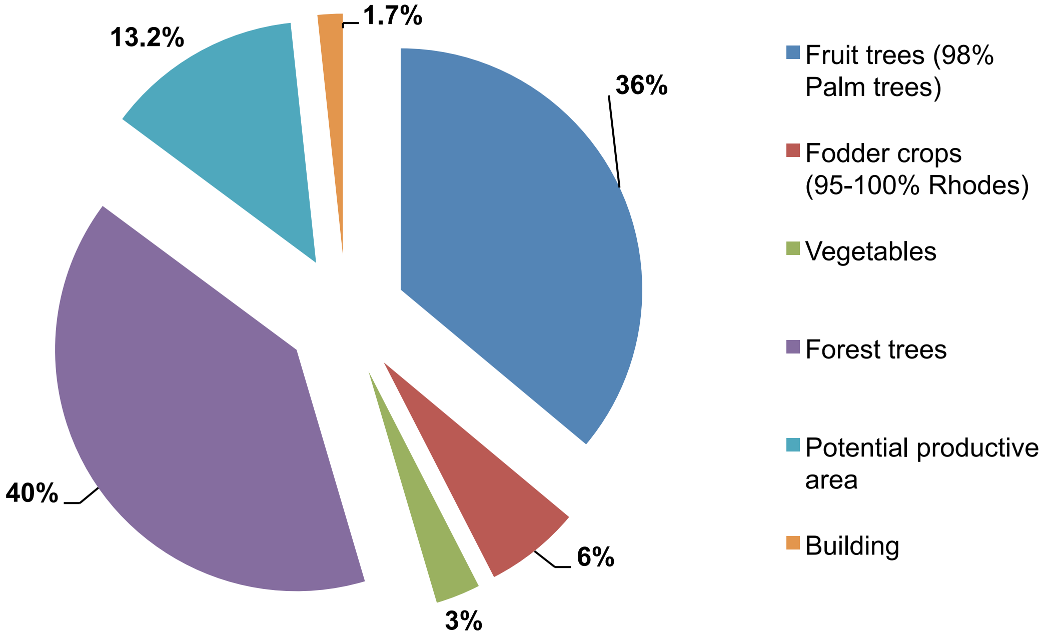

Figure 4.14 Percentage of land use per crop (ADFCA, 2011c; SCAD, 2016).

Table 4.7 Cultivated land per crop, ha (SCAD, 2016).

Region/Items	AD	AA	WR	Total
Total farm size	8,967.90	45,250.30	20,768.60	74,986.80
Fruit trees				
Palm trees	2,266.30	14,401.80	10,268.30	26,936.40
Other fruits	51.2	176.1	68.5	295.8
Total	2,317.50	14,577.90	10,336.80	27,232.20
Fodder crops*				
Rhodes grass	354	3,635.65	630.3	4,619.98
Alfalfa	0	191.35	6.367	197.72
Total	350.4	3,827.00	636.7	4,817.70
Vegetable crops				
Open field	349.6	642.9	387.2	1,379.70
Under protective cover	69.9	345.5	140.3	555.8
Total	419.5	988.4	527.5	1,935.50
Forest trees				
Current fallow	3,209.40	17,970.60	6,950.00	28,130.00
Windbreaks	466.4	476.2	727.5	1,670.20
Total	3,675.80	18,446.80	7,677.50	29,800.20
Potential productive area	2,051.10	6,644.00	1,233.50	9,928.70
Buildings	149.8	766.2	356.5	1,272.50

* Estimated percentage of Rhodes grass land use versus alfalfa based on data obtained from ADFCA statistical report (ADFCA, 2011c).

Assessing the cropping trend from 2011 to 2016 shows that there was a decrease in the cultivation of fruit trees from 2013 to 2015, a reduction in the current fallows from 2011 to 2012, and a sharp decline in fodder crops from 2011 to 2013 but with a gradual increase in the following years (Figure 4.15).

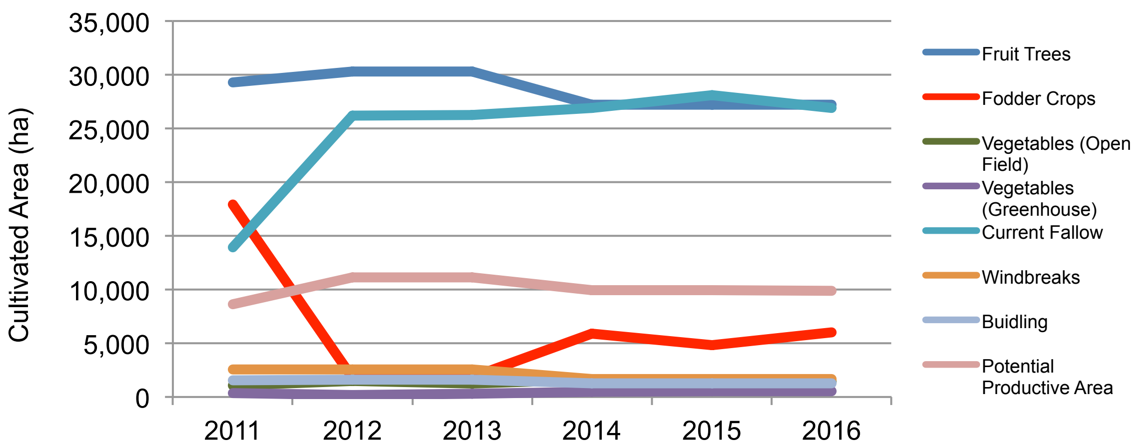

Figure 4.15 Trend in cultivated area per crop group, 2011–2016 (SCAD, 2012, 2013, 2016, 2017b).

The main agriculture-produced crops with input to the ADE local market – the focus of this study – are palm trees, fodder crops and seasonal vegetables. Palm trees and fodder crops are perennial, which means they are cultivated all year round, whereas vegetables are mostly cultivated during the winter season, when temperature and humidity are lower than in the summer season. Details of these three groups are presented in the following subsections.

4.5.5.1 Palm Tree

The palm tree (*Phoenix dactylifera L.)* is one of the important and oldest (at least 5,000 years) crops, not only in the UAE but also in the Middle East and North Africa. The date was the main food source for survival in the desert environment (FAO, 2002; ADFCA, 2012; Shahin and Salem, 2014) because of its high tolerance to harsh environments and high nutritional value (Chao and Krueger, 2007; El-Juhany, 2010), with high simple sugars, pectin, vitamins and minerals (ADFCA, 2012; FAO, 2012b). In the UAE, since its early development the palm tree has been given special attention, therefore this creates a cultural and heritage link with palm trees in the country (FAO, 2015a). The UAE is the seventh largest date-producing country worldwide (El-Juhany, 2010), with exports varying from 6% to 37% (average 24%) of total production (UAE 2000–2013 date export data obtained from the FAOSTAT database to calculate the percentage of date exports).

According to FAO (2015a), ADE produces high-quality date fruit and begins production at 4 years of age, compared to 6–8 years in other countries (SCAD, 2011a). In 2015, there were 5,899,072 palm trees under cultivation in ADE: 53% in AA, 38% in WR and only 8% in AD (SCAD, 2016). The number decreased by 4% compared to palm trees cultivated in 2010. The number of bearing trees is recorded as 73% in 2010 (SCAD, 2010), which is close to the rate of 71% recorded in 2016 (Government of Abu Dhabi, 2016), but more than the FAO estimate of 50% for the UAE (FAO, 2015a).

The total production of dates grew every year until it reached 99,139 tonnes, followed by a decline of 5.6% in 2014 and 2015. There are many (120) types of palm tree in the UAE, but the government's intention is to focus on cultivating 11 types that have a high production capacity, with an average of 0.06854 tonne/tree (62 kg/tree) and a range between 0.031609 and 0.08708 tonne/tree (32–79 kg/tree; Government of Abu Dhabi, 2016). However, the quantity that enters the market is only 35% of total production capacity (this impacts the yield/ha and annual total value). The production rate, calculated by dividing the quantity produced in 2016 by the cultivated total area (200 trees/ha), amounted to 3.4554 tonne/ha, which is 0.018 tonne/tree (18 kg/tree). This rate is four times less than if the full required production capacity is achieved. The quantity delivered by farmers and its related value from

2008 to 2016 were obtained from SCAD reports (2011b, 2016, 2017b). These were used to draw the growth pattern, as shown in Figure 4.16.

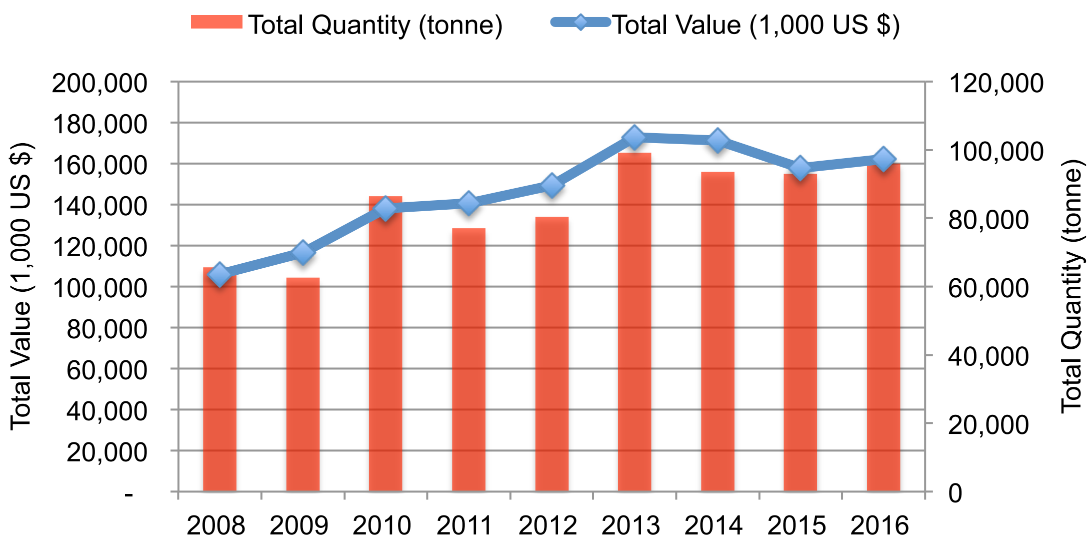

Figure 4.16 Total quantity (tonne) and total value (1,000 US $) of dates supplied by farmers, 2008–2016 (SCAD, 2011b, 2016, 2017b).

4.5.5.2 Fodder Crops

The fodder crops cultivated in ADE are Rhodes grass, alfalfa and panicum (ADFCA, 2011c). These are permanent crops and have the highest water use among all crops (MOEW, 2010). Rhodes grass used to be widely cultivated (>90% of total cultivated fodder crops; SCAD, 2011b) for its high tolerance to salinity and harsh climate (Pitman, McDonnell and Dawoud, 2009). The estimated water use for Rhodes grass is between 13,000 m^3/ha (MOEW, 2010) and 20,000 m^3/ha (Pitman, McDonnell and Dawoud, 2009). According to EAD, in 2008 water for Rhodes grass consumed about 55% of total water use in the agricultural sector, followed by 32% for palm trees (EAD, 2012a), then 9% by other fruit trees and vegetables, whereas 3% accounts for agricultural leaching (Pitman, McDonnell and Dawoud, 2009; Bollaci *et al.*, 2010).

In 2010, the government realized that Rhodes grass cultivation consumes a high amount of water, to the extent that it was found more economically feasible to import fodder crops instead. Accordingly, Rhodes grass subsidies were reformed. The ADE government stopped buying Rhodes grass from farmers and only permitted farmers with livestock to grow it (limited to up to 10% of their cultivated area) and provided them with US $24,506 per year (US $1,906 per month) to encourage them to gradually phase it out (McDonnell and Fragaszy, 2016). Prior to 2010, the government bought Rhodes grass from farmers at a high price (US $1,348 per tonne of dry Rhodes grass) and sold it to livestock owners at a lower price (US $82/tonne; Pitman, McDonnell and Dawoud, 2009).

Figure 4.16 shows the changes in fodder cultivation patterns, which increased by 15.6% from 2005 to 2010, then decreased by 22.6% from 2010 to 2011 (SCAD, 2013). From 2011 to 2012, there was a sharp (90%) decline due to the subsidy reform, but it increased gradually (<2%) the following year and more than doubled in 2016 (SCAD, 2017b). As shown in Figure 4.17 and Table 4.8, fodder crop cultivation is by far the highest in AA compared to WR and AD.

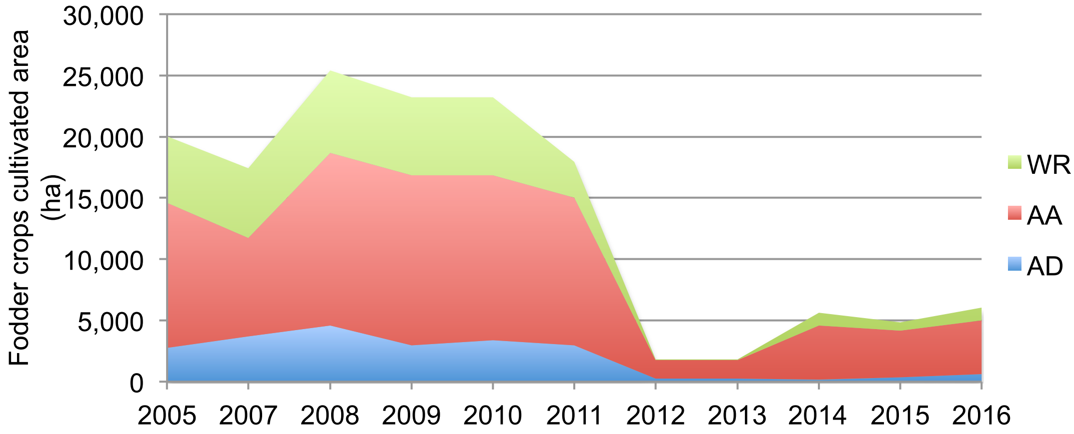

Figure 4.17 Fodder crops cultivation area dropped in 2012 due to policy reform (SCAD, 2013, 2017b).

By using the data presented in Table 4.8, the calculated total fodder produced is almost the same across the three regions, at 30.76 tonne/ha and US $409/tonne, with only small variations.

Table 4.8 Fodder crops cultivation area, quality and value across ADE's three regions (SCAD, 2016).

	AD	AA	WR	Total
Fodder cultivation area (ha)				
Rhodes	354	3,636	630	4,620
Alfalfa*		191	6	198
Total	354	3,827	637	4,818
Quantity produced (tonne)				
Rhodes	11,828	108,690	21,736	142,255
Alfalfa		5,721	220	5,940
Total	11,828	114,411	21,956	148,195
Value of production (US $)**				
Rhodes	4,725,072	45,311,557	9,474,060	59,416,187
Alfalfa		924,726	193,348	1,212,575
Total	4,725,072	46,236,282	9,667,408	60,628,763

**Alfalfa production is estimated based on its ratio to Rhodes production obtained from the ADFCA statistical report (ADFCA, 2011c). **Value of production is US $405.81/tonne, calculated by dividing total value of production by total quantity produced in 2015 (SCAD, 2016).*

4.5.5.3 Vegetable Crops

The cultivation of vegetable crops is by two methods: open field and greenhouse farming. Open field is done during winter months (September to April), which are characterized by lower temperature and humidity compared to summer. A greenhouse is a protected-coverage house with a cooling system that enables cultivation (theoretically) all year round in three to four cycles (three months each cycle). An additional benefit of the greenhouse is optimizing water use and increasing crop yield as well as water productivity (FAO, 2013; Al Qaydi, 2016; Yang *et al.*, 2017). However, water and energy use for the cooling system should be included, not only irrigation, for the assessment and evaluation of greenhouses (Hirich and Choukr-Allah, 2017). Most greenhouses are used to cultivate cucumber and, at a lower percentage, tomato, due to the cucumber's short harvesting time and good economic return. The vegetable yield rate can become high and rewarding if freshwater with 1,500–5,000 ppm salinity is used, which explains why farmers build brackish water desalination plants to supply their greenhouses (FAO, 2012b). The total number of greenhouses increased by 67% from 2011 to 2015, reaching a total of 16,715 greenhouse facilities covering 555.8 ha (SCAD, 2016).

The cultivation of vegetables has fluctuated, but in an increasing direction since 2007, as shown in Figure 4.18. From 2007 to 2011, the majority of vegetables produced were tomatoes, which represents more than 70% of total production. In 2012, tomato production decreased dramatically (becoming 19% only), while a variety of other vegetables increased, such as cucumber (19%), cabbage (14.3%), onion (7.5%) and eggplant (2.2%).

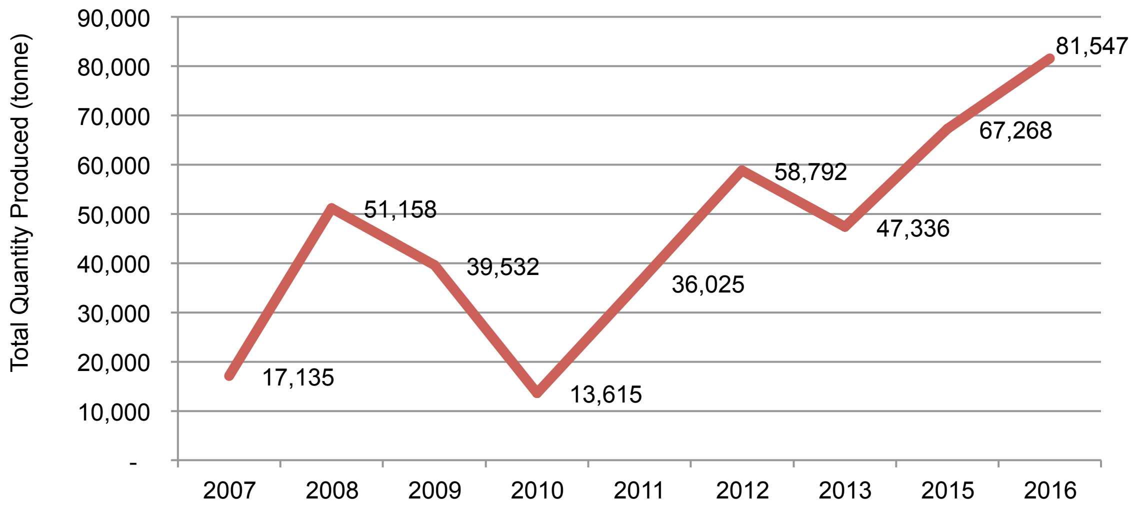

Figure 4.18 Growth of total vegetable production in ADE (SCAD, 2011a, 2012, 2013, 2016).

In 2016, there was a sharp increase in total production of the main vegetables: cucumber (29%), tomato (23%), cabbage (11%), potato (6%), cauliflower, corn and pepper (5%), and onion and eggplant (4%). Table 4.9 demonstrates the different vegetables produced, cultivated area and value in 2016. It also shows the calculated average yield (tonne/ha) and average value (US $/tonne).

Table 4.9 Vegetable production, cultivated area, yield and value (SCAD, 2017b).

Type	Quantity Produced (Tonnes)	% of Total Quantity Produced	Cultivated Area (ha)	% of Total Cultivated Area	Average Yield (Tonnes/ha)	Total Value (US $)	Average Value (US $/Tonne)
Cucumber	22,776.00	32.10%	428.78	2.20%	53	16,123	0.71
Tomato	17,237.20	24.30%	370.09	1.90%	47	11,331	0.66
Cabbage	7,359.40	10.40%	192.83	1.00%	38	2,607	0.35
Onion	3,477.00	4.90%	131.23	0.70%	18	1,763	0.76
Potato	3,294.50	4.60%	115.85	0.60%	30	2,687	0.77
Water melon	3,204.70	4.50%	42.18	0.20%	25	921	0.86
Sweet melon	3,121.60	4.40%	27.88	0.10%	6	135	0.87
Corn	2,495.40	3.50%	83.88	0.40%	37	3,304	1.06
Bean	2,308.80	3.30%	38.34	0.20%	7	382	1.34
Hot pepper	1,997.80	2.80%	13.38	0.10%	31	442	1.05
Sweet pepper	1,067.70	1.50%	52.24	0.30%	38	2,281	1.14
Eggplant	553.1	0.80%	91.03	0.50%	36	1,406	0.43
Carrot	541.3	0.80%	2.95	0.02%	19	50	0.9
Cauliflower	514.4	0.70%	29.98	0.20%	17	273	0.53
Beet	421.3	0.60%	14.91	0.10%	10	68	0.46
Pumpkin	285	0.40%	22.54	0.10%	24	368	0.68
Marrow	154.9	0.20%	101.48	0.50%	25	2,309	0.93
Leafy herbs	147.8	0.20%	50.2	0.30%	11	656	1.19
Other vegetables	54.6	0.10%	125.71	0.60%		1,588	0.5
Total	71,012.50	100%	1,935.48	100%		48,694	

4.6 Agriculture's Contribution to Local Market and Food Security

This section looks at the contribution of ADE's agricultural production to the Emirate's food availability and security, and the level of dependency on food imports. The UAE, as with most GCC countries, is highly dependent on food imports. According to AGEDI, 87% of the food supply in the country is imported: 95% cereals, 81% vegetables and 75% meat (AGEDI, 2015b). UAE also plays a role as a regional trade hub for commodity imports and re-exports. This is shown in the ADE food balance in Figure 4.19.

The analysis of ADE 2015 data (SCAD 2016) on the value of imports, exports and re-exports for different food groups demonstrates how imports have the highest-value percentage for most food commodities, especially when compared to domestic production (Figure 4.19). The date palm is the only product that has a high-percentage production value (90%), whereas imports contributed 7% and exports 3%.

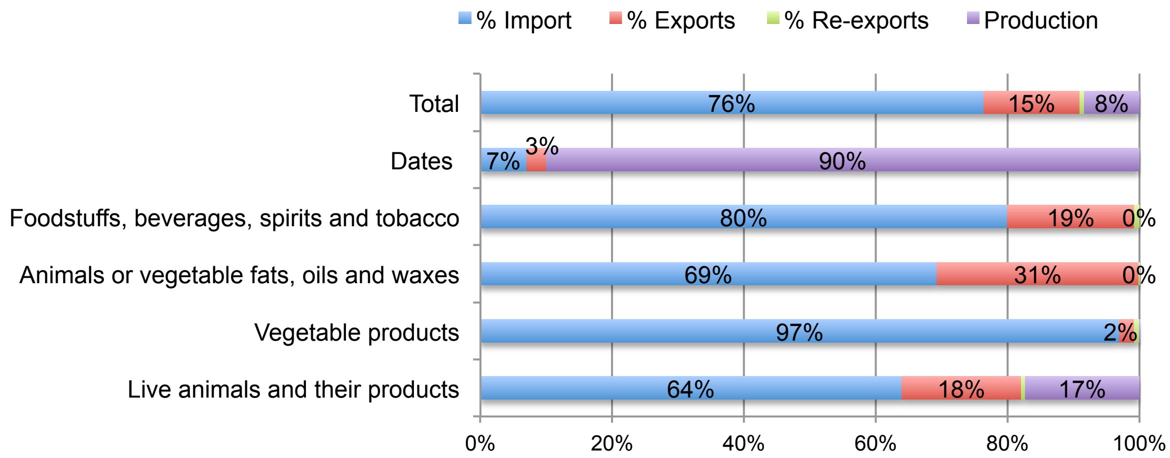

Figure 4.19 Percentages of imports, exports, re-exports and production values in ADE (SCAD, 2016).

ADE's latest food balance sheet available is for 2014, obtained from SCAD's (2015) report, where missing information for some food items was obtained from the UAE 2013 food balance sheet (FAOSTAT, 2013). This data has been aggregated for different food groups to present food supply calories (kcal/capita/day) and quantity (kg/capita/year), as shown in Table 4.10.

Table 4.10 ADE 2014 food balance sheet (FAOSTAT, 2013; SCAD, 2014).

Food Group	Kcal/Capita/Day	%	Kg/Capita/Year	%
Cereals	1,871	55	245.2	38
Meat and seafood	372.4	11	73.8	11
Dairy and eggs	330.8	10	74.3	12
Oil	238.6	7	10.4	2
Sugar and stimulants	228.1	7	24.8	4
Fruits	95.4	3	64.1	10
Starchy roots and pulses	88	3	20.6	3
Vegetables	74.4	2	90.2	14
Dates*	32	0.90	7.49	1
Non-alcoholic beverages	29.7	0.90	26.8	4
Spices	27.8	0.80	2.8	0.40
Nuts	14.8	0	2	0.30
Total	3,403	100	642	100

** Information for dates obtained from FOSTAT 2013 UAE food balance sheet (FAOSTAT, 2013)*

Table 4.10 demonstrates that the highest calorie (55%) intake per person in ADE comes from cereals, followed by meat and seafood with a much lower percentage (11%). The highest quantity (kg/capita/year) is also cereals (38%), followed by vegetables (14%). Dates, however, are among the lowest calorie and quantity intakes, 1% and 0.9%, respectively.

Based on the food supply balance sheet presented in Table 4.10, the total food supply required in tonnes and kcal for ADE for 2016 is calculated compared to domestic production's (obtained from SCAD, 2017b) contribution for the same year for various food groups (Figure 4.20).

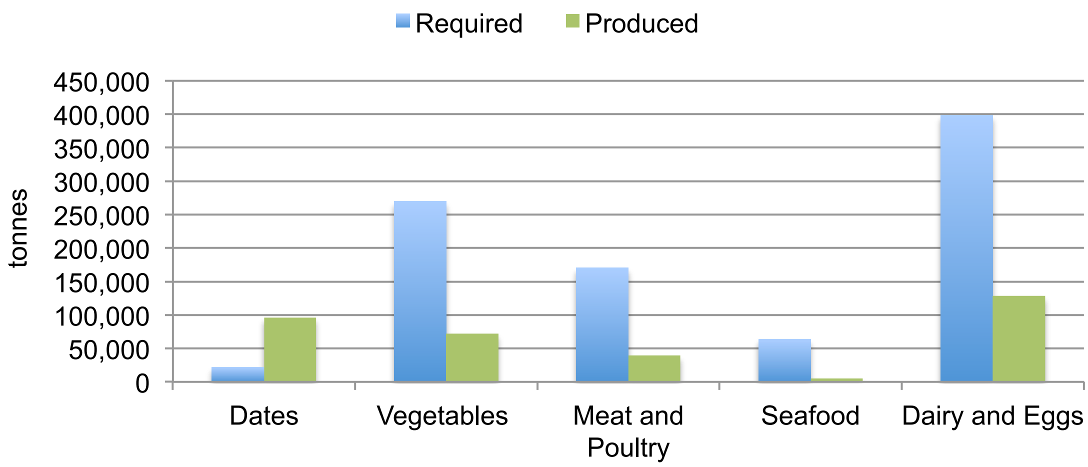

Figure 4.20 Food supply required versus produced in 2016

The analysis of these data, as presented in Figure 4.20, elucidates the difference between required and domestic production in ADE, which shows that all food groups are far from self-sufficiency except the date palm, which is way higher than is required. The gap in meeting the required demand is the biggest in vegetables, followed by dairy and eggs, then meat and poultry, and finally seafood.

Furthermore, the detailed breakdown of supply of the main vegetables and dates (kcal/capita/day and kg/capita/year) was also obtained from both ADE's 2014 food balance sheet and UAE's 2013 food balance sheet from the FAOSTAT database (2013). This information was used to calculate the required food in quantity and calories (multiplying these units by the ADE population) for each food item for 2016 for ADE as well as UAE (Table 4.11). The UAE's latest domestic food production (FAOSTAT, 2016) and ADE production (SCAD, 2017b) for the same year are used to compare the required food and self-sufficiency percentages for vegetables and dates. This shows that the vegetable group in total is meeting only 27% and 24% for ADE and UAE, respectively. In ADE, there is a higher self-sufficiency percentage in some vegetables, such as cabbage (170%), cucumber (91%), pepper (47%), eggplant (42%) and tomato (35%).

Table 4.11 Domestic crops, quantities produced and self-sufficiency ratios for ADE and UAE.

Crop	Food Supply Quantity (kg/capita/y)[a]	Food Supply Quantity (kcal/capita/ day)[b]	UAE Production 2016 (FAOSTAT, 2016)	ADE Production (SCAD, 2017b)	2016 UAE Required (tonne)	% of UAE Self-sufficiency	ADE Required (tonne) 2016	% of ADE Self-sufficiency
Date[c]	7.49	32	671,891	96,037	69,432	968	21,781	441
Vegetables								
Cabbage	1.9	0.8	13,269	9,378	17,613	75	5,525	170
Corn	1.14	8	3,420	3,932	10,568	32	3,315	119
Cucumber	8.9	4.1	27,324	23,641	82,503	33	25,881	91
Pepper	3.3	1.5	3,983	4,480	30,591	13	9,596	47
Eggplant	2.9	2.3	16,767	3,575	26,883	62	8,433	42
Tomato	18.3	9	47,523	18,566	169,641	28	53,216	35
Marrow	3.6	3	18,020	2,034	33,372	54	10,469	19
Sweet melon	1.2	0.9	n.d.	503	11,124	n.d.	3,490	14
Cauliflower	1.5	0.6	5,881	466	13,905	42	4,362	11
Bean	1.2	2.1	1,598	288	11,124	14	3,490	8
Onion	16.2	18.6	25,752	3,146	150,174	17	47,110	7
Watermelon	8.4	3	2,870	1,541	77,868	4	24,427	6
Carrot	4	3.9	39,138	557	37,080	106	11,632	5
Okra	1.2	1	2,007	20.4	11,124	18	3,490	1
Others	16.46	15.6	n.d.	n.d.	176,130	n.d.	55,252	n.d.
Total	90.2	74.4	207,552	72,127	859,700	24	269,688	27

** a and b Food supply quantity (kg/capita/year) and calories (kcal/capita/day) obtained from SCAD Food Balance Sheet (SCAD,2014); c Date production data and supply obtained from 2013 FAOSTAT database (FAOSTAT, 2013; SCAD, 2014).*

Date palm production is significantly higher than required, even if the percentage of exports is considered. This makes domestic date supply more than three and seven times those required for ADE and UAE, respectively.

The ADE information presented in Table 4.11 is used to calculate the projection of food required in Chapter 7 to help run different scenarios and assess each one in terms of quantity, self-sufficiency and total water demand.

4.7 Chapter Summary

A fast-growing population and urbanization that have led to an increase in water demand while facing negligible surface water and finite groundwater combine to create the biggest challenge ADE is currently facing. The municipal and commercial water demand is met through seawater desalination, two-thirds of which is used for irrigation in households, leaving only one-third collected for wastewater treatment, half of which is also discharged to the sea. Agricultural irrigation, including forestry, amenities and livestock, relies almost exclusively on groundwater. In the last five decades, heavy governmental subsidies have encouraged agricultural development. This has influenced the quantity and quality of groundwater. Currently, the government (ADFCA) provides water supply to farms (25% of the total) that have no access or have high-salinity groundwater. The main water resources for ADFCA supply consist of seawater desalination (78%), groundwater (17%) and treated wastewater (5%). Small-scale brackish (groundwater) desalination is also installed in some farms (mainly commercial farms); however, brine discharge methods – which are not regulated – may increase groundwater deterioration.

In an arid country such as the UAE that is characterised by its harsh and high-temperature climate, significant irrigation is required to counter high evapotranspiration. This is exacerbated by low-nutrient soil and low water holding capacity. Farmers' inefficient water use as well as their misuse of groundwater has been increasingly highlighted. The government has currently realized that the impact of the current water use pattern is threatening the future availability of groundwater in the country. The subsidy reform for Rhodes grass, in 2010, which aimed to phase it out, is an example of the government's practical measures to save groundwater.

In general, the true relation between farm produce and food security or self-sufficiency objectives can be questioned, which is clearly shown in the cultivation of palm trees and vegetables. Palm tree cultivation shows that about 30–50% of cultivated palm trees are not fruit bearing, the average bearing capacity is much lower than the recommended capacity, total production is more than four times what is required and the percentage of exports is very small considering the high quantity produced. The production of vegetables, mostly cultivated during the winter season (6–7 months per year), only meets a small fraction (27%) of the required quantity. In total, more than 90% of vegetables are imported.

ADE's great challenge is to create a balance between increasing agricultural production to support food security policy and at the same time reducing water use and non-renewable groundwater aquifers. However, no studies on past and current farming practices provide any measurements of groundwater abstraction rate and water use per crop.

In this research, a farmer perception survey was conducted to fill some of the gaps demonstrated in this chapter, which mainly focus on current farming practices and water use across farms and their impacts on water resources in ADE. The following chapter provides details on the survey data collection, data analysis and discussion.

Chapter 5. Assessing the Current Farming Practices in ADE

5.1 Introduction

As indicated in Section 4.5, the establishment of the agricultural sector in ADE has been inconsistent with policies that relate directly or indirectly to agriculture. This has created misunderstanding behind developing such policies and their intended objectives among farm owners and farmers. This is reflected in the current farming practices and farmers' inability to devise solid and long-term plans needed for their farm improvements.

The agricultural sector relies on 71% of the total groundwater supply and 52% of the total water resources (Section 4.3). This makes farmers the main users of irrigation water, especially groundwater. It is necessary to understand current farming practices, and farmers' awareness of the government's water and agriculture strategies and policies, in order to identify suitable policies to optimize and control groundwater abstraction. The survey was undertaken to explore these areas and enable the development of empirical data on cultivated crops, crop yield, value and water consumption across ADE's three regions (AD, AA and WR). It also helps to identify the key variables that influence farmers' perceptions, their knowledge and willingness to participate in adhering to any future sustainable governmental strategy.

This chapter focuses on data analysis from the survey, covering descriptive data analysis, water resources, farm production, marketing and crop selection, farmers' perceptions and awareness of the current associated policies and subsidies.

5.2 Descriptive Data Analysis

In this section, demographic analysis data on the sampled farms such as location, farm size, ownership type, farm owner age, farm owner gender and farm management type are displayed. The farms' purpose, their general practices in fertilizers and irrigation methods used are also explained. **Appendix D** provides descriptive data on the farms across the three regions mentioned previously.

5.2.1 Demographic Information

As mentioned in Section 3.3.2.6, 42%, 37% and 19% of the sample were from the 2–2.9, 3–3.9 and 4–4.9 ha size categories, respectively. The same distribution pattern almost imitates the ADE farm population and farm size distribution shown in Figure 5.1, which indicates that the sample does represent the actual farm population.

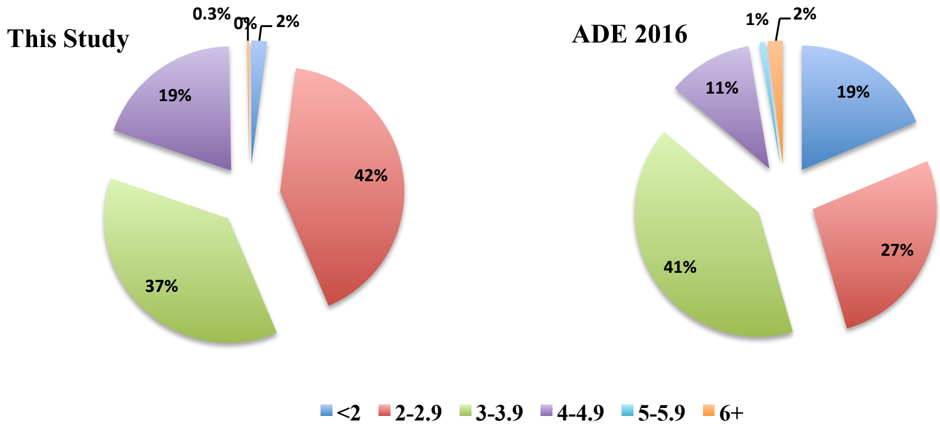

Figure 5.1 Percentage of farms sampled and ADE farm distribution in 2016 (SCAD, 2017b) across various farm size categories (ha).

The farm ownership types are 90% single ownership, 8.1% inheritors and 2.3% joint ownership by husband and wife. About 85% of the single owners are male and only 16% are female. The owners are between 30 and 70 years old. The majority (85%) of them are in their 50s and 60s. Only 14.9% of farm owners manage their farms themselves, while the majority of farms (82.5%) are managed by delegating farm management responsibilities to representatives (Figure 5.2). The remaining 2.6% of farms are leased and managed by tenants.

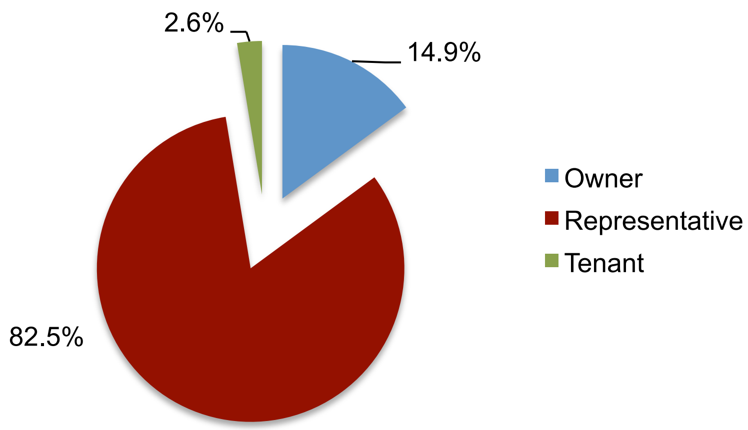

Figure 5.2 Distribution of farm management types.

5.2.2 Farming Intent

To understand the main purpose of running the farms, we asked the participants to select which of the two options below applies to them:

- Commercial: indicates that the farmer is utilizing most of the land and facilities on the farm to sell farm produce and generate profit. Usually they have more labourers and equipment.
- Personal: implies that the farmer sets up his/her farm for mainly family use, where most of the farmland and facilities are used for this purpose.

For the latter category, owning a farm gives the family a prestigious status rather than a source of income. These farm owners usually obtain their main source of income from different sources, such as jobs in the government or private sector. Therefore, the majority of these farms are used for the family's leisure during weekends and vacations. Farmhouses, gardens and swimming pools are deliberately built for family use.

Currently, about 81% of farmers run their farms for personal purposes, while only 19% of farms are for commercial use. When the farmers were asked broadly if their farms generate profit, about 66% answered "yes", a number much higher than the total number of commercial farms. This indicates that even though the primary purpose of the majority of these farms is not purely commercial, they still generate some profit through selling some of their farm produce.

5.2.3 Type of Fertilizer

There are two types of fertilizers used by farmers: organic (animal manure) and inorganic (chemical). The latter is manufactured chemically and is available at the local market. Organic fertilizer can be procured from the local market or as compost that the farmers develop using manure from animals raised on their farm or on nearby farms. ADFCA has increased its attention to encouraging farmers to use more organic fertilizers with more control over the use of chemical fertilizers, as emphasized in the guidelines and code of practice that it has developed (ADFCA, 2011b). Not surprisingly, most of the farms use organic fertilizer (68%) or both organic and inorganic fertilizer (29.7%), whereas only a small percentage (2%) use inorganic fertilizer only.

5.2.4 Irrigation Systems

The irrigation system used on the farms is mostly drip irrigation (95%), with only a small percentage using sprinkler (1% of the total sample) and flood irrigation (4% of the total sample). The sprinkler system is used in 3 out of 7 farms that cultivate turf grass, and the flood system is used in 9 out of 19 farms cultivating alfalfa and 6 out of 337 farms cultivating palm trees.

This segment demonstrates that the majority of farms are not more than 5 ha in size and that most of the AD farms fall within the small size, while AA and WR are within the large farm size categories. These farms are mostly established for family leisure and vacations, but not as the main source of income, which is in line with what was stated in other literature (MOEW, 2010; McDonnell and Fragaszy, 2016). The age of farm owners may indicate a legacy of interest in farming among the older generation rather than the younger one, between the ages of 20 and 39. It also may indicate that the younger generation has less opportunity to obtain free agricultural plots. Furthermore, the current farm management type that shows less involvement of the farm owner could influence further development and better implementation of any new policies. This also could prevent better communication with Abu Dhabi Farmer Service Centre (ADFSC). ADFCA and ADFSC have promoted the utilization of organic fertilizers and drip irrigation methods, which is clearly shown on the majority of farms.

5.3 Water Resources

As noted in Section 4.5.4, farm water resources can be farm wells (privately owned wells, operated and maintained by farmers), private brackish groundwater desalination systems and the ADFCA collective irrigation network supply. Details of the sampled farm water resource supplies are explained in the following subsections.

5.3.1 Farm Wells

The total number of farms with private wells represents about 76% of the total farms sampled in AA and WR, whereas it is only 28% of the farms in the AD region. The total number of wells is 519, of which 57 are in AD, 302 in AA and 160 in WR (**Appendix E** shows the detailed information on farm wells in these three regions). On average each farm has between one and three wells. More than half of farms have two wells, almost a quarter (22%) have one or three wells in just about equal percentages (11% and 10%) and the remaining quarter (24%) have no wells in the total farm sample (Figure 5.3).

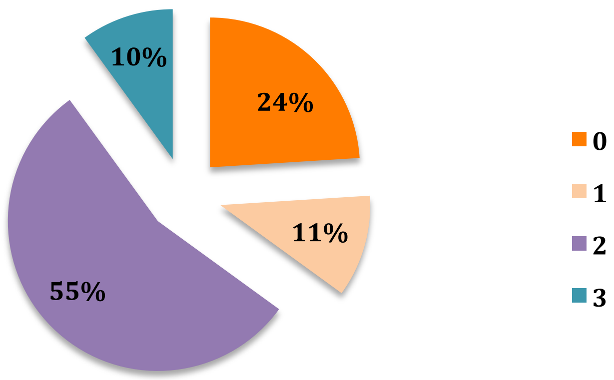

Figure 5.3 Wells owned by farms, percentage of each number.

Figures 5.4–5.7 illustrate the variation in well depth, working hours per day, pump capacity and salinity range across the three different regions. Figure 5.4 shows that AD has the lowest number of wells with a normal depth of 126 m, ranging from 10 to 200 m, and the majority lie within the 101–150 and 151–200 m depth ranges, for 27 and 21 wells, respectively. The average well depth in AA is 205, where 42, 39, 78, 45, 23, 63 and 12 wells lie within the 51–100, 101–50, 151–200, 201–250, 251-300 and 301–400 m depth ranges, respectively. In WR, the average well depth is 76 m, with the majority lying within the 10–50 and 51–100 m depth ranges (28 and 130 wells, respectively).

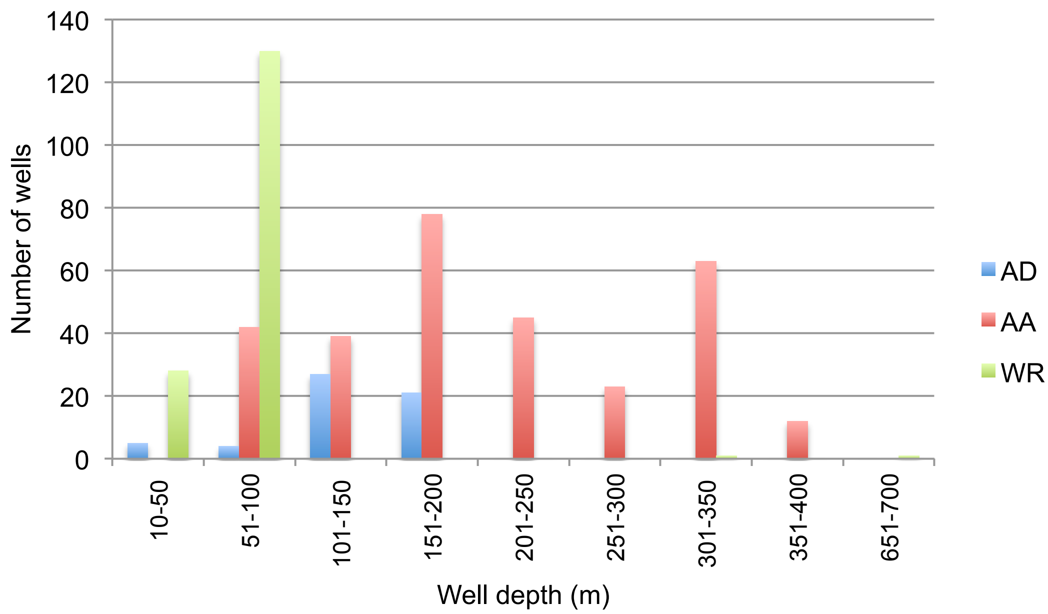

Figure 5.4 Distribution of well depth ranges in ADE regions.

Wells on these farms work from 2 to 24 hours per day. The working hours are categorized as shown in Figure 5.5, in order to help understand the extent of the use of wells in the three different regions. These categories are 2–5, 6–10, 11–15 and 16–24 working hours per day. AD farms works their wells from 2 to 15 hours, with an average of 8 hours per day. AA and WR farms operate their wells from 3 to 24 hours and from 6 to 15 hours respectively, with an average of 10 hours per day.

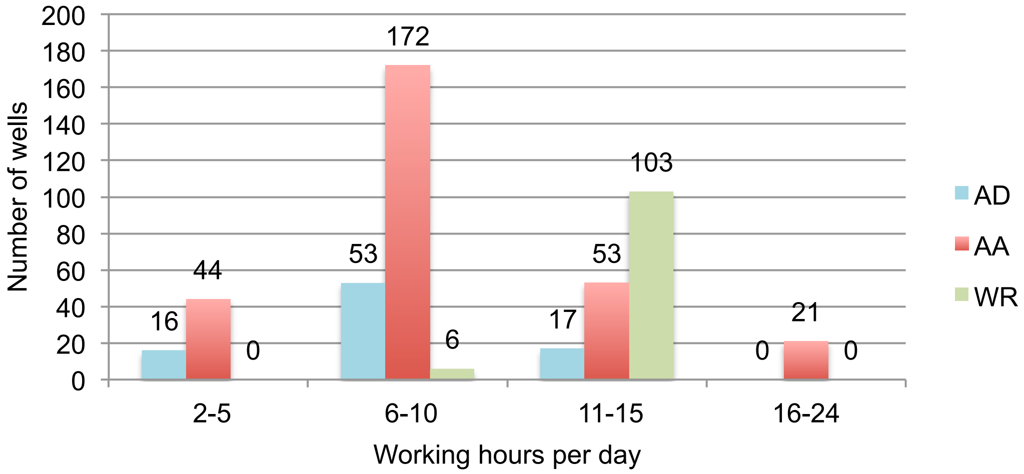

Figure 5.5 Well working hours per day for farms across ADE regions.

Figure 5.6 demonstrates that the pumping capacity in AD ranges from 1.5 to 10 hp (average of 9 hp), while in AA it ranges from 8 to 25 hp (average of 16 hp), and in WR it ranges from 7 to 15 hp (average of 9 hp).

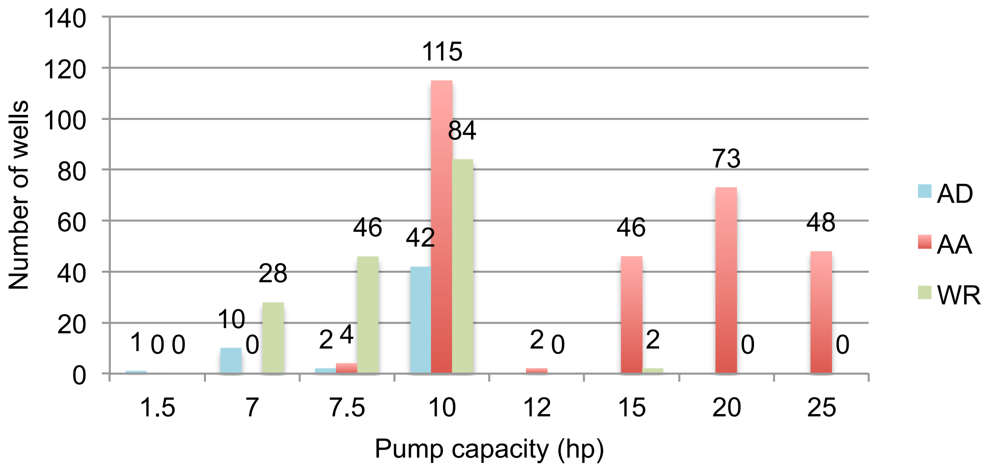

Figure 5.6 Distribution of pump capacity ranges.

The salinity of the groundwater abstracted from wells on the farms as shown in Figure 5.7 ranges from 2,000 to 27,000 ppm. It ranges from 5,000 to 27,000 ppm in AD (N=49, missing

= 8, mean = 12,714 and SD = 4,953), from 1,100 to 25,000 ppm in AA (N = 291, missing = 11, mean = 7,805 and SD = 4,830), and from 3,000 to 12,000 ppm in WR (N = 160, missing = 0, mean = 6,688 and SD = 2,927).

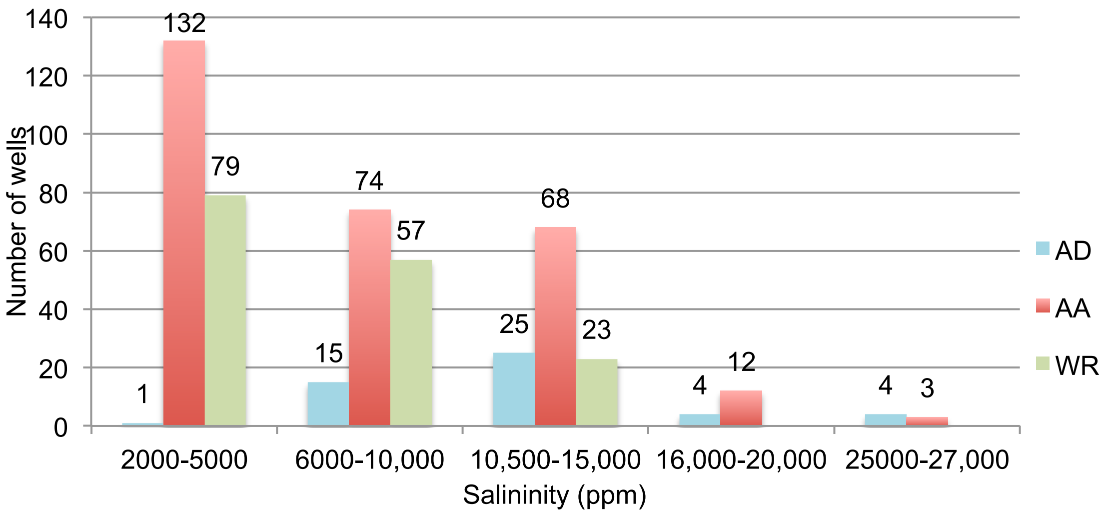

Figure 5.7 Distribution of well salinity in ADE regions.

5.3.2 Collective Irrigation Network

The survey showed that 45% of all farms received supplies from the collective irrigation stations, of which 97.4% were in AD and 29.5% in AA. However, not all the surveyed farms in WR were connected to this network. This may be due to the lack of sufficient ADFCA water supply capacity in this region, where there are only 3 stations (compared to 14 in AD and 12 in AA) with 2% of the total network capacity. Table 5.1 shows the number and percentage of farms with and without a network connection.

Table 5.1 Number and percentage of farms with and without a collective irrigation connection.

Region	ADFCA Collective Irrigation Connection				
	Yes		No		Total
	Count	%	Count	%	
AD	112	97.40	3	2.60	115
AA	44	29.50	105	70.50	149
WR	0	0.00	80	100.00	80
Total	156	45.30	188	54.70	344

The collective irrigation connection for the farms is supplied 2–6 times per week over 0.5–9 hours, through pipe connections of either 5.1 or 7.6 cm (2 or 3 in). The salinity varies from 500 ppm to 7,000 ppm, which indicates that the source of water is either desalinated, groundwater or a mixture of both. This confirms the data collected from ADFCA shown in

Section 4.5.4. Future agricultural development could lead to an increase in water demand in these regions, which will put pressure on ADFCA to supply more water through its collective irrigation stations (particularly in AD) and increase groundwater pumping in AA and WR.

5.3.3 Brackish Groundwater Desalination

The total number of farms that have desalination plants is 37, 8 of which are in AD, 22 in AA and 7 in WR. The majority of these farms (more than 50%) were established for commercial use. The production capacity of these plants ranges from 45.46 m^3/day (10,000 imperial gallons) to 272.76 m^3/day (60,000 imperial gallons), operating from 10 to 20 hours per day. Some of these farms (13 out of 37), representing 7 farms in AD and 6 in AA, also receive a collective irrigation water supply.

The brine disposal methods used by farms that own desalination plants are summarized in Table 5.2. This shows that the majority of farms discharge their brine into old wells, and only a small percentage either utilize it for fish farming and for irrigating forest trees or discard it through evaporation ponds. However, 32% of the farmers did not indicate any specific method by electing to choose the “Others” option. Although the percentage is very low (8%), it is quite encouraging to find that some farmers have started to use the rejected brine in a productive manner for fish farming and forest irrigation in the middle of the desert.

Table 5.2 Brine disposal methods used on the sample farms.

Brine Disposal Method	Number of Farms	Percentage
Injection into an old well	20	54
Fish farming and irrigation of forest trees	3	8
Evaporation pond	2	5
Others (8) and no answer (4)	12	32
Total	37	100

As demonstrated in this section, the main water resource for ADE farms is groundwater. The majority own from 1 to 3 wells operating long hours each day. The depth of wells varies from 10 to 400 m, and most of the deeper wells occur in AA. This confirms the recent increase in the depth of wells in AA stated by EAD (2017). The groundwater salinity at these farms varies from 2,000 to 27,000 ppm, and most of the wells in AA and WR have the lowest salinity (2,000–10,000 ppm). ADFCA collective irrigation is also considered as an important water resource for some of the farms, especially in AD where there is little or no access to groundwater.

Although the percentage is small for brackish groundwater desalination, it is expected that more farmers would consider it as groundwater deteriorates, as stated by the ADE government (Government of Abu Dhabi, 2013). This seems to have been confirmed by the survey, as 93% of respondents stated that they would prefer to switch to desalination when asked about their alternatives should groundwater become unsuitable for agricultural production. However, the current brine discharge methods (such as discharge to the aquifer or evaporation ponds) with no regulatory framework could lead to groundwater and soil contamination (McDonnell and Fragaszy, 2016) and government action.

The aquaculture farming method, on the other hand, may provide a suitable and sustainable solution. It was recently launched and promoted by the International Centre of Bio-saline Agriculture (ICBA), working in conjunction with Ministry of Climate Change and Environment (MOCCAE). They have worked together to study the feasibility of using brine from inland and coastal desalination plants to develop modular farms for fish farming and growing of salt-tolerant crops such as halophytes. Their studies show that there is potential for both types of production in the UAE and certainly in Abu Dhabi (ICBA, 2016).

5.4 Farm Production

Because one of the key research objectives is to evaluate farm productivity and water use efficiency for different crops produced by farmers, it was important to learn the cropping patterns, yields, produce value and water use. Therefore, the farmers were asked to provide comprehensive information on their cultivated crops relating to the extent of cultivated area, quantity produced (crop yield) per unit of area, number of growing cycles, pump capacity, duration of irrigation per day, amount of water consumption per day, type of farming and type of irrigation system (**Appendix F**).

Most of this information was successfully obtained to the farmer's best knowledge, except for crop value and water consumption. To fill this gap, crop value (US $/tonne) was obtained from the Abu Dhabi Statistic Yearbook (SCAD, 2017b) and water consumption was calculated using the theoretical flow rate equation, farm pump capacity, duration of irrigation and irrigation system used (Section 5.4.4).

5.4.1 Cultivated Crops and Land Use

As expected, the analysis of the sampled farms showed that the main cultivated crops are palm trees, fodder crops and seasonal vegetables. Almost all the farms (98%) grow palm trees, with 72% of the total agricultural cultivated area being used, as shown in Figure 5.8 (see also **Appendix F**), followed by vegetables, cultivated by 69% of the farms and representing over 13.9% of the total cultivated area. Each crop type is usually cultivated separately per 0.1 ha or a mix of vegetables created, with almost half the area with leafy herbs and the other half with different vegetables, such as tomato, marrow, cabbage, etc. (Mixed vegetables). The most cultivated vegetables are corn (which is considered a vegetable in this research), cucumber, tomato and mixed vegetables, which are cultivated over an area of 14, 13.9, 11, and 9.2 ha by 14%, 7%, 12% and 12% of the farms, respectively. The remaining vegetables (marrow, eggplant, cabbage, bean, onion, sweet melon and pea) are cultivated by 8% to 0.3% of the farms with an area from 14.1 to 0.5 ha.

The third crop group is fodder crops (13.4%), mainly Rhodes grass, which covers an area of 50.1 ha and is cultivated by 42% of farms. In addition to Rhodes grass, alfalfa and panicum are also cultivated as part of fodder crops, but in a smaller percentage (7% and 2% of total farms. with an area of 13.5 and 2.4 ha, respectively).

Furthermore, it was found that turf grass (Latin name *Cynodon dactylon*) was also cultivated by some farmers (a small percentage), although it is not recorded by any of the ADFCA or SCAD statistical annual reports. Similar to fodder crops, it is cultivated all year (with salt tolerance up to 7,000 ppm; Basheer, 2000), but sold by the square metre to decorate lawns and sports fields. The survey results show that it is cultivated by 2% of the farms covering an area of 3.6 ha.

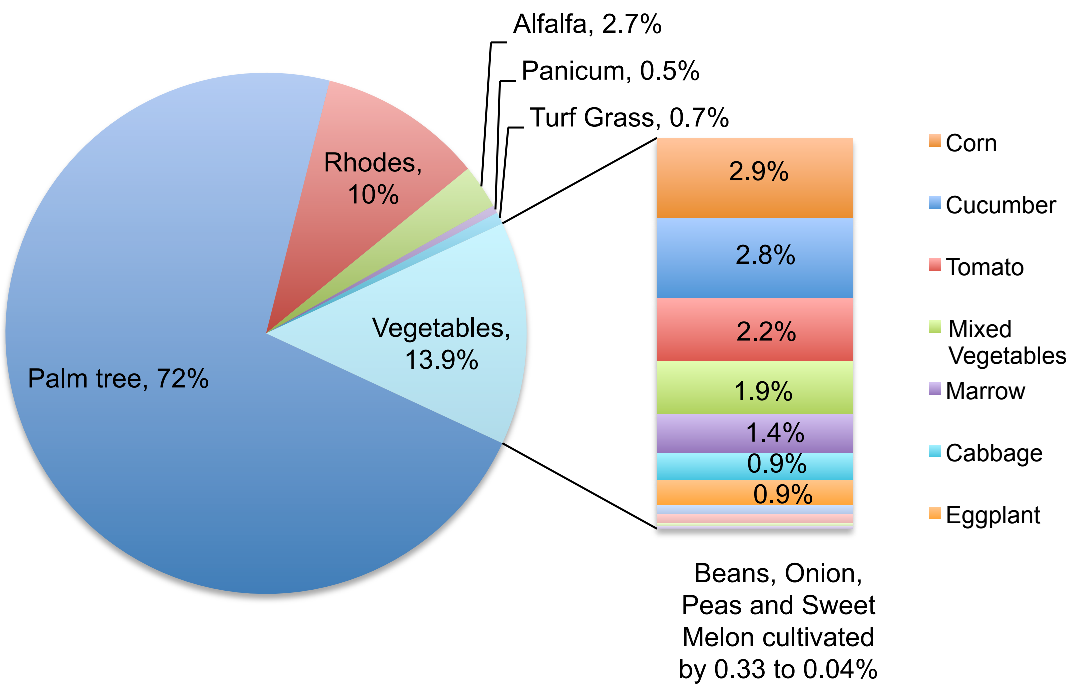

Figure 5.8 Distribution of percentage of crop area cultivated by the sampled farms.

As shown in Figure 5.9, the cultivated area per crop across the three regions shows that AA is the highest in cultivating palm trees, fodder crops (Rhodes grass and alfalfa) and turf grass. In contrast, AD is the highest in cultivating vegetables. In total. AD cultivates 50% of the entire vegetable cultivated area, which is almost double any of the other regions (see distribution of percentage of cultivated area per crop per region in **Appendix G**).

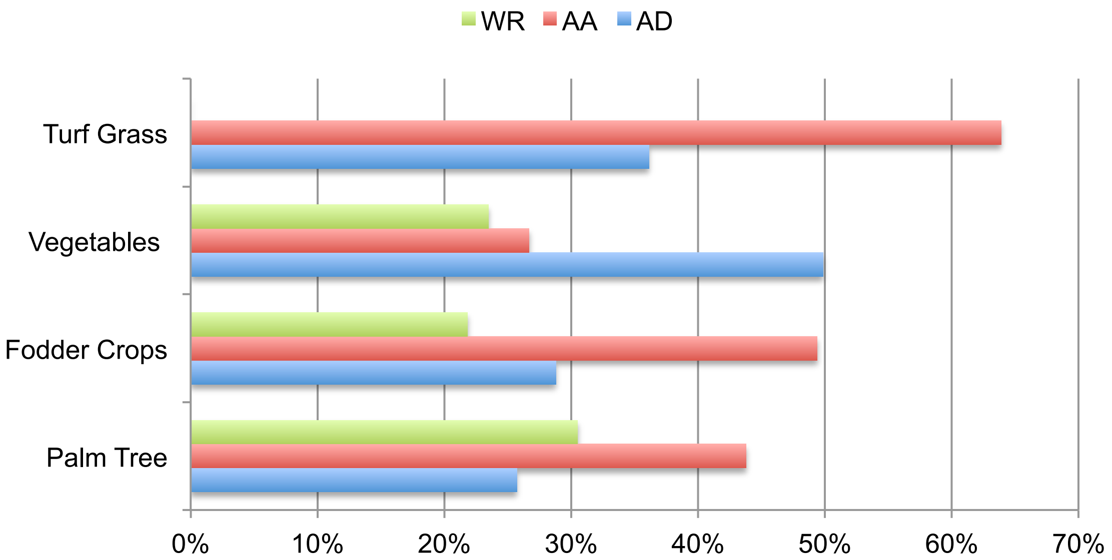

Figure 5.9 Percentage of cultivated area by turf grass, vegetables, fodder crops and palm trees across ADE regions.

The percentage of total land use in agriculture production (see Table 5.3) is 47% of the overall farming area, with all the three regions having almost the same percentage (50% AD, 43% AA and 48% WR). This land use ratio is close to the land use ratio (51%) recorded in the ADE 2016 statistical report (SCAD, 2017b). A detailed breakdown is shown in **Appendix H**.

Table 5.3 Percentage of land use per region.

Region	Total Farm Area	Total Cultivated Area	Land Use Ratio
AD	289.083	145.4	50%
AA	482.106	208.2	43%
WR	287.079	138.3	48%
Total	1058.3	492.16	47%

Furthermore, the distribution of the crop cultivated area percentage of the total cultivated area is comparable to the ADE report, except for the following crops (Figure 5.10):

- Panicum and turf grass, which are not recorded in the ADE report in 2016.
- Seasonal vegetables in the ADE report show a much lower percentage, which can be explained by the difference in timing of the data collection between the study

survey (conducted in the first four months of the season, when farmers usually cultivate more vegetables than in the following three months) and SCAD, which usually conducts this process by the end of the season (obtained from the interview with ADFCA SME, 2016).

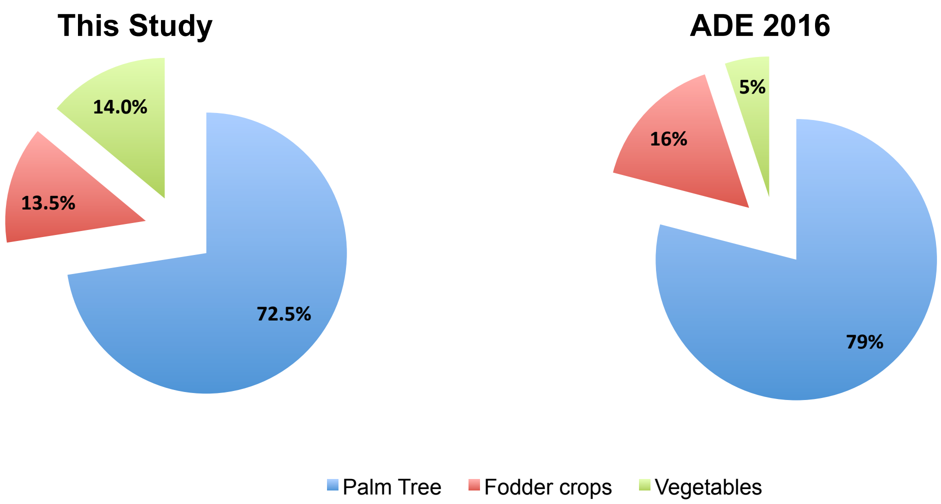

Figure 5.10 Percentage of cultivated area in this study and ADE 2016 report (SCAD, 2017b).

5.4.2 Crop Yield

The total crop yield per ha per harvesting cycle and the total number of cycles were obtained from the surveyed farms to the best of the farmers' knowledge, since they do not keep such records. To assess farm agricultural production and annual crop productivity per ha, the reported crop yield per ha per cycle was multiplied by the number of cycles and total cultivated area. Figure 5.11 shows each crop's average annual production rate per ha, indicating cucumber with the highest rate and palm tree with the lowest rate.

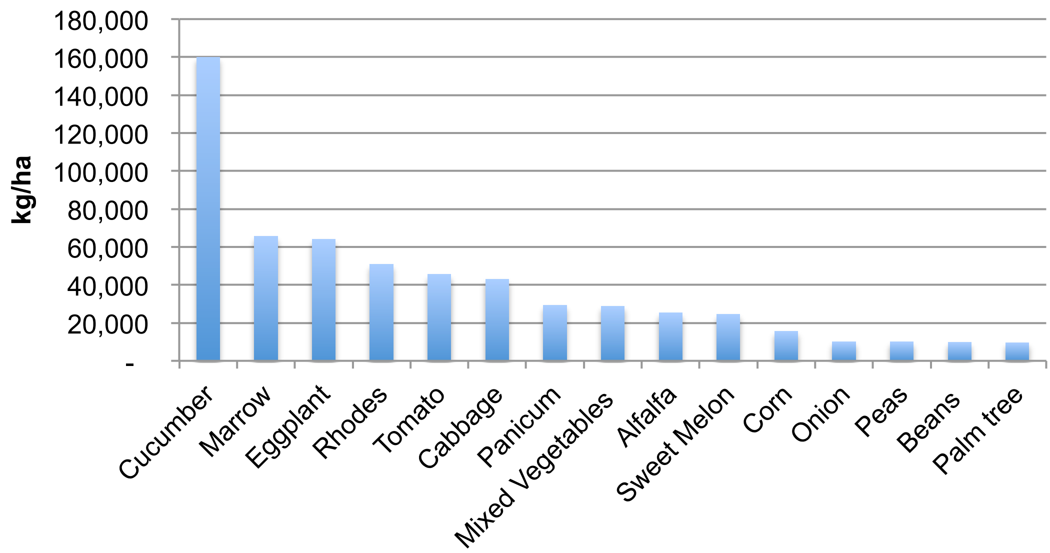

Figure 5.11 Average annual production rate per crop.

The total annual quantity produced per crop is calculated by multiplying the annual production rate (kg/ha) by the total cultivated area. Figure 5.12 shows that 43% of the total agricultural production by weight is vegetables, 30% dates and 27% fodder crops. Cucumbers represent two-thirds of the total vegetables produced and a quarter of total agricultural production.

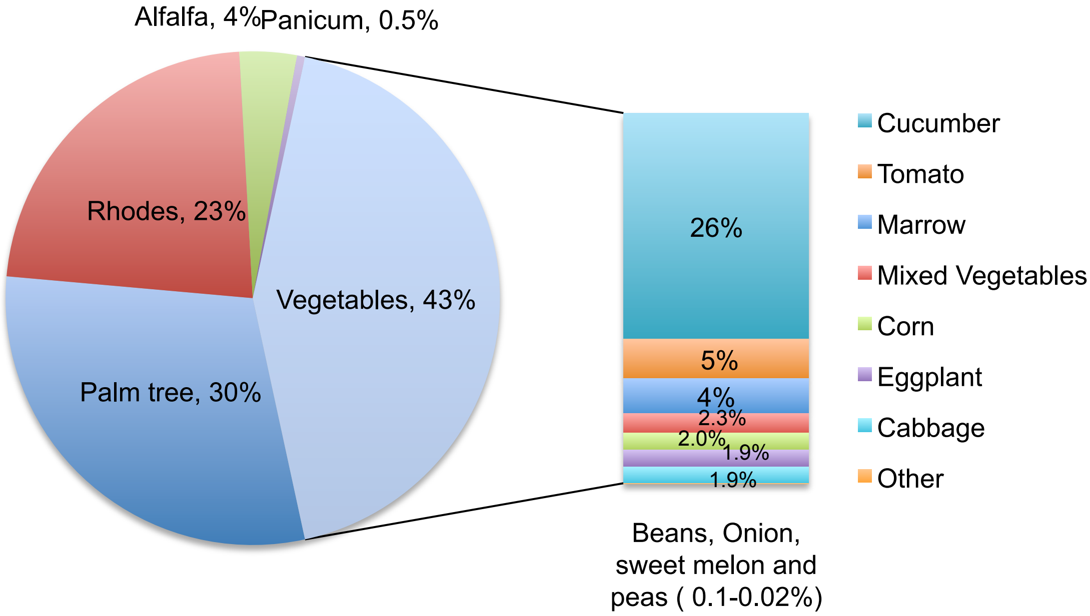

Figure 5.12 Percentage of weight produced per crop.

Figure 5.13 shows the percentages of total production of dates and seasonal vegetables in this study, which resemble the percentages in the ADE 2016 data. However, total fodder crops produced are 27% in this study, which is 6% more than in the ADE report. This could be due to the farmers' reluctance to declare the actual production to ADFCA/SCAD so as not to lose the allocated subsidies (since the Rhodes grass subsidy reform in 2010, it should only be planted on not more than 10% of the total farm area). This is confirmed by the gradual increase in the cultivation of Rhodes grass, as shown in Section 4.5.5.2. This indicates that policy implementation and enforcement should be revisited.

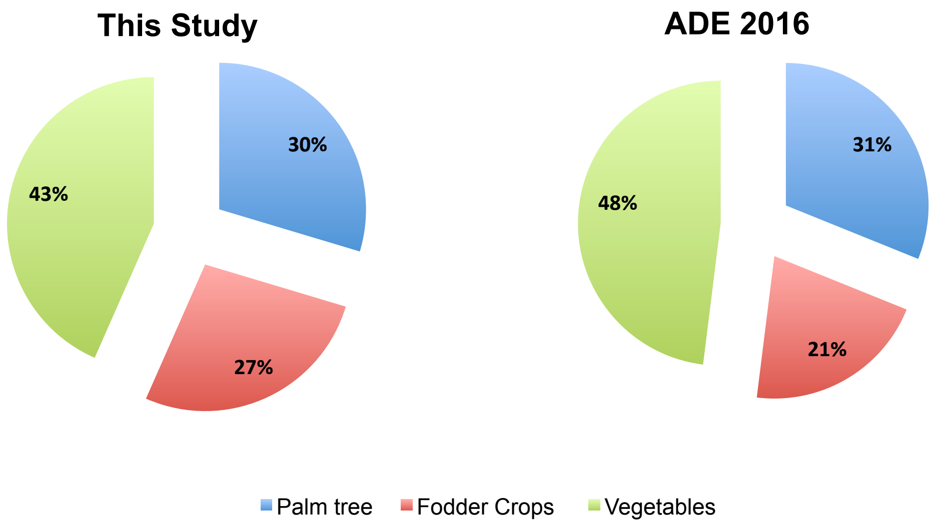

Figure 5.13 Percentage of total produced in this study and ADE 2016 report (SCAD, 2017b).

The average annual crop yield rate (kg/ha) for palm trees obtained in this study is 9,621, which falls within the range of 8,380–11,750 kg/ha measured in Oman (FAO, 2007). The remaining studies show a much lower rate, such as 2,700 as estimated in UAE (FAO, 2007), 3,000 obtained from survey data in Oman (Al Said *et al.*, 2007), 4,272 estimated in Oman and 4,800 recommended in UAE (FAO, 2007). The Rhodes grass yield rate (kg/ha) varies in other studies between 5,000 (Mazahrih *et al.*, 2016) in Oman and 60,000 in Saudi Arabia (Patil *et al.*, 2015). In this study (at 50,971 kg/ha), it is within the highest productivity value. The studies of the alfalfa production rate show large variations, from 3,852 (Al-Gaadi, Madugundu and Tola, 2017) to 35,100 (Patil *et al.*, 2015) in Saudi Arabia. In this study, the rate falls within the highest production rate (25,750 kg/ha).

The production rates (kg/ha) for most of the vegetables in this study are close to or within the ranges obtained from different studies, as follows:

- Corn (15,576 kg/ha) is a little higher than the range that varies from 4,000 in Oman (Al Said *et al.*, 2007) to 11,190 in Saudi Arabia (Patil *et al.*, 2015).

- Tomato (44,390 kg/ha) varies from 8,000 in Oman (Al Said *et al.*, 2007) to 66,500 (Algharibi *et al.*, 2013).
- Cucumber (160,000 kg/ha) also falls between 24,000 in Oman (Al Said *et al.*, 2007) and 150,000 in Saudi Arabia (Alomaran and Luki, 2012).
- Cabbage (43,056 kg/ha) falls between 49,300 in Oman (Al-Said *et al.*, 2012) and 53,256 in Romania (Domuţa *et al.*, 2017).
- Onion (10,125 kg/ha) is within 3,000 and 18,000 in Oman (Al Said *et al.*, 2007).
- Sweet melon (24,667 kg/ha) is close to the 23,800 measured in Oman (Al-Said *et al.*, 2012), but >60% higher than the 14,000 measured in Oman (Al Said, 2007).
- Eggplant (45,238 kg/ha) is a little higher than the range of 12,390–33,700 obtained in Lebanon (Karam *et al.*, 2011) and falls within the range of 40,900–78,700 measured in Turkey (Çolak *et al.*, 2015). However, it is much higher than that recorded in Oman (Al Said *et al.*, 2007) and Saudi Arabia (Hashim *et al.*, 2012), which is 7,000 and 8,335, respectively.

5.4.3 Crop Value

During the survey, it was difficult to obtain crop value per tonne from the farmers because, as mentioned earlier, they were reluctant to share such records as they considered them sensitive and private information. Therefore, the average value in US dollars per tonne for each crop produced was estimated by dividing the total value of crops by the total crop produced as presented in the Abu Dhabi Statistical Yearbook (SCAD, 2017b). However, crops with no such information from the statistical report were obtained from the local market through personal communication, such as turf grass (US $1.62/sqm) and panicum (US $189/tonne).

The analysis shows that the highest crop value comes from palm trees, which represent 52% of the total value, with the remaining 48% shared by the rest of the crops (36.8% seasonal vegetables and 11% fodder crops). More detailed information for cultivated crops is summarized in **Appendix F**, which includes the number and percentage of farms, total cultivated area per crop, average yield per ha, calculated total annual production, average value per tonne and calculated total value.

5.4.4 Crop Water Consumption

The farmers do not usually keep a record of the volume of water used in irrigation. Therefore, it was necessary to find a suitable way to obtain these data. Other relevant detailed information that can be used to calculate water consumption was collected, namely pump capacity, irrigation duration per ha for each cultivated crop and irrigation method used. The water flow rate (imperial gallons/minute) is calculated using the following equation (Fipps, 1995):

$$Water\ flow\ rate\ (igpm) = WHP \times \frac{\mu \times K}{H(ft) \times F}$$

Eq 5.1

where WHP is water horsepower (the power of the irrigation pump in horsepower); μ is pump efficiency = 0.85; K is a constant factor = 3286.8; and H is irrigation head (ft). Different irrigation systems have different irrigation heads (Apex, 2014; Fipps, 1995), as specified below:

- Irrigation head for flood irrigation = 40 ft
- Irrigation head for drip irrigation = 80 ft
- Irrigation head for sprinkler = 105 ft

F is friction loss = 2.26, calculated based on the average of four farms (Table 5.4), using measurements of actual flow rates and inputting the recorded values in Equation 5.1.

Table 5.4 Characteristics of the four farms used to calculate the average irrigation flow rate.

	Farm-1	Farm-2	Farm-3	Farm-4
Location (region)	AD	AD	AA	AA
Farm size (ha)	1.5	2.2	2.2	2.2
Main purpose	Personal	Mixed	Mixed	Personal
Pump capacity (hp)	10	15	10	10
Irrigation tank parameters				
Width (m)	3.8	7.4	6.5	8
Length (m)	8.7	6	8	6
Height (m)	2.4	2	2	1.9
Irrigated crop	Palm tree	Palm tree	Palm tree	Palm tree
Irrigated area (ha)	0.2	0.53	0.12	0.1
Irrigation method	Drip	Drip	Drip	Drip

The assumption made is that all surveyed farms are operating their irrigation pump at its highest capacity with the same flow rate all the time. This can be supported by the fact that farmers usually tend to focus on pumping as much water as possible without paying attention to control of the flow rate. This was observed during the implementation of the survey.

Water consumption per day for each cultivated crop (m^3/day) was calculated by multiplying the water flow rate (m^3 converted by using Equation 5.1) by the irrigation duration (min/ha) and the total area cultivated by the crop. The total water consumption for each crop per year was then calculated by multiplying the water consumption per day by the growth duration for each crop (number of cultivated cycles by the duration of each cycle). The growth duration for all vegetables cultivated in open field is almost the same as that indicated by the ADFSC open field vegetable production guidelines (ADFSC, 2013), which start from the middle of August or the beginning of September to April or May. This duration covers the whole plant lifecycle, from seed sowing, transplanting, to flowering and harvesting. Therefore, it is estimated in this study that the growth duration for open field vegetables is 7 months and 3 months per cycle, while for vegetables cultivated in greenhouses it is estimated as 3 or 4 months and 3 months per cycle, depending on the type of the crop. Other crops such as palm trees, fodder crops (such as Rhodes grass, alfalfa and panicum) and turf grass have a whole year's growing duration.

In order to assess the annual water consumption per crop, it is calculated by multiplying water consumption per day by crop growth duration. The details are provided in **Appendix I**. The analysis of the average annual water consumption per hectare (m^3/ha) shows four categories (from high to low), as in Table 5.5. Most of the seasonal vegetables such as onion, sweet melon, mixed vegetables, bean, tomato and cabbage fall within the highest water use range: categories 1 (25,000–30,500) and 2 (20,000–24,000). Water use for the remaining vegetables such as eggplant, marrow and corn ranges from 12,500 to 19,000, whereas cucumber and pea fall in the lowest water use category (8,000–10,500).

Table 5.5 Distribution of crops' average annual water consumption

Category No.	Crop	Average Annual Water Consumption (m^3/ha)	Category Range
1	Mixed vegetables	30,422	25,000–30,500
	Onion	29,970	
	Sweet melon	27,133	
	Bean	26,146	
2	Tomato	23,978	20,000–24,000
	Rhodes grass	23,850	
	Alfalfa	22,774	
	Palm tree	*22,745*	
	Cabbage	20,422	
3	Eggplant	18,377	12,500–19,000
	Marrow	17,720	
	Corn	16,527	
	Turf grass	15,051	
	Panicum	12,096	
4	Cucumber	10,096	8,000–10,500
	Pea*	8,880	

** Peas is cultivated by one surveyed farm.*

Fodder crops such as Rhodes grass, alfalfa and palm trees fall in the second highest category. Panicum (12,096), however, shows the lowest water use within the fodder crops. This may be due to the fact that panicum has much less demand than Rhodes grass and alfalfa, therefore famers pay less attention to it.

In order to evaluate the distribution pattern of water use rate (m^3/ha) per cultivated crop across the surveyed farms, descriptive statistics (mean, median, min, max, SD, Skewness and Kurtosis) and test of data normality (Kolmogrov-Smimrnov and Shapiro-Wilk) were conducted (detail data provided in **Appendix J**). This shows that majority of the data is normally distributed but either skewed to the right or to the left, therefore box plot diagram is developed to visually summarise water use patterns across the farms. Figure 5.14 is a box plot of the minimum, maximum and median of the average water consumption rate (m^3/ha) for each cultivated crop. It shows that the range between minimum and maximum is large for the majority of 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 (representing 50% of the farms) is also large and varies from 3,806 to 12,686 in cucumbers to from 14,800 to 44,399 in mixed vegetables. These variations are higher among some crops more than others, such as palm trees, mixed vegetables, cabbage, tomato, onion and alfalfa.

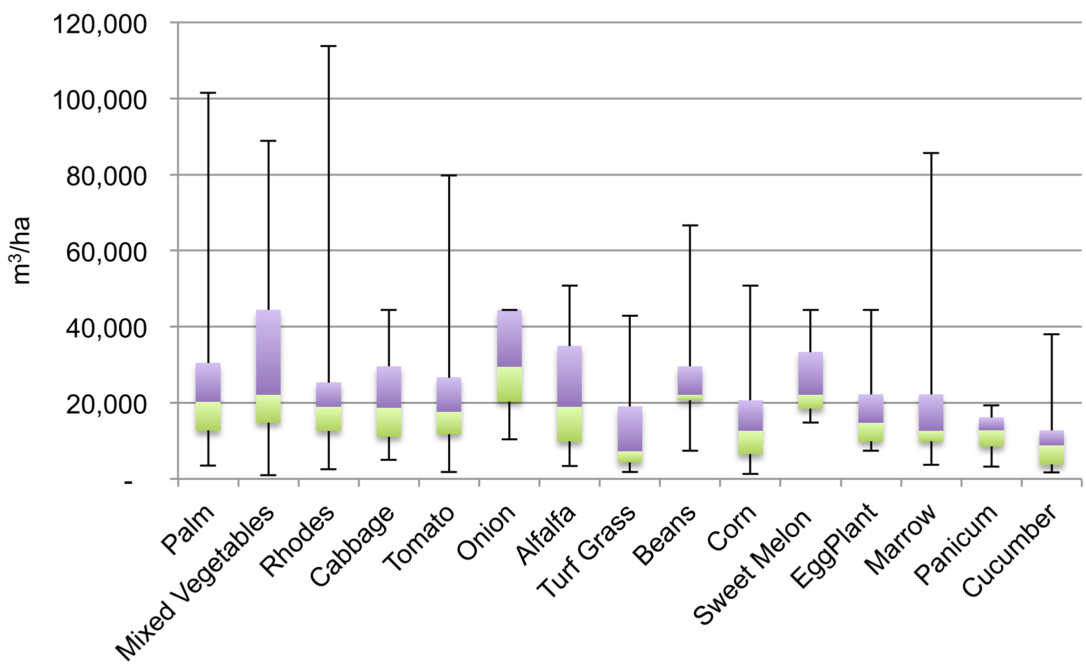

Figure 5.14 Box plot for water consumption m^3/ha/year for each cultivated crop.

Furthermore, the correlation of the annual water consumption with the total value per crop for each farm shown in Figure 5.15, illustrating that for almost all crops increasing water consumption does not lead to increased crop production and consequently production value. This is clearly shown in palm trees and Rhodes grass, with the highest water consumption and the lowest value on some farms (i.e. depicting high water consumption and low value). The only crop that shows high value is cucumber for most of the farms.

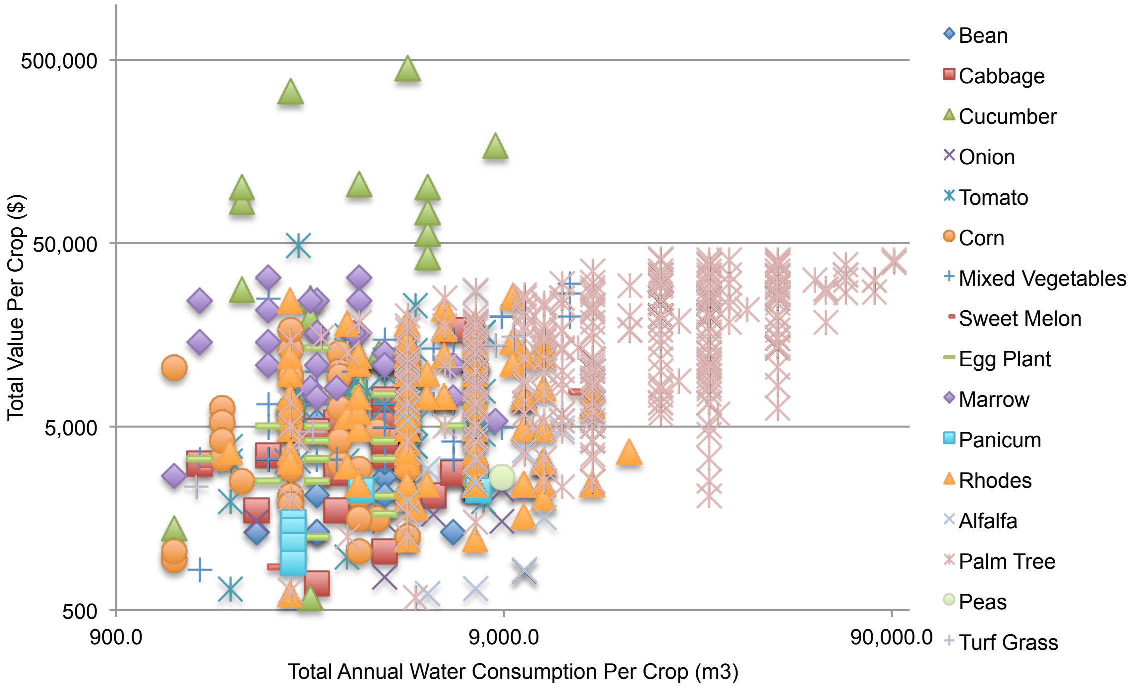

Figure 5.15 Annual total water consumption versus total value per crop per farm.

To summarize, as shown in Figure 5.16, palm trees are the highest cultivated crop, consuming about 80% of total water use but producing about 30% of total production, with 52% of the total value. Vegetables represent the second highest cultivated crops with 9.1% of total water use but producing the highest quantity (43.%), with 37% of total value. Fodder crops have lower percentages in cultivated area, production and value (13.4%, 27% and 11%, respectively), whereas they have a little higher water consumption percentage (11%) compared to vegetables.

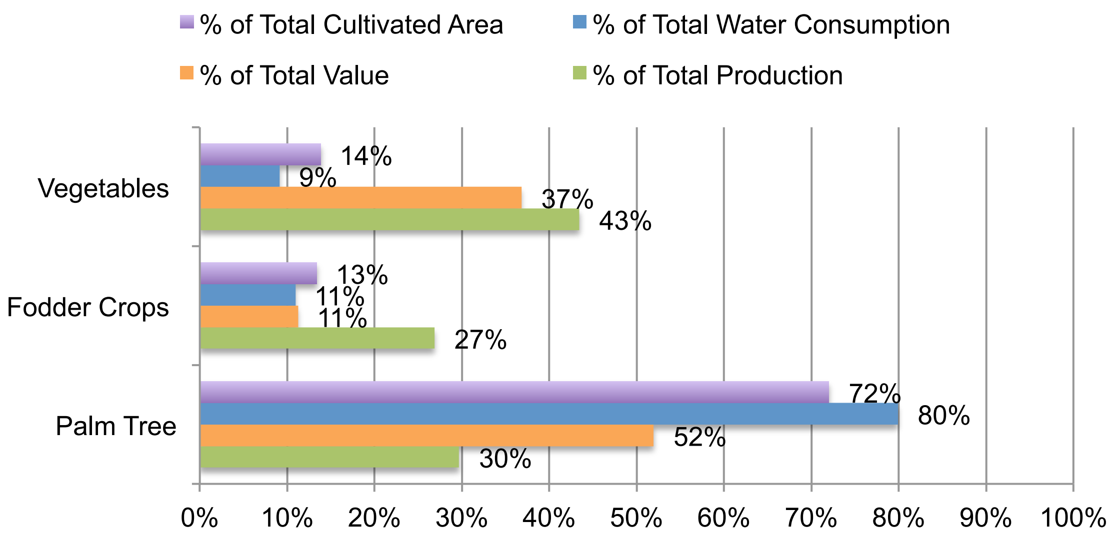

Figure 5.16 Percentage of total water consumption, total production and total value for vegetables, fodder crops and palm trees.

This section shows that the average annual water use rate (m^3/ha) for most crops demonstrates large variations across the farms, which indicates that water use is estimated randomly by farmers. Palm tree average water consumption obtained (22,745 m^3/ha) falls within the rate seen in studies conducted in UAE, Oman (FAO, 2007), Kuwait (Bhat *et al.*, 2012) and Tunisia (Haj-Amor *et al.*, 2018), which range from 15,000 to 29,700 m^3/ha. FAO recommendation is 14,700 m^3/ha for mature trees in UAE, whereas its measurement in Oman shows a range from 9,320 to 16,080 (FAO, 2007). A further lower rate is noted in a real measurement study conducted for a one-year cycle in Dubai by ICBA, which indicated that water consumption might vary between 3,600 and 10,800 m^3/ha between winter and summer (Green *et al.*, 2014). For Rhodes grass, the water consumption rate (m^3/ha) obtained from different studies ranges from a low rate (13,000) estimated in UAE (MOEW, 2010) to a higher one (163,294) measured in Saudi Arabia (Hashim *et al.*, 2012), whereas the rate shown in this study (23,850) is close to what is estimated (20,000) in UAE (Pitman, McDonnell and Dawoud, 2009). Alfalfa water consumption varies between 5,520 (Al-Gaadi, Madugundu and Tola, 2017) and 60,390 (Patil *et al.*, 2015) in Saudi Arabia, whereas in this study (22,774) it falls within a range similar to that for Rhodes grass (detail presented in **Appendix K**).

The vegetable water consumption rate (m^3/ha) obtained in this study shows different positions compared to other studies, as follows:

- For corn (16,527 m^3/ha) it varies between 9,892 (Patil *et al.*, 2015) and 45,260 in Saudi Arabia (Hashim *et al.*, 2012).

- For tomato (23,978 m^3/ha) it is higher than was measured (2,740–8,050) in Oman (Al-Said *et al.*, 2012; Algharibi *et al.*, 2013) .
- For cucumber (10,096 m^3/ha) it is much higher than the 1,090–3,550 in Saudi Arabia (Aly, Al-Omran and Khasha, 2015).
- For cabbage (20,422 m^3/ha) it is higher than 4,375 in Romania (Domuţa *et al.*, 2017) and 14,400 in Oman (Al-Said *et al.*, 2012).
- For sweet melon (24,667 m^3/ha) it is higher than 4,970 in Oman (Al-Said *et al.*, 2012).
- For eggplant (18,377 m^3/ha) it is lower than 58,080 in Saudi Arabia (Hashim *et al.*, 2012).
- For bean (26,146 m^3/ha) it is lower than 30,300 in Saudi Arabia (Hashim *et al.*, 2012).

5.4.5 Water Productivity

As explained in Section 2.5.2, agricultural productivity can be improved by improving water and land productivity. Water's physical (kg/m^3) and economic (\$/m^3) productivity has significantly been used globally in recent studies where it is suggested as a measure/indicator to assess the productive use of water per crop, especially in water-scarce environments (Kijne, Barker and Molden, 2003; Platonov *et al.*, 2008; Al-Said *et al.*, 2012; Ali and Klein, 2014).

The analysis shows that the cultivation of cucumbers (mostly in greenhouses) demonstrates by far the highest performance among all cultivated crops (as reported by the surveyed farms), whereas that for palm trees is one of the lowest. Figure 5.17 shows water productivity per cultivated crop.

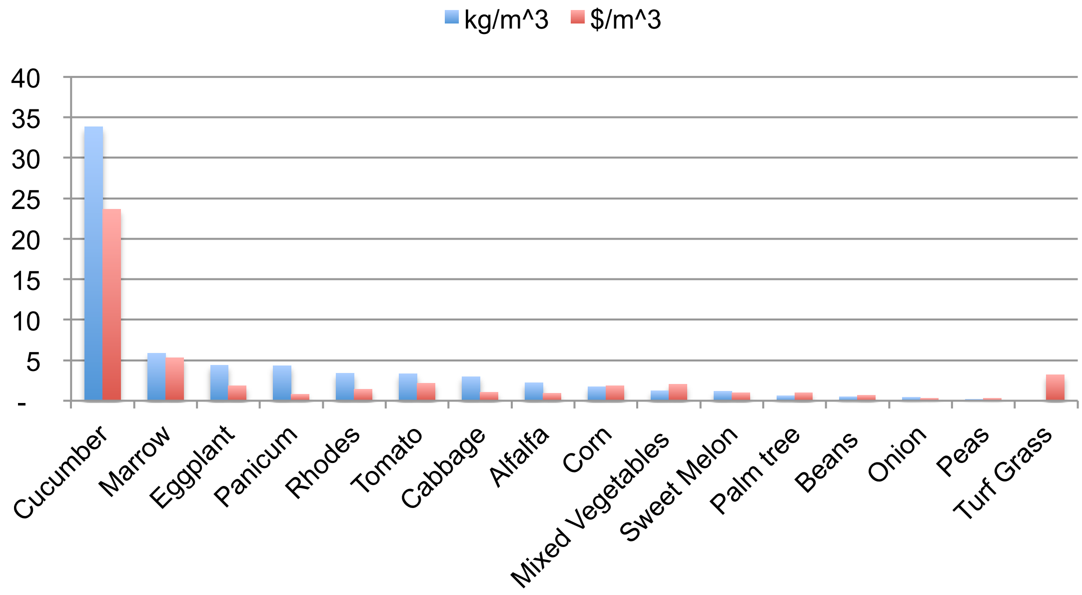

Figure 5.17 Water productivity per cultivated crop.

Comparing water productivity for the same farm produce for the three regions shows that it follows almost the same pattern as shown in Figure 5.18, which suggests high consistency and confidence in the survey results and analysis. 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.

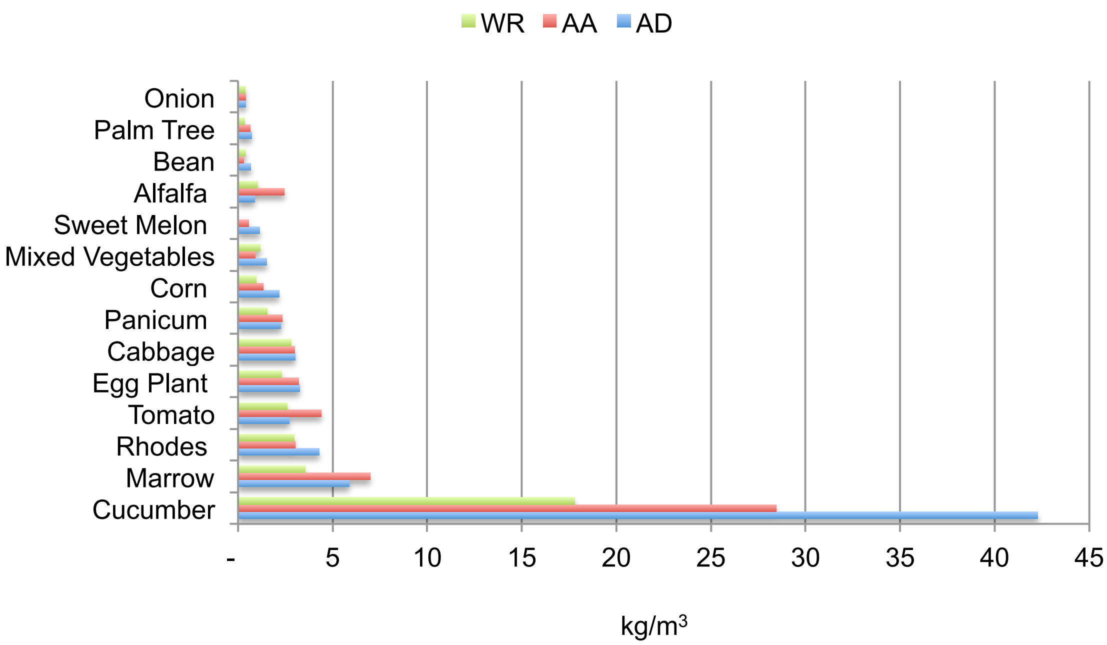

Figure 5.18 Water productivity for different cultivated crops across ADE's three regions.

This section has demonstrated that palm tree water productivity (0.59 kg/m^3) is 50% higher than FAO estimates (0.2–0.26 kg/m^3) for UAE (FAO, 2007), less than FAO estimates (0.71–

0.89 kg/m^3) for Oman (FAO, 2007) and within the range (0.59–1.5 kg/m^3) measured in Oman (Al-Mulla and Al-Gheilani, 2018), whereas its \$/m^3 falls within the range (0.6–1.64) estimated in Oman (Al-Mulla and Al-Gheilani, 2018). The Rhodes grass water productivity (kg/m^3) range is from 0.44 in Saudi Arabia (Patil *et al.*, 2015) to 0.85 measured in Oman (Mazahrih *et al.*, 2016), whereas it is much higher in this study (3.40). Similarly, it is much higher in this study (US \$1/m) than the US \$0.45/m measured in Oman (Al-Said *et al.*, 2012). Alfalfa water productivity (kg/m) varies from 0.38 in Saudi (Patil *et al.*, 2015) to 0.87 in California (Nafchi, 2016), whereas it is much higher in this study (2.2). For panicum, although there are few studies conducted, the results in this study were found comparable to the study conducted in Saudi Arabia by Hashim *et al*. (2012) for water consumption and water productivity (kg/m), but higher in production rate.

For vegetables, the water productivity (kg/m^3 and \$/m^3) of corn, tomato and cucumber in this study is within the range found in other studies, although the values in some of these studies are much higher, as follows:

- For tomato, 3 kg/m^3 is lower than 11.9 in Oman (Al-Said *et al.*, 2012), but falls within the 1.3–3.5 estimated in Oman (Algharibi *et al.*, 2013).
- For cucumber, 33.8 kg/m^3 falls within the range of 14.4–48.3 recorded in ADE (Al Hammadi, 2014), 27.9–64.2 in Saudi Arabia (Aly, Al-Omran and Khasha, 2015) and also 42.25–61.5 in Saudi Arabia (Alomaran and Luki, 2012).
- For eggplant, 3.2 kg/m^3 is higher than the 1.43 in Saudi Arabia (Hashim *et al.*, 2012) and the range of 0.27–0.56 in Lebanon (Karam *et al.*, 2011), but much lower than 12.2–21.9 in Turkey (Çolak *et al.*, 2015).
- For cabbage, 2.98 kg/m^3 is lower than the 7.8 in Oman (Al-Said *et al.*, 2012) and the range of 4.7–11.6 in Romania (Domuţa *et al.*, 2017).
- For bean, 0.51 kg/m^3 is lower than the value found of 1 in Saudi Arabia (Hashim *et al.*, 2012).
- For sweet melon, 1.14 kg/m^3 is lower than the 5.7 in Oman (Al-Said *et al.*, 2012).

5.4.6 Crop Yield Response to Water

Furthermore, comparison of the study results with previous studies and reports was carried out to ascertain the reasonableness of the data collected. The data for the crop yield rate for different crops were plotted against the water consumption rate (water curve function) to give an indication of how each crop yield responds to water. These curves were produced and then compared with curves for the same crop developed in different studies, referred to as R1, R2 and R3, as appropriate (a list of references relevant to each crop and location and data method are provided in **Appendix L**).

The following subsections demonstrate water curve functions as explained above for the main cultivated crops: the palm tree, Rhodes grass, alfalfa, cucumber, corn, eggplant, onion and tomato.

5.4.6.1 Palm Tree

The increase of palm tree yield in response to water in this study is calculated and demonstrated in Figure 5.19. This figure also shows the comparison of palm tree yield response to water in this study and two other studies: R1 (FAO, 2007) and R2 (Al-Qurashi, Ismail and Awad, 2016) conducted in Saudi Arabia. Even though the yield per hectare in this study is lower, it has the same increase rate as R1, which was conducted on 17-year-old trees using different irrigation methods. Nevertheless, R2, conducted on 5-year-old tissue culture derived palms shows a lower yield rate but a higher rate of increase, which may be justified by the young age and the type of species used (Al-Qurashi, Ismail and Awad, 2016).

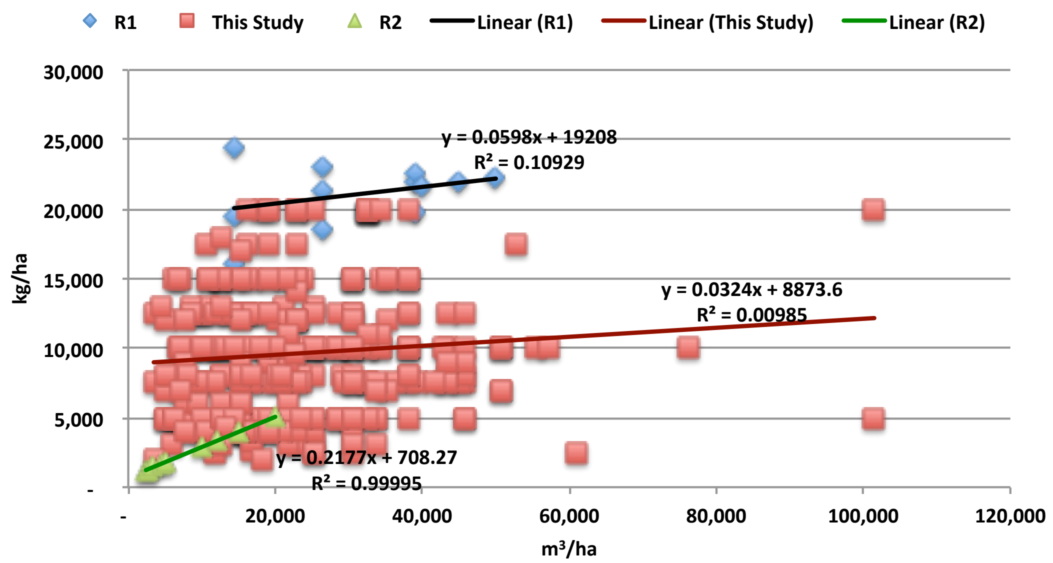

Figure 5.19 Palm tree yield response to water.

5.4.6.2 Rhodes grass

The Rhodes yield response to water shows a similar trend as in R1 (Irrigation Research Lab, 2007), which was conducted in Oman but with a much lower production rate (see Figure 5.20). R2 (Mazahrih et al., 2016), also conducted in Oman, shows a slightly higher trend. This may be due to the drip irrigation system used in ADE, which has higher water application compared to the sprinkler system, as is also noted in other studies, as stated by Mazahrih et al. (2016).

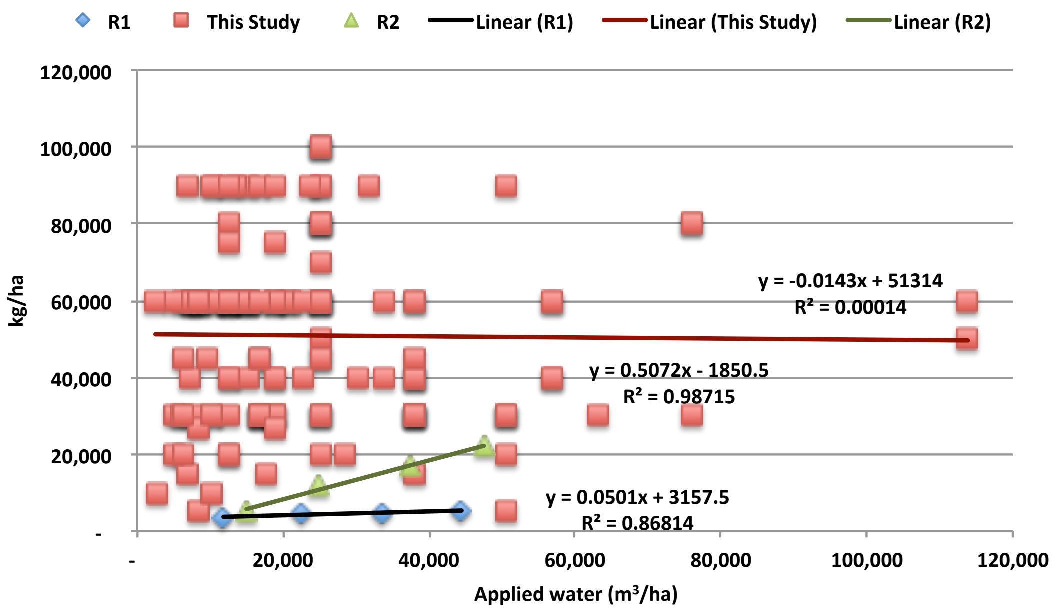

Figure 5.20 Rhodes yield response to water.

5.4.6.3 Alfalfa

Figure 5.21 demonstrates that the trend of yield response to water for alfalfa in this study has the same trend as measured in R1 (Nafchi, 2016) conducted in Iran, but with a higher production rate. This may be due to the fact that alfalfa yield measured in Iran was by "dry" as opposed to the "wet" yield measurement used in this study.

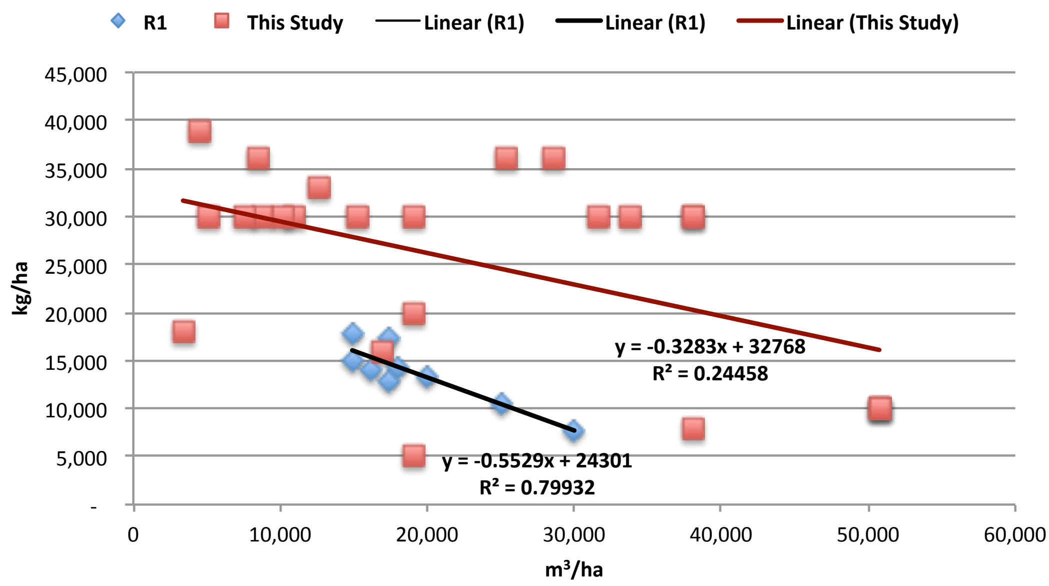

Figure 5.21 Alfalfa yield response to water.

5.4.6.4 Cucumber

The comparison for cucumbers cultivated in the survey was done with other studies using the same farming technique (greenhouses). As shown in Figure 5.22, R1 (Aly, Al-Omran and Khasha, 2015) and R2 (Alomaran and Luki, 2012) were both conducted in Saudi Arabia, and R3 (Rahil and Qanadilo, 2015) was conducted in Palestine. They all have almost the same trend but a lower productivity rate, especially R3. The difference in productivity rate may be because most of the farmers in this study cultivated cucumbers in soilless (hydroponic) greenhouses, whereas the other studies (R1, R2 and R3) used soil greenhouses. This technique increases production by twofold, as highlighted by the International Centre for Agriculture Research in the Dry Areas (ICARDA) study conducted in UAE (Ouled Belgacem, 2017).

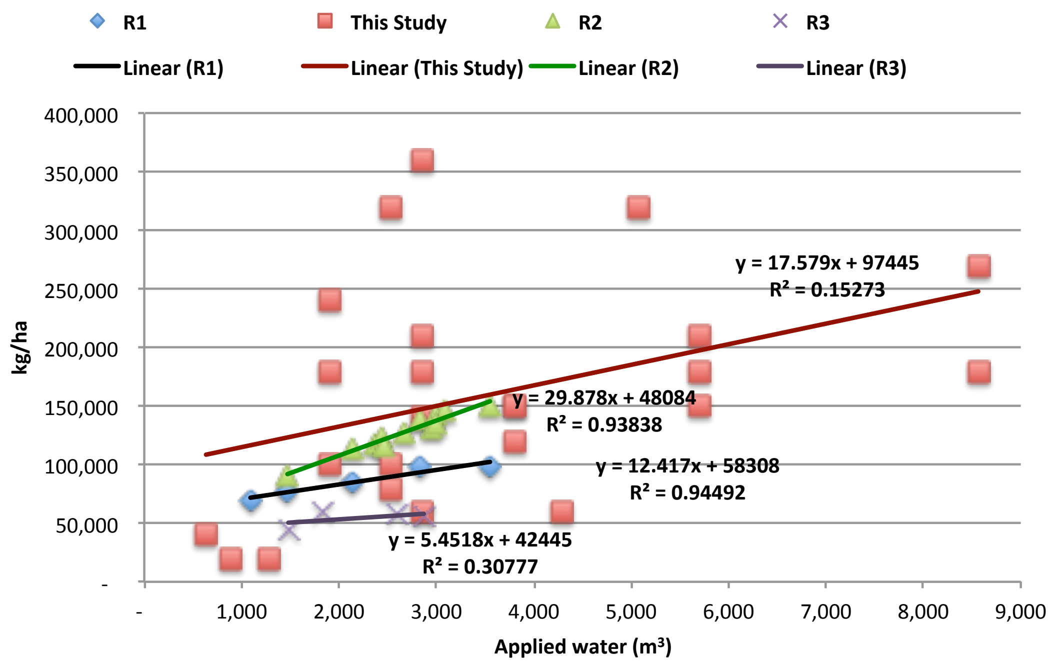

Figure 5.22 Cucumber yield response to water.

5.4.6.5 Corn

The corn yield response to water is compared to R1 (Payero *et al.*, 2008) measured in Nebraska and R2 (Dehghanisanij *et al.*, 2009) measured in Iran. Both Nebraska and Iran are located in semi-arid regions, where the studies took place from April to October. Both studies show a similar trend to this study but with a lower production rate (see Figure 5.23). This difference in production rate may be related to the fact that R1 and R2 were cultivated during the summer season (from April to October), whereas in this study cultivation took place during the winter season (September to December).

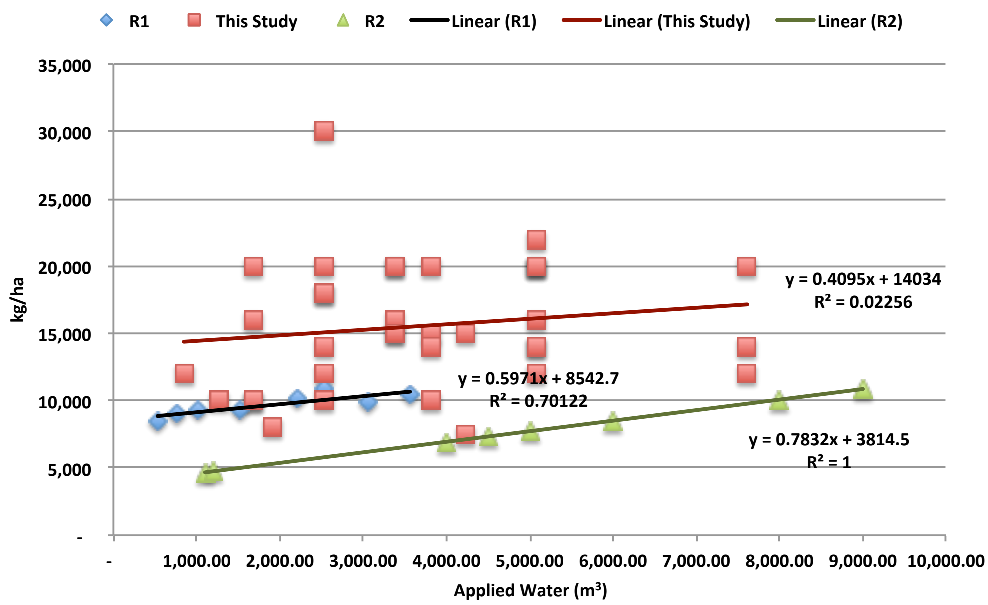

Figure 5.23 Corn yield response to water.

5.4.6.6 Eggplant

Figure 5.24 shows the comparison between the eggplant yield response to water and R1 (Çolak et al., 2015) in Turkey and R2 (Karam et al., 2011) in Lebanon. It shows that in both studies the increasing trend is higher than the trend in this study, which is expected since the countries of the other studies fall within Mediterranean climatic conditions, which are less than the arid climate in ADE. However, R1 has a much higher production rate, which may be due to the soil type (clayey-silt) and the use of surface irrigation, whereas the study done in R2 was during the summer season (May to September), which may affect the productivity rate.

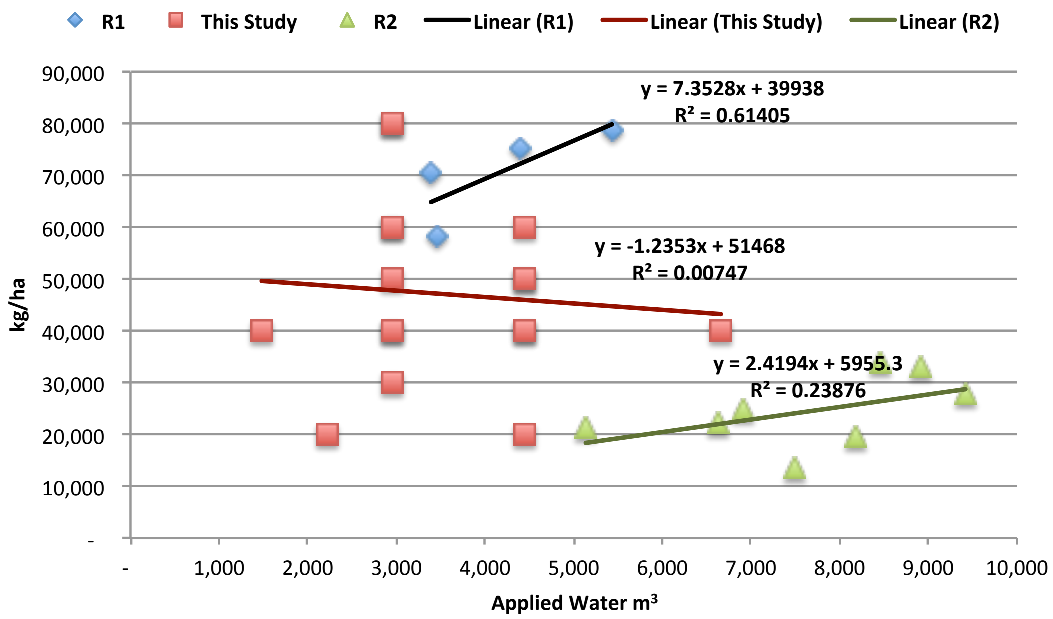

Figure 5.24 Eggplant yield response to water.

5.4.6.7 Onion

Figure 5.25 illustrates the onion yield response to water in comparison with two studies conducted in New Mexico (R1 and R2; Al-Jamal et al., 2000) using coated onion seeds and subsurface irrigation, which could justify the increasing trend and high production rate compared with this study. However, R3 (Nagaz, Masmoudi and Ben Mechlia, 2012), conducted in Tunisia (sandy soil with lower organic matter), has the same trend as this study but a lower production rate, which may be due to the summer cultivation season (March to August).

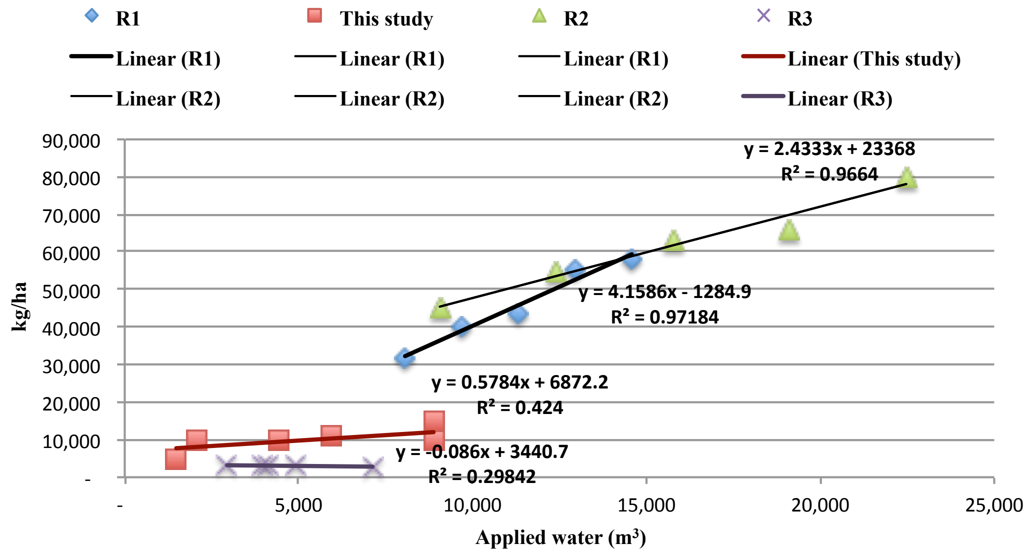

Figure 5.25 Onion yield response to water.

5.4.6.8 Tomato

Figure 5.26 shows that R1 (Algharibi et al., 2013) in Oman is comparable with the study trend for tomato, whereas R2 (Wahb-Allah and Al-Omran, 2012) in Saudi Arabia has an increasing trend and a higher production rate. This may be due to the fact that tomatoes in R2 were cultivated using greenhouses, which makes sense to have a higher trend and production rate.

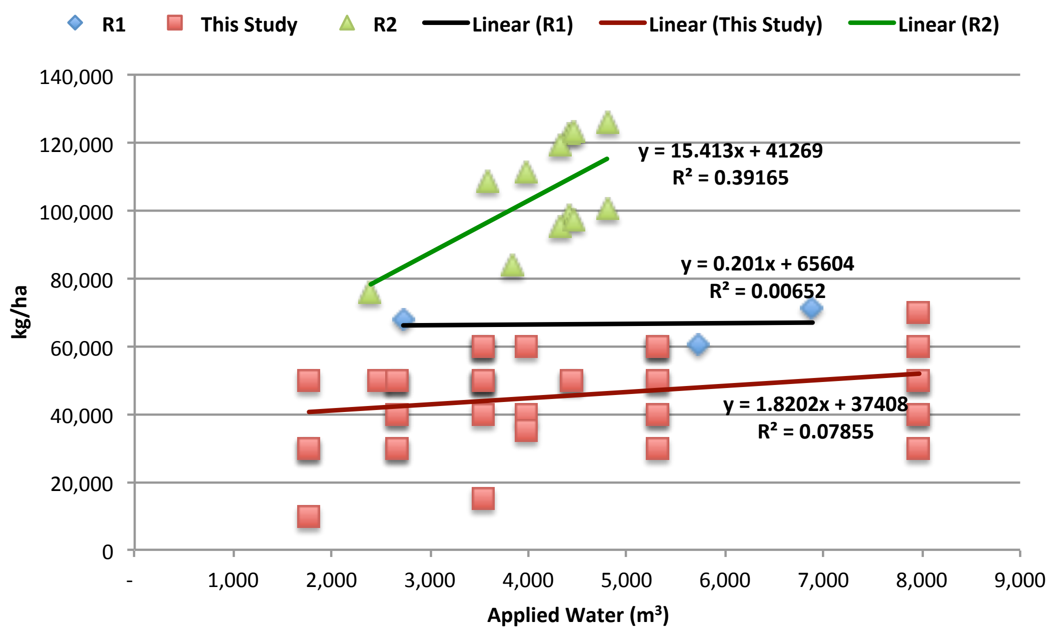

Figure 5.26 Tomato yield response to water.

5.5 Marketing Farm Produce and Crop Selection

The commercial farmers' responses to questions about the method of marketing and selling farm produce centred around five different ways. As shown in Figure 5.27, more than 80% of the farmers do sell their farm produce, with only 10.8% using it for their personal benefit. Some farmers tend to use more than one way to sell some specific produce, such as the different types of vegetables, in order to get as good a price as they can. The method of selling "directly to local market" is used by 18.6% of farmers, while through "private distributors" is used by 14.2% and "directly to customers" is adopted by 9.6%. However, only 8.4% of the farmers employ ADFSC to sell their produce. Almost all the farms that produce dates sell their dates through Al Faoh, a government-owned company (Al Foah, 2016). In this way, they are sure to benefit from government subsidies for growing palm trees and ensure the selling of their dates at a good price.

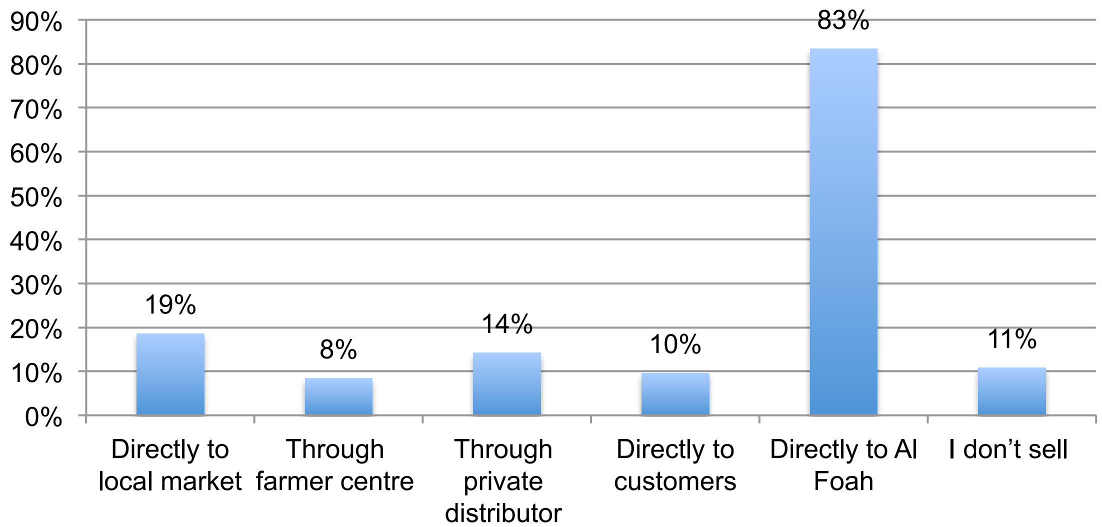

Figure 5.27 Different marketing methods selected by farmers.

In general, the selection of the type of crops to be planted is influenced by the demand and expected prices (information obtained during the survey). However, very little is known about any other reasons that tend to drive this decision-making and by whom. Thus, the respondents were asked in the questionnaire to indicate who makes the decision to choose crops to plant and on what basis they do so. The majority of the respondents (92%) stated that the farm owner chooses the crops to be planted, whereas only a small percentage (2%) rely on ADFSC's recommended list, and some (6%) rely on both.

Figure 5.28 demonstrates farmers' different responses for the reasons behind their crop selection, even though 45% of them did not provide any response. The main responses are prefer palm trees (14%), market needs (10%), personal needs (8%), to provide animal food

(8%), to obtain government subsidies (6%) and according to soil and water condition (4%). The remaining responses were all around 1%: as seeds available, ADFSC list, provide dates, seasonal crops and tenant needs.

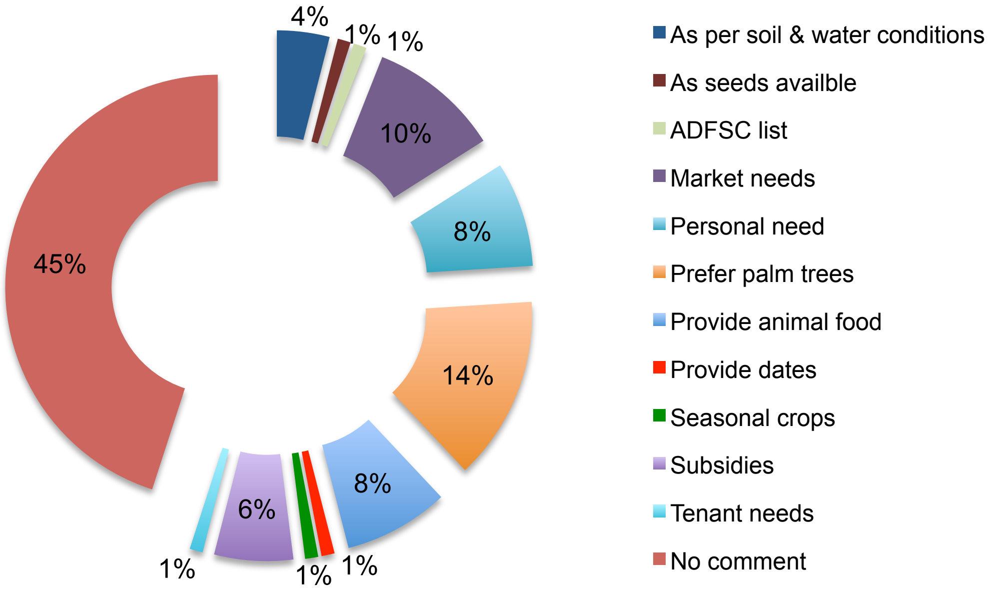

Figure 5.28 Farmers' crop selection justifications.

In order to understand if the farmers are satisfied with their current farming plans or whether they are planning to have different plans in the future, they were asked if they were going to continue with their existing plans. Almost 94% of them answered in the affirmative (i.e. that they will continue with their current plans), with only 6% responding that they would change their farming plans. Even though a very small percentage provided explanations on their future plans (as shown in Table 5.6), the majority of the respondents are planning to build greenhouses and also increase their farming capacity.

Table 5.6 Different responses on future farming plans.

Farmers Future Plan	Counts
All farm area is planted with palm trees so no place for development	1
Build greenhouses (Increase farming area, desalination, fish tank, chicken farm)	6
I don't know	1
I'm looking for investors	1
Improve agricultural methods	2
If freshwater supply increase, agricultural development will increase	1
Increase farming area	1
Increase the growing of palms and vegetables	4
Make agreement with ADFSC	1
Raise more animals	1
Total	19

The analysis in this section shows that the majority of the farmers are selling their farm produce mostly through Al Foah, where the crop they refer to is the palm date. Only a small percentage use ADFSC's services to sell their produce and/or to select crop types, even though they have the advantage of a minimum guaranteed price. This may be due to the low quality of their produce or their ability to negotiate higher prices than are guaranteed by ADFSC.

5.6 Farmer Perception and Awareness

As highlighted earlier, one of the major focuses of this research is to identify factors that influence farmers' perceptions and assess their awareness of different agricultural and water policies, as well as their willingness to participate to achieve sustainable farming. To gain this knowledge, the survey questions included farmers' views on the drinking water tariff, water issues in the country, groundwater abstraction control and agricultural subsidies. Further questions were also directed to the farmers to give them a chance to provide any specific comments, concerns or requirements.

5.6.1 Drinking Water Tariff

Since there is no drinking water network supply for some of the farms, desalination drinking water is supplied to them through tankers in different regions by distribution companies (ADDC and AADC). Therefore, the farmers were asked whether they received a drinking water supply. Only 18 (5%) farms from the total sample said that they receive their drinking water supply. These farmers were asked about their views on the drinking water tariff that had been introduced in January 2015: 8 out of the 18 said they agree with the introduction of this new tariff, and 7 out of 18 stated they did not agree, while 3 stated that they do not know. The same group of farmers who received a drinking water supply via tankers also shared their views, among four options, on the reasons behind introducing the drinking water tariff. Figure 5.29 elicits these reasons mentioned by the participants: 56% stated the reason as reducing water consumption, 17% mentioned sharing water cost with the government, 6% selected both answers, whereas 21% said "I do not know".

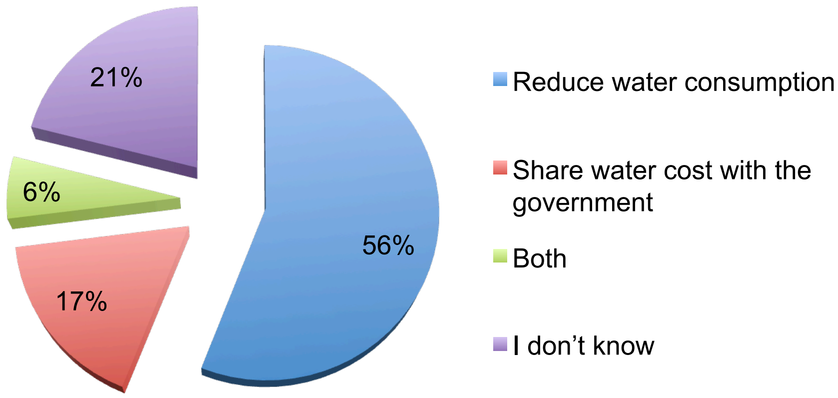

Figure 5.29 Participants’ responses on the reason behind introducing the drinking water tariff.

When this group of farmers were asked if they use drinking water in irrigation or not and whether the tariff influenced their water use pattern, 4 out of 18 participants stated that they use the drinking water for irrigation, and 9 out of 17 responded that the tariff does not change the way they manage their farm. The remaining number indicated that the tariff has changed their practices in the farm.

5.6.2 Water Issues in Abu Dhabi Emirate

The absence of natural fresh water and the overuse of non-renewable groundwater will lead to depletion of groundwater aquifers in 30 years’ time, as expected by EAD and explained in Section 4.5. This has been exacerbated by high consumption in all sectors, especially in the agricultural sector. The continuous development of the agricultural sector (the highest water user) will require different measures to be sustained with minimum waste in terms of water use and environmental impact. For these reasons, it is important to understand the farmers’ awareness of water-related issues in ADE. They were thus asked to provide their views about drinking water issues, groundwater depletion, deterioration in the quality of groundwater and ADFSC’s measures to control groundwater pumping. The responses obtained are shown in Figure 5.30. Even though only 5% of the total sample are receiving a drinking water supply, as explained in the previous section, the responses show that 78% of the total answered “No” and 10% said “Yes”, with the remaining 12% indicating “I don’t know”.

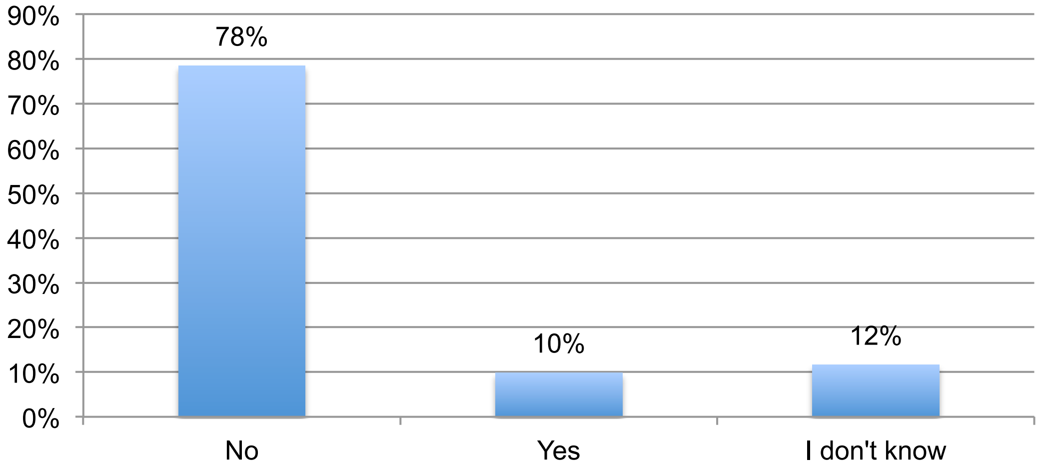

Figure 5.30 Farmers' view on the drinking water issues in ADE.

Moreover, the farmers were questioned on their knowledge about groundwater depletion and if they have noticed a deterioration of the quality of the groundwater. The responses to these two questions, in the form of percentages of "No", "Yes", "Only in some wells" and " I do not know", are shown in Figure 5.31. This indicates that about 50% and 60% of the farmers know about groundwater depletion and realized its quality deterioration, respectively.

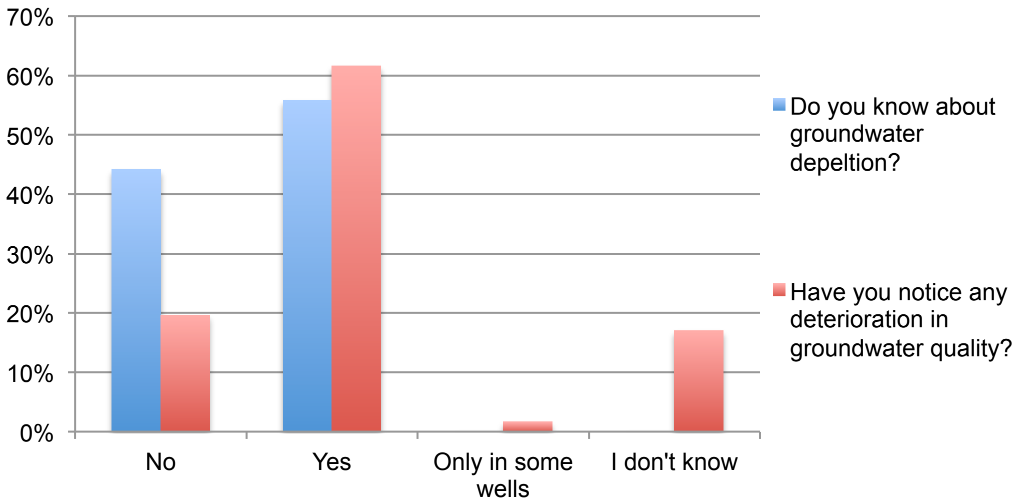

Figure 5.31 Farmers' view on groundwater depletion and deterioration.

In order to assess any possible influences on the farmers' answers, the results were also subjected to further analysis by running statistical correlation (using a Chi-square test) between farmers' responses and different farm categories such as location, size, ownership type, farm manager and if the farm generates profit. The value of the Chi-square test, degree of freedom and its significance are all included in Tables 5.7 and 5.8.

Table 5.7 Correlation of farmers' knowledge on groundwater depletion

Category	Subcategory	Do You Know about Groundwater Depletion?			Chi-Square Value	Degrees of Freedom	Asymptotic Significance (2-Sided)
		No	Yes	Total			
Farm location	AD	74	25	99			
	AA	13	136	149			
	WR	58	22	80			
	Total	145	183	328	139.459	2	0.000
Farm size (ha)	<2	5	2	7			
	2–2.9	81	46	127			
	3–3.9	15	111	126			
	4–4.9	43	24	67			
	>6	1	0	1			
	Total	145	183	328	87.231	4	0.000
Ownership type	Single owner	127	166	293			
	Inheritors	16	10	26			
	Joint ownership	1	7	8			
	Total	144	183	327	6.517	2	0.038
Farm owner gender	Female	28	18	46			
	Male	99	148	247			
	Both	8	10	18			
	Total	135	176	311	6.83	2	0.033
Farm manager	Owner	33	15	48			
	Representative	107	163	270			
	Tenant	4	5	9			
	Total	144	183	327	14.024	2	0.001
Generate profit	Yes	106	39	216			
	No	39	72	111			
	Total	145	111	327	5.772	1	0.016

Table 5.7 shows the responses to groundwater depletion. In general, 56% of 328 responses answered "Yes" and 44% answered "No". The test shows a statistical significance correlation at a P value (probability of error) of <0.05 of those responses with farm location, farm size, ownership type, owner gender, farm manager and if the farm generates profit at Chi-square values of 139.459, 87.231, 6.517, 6.83, 14.024 and 5.772, respectively.

Table 5.8 demonstrates that the responses to the farmers' perception of groundwater deterioration show 20%, 60%, 2% and 18% answers of "No", "Yes", "Only in some wells" and I do not know", respectively. The test demonstrates a positive and statistically significant correlation of those responses with farm location, farm size, ownership type, owner gender, farm manager and if the farm generates profit, at Chi-square values of 176.02, 67.356, 14.351, 6.797, 25.666 and 13.541, respectively, and P value <0.05.

Table 5.8 Correlation of farmers' knowledge of groundwater deterioration.

Category	Subcategory	Have You Noticed any Deterioration in Groundwater Quality?				Total	Chi-Square	Degrees of Freedom	Asymptotic Significance (2-Sided)
		No	Yes	Only in Some Wells	I Don't Know				
Farm location	AD	15	27	1	59	102			
	AA	21	122	4	2	149			
	WR	31	48	0	0	79			
	Total	67	197	5	61	330	176.02	6	0.000
Farm size (ha)	<2	5	6	0	0	11			
	2–2.9	29	63	2	50	144			
	3–3.9	30	123	2	6	161			
	4–4.9	2	3	1	3	9			
	Total	66	195	5	59	325	67.356	12	0.000
Ownership type	Single owner	59	182	5	49	295			
	Inheritor	6	9	0	11	26			
	Joint ownership	2	6	0	0	8			
	Total	67	197	5	60	329	14.351		0.028
Farm owner gender	Female	11	24	1	11	47			
	Male	47	158	4	39	248			
	Both	5	8	0	6	19			
	Total	63	190	5	56	314	6.797	6	0.34
Farm manager	Farm owner	16	16	2	13	47			
	Representative	49	178	2	44	273			
	Tenant	2	3	1	3	9			
	Total	67	197	5	60	329	25.666	6	0.000
Generate profit	Yes	57	119	3	39	218			
	No	10	77	2	22	111			
	Total	67	196	5	61	329	13.541		0.004

The results of this test validate that the majority of the farmers are aware of groundwater depletion and deterioration. To be specific, AA region and farm size of 3–3.9 ha has the highest percentage of farmers who agreed to the existence of the issue of groundwater depletion and quality deterioration, especially among those farmers with more wells. The farmers' knowledge of groundwater issues is generally influenced by their experiences.

5.6.3 Farmers' Views on Groundwater Abstraction Control

As discussed in Section 4.5, it has been realized that control of groundwater abstraction is an important step that the government should take to preserve its aquifers. EAD in coordination with ADFSC is currently working to develop a proper mechanism to install meters in all wells (including farm wells), collect the required information and define the limit of pumping rate per day for different areas and different farms. This would be the initial stage of controlling and preserving the groundwater reserve, which could further continue to develop a tariff structure as an incentive to reduce the overuse of groundwater. Accordingly, the farmers were asked to provide their perceptions of the government's (EAD/ADFSC) decision to take measures to control the abstraction of groundwater. The analysis shows that about 70% disagree, 23% stated that they do not have productive wells and only 7% agree with such a decision. Historically farmers were free in their use of groundwater, with limited oversight that offered practically no restriction on the number of wells, their depth and the quantity extracted. This indicates that the government needs to consider farmers' involvement and proper enforcement mechanisms to control groundwater abstraction.

5.6.4 Farmers' Views on Agricultural Production and Related Government Subsidies

As explained in Section 4.5, the historical development of the agricultural sector in ADE elucidated the social and cultural interest of farming (including livestock). However, until the last few years, less attention was given to commercial farming. To assess the farmers' perception of the value of current agricultural production, they were asked if they think that their farm produce is valuable, and whether it generates profit or not. More than 52% of the participants stated that they think their farm produce is valuable, and 16.3% think it is indirectly valuable to the country, whereas 31.7% of the sampled respondents stated that they think their farm produce is not valuable. The majority of the farmers who think their product is directly or indirectly valuable also indicated that their farm generates profit, where they relate their view to the importance of meeting local demand, especially for dates (Figure 5.32). However, 76% of the farmers who think of their farm produce as not valuable indicated that their farms do not generate profit.

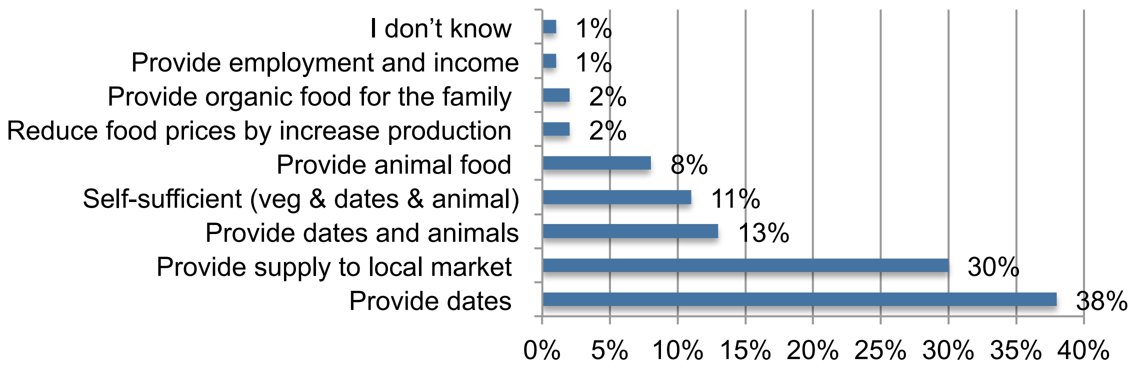

Figure 5.32 Summary of participants' views on the value of their farm produce.

The survey also assessed farmers' perception of the government's subsidy plans by asking them to provide their view on whether the government should reduce or stop the subsidies. The analysis shows that 85% of farmers stated that they do not agree with a reduction or stopping of the subsidies, especially for farms that consume more water (farms representing 50% of total water consumption).

5.6.5 Other Comments

The final question in the survey questionnaire was an open-ended question to obtain any other comments from the participants. About 60% did not provide any comment, but the remaining 40% requested a drinking water supply, improvements in the services provided to farmers, provision of irrigation water supply, and the need to provide more attention to the palm tree (Figure 5.33).

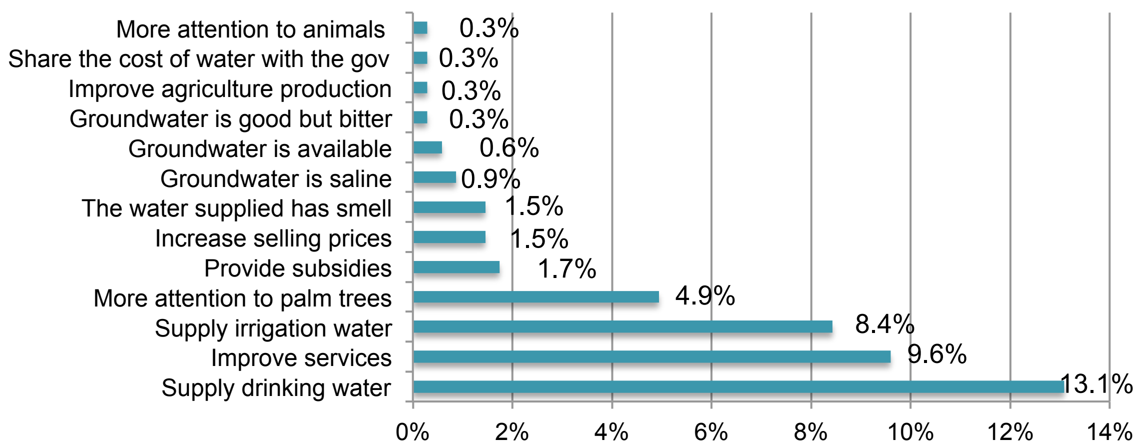

Figure 5.33 Summary of other comments provided by farmers.

The farmer perception and awareness analysis shows that, although only 5% of farms receive a drinking water supply, the majority of them realized the government's intention to reduce water consumption. This could be related to the introduction of the drinking water tariff structure in 2015. From the total sampled farms, the majority of farmers also realized the issues related to groundwater depletion and deterioration, where most of them are influenced by their practical experience and daily needs. Therefore, there is a strong link between their awareness and farm location (such as AA) and farm size (such as 3–39 ha). However, despite their awareness, the majority of them still do not agree with government control of groundwater abstraction.

More than 50% of the farmers view their farm produce as valuable to supply dates, provide animal food and increase self-sufficiency. The majority of farms do not agree with reducing or stopping government subsidies. This is also shown in the farmers' general comments. Although only 40% of the surveyed farms answered this question, the majority highlighted the need for a drinking water supply, improved services, irrigation water supply and paying more attention to palm trees.

5.7 Chapter Summary

This chapter presents the results of the survey questionnaire aimed to develop a comprehensive understanding of the current farming practices and their impact on water resources in ADE. The analysis of the survey data provided inclusive empirical data on the current cropping pattern, crop yield, water use per crop, water productivity, and farmers' perception and awareness on related water issues and policies. This data is presented for the first time in the country (to the author's best knowledge), which could have great value for policy-makers to optimize water use in the agricultural sector. In this research, the data are used to run different policy scenarios as part of the proposed Agriculture-Water Policy Framework (Chapter 7).

In the next chapter, the management, regulation and policy development of water use in agriculture are investigated through semi-structured interviews with selected experts from different water- and agriculture-associated entities.

Chapter 6. Managing and Regulating Water Use in Agriculture

6.1 Introduction

This chapter focuses on regulation and management of water use in agriculture and the development and implementation of related policies across associated organizations. It also covers the influence of these organizations on water use.

It consists of two main parts. The first maps the roles and functions of the different entities associated with water and agriculture management and operations. This provides understanding of the interrelation between these entities and the way their roles and efforts overlap. The second section provides analysis of the primary data that are obtained from the semi-structured interviews. It assesses how the participants perceive the most critical water issues and categorize their suggested solutions, including the development and implementation of agricultural water use policies, contentious development of agriculture and forestry, groundwater and desalination use for agriculture and anticipated alternative resources.

6.2 ADE Governmental and Institutional Structures

The Executive Council (EC) is the highest authority in ADE and has the final decision-making power in water, energy and agriculture issues. It is chaired by His Highness Sheikh Mohamed bin Zayed Al Nahyan, the Crown Prince of ADE and deputy supreme commander of the UAE Armed Forces. The members of the EC are either chairs of different local government authorities or individuals selected by the ruler of ADE (Ruler). The Ruler is also the president of the UAE: His Highness Sheikh Khalifa bin Zayed Al Nahyan. The main roles of the EC are to assist the Ruler to execute his duties, to help develop ADE plans and policies and to ensure their effective implementation. All of ADE governmental local authorities and entities sit under the EC (Abu Dhabi Government, 2018a).

There are 14 different governmental organizations (in addition to the Permanent Committee for Water and Agriculture Strategies, PCWAS) that share responsibility for water and agricultural management and were included in this study. Each organization has a different area, scope and objectives, with overlapping of duties occurring in some areas. To illustrate their relevance in this research, these organizations were categorized based on their main roles and focus (Table 6.1). Each group was also given an abbreviated name for easy reference. Demarcation of the roles and responsibilities of these organizations within these groups is explained in the following sections.

Table 6.1 Water and agriculture-related organizations in Abu Dhabi.

Group Name	Organization	Main Focus	No of SMEs Interviewed
Governance (GOV)	General Secretariat of Executive Council (GSEC)	Administers EC work and responsible for all Abu Dhabi policies and strategies	2
	Executive Affair Authority (EAA)	Provides necessary policy advice and recommendations to the EC Chairman on all Abu Dhabi Government portfolio	2
	Permanent Committee for Water and Agriculture Strategies (PCWAS)*	Facilitates and aligns water and agriculture strategies and policies	3
	Ministry of Climate Change and Environment (MOCCAE)	Federal office that addresses climate change and environmental issues at a country level, and develops appropriate water and agriculture policies along with mitigation plans to support their implementation	3
Research (RESEARCH)	Abu Dhabi Food Security Centre (FSCAD)	Develop food security strategy and ensure emergency food security planning for Abu Dhabi Emirate and the UAE	1
	International Centre for Bio-saline Agriculture (ICBA)	Undertakes research on the development of agricultural production in a marginal environment at an international level	3
	Abu Dhabi Global Environmental Data Initiative (AGEDI)	Disseminates actionable and improved environmental data to provide support to achieve sustainable development	1
Regulatory (REG)	Regulation and Supervision Bureau (RSB)	Responsible for regulating and ensuring security of supply of desalinated water, wastewater and electricity	3
	Environmental Agency of Abu Dhabi (EAD)	Responsible for setting policies to protect the environment in all aspects, including natural resources such as groundwater	5
	Urban Planning Council (UPC)	Responsible for sustainable planning of urban communities, which includes developing guidelines to promote sustainable landscaping	1
Desalination (DESAL)	Abu Dhabi Water and Electricity Authority (ADWEA)	Responsible for the production, transmission and distribution of water and electricity	3
	Abu Dhabi Water and Electricity Company (ADWEC)	Responsible for ensuring the availability of water and electricity supply to meet forecasted demand	6
Agriculture/Forestry	Abu Dhabi Food Control Authority (ADFCA)	Ensures food safety and suitability, and services provided to farmers through Farmer Service Centre (FSC)	3
Landscaping (AFL)	Abu Dhabi Farmer Service Centre (ADFSC)	Provides direct interaction with farmers, facilitates marketing of farm products and provides different services such as awareness and training	1
	Department of Municipal Affairs and Transportation (DMAT)	Responsible for developing side roads and island landscaping as well as public areas and parks	2
Total number of SMEs interviewed			36

** PCWAS is a committee (Permanent Committee for Water and Agriculture Strategy). Three SMEs were interviewed from the PCWAS which also have permanent jobs at ADWEC, RSB and EAD.*

6.2.1 Governance (GOV)

The Governance group (GOV) consists of the General Secretariat of the Executive Council (GSEC), Executive Affair Authority (EAA), Permanent Committee for Water and Agriculture Strategies (PCWAS) and Ministry of Climate Change and Environment (MOCCAE). The four parties share responsibility/involvement in the development and implementation of water- and agriculture-related policies and strategies.

General Secretariat of the Executive Council (GSEC)

The GSEC is an office that sits in the EC to operate and drive the EC's work. It is also responsible for ADE general policies and strategies, including agriculture and water policies. GSEC administers the development of these policies and obtains EC approval and final decision (Abu Dhabi Government, 2018b).

Executive Affairs Authority (EAA)

The EAA provides strategic policy advice to the EC Chairman (His Highness), which includes analysis, studies and policy recommendations across all government sectors. It plays an important role in ensuring coordination between the entities during the development and implementation of special projects and policies. It also defines policy gaps and makes recommendations required for better outcomes (Abu Dhabi Government, 2017).

Permanent Committee for Water and Agriculture Strategies (PCWAS)

The PCWAS was established in 2009 (Decree No. 87) to work in tandem with the GSEC and EAA in supporting the EC to facilitate and align water and agriculture policies and planning to prevent overlaps and duplications in related projects and activities (El Masri, 2010). Members of the PCWAS are representatives of ADFCA, EAD, ADWEA, ADSSC, Regulation and Supervision Bureau (RSB) and Department of Municipal Affairs and Transport (DMAT).

Three SMEs who are members of PCWAS were interviewed, who were mainly holding key positions in ADWEC, RSB and EAD. Although their options and perceptions as members of PCWAS were obtained and considered, the interview responses were registered as a reflection of the entities for which they work.

Ministry of Climate Change and Environment (MOCCAE)

MOCCAE is a UAE federal entity established in 2016 as an expansion of the Ministry of Environment and Water. It supports the country in improving its efforts to address climate change and all environmental issues by developing the required policies and mitigation plans. Its roles include managing all aspects related to agriculture, livestock and fisheries sectors to ensure food security in the country. It also maintains the sustainable development of all resources as well as ensuring water conservation (MOCCAE, 2016).

In the last few years, MOCCAE has been working on developing a food diversification strategy for the country that includes agriculture and water use strategies and related policies. MOCCAE has been coordinating with all federal related stakeholders (Strategic Partners) from the seven different Emirates, including ADE local entities such as ADFCA, GSEC, EAA and EAD.

6.2.2 Research (RESEARCH)

Related research (RESEARCH) organizations are the Abu Dhabi Food Security Centre (FSCAD), International Centre for Bio-saline Agriculture (ICBA) and Abu Dhabi Global Environmental Data Initiative (AGEDI). These organizations contribute to research and development studies in the water, agriculture and food sectors.

Abu Dhabi Food Security Centre (FSCAD)

FSCAD was created in 2010 to develop a food security strategy for ADE and ensure emergency food security planning, not only for ADE but for the whole of UAE. FSCAD is also involved in monitoring national and international food prices to protect the country from any potential threats of unsustainable market prices, and encourage the production of local food commodities to increase diversification of food production. It communicates with all related local and federal government entities, especially ADFCA, to help develop the needed plans to secure food supplies and food safety for the country (FSCAD, 2015).

International Centre for Bio-saline Agriculture (ICBA)

ICBA is a non-profit international organization established in 1999 sponsored by different national, regional and international organizations, including the UAE government. It established its research development programmes in 30 countries focusing on the expansion of agricultural production in marginal environments using saline and treated wastewater (ICBA, 2017). During the last seven to eight years, ICBA has worked in UAE in collaboration with the Ministry of Environment and Water (now Ministry of Climate Change and Environment) and Environment Agency-Abu Dhabi (EAD) in developing some important strategies such as the water resources master plan for ADE, the UAE water conservation strategy, the sustainable agriculture strategy and the safe disposal of reverse osmosis brine (ICBA, 2014, 2017).

Abu Dhabi Global Environmental Data Initiative (AGEDI)

AGEDI is a program launched by the ADE government in 2002 to disseminate actionable and improved environmental data and provide support to achieve sustainable development at the local, regional and global levels (EAD, 2011). AGEDI receives support and collaboration from local partners such as EAD and MOCCAE, and from global partners such as the United Nations Environment Programme (UNEP). This collaboration facilitates easy access to different kinds of expertise and information (AGEDI, 2013).

6.2.3 Regulatory (REG)

The three regulators in the Regulatory group (REG) are the Regulation and Supervision Bureau (RSB), Environmental Agency Department (EAD) and Abu Dhabi Urban Planning Council (UPC). These three entities focus on regulating drinking water, groundwater drilling and providing guidelines for landscaping, respectively.

Regulation and Supervision Bureau (RSB)

RSB was established under Law No. 2 1998, article 44 (RSB, 1998). It is responsible for regulating and ensuring security for the supply of desalinated water, wastewater (collection, treatment and supply of treated wastewater) and electricity in ADE. It supervise and regulates the companies that are providing these services to ensure continuous improvement of high-quality standards and reliable supply to its consumers (RSB, 2013).

Environment Agency-Abu Dhabi (EAD)

EAD is responsible for protecting the environment (air quality, desert, marine ecosystem and groundwater) through setting polices and strategies and regulating groundwater drilling. EAD also helps with maintaining and operating forestry in ADE, as well as owning and operating 4,000 groundwater wells that are required to supply irrigation for forestry. Therefore, EAD plays three main roles: regulator, producer and user. Currently, there is a high-level discussion to move the responsibility for managing and operating forestry to DMAT.

Urban Planning Council (UPC)

UPC is responsible for sustainable planning of urban communities in ADE, which includes strategic framework planning for the development of the three regions within it (UPC, 2017).

As part of UPC planning, there is a focus on promoting water and energy conservation, which is shown through its set of manuals and guidelines and also through the Estidama "Sustainability" Pearl Rating system, which defines the thresholds for water and energy use for any new developments (UPC, 2010). In terms of landscaping, UPC provides guidelines that promote sustainable landscaping by using native plants and low water use trees, as well as preventing the use of desalination or groundwater for irrigation and generally promoting treated wastewater use.

6.2.4 Desalination and Treated Wastewater (DESAL)

Those in the Desalination group (DESAL) are mainly involved in producing and distributing desalinated seawater as well as distributing treated wastewater (the latter distribution role was handed over to ADWEA in 2016). The main entities responsible are Abu Dhabi Water and Electricity Authority (ADWEA) and Abu Dhabi Water and Electricity Company (ADWEC).

Abu Dhabi Water and Electricity Authority (ADWEA)

ADWEA was established in 1998 to take responsibility for the production, transmission and distribution of water (desalination) and electricity in ADE (ADWEA, 2013). ADWEA has 100% ownership of ADWEC, which is the sole buyer and seller of water and electricity, Abu Dhabi Transmission and Despatch Company (Transco) and the two distribution companies: Abu Dhabi Distribution Company (ADDC) and Al Ain Distribution Company (AADC; ADWEC, 2016a).

6.2.5 Agriculture/Forestry/Landscaping (AFL)

The Agriculture/Forestry/Landscaping group (AFL) consists of the main irrigation water user entities. These entities demand water to meet their mandates, such as the Abu Dhabi Food Control Authority (ADFCA) and Abu Dhabi Farmer Service Centre (ADFSC), which are responsible for agriculture and livestock production, and the Department of Municipal Affairs and Transport (DMAT), which is responsible for landscaping and part of the forestry (the majority of forestry is managed by EAD).

Abu Dhabi Food Control Authority (ADFCA)

ADFCA was established in 2005 (Law No. 2 of 2005) to ensure food safety, quality and suitability for ADE. In 2007, the responsibility for ensuring sustainable agricultural production to meet food security demand (Law No. 9) was added to ADFCA to be part of its mandate (ADFCA, 2014, 2015). Since then ADFCA has been working on developing plans, strategies and policies to sustain agricultural growth. In 2009, ADFCA launched a Farmer Service Centre (ADFSC) under Law No. 4 to take responsibility for implementation of ADFCA's agriculture plan and policies, and to ensure services are provided to farmers through ADFSC extension offices (ADFCA, 2014). These services can include water supply, fertilizers, seeds and ensuring that farmers improve water use in their agricultural practice.

Abu Dhabi Farmer Service Centre (ADFSC)

ADFSC is the ADFCA organ to directly interact with farmers to implement the reform of agricultural practice to be more sustainable, to foster agricultural development with innovative practices and to improve the competitiveness of local products (ADFCA, 2011a).

Department of Municipal Affairs and Transport (DMAT)

DMAT consists of three municipality offices: Abu Dhabi Municipality (ADM), Al Ain Municipality (AAM) and Western Region Municipality (WRM). These offices are responsible for side and island road landscaping and public parks in AD, AA and WR, respectively. DMAT is involved with developing all municipal and transport policies and regulations, monitors the implementation of these policies and unifies all activities across the three departments (DMAT, 2017). However, any water and power policies and regulations that are developed by RSB should be part of DMAT's role to ensure proper implementation across its departments. This Information was obtained from the interview with the SME from DMAT.

Until recently, DMAT was also responsible for the distribution of TW supplied by Abu Dhabi Sewage Service Company (ADSSC), but in 2016 this role was moved to be part of Abu Dhabi Distribution Company (ADDC) and Al Ain Distribution Company (AADC) responsibilities under ADWEA management.

6.2.6 Observations

Although the information available on the roles and mandates of the entities is limited, there are some high-level critical observations:

- GSEC, EAA and PCWAS represent the higher authorities in ADE to focus on reducing duplication and double handling, as well as aligning and facilitating the integration between entities to ensure effective communication and coordination.
- Even though GSEC has the main role of approving all policies and strategies, including water use and agriculture policies, there are no clear definitions of the nature of its authority over other entities.
- Among all the entities and authorities associated with water and agriculture, there is no one identified entity that is responsible for developing a water use policy. However, there are shared interests between the entities in water use, such as EAD (responsible for forestry), DMAT (responsible for road and island road forestry and landscaping) and ADFCA and ADFSC (responsible for farming and local food production).

- MOCCAE has the main role of developing the overall countrywide agriculture- and water-related policies, so it conducts a wide range of workshops in coordination with different authorities, but the ministry's level of influence on those authorities is not clear.
- It has been noted that there is no clear demarcation between the roles of entities such as producers, users and regulators. Some entities have duplicated roles as a water producer and at the same time as a water user, such as ADFCA, which owns and operates groundwater fields, supplied to the farms under the collective irrigation system (Section 4.6.4.2). EAD, in addition to its main role as groundwater regulator, also owns and operates water well fields that supply forestry. This could create a conflict of mandates within the same entities.
- Some entities' mandates conflict with those of other entities, such as agricultural production and groundwater abstraction control. This clearly occurs between ADFCA, whose main objective is to increase local agricultural production, putting pressure on water demand, and EAD, whose main mandate is to protect groundwater reserves and regulate well drilling.
- The responsibility for managing forestry is divided between EAD and DMAT. Therefore, the policy development process and the responsibility matrix for the implementation of each policy developed are not clearly defined. (There is a current discussion to move the responsibility for managing the forestry to DMAT.)
- The mechanism to use the studies and recommendations by FSCAD, AGEDI and ICBA is not clear. There is a need to define how the sector benefits from research and studies, and what triggers the need and approval for a certain study.

The current information that is publicly available on these entities is not complete enough to understand how they are developing and implementing policies related to water use. Furthermore, there is no record of existing water use policies, either in agriculture or in any of the other sectors. This is in addition to the lack of documented procedures to demonstrate how the entities are communicating and coordinating with each other with defined roles and responsibilities. Therefore, and as mentioned in Section 3.3.3, semi-structured interviews were conducted. The majority of the selected SMEs hold managerial positions with more than 20 years' experience in water, agriculture and different environmental aspects. Table 6.2 shows the number of SMEs interviewed at each authority level.

Table 6.2 Number of SMEs interviewed in each managerial category.

Level of Authorities	Count
CEO/Managing Director	2
Advisor	7
Director	7
Manager/Head of Section	10
Senior Engineer/Senior Manager	7
Principal Scientist/Researcher	3

The technique for selecting interviewees, interview questionnaire design and protocol, general observation and data analysis methods are all presented in Section 3.3.3. However, the data analysis and discussion of the results and findings are the subjects of the following sections.

6.3 Data Analysis

During the analysis, the responses from the interview transcripts were grouped under each focused area (Table 6.3). The main categories, themes and subthemes were identified under each of the four areas. Table 6.3 shows the seven categories and between two and four themes that were identified under each category.

Table 6.3 Main categories and themes developed from the semi-structured interviews.

Main Focus Area	Category	Code/Theme
Critical water issues	Water use	High agricultural water use
		High domestic water use
		Low efficiency in water use
	Groundwater supply	Limitation of groundwater quantity
		Salinity increase of groundwater quality
		Increasing groundwater abstraction
	Desalination supply	Negative environmental impact
		High production cost
		Increasing desalination demand
		Impact of nuclear power plant on desalination capacity
	Treated wastewater supply	Low treated wastewater utilization
		Need for treated wastewater infrastructure
	Information and knowledge	Lack of information on consumption
		Absence of information on real cost of water
		Non-reliable data on groundwater
		Not enough public awareness
	Water planning	Lack of integrated planning
		Lack of proper allocation of skilled staff
	Water scarcity	Absence of natural freshwater resources such as lakes, rivers or considerable precipitation that can recharge groundwater aquifers
Agricultural water use policy	Existing policies	Absence of direct and clear water use policy
	Underdevelopment policies	Improvement in treated wastewater utilization
		Improvement in water use efficiency
		Control of groundwater use
Agricultural/forestry development	Water use	Agricultural/forestry water use
	Vision and objectives	Clear long-term vision and objectives
	Research and studies	Economic studies on water productivity, agricultural production yield and value, and selected technologies
Agricultural water resources	Groundwater	Definition of aquifers and rate of pumping and restricted areas/aquifers
		Small-scale desalination of saline groundwater
	Desalination	Economic evaluation of desalination use in agriculture
	Treated wastewater	Improvement of treated wastewater utilization and assessment of its suitability for agriculture

Analysis of the participants' responses under each theme and subtheme were combined and presented with the aid of either a chart or a table, together with quotations from the different groups to support their discussions. The views and perceptions are discussed in detail across the focus areas in the following subsections.

6.3.1 Critical Water Issues

In order to understand the participants' views and their level of awareness of water-related issues, the interviews were questioned on their view of the most critical water issues in ADE and then asked to explore the reasons behind them, as well as their suggestions (and/or the established measures) to alleviate them.

The SMEs' views on this matter are focused on seven categories associated with diverse themes (Table 6.4). This clarifies graphically the level of the group's recognition of any of these seven critical categories and the associated themes. In the table, a full circle indicates two and more interviewees in the entity, a half-circle indicates one interviewee in the entity, an empty box indicates no one from the entity and a black (shaded) box indicates that no one from the entire group underlined the issue during the discussion.

It can be comprehended from the table that there is good recognition of the high water use and low efficiency of water use, limitation of groundwater quantity and quality, lack of integrated water planning and the absence of natural freshwater resources (highlighted at least by one SME from each group). However, the rest of the themes were not completely identified by all the groups, such as desalination supply, information and knowledge, and treated wastewater supply.

Table 6.4 Critical water issues perceived by the SMEs.

Category	Theme (Code)	GOV			RESEARCH			REG			DESAL		AFL		
		EAA	GSEC	MOCCAE	FSCAD	ICBA	AGEDI	RSB	EAD	UPC	ADWEA	ADWEC	ADFCA	ADFSC	DMAT
Water Use	High agriculture water use	●	◐	●	◐	●	◐	◐	●	◐	◐	●	●	◐	◐
	High water use per capita	◐	●	◐		◐		●	●	◐	◐		◐		◐
	Low water use efficiency	◐		◐	◐	◐			◐	◐		◐			●
Groundwater Supply	Depletion of groundwater quantity	◐		●	◐	●			●	◐		●	◐	◐	
	Depletion of groundwater quality	◐			◐	◐			●			◐	◐	◐	
Desalination Supply	Negative impact on environment	◐		◐		◐	◐		●			●			◐
	High production cost			◐	■	■	■	◐	◐		◐	◐	■	■	■
	High water demand	◐	◐		■	■	■			◐	◐	●	■	■	■
	Impact of nuclear power on water production	■	■	■	■	■	■	■	■	■		●	■	■	■
Information & knowledge	The need to improve Knowledge base	◐				◐	◐	◐		◐		●			◐
	The need to Educate consumers/farmers		◐	◐		◐		◐				●			
	Lack of integration between different databases	◐			■	■	■	■	■	■	■	■			●
Water planning	Lack of integrated water planning	◐				◐		●	◐	◐	◐	●			◐
Water Scarcity	Absence of natural freshwater resources	◐				◐	◐		●		◐	●	●		◐
Treated Wastewater Supply	Low treated wastewater utilisation	◐	◐			◐			◐			◐	■	■	■
	Need to build treated wastewater infrastructure	◐			■	■	■	■	■	■	◐				◐

● Two and above from the entity; ◐ One from the entity; □ No one from the entity; ■ No one from the group

6.3.1.1 Water Use

All the groups perceived that the most critical water issue was the high water use in agriculture as well as in the domestic sector, but with an emphasis on the groundwater use in agriculture as being more crucial. It is characterized as "unsustainable water use" by DESAL and AFL. GOV and REG indicated that the government's agriculture subsidies are responsible for the unreasonable use of water instead of promoting water conservation. RESEARCH and AFL also stated that farming practices such as employing irrigation methods, water management and crop selection schemes have led to the high water use and over-pumping of groundwater. AFL in particular expressed strong views on the state of high water use in agriculture: "The use of water in agriculture is frightening especially in terms of groundwater and desalination water use."

The participants commented that the increasing agricultural water use has affected the quantity and quality of non-renewable groundwater. GOV highlighted that the high abstraction of groundwater would lead to the drying up of aquifers in the Emirate. In fact, they stated, "some aquifers in Abu Dhabi are already dried up". They indicated that this led to increased desalination supply in order to replace a groundwater shortage in agriculture, where they further added: "Limiting unsustainable groundwater use is critical because of its long-term impact on the country's security, which does not have agricultural capabilities, and of the environmental damage of desalination production." They also anticipated the importance of mitigating the "unsustainable" use of groundwater while moving away from high carbon and energy-intensive water production via "desalination" to a more energy-efficient and less carbon-intensive processes.

Similarly, REG noted the significant impacts of increasing groundwater use on its future reserves, stating that "Increasing use of groundwater for agriculture will lead to groundwater disappearance." In addition, they expressed their views on the severe exploitation of groundwater currently ongoing: "We are pumping 20 times more than the recharge which leads to both deterioration of the groundwater quality and drop down in the water table level."

DESAL's comments were more focused on the high domestic water (desalinated water) use, where they said: "Consumption per capita in Abu Dhabi is very high compared to the rest of the world." They indicated some of the reasons behind such high use: "High-quality desalinated water has been provided for free for many years therefore people disregard water and misuse it."

6.3.1.2 Groundwater Supply

All the groups highlighted the decline in quantity and quality of groundwater as critical water issues (at least one SME from each group). Particularly the increase in groundwater salinity and depletion of its quantity were noted as affecting agricultural production.

6.3.1.3 Desalination Supply

Desalination is also noted as a critical water issue, since it is the main source for the domestic water supply that can create a risk of no alternative source. As noted in the water use category, the increase in water use has led to increased desalination production, which has resulted in increasing the pressure on the environment. The SME from RESEARCH noted: “Increasing the number of desalination plants in the Persian Gulf will lead to increase the salinity, not only in the UAE but from all the GCC countries.”

There was a greater focus among the SMEs from DESAL on desalination issues, as most of them professed this as “the current most pressing issue”. They explained their concern about the increasing demand, that had reached 10% per year since 2001 and had led to increasing desalination production capacity (Section 4.2). The SMEs from the DESAL group also raised their concern about the expected impact of the new nuclear power plant (standalone power generation), which is disconnected from the traditional co-generation of power and water (Section 4.2). The increase in power-only production is expected to create a lag in water availability because of its historical strong link with power generation. Consequently, this will push for the need to build standalone desalination plants such as those employing reverse osmosis (RO), which relies on electrical power rather than thermal energy.

6.3.1.4 Information and Knowledge

The main issue raised in relation to information and knowledge was the lack of data, studies and consumer awareness of water-related issues. This is perceived as a significant gap across the sectors. There were three themes identified: education of consumers, developing a knowledge base (accurate information on groundwater, real cost of water, consumption, etc.) and integrating databases (pools) from different entities. All the groups (at least one SME from each group) highlighted the need to improve the knowledge base and consumers’ awareness, whereas only GOV and AFL pointed out the issue related to the integration of the entities database.

In general, most of the participants perceived that the lack of complete and accurate information and data was the main obstacle to having a complete understanding of the issues needed to help develop suitable policy and associated action plans. They also specified that the absence of data on groundwater abstraction, crop water requirements and new irrigation methods could be the reason behind the high agricultural water use.

6.3.1.5 Water Planning

All the groups (at least one SME from each group) observed that there was a lack of integration between the entities. GOV and RESEARCH noted that integration is required between the entities not only within the water sector, but also with the food and energy sectors. REG added that this integration should feature at the policy-making and planning stages to avoid any conflicts between water policy, agriculture and food security policies. They highlighted the issue related to the lack of agriculture and water strategy: "The absence of the agriculture and water strategy is a big issue. People and entities do not know the general priority and each entity has its own priority." However, they also mentioned that things have changed in the last two years, where efforts have been noted on both supply- and demand-side management.

This issue was further voiced by the SMEs from the DESAL group, who added that integration between desalination, groundwater and treated wastewater should also occur from the regulatory point of view. They put the emphasis on treated wastewater supply, since it has currently moved to their jurisdiction, where they need to be more focused and develop intensive planning to build the required infrastructure and develop a suitable regulatory framework.

6.3.1.6 Water Scarcity

The water scarcity issue was highly recognized by the majority of interviewees. They highlighted the absence of natural freshwater and the negligible groundwater recharge, which indirectly refers to low precipitation.

6.3.1.7 Treated Wastewater Supply

GOV, RESEARCH, REG and DESAL groups (at least one SME in each) pointed out the current low utilization of treated wastewater (Section 4.3). They interpreted this as being a huge waste, which can be retrieved and used in irrigation instead of using desalination. However, it was not mentioned by the SMEs from the AFL group. Furthermore, the need to build treated wastewater infrastructure was only mentioned by the SMEs from GOV, DESAL and AFL and was missed during the discussion with SMEs from RESEARCH and REG.

6.3.2 SMEs' Suggestions to Alleviate Water Issues

In order to encourage SMEs to elaborate more during the interview, they were questioned on the reason behind these critical water issues and then their suggestions for improvements. In the discussions they pointed out the lack of integrated planning, agricultural expansion, increasing interest in farming, unsustainable use of water, and lack of public knowledge on water value and the real evaluation of groundwater value and cost.

Almost all of the SMEs realized it was essential to create an action plan to reduce the stress on water resources, as stated by one of the AFL SMEs: "It is very difficult to continue on the same existing water use pattern." The suggestions offered by the groups mainly concentrated on developing a holistic strategy and knowledge base, increasing public knowledge and awareness, reducing water use, introducing innovative technologies, increasing or introducing tariffs and integrating water planning and policy (Figure 6.1).

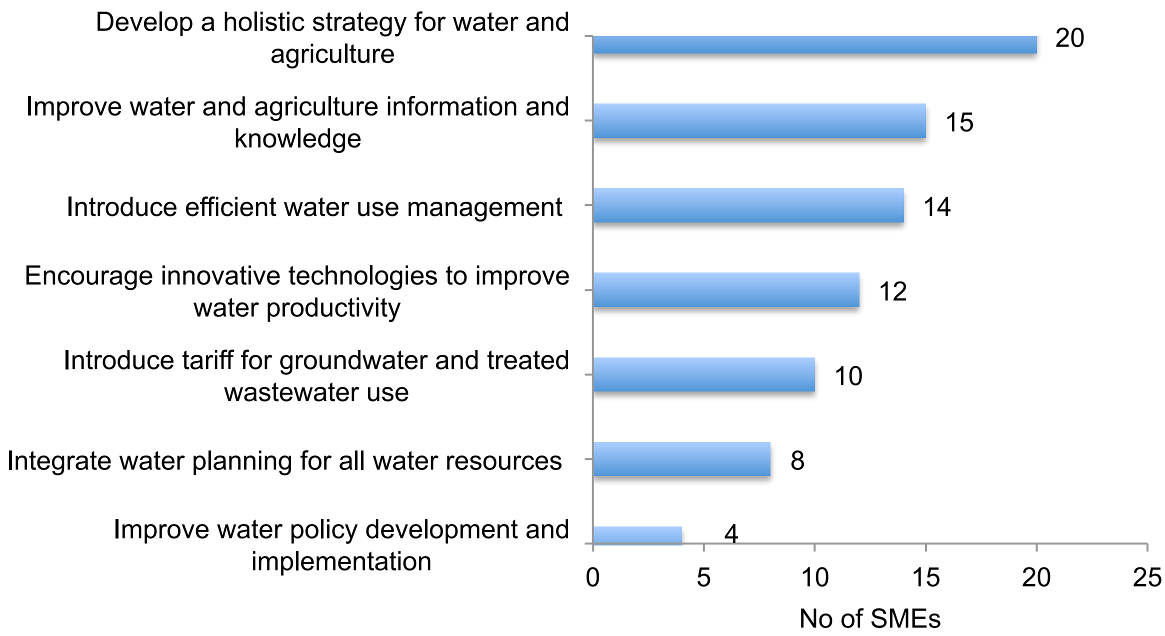

Figure 6.1 Interviewed SMEs' suggestions to alleviate the critical water issues in ADE.

Table 6.5 exemplifies the distribution of the different suggestions as proposed by each group of study respondents. It shows that all suggestions were made by at least one SME from each group, except introducing water tariffs and improving water policy development and implementation, which were not mentioned during the discussions with any of the SMEs from DESAL or GOV and AFL, respectively.

Table 6.5 SMEs' suggestions to alleviate critical water issues.

Category	GOV			RESEARCH			REG			DESAL		AFL		
	EAA	GSEC	MOCCE	FSCAD	ICBA	AGEDI	EAD	RSB	UPC	ADWEA	ADWEC	ADFCA	ADFSC	DMAT
Develop a holistic strategy for water and agriculture	◐	●	●	◐	●	◐	●	◐	◐		●	●		
Improve water and agriculture information & knowledge	●		●	◐	◐	◐	●	●	◐	◐	◐			●
Introduce water use efficiency management	◐				●	◐	●		◐	●	◐	◐		◐
Encourage innovative technologies to improve water productivity		◐	●		●	◐			◐	◐	●			◐
Introduce tariff for groundwater and treated wastewater use		◐	◐	◐			◐	●	◐	■	■		◐	◐
Integrate water planning for all water resources	◐			◐			◐	◐		◐	◐	◐		◐
Improve water policy development and implementation	■	■	■		◐	◐	◐				◐	■	■	■

● Two and above from the entity ◐ One from the entity □ No one from the entity ■ No one from the group

The participants' suggestions are summarized in the following subsections.

6.3.2.1 Develop a Holistic Strategy for Water and Food (Agriculture)

More than 50% of the interviewed SMEs suggested the importance of developing a new strategy that was comprehensive with a holistic approach. They stressed that the absence of such a strategy may create a failure to achieve the government's strategic objectives. They also suggested this strategy should be developed in a way that balances sustainable and economic agricultural production, water use in agriculture and food demand with its economic viability.

They emphasized that creating this balance was quite challenging, as stated by AFL, "the challenge is to create a balance between the sustainable uses of water and to sustain the groundwater reserve". DESAL added: "we need to balance between food demand and the cost of food production. Maybe it is better to produce the same food in another country with a more suitable environment."

However, some SMEs were against domestic agricultural production, such as the SME from the REG group, who indicated: "Realistically, we are living in the desert, therefore UAE will never be sustainable with its water use; we can move away from growing food to slow down the water demand a little but we will not solve it." Others saw local food production as feasible if changes were ensured in current practices such as utilizing TW, crop selection, irrigation and agricultural methods. They also suggested reducing government subsidies, which they believe would encourage farmers to preserve resources. These groups also suggested decommissioning some of the forest trees that are of high water use and no clear and measured value. It is confirmed by GOV that currently there are no incentives for farmers to preserve water since they are not paying for it.

The suggested strategies were more likely to change the current practices and induce a new approach with a different mindset that could be suitable with the given environment and the given needs. The SME from the RESEARCH group noted: “we need to revisit the way we use groundwater and we should focus on water rather than on food production as it can travel easier than water”. They added the need to understand the difficulty the country was facing, such as the growing water and food demand when the population rate was increasing as well as the vulnerability of groundwater to meet agricultural water demand: “We obviously have an increasing amount of treated wastewater. We can pay for desalination but if we lose the groundwater system, we are not going to get it back. The problem is we are not only losing the quantity but also losing the quality.”

6.3.2.2 Improve Water and Agriculture Information and Knowledge

Nearly 42% of SMEs suggested developing information and knowledge that focused on three main areas: increasing awareness among consumers, improving the knowledge base and integrating data pools from different entities to be accessible for decision- and policy-makers.

Most of the SMEs considered that the public need to realize the difference between cultural heritage and the real cost of water. The SMEs also stressed the need to understand the methods of conservation of such heritage and their impacts on future water demand. This will help to change people’s mindset, especially farmers, towards water conservation and understanding the government’s positions, thereby encouraging them to work with the government to meet its objectives and targets.

However, some frustration was noted on what they believed was the “current misuse” of water, especially among the younger generation, as stated by the DESAL SME: “Consumers do not care and are not interested to pay attention … Consumers who are in their 50s are more conscious and pay more attention to water conservation.”

Some added that any support or help the government provides should be tailored to encourage consumers to play a role as part of solving the problem and to participate in meeting the objectives. As mentioned by the SME from the RESEARCH group: “We need to differentiate between helping people and making them helpless with providing support to the people and offer them incentive to work harder alongside the government in order to be part of the solution which would be faster and more effective.”

6.3.2.3 Introduce Efficient Water Use Management

The third SME suggestion was on managing water use through reducing agricultural water use, controlling groundwater abstraction and reducing domestic water use (38% of interviewed SMEs).

First, reducing agricultural water use is suggested through introducing more water-efficient crops and irrigation technologies, efficient water use technologies (such as hydroponic systems) and limiting and controlling water use on farms, especially those established for personal use. They highlighted that there was excessive irrigation in the agricultural sector, which if reduced will not necessary mean reducing agricultural production.

Second, controlling groundwater abstraction was mentioned by the SME from the AFL group: "In my opinion regulation of the groundwater abstraction will limit the misuse of water because from my experience any quantity of water available for the farmer will be used entirely even if they have a river of water." They added: "If the farmers know they will be paying if they are using more than the allowed limit they will be careful."

The third suggestion was reducing domestic water use through the promotion of water-saving technologies and the introduction or increase of water tariffs, which will be expanded on in the following section.

6.3.2.4 Encourage Innovative Technologies to Minimize Water Wastage and Improve Productivity

Innovative technologies were suggested by 33% of the interviewed SMEs. They stated the need to encourage the development and use of innovative technologies that enhance water productivity and reduce wastage, such as hydroponic and aquaponic systems. They also suggested providing means of water storage such as the current aquifer storage technique which is installed to store desalination water in Liwa aquifer in the WR (Section 2.5.4.2). However, DESAL's opinion is that such storage would not be enough for future demand and suggested further options to be explored. Some of the SMEs believed that there is a potential to use innovative technology to find alternative water resources for irrigation, such as the dehumidification and treated wastewater suggested by GOV, which also realized that this area requires further research and development.

6.3.2.5 Introduce Water Tariffs for Groundwater and Treated Wastewater Use

The DESAL group stated that as a drinking water tariff was introduced in 2015 and increased in 2017, there was also a plan to further increase it to reflect the full water production cost. The government's objective for this increase was to help change people's behaviour and water use pattern, especially on non-essential use such as for gardening (irrigation), swimming pools and car washing. A similar approach was suggested for groundwater. The SME from REG underlined the government's initiative to encourage government offices to reduce water use, stating: "Currently, the government is working on reducing water use in mosques through promoting installation of low flow faucets." He also explained that since 2011, all government buildings have been paying the full cost of water and do not receive any subsidies from the government. This decision has encouraged them to introduce different means to reduce water use in these buildings, as shown in Section 4.3.

6.3.2.6 Integrated Water Planning and Management for All Water Resources

Most of the SMEs highlighted that there were many entities involved, either directly or indirectly, in managing water systems. This has resulted in fragmented and uncoordinated efforts. Therefore, 8 out of the 36 interviewed SMEs suggested improvement in water planning through establishing an integrated approach at the water policy level, water planning and water management. Some added that there was a need to re-assign one entity to take responsibility for managing all water resources. Others suggested aligning agriculture policy with water policy to avoid any conflicting output.

6.3.2.7 Improve Water Policy Development and Implementation

Although water policy was an underlying theme in all the six suggestions mentioned earlier, it was also directly suggested by some of the SMEs (4 out of 36 interviewed SMEs). Specifically, they suggested that policies need to be clearly scoped with defined implementation and auditing mechanisms. An SME from the GOV group stated: "We should work on developing a proper definition for food security, minimum nutrients per person, groundwater reserves and conservation priorities."

6.3.3 Policy Development

Water use in irrigation and mainly agriculture is the highest among all sectors (Section 4.3), which influences the groundwater reserve and thus puts pressure on desalination and treated wastewater supplies. The review of the historical development of agriculture-related policies shows that they are disconnected, while there is no accessible record demonstrating these policies. Therefore, in order to develop an in-depth understanding of water- and agriculture-related policies, interviewees were asked about the existing agricultural water use policies and those that are currently in the review and approval process. There were also enquiries about the way these policies were formulated and used for implementation, and the main barriers to successful implementation.

6.3.3.1 Water Use Policy in Agriculture

Although most of the interviewees stated that they were not aware of any existing policy specific to water use in agriculture and forestry, they indicated that there are a number of existing policies that are related to or may be affected by water use in agriculture. These policies were not integrated with each other, as stated clearly by DESAL: “In general, we develop policies in isolation. I am not aware of any entity who develops policy for water use in agriculture; this should be a good starting point.”

However, GOV highlighted that there was a water use policy related to desalinated water use, but stated also that there was ambiguity with this policy. An example of this can be found in the way Law No. 2 has been framed, which stated that the utility has to respond and meet all reasonable water demand, as shown in Article 30 (Duty to match capacity to demand):

> It shall be the duty of the Abu Dhabi Water and Electricity Company to ensure that sufficient production capacity is provided to ensure that, at all times, all reasonable demand for water and electricity in the Emirate is satisfied. (RSB, 1998, p. 25)

Reasonable water demand is not clearly defined in this article. This raises important questions about what extent, what quantity and for what purpose agricultural water demand should be considered reasonable. DESAL, however, viewed the only existing water use policy in agriculture as limiting desalinated water use in irrigation via house connection permits that are provided through distribution companies (ADDC and AADC). They also indicated that this policy defines the land use for irrigation, but there are no defined measures of the allowed quantity. They further added that at house connection there is no physical segregation between water connections for domestic use and for irrigation use; therefore, they concluded that it is difficult to measure how much is used in each.

The majority of SMEs indicated that policies or decisions related to agriculture, such as permits for drilling wells, distribution of farms and government subsidies, have great impacts on water use. DESAL highlighted that the late Sheik Zayed's greening policy (in the 1970s) is one of the major policies that directly affected water use. They expressed that the public and cultural-social link to his legacy creates difficulties in altering this policy. Conversely, the latest agricultural subsidy reform to discourage or stop the growing of Rhodes grass (2010) has resulted in a saving of 40% of water consumption in agriculture, as stated by AFL (ADFCA's estimation based on the amount of Rhodes grass planted and not based on the actual volume of water reduced). Some of the participants could not identify any of the policies, but they mentioned some of the government activities that could promote water use saving. These include providing guidelines to restrict/reduce water use in irrigation and developing a funding programme to build hydroponic systems (technologies with less water use).

6.3.3.2 Policy Development Process

The majority of participants stated that the government office represented in GSEC took the role of managing the development of and finalizing water and agriculture policies. However, the related entity could initiate the process and put out its recommendations in order to discuss them with different related stakeholders under the management of GSEC, who will eventually make sure to obtain final approval from the EC. A good example is ADWEA's initiative to manage treated wastewater utilization and distribution through ADDC and AADC. GSEC approved this suggestion and instructed ADWEA to conduct the necessary arrangements and studies to define the scope, budget and timeline required, as well as the development of the implementation mechanism for this policy.

6.3.3.3 Barriers to Successful Policy Implementation

The SMEs pointed out a number of barriers that they viewed as preventing successful implementation of policies. Table 6.6 shows the interviewed SMEs' perceptions of the main barriers to successful policy implementation.

Table 6.6 SMEs' perception of the main barriers to successful policy implementation.

Category	GOV			RESEARCH			REG			DESAL		AFL		
	EAA	GSEC	MOCCAE	FSCAD	ICBA	AGEDI	EAD	RSB	UPC	ADWEA	ADWEC	ADFCA	ADFSC	DMAT
Communication	◐	●		◐	●		●	●	◐	◐	●	●	◐	
PolicyiIntegration	●	◐	◐		◐		●	●		◐	●	◐		◐
Information & knowledge	◐	◐	●			◐	●	●		■	■			●
Implementation mechanism		●		◐	●		◐			■	■	◐		
Enforcement	◐	◐			◐		●	◐	◐		◐	●		◐
Auditing & review	●	◐			●		◐	◐		■	■	■	■	■
Time, effort & budget			◐		●		◐		◐	●	◐	◐	◐	
Willingness to change	■	■	■		◐	◐	●	◐	◐	■	■	◐		
Clear government direction and defined roles	◐	●		◐			●	◐			●	◐		◐

● Two and above from the entity ◐ One from the entity □ No one from the entity ■ No one from the group

All the groups (at least one SME from each group) indicated that the main barriers to policy implementation are communication, integration, enforcement, time/effort/budget, and clear government direction and defined roles. However, there are some barriers that were highlighted by some SMEs but not from all the groups, such as information and knowledge, implementation mechanisms, auditing and review, and willingness to change.

Communication

At least one SME from each group pointed out that the main barrier to successful policy implementation was the lack of communication between entities at the different stages of policy development and implementation. The SME from AFL translated the lack of communication into a lack of transparency, bureaucracy, unwillingness to share information, and lack of collaboration and coordination, not only between entities but also with consumers.

The GOV SME explained the current gap in communication that affects policy implementation: "Currently I notice that there is good coordination between the entities during the development of the policy but in the implementation phase, the coordination is not that good. Occasionally, some parties are not involved and their involvement is absolutely necessary. For example, in phasing out Rhodes cultivation, farmers should be involved as early as possible to be educated about the new policy and their alternatives should be discussed."

This was also confirmed by RESEARCH, who expressed the opinion that end users should also be consulted and their trust gained: "The executors who are affected by the policy should be onboard to gain commitment and buy-in for the policy. You will find a lot of counter measures against the policy, for example farmers are not convinced on drilling restriction or reducing groundwater abstraction." They further explained: "You will be surprised on the achievement and commitment if the policy is communicated properly with the right parties."

The SME from REG indicated the absence of communication when he specified: "It is a black box. For some policies, we are lucky to get a copy but we do not know what is the rationale behind the development of these policies."

Policy Integration

Similar to communication, at least one SME in each group indicated that the lack of policy integration and the disconnection between different policies raised barriers to successful implementation. This was observed by a SME from GOV, who stated: "Lack of coordination and integration between developed policies by different entities each having its own priority led to conflicting policies. A good example is restricting the drilling of water by EAD while ADFCA is supporting farmers to drill more wells."

Information and Knowledge

All the groups (at least one SME from each group) except the SMEs from DESAL pointed out how issues related to information and knowledge can be an obstacle to successful policy implementation. The information and knowledge issues perceived are the lack of reliable and accessible data (especially on groundwater, cost of water and information on consumption), the lack of education and awareness for consumers and the absence of links and integration between different data pools and different studies. The SME from the REG group stated: "The challenge is that there is a lack of information on groundwater and agriculture water use … We do not have enough confidence in the figures we have on groundwater."

Implementation and Enforcement Mechanisms

All the groups (at least one SME from each group) except those from DESAL raised the idea that the lack of implementation mechanisms and enforcement formed one of the main barriers to successful policy implementation. They stated that a higher authority's support was required to strengthen the entities' position during implementation and enforcement, which was a weakness at this time, as identified by one of the SMEs from REG: "These policies are developed with some consultation between the authorities and with heavy involvement by EAD. However, it does not go very far, it is only on paper." The RESEARCH SME added that there is a need to empower water governance by providing them with more authority/power to enforce water-related policies and regulations.

Auditing and Review

The GOV, RESEARCH and REG groups indicated the importance of periodical review of existing policies, developing auditing mechanisms and monitoring programmes to assess the output of each policy and define changes needed (if any).

Time, Effort and Budget

All the groups (at least one SME from each group) highlighted the existing fragmented effort, budget and time among the entities because of conflicts among entities' priorities in allocating their resources. The SME from the DESAL group stated: "The development of new policy is not easy and takes a long time because there are many stakeholders that should be involved and will affect a lot of parties which could also result in penalties. One example is the new law on groundwater; EAD spent years until it reached this stage before finally getting the approval." They added: "I know that all entities are working to improve water use efficiency in agriculture (ADFCA, FSC, DMA and EAD). But there are more distracted and fragmented efforts where everybody is doing his own bit with their concepts, strategy, objectives and mechanism."

Willingness to Change

At least one SME from each of the groups, apart from GOV and DESAL, stressed that resistance to change and cultural attachment to the current agricultural heritage can be one of the main barriers to implementing the policies.

Clear Objectives and Defined Roles and Responsibilities

All the groups, with one or more SMEs, raised the issue related to policy clarity with clear roles and responsibilities, and noted that a clear government direction is highly important to achieve successful implementation. The SME from the DESAL group stated: "In terms of policies we do not have a clear direction from the government other than some instruction to build more capacity."

6.3.3.4 The Importance of Communication and the Current Level of Communication between the Entities

As was demonstrated earlier, the main factor for the successful implementation of policies was communication. Therefore, more emphasis was directed to this area by further probing interviewees' views on the importance of communication and also exploring the current level of communication between the entities.

All SMEs confirmed that communication and coordination between entities were essential in order to understand the real issues, develop suitable policies and make decisions, whereas a lack of communication and coordination can cause wastage in water systems. It was expressed as the most important thing that should be part of everything; therefore GOV participants indicated that one of the main pillars in the Abu Dhabi 2020 and 2030 visions is improving communication and coordination.

The SME from REG group advised: “Absolutely, coordination is necessary, as these policies need to be developed jointly because of cross-cutting issues that span across a wide spectrum of economic, social and environmental objectives.” They also referred to the establishment of PCWAS as the government’s response to the realization of the need to improve communication between various entities. Although DESAL also agreed with the importance of communication, they stated that at a certain point in time there is a need to focus on implementation to avoid wasting time and to eliminate bureaucracy.

The current level of communication and coordination between the entities has improved. However, there was definitely a need for more improvement, as stressed in the following quotes from AFL: “Communication is a big issue in this sector. Each entity is focused on their own objectives and do not have a good view/interest to understand other entities’ objectives … The inaccuracy of information is due to lack of collaboration and transparency. Entities sometimes fake figures (or hide them) in a bid to protect their status without realizing the impact. This leads to inaccuracy of information, which was not intended in the first place … There are some improvements but it still needs to be better. Currently there is some sense of conversion competition amongst the entities.” The SME from REG added: ”We do not do enough of it. We have a number of water-related committees and they do not meet that often.”

In general, the SMEs realized the level of improvement of communication among the entities. They also appreciated the government’s efforts to help facilitate communication and coordination between entities and eliminate overlapping and double handling through GSEC, EAA and PCWAS.

6.3.4 Agriculture and Forestry Development

The continuous development of the agriculture/forestry sectors by government is one of the main areas of this study. Therefore, this question was asked of the participants and their opinion sought on a hypothetical reduction or stopping of agriculture in Abu Dhabi. By analysing the responses from the different groups, the main categories and associated themes/codes were developed in relation to water use, vision and objectives, and research and studies, as explicitly defined in Table 6.7.

Table 6.7 Agriculture and forestry development main categories and related codes.

Category	Theme/Code
Water use	Alternative water resources for agriculture
	Crop selection
	Soil type and soil treatment
	Innovative technologies
	Improve water use efficiency
Vision and objectives	Clear vision and defined objectives
	Set targets to contribute to food security
	Change mindset to be business oriented
Research and studies	Economic evaluation
	Water productivity
	Production value per crop
	Production yield per crop

6.3.4.1 Agriculture Development

The majority of SMEs either fully or partially agreed to the caveats, with only a few of them disagreeing with continuous agriculture development in Abu Dhabi. The participants who agreed believed that agriculture was extremely important and should be preserved while minimizing wastage and maximizing benefits. These benefits were not only economic viability but having the least negative environmental impacts, offering food security, cultural and social contributions, as well as influencing employment in ADE.

One of the SMEs in the RESEARCH group raised the high dependency of the country on food imports and explained: “We can’t always be 100% depending on food imports.” He indicated that there are many opportunities for improvement in current farming practices as described: “Most farm owners in the UAE do not have farming skills so they do not know about the highly efficient farming practices. If the farm owner’s objectives are to sell to the market they will make an effort to produce the required crop with the necessary quality.” As presented by AFL: “We can increase agricultural production with the same water used by improving water use efficiency.” Similarly, the GOV SME added: “Which do you want, you want your water or food production? I hope that we can use less water and produce more food by using certain technologies. Our current system is not efficient so we can reduce water while increasing food production.”

RESEARCH emphasized encouraging farmers to be business oriented, to think about improving productivity and to create high-quality branded production that could support diversifying food resources and reduce the full reliance on imported food. They also agreed that increasing agricultural output does not necessarily mean increasing water use. As a result, they saw that there are great opportunities in ADE, since there is currently a big gap in efficiency in terms of farming practices and water use.

AFL agreed with the RESEARCH group in their view on changing farms from personal use to business use, which will inspire farmers to pay attention to how much they pay and how much they get in return from their farm produce. They illuminated that even though the agricultural sector is heavily subsidized at the moment, the government's hidden intention is to gradually remove the subsidies and encourage farmers to increase their farm return to help the growth of the share of agriculture in the country's GDP (currently it is less than 1%). Increasing farm return could be possible, especially for some of the UAE's unique products such as palm trees that have commercial as well as social and cultural value. AFL also outlined that in the past farmers focused only on increasing production without paying attention to price, quality and wastage, but today and with the support provided by ADFCA and ADFSC they have started to talk about prices and efficiencies, which is considered a step forward.

In addition, the participants who support the continuation of agricultural development with caveats believed that it was not possible to be sustainable with the given environment. They suggested focusing on the high quality and cost-effectiveness of produce, but this would require taking different measures, as suggested by REG: "Agricultural development is very important for the country to maintain food security and cultural practices, but we need to ensure sustainable agricultural practice. We cannot say do not farm. But we need a lot of improvements, crop productivity, crop value and highly efficient water use."

GOV added: "We need to work on developing an agricultural policy that clearly defines the agriculture and food security targets, which is not clear for now and we don't really understand what the food production target is in the Emirate."

On the other hand, some of the participants suggested growing the required food in different countries with a suitable environment, which would facilitate more efficient production than the local food supply that is not cost-effective, especially if desalination water is used. They indicated that if the government's heavy subsidies were removed, especially for water, the cost of local produce would not reflect the true cost. Nevertheless, some of them support the use of treated wastewater, innovative technologies and changing farming practices to help to support agricultural production, although they raised the question of the real benefit of local food production and the target to fulfil the food security requirement.

Moreover, the participants who disagreed on the continuous development of agriculture found it not feasible from an ecological perspective. They indicated that the cost of development is very high and cannot be recovered by the revenue from the selling price, and at the same time it is not possible to achieve the required quality that can compete with imported produce. As stated by the RESEARCH group: “One of the challenges in the agriculture sector in the country is that we are using a lot of water to produce low quality and low value produce. Therefore it is questionable to continue farming in the same way.”

In summary, the interviewees who emphasized the importance of agriculture development in the Emirate also understand the difficulty in achieving this sustainably. Table 6.8 summarizes the number of respondents from different groups in terms of those who fully agreed, partly agreed and fully disagreed on the question of continuous agriculture development.

Table 6.8 Summary of SMEs’ views on continuous agricultural development in ADE.

Group	Total No. of SMEs	SMEs’ View	Count	Main Comments
GOV	7	Agreed	3	It is important mainly for food security and can be developed by focusing on maximizing benefits, minimizing cost and environmental impact
		Partly agreed	4	Only for certain products and in certain areas
		Disagreed	0	
RESEARCH	5	Agreed	2	It is highly important for food security and increases agriculture’s GDP contribution
		Partly agreed	3	Need to limit agriculture development to efficient farms
		Disagreed	0	
REG	8	Agreed	0	It is important for food security
		Partly agreed	6	With limitation and careful measures on crop selection and type of water used
		Disagreed	2	Not possible with the existing environment
DESAL	9	Agreed	3	It can be developed by using treated wastewater
		Partly agreed	4	Only for certain products and in certain areas
		Disagreed	1	The environment does not support agricultural production
AFL	7	Agreed	4	For food security and contribution to GDP
		Partly agreed	1	Should be balanced carefully with efficient water consumption and other sustainable dimensions
		Disagreed	1	Not economically viable
Summary	36	Agreed	12	
		Partly agreed	18	
		Disagreed	4	

6.3.4.2 Forestry Development

Most of the SMEs asserted that forestry was beneficial, but not to the extent of using desalination that increases the maintenance cost. Therefore, they recommended that some of the forest trees should be decommissioned, specifically those located in the wrong places with no clear and identified value/benefit. They also acknowledged that studies have to be conducted to quantify the significant benefits of forest trees and to define the right forest tree types for the right places.

Some individuals from DESAL and REG are against the development of forestry in ADE, since economic value and benefit are not clear, especially if irrigated by desalination, which is a very expensive way to maintain forestry. This was clearly stated by DESAL: "Developing forestry does not make sense in this country. We should not expand forestry. Although there is some benefit obtainable from forestry and also it is nice to look at, it does not make sense." REG indicated that currently there is a plan to decommission some of the forest trees along with trying to plant some of the forest productive trees and native forest trees with much less water use.

Nevertheless, most views did not fully agree with interrupting the growth pattern created by the late Sheik Zayed to improve water use efficiency and to focus on the most beneficial forest trees.

6.3.5 Water Resources for Agriculture/Forestry

The focus of this section is to assess the SMEs' awareness of the current deterioration and depletion of the groundwater, their propositions on alternative water resources for agriculture development and their perceptions on the complete reliance of agriculture on desalination or groundwater.

The analysis shows the awareness of all participants about the issues related to groundwater and their understanding of the need to preserve it, as it is fossil water and receives almost no natural recharge. Therefore, at the present time, there are many discussions among the groups on the use of recycled water (treated wastewater) in agriculture in order to reduce the pressure on groundwater and ultimately desalination. They strongly disagree on the complete dependence on groundwater in the future, particularly in vulnerable areas with high salinity.

The SMEs held similar positions when they were asked about the full reliance on desalination given its negative impacts on the environment and its demand for natural gas and oil. GOV strongly disagreed on the full use of desalination for agricultural production, but they suggested that desalination could only be used for high-value agricultural production: “In the absence of actual data on the current groundwater reserves and abstraction rate, it is difficult to make sound decisions on whether we need alternative water resources and what agricultural produce we should target.”

DESAL emphasized this issue, since it means more demand for natural gas and oil, thereby leading to wasting of natural resources with great negative impacts on long-term sustainability goals. They also stated that they should not blindly encourage decisions; all aspects of the issue should be looked at in an integrated way, without dismissing any area that could be affected directly or indirectly. On the other hand, REG found it almost impossible to fully rely on desalination and doubtful to rely completely on groundwater. They suggested a shift in the efforts to reduce water use and minimize groundwater abstraction, rather than trying to find an alternative to groundwater.

Even though RESEARCH stated that groundwater is the main source of water for agricultural production, they added that treated wastewater can be used as an alternative wherever suitable and that desalination can only be used to meet the shortage. However, they also recommended the need to have a cost-effective study to choose the most viable water resource suitable for different types of agricultural production.

6.4 Thematic Analysis Diagram

In order to develop meaningful results from the qualitative data analysis (the content analysis presented in the previous sections), a thematic network can be developed that illustrates the narrative of the themes that emerged from the qualitative data (Altheide and Johnson, 1994; Attride-Stirling, 2001; Braun and Clarke, 2006). As suggested by Attride-Stirling (2001), this analysis technique provides an effective and practical procedure for conducting data analysis that enables systematic understanding of the textual data and underlying patterns enhanced by a visual presentation.

The analysis of the interview data shows five main themes that are directly linked to the critical water issues in ADE with the need for careful attention and better management: water resources, water use, knowledge and information, policy, and water planning. The data analysis further highlight the SMEs’ (interviewees’) suggestions to eliminate and overcome the current situation on critical water issues.

The thematic network in this study is developed based on the five main themes and further incorporates the SMEs’ proposed solutions, as shown in Figure 6.2. Each of these themes is broken down to lower-order themes and subthemes demonstrating related issues.

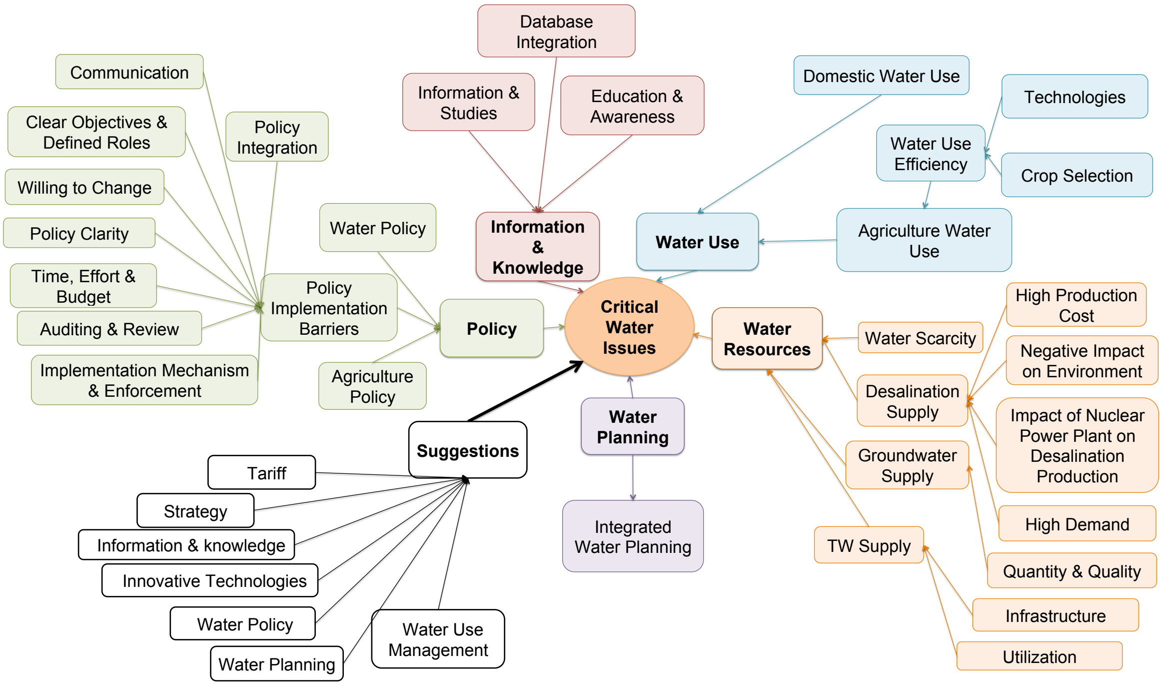

Figure 6.2 Thematic network of key themes obtained from semi-structured interviews.

The SMEs' main views on the critical water issues are summarized in the following subsections.

6.4.1 Agriculture Desalination and Groundwater Use

All interviewees understood the issues related to groundwater and desalination, yet they disagreed on full reliance on either of them. Treated wastewater has been seen as a good alternative to meet the deficiency of groundwater and to replace desalination in the agricultural sector.

6.4.2 ADE's Critical Water Issues

All the interviewees realized that high water use, in particular in agriculture, and its impact on groundwater were the most critical water issues. They stressed the three most vulnerable areas that with careful management can provide suitable solutions.

The first is developing an integrated and holistic strategy for both water and agriculture to avoid any negative and conflicting output. This is also applicable to water policy development. During the last few years, the government (EC) has also realized the need for a more integrated approach in water and the agricultural sector; therefore, it has assumed the role of facilitating coordination between the entities to reduce any double handling and duplication of effort (Section 6.2.1).

The second area is improving the status of information and knowledge. Currently, the information is scattered in different places, such as desalination data in ADWEA, ADWEC and distribution companies; groundwater data between EAD, ADFCA, ADFSC and DMAT; farm produce and related practices within ADFCA and ADFSC; and agriculture- and water-related studies fragmented across all entities, but with a greater focus in FSCAD, ICBA and AGEDI. This is also emphasized by recent studies (Pitman, McDonnel and Dawoud, 2009; McDonnell and Fragaszy, 2016). The interviewees highlighted the need for the integration of these fragmented data from all different entities to be centralized in one data pool, which will improve the accuracy of the data and avoid any inconsistency.

Finally, effort should be put into reducing water wastage, which can be done by improving education and awareness programmes and encouraging utilization of different technologies that aid less water use (Pitman, McDonnel and Dawoud, 2009; EAD, 2012b). A tariff is also strongly suggested by the interviewees, which has been realized as the shortest distance to reach the required objective, something equally suggested in the literature (McDonnell and Fragaszy, 2016).

6.4.3 Existing Agriculture Water Use Policies

A gap in the policy related to water use is obvious, especially in agriculture. There is no record of any water use policy to explain the type and fractions of water used and for what purposes. All the policies underlined are indirectly affecting water use. One example of these policies is reform of agricultural policies such as that for Rhodes grass, which was reformed in 2010 and is estimated to save about 40% of total water use in irrigation (EAD, 2012b). Another example is the negative impact of water use from the generous subsidies provided to farmers (Woertz, 2013) and the increase in domestic agriculture targets (EAD, 2017), which both encourage farmers to increase the cultivated area and thus water use.

6.4.4 Policy Development and Implementation Process

Although there is no documented record on the procedure for policy development, it seems that there is a mutual understanding among the entities that it should be done under EC/GSEC management. They also noted that for any policy initiatives, communication with stakeholders should be mandatory under GSEC supervision.

6.4.5 Barriers to Successful Policy Implementation

Even though there are some good policies in the water and agriculture sectors, where at the early stage of development all related parties put in effort under the supervision and management of the EC, there are some highlighted barriers that could prevent successful implementation of these policies. In recent years, although communication between the entities has improved, the absence of policy integration, information and implementation and enforcement mechanisms affected successful policy implementation, as shown in the Rhodes grass policy reform (Sections 4.6.4.2 and 5.4.1).

6.4.6 Agriculture's Continuous Development

The development of agriculture in ADE is important to most groups, and they understand how difficult it is to minimize wastage and increase water and agriculture productivity. However, some members of these groups, such as DESAL and REG, were more sceptical. They see agricultural production as having a negative impact on non-renewable groundwater reserves (which are considered the country's strategic reserves) and on desalination.

6.5 Chapter Summary

This chapter shed light on managing water use in agriculture across 14 entities associated with both sectors. Interviews were conducted with 36 experts (SMEs) to enable them to express on their views on the most critical water issues, their anticipated suggestions to elevate these issues, the current water use policy, the development and implementation of policies, the main barriers to successful policy implementation, and continuous development of agriculture and alternative water resources.

The data from the interviews show that the interviewees identified five main areas as the major reasons for the critical water issue in ADE. These areas reciprocally are scarce and limited freshwater resources, high water use particularly in the agriculture sector, lack of integration in water planning, the absence of a clear and integrated policy, and fragmented and incomplete knowledge and information. The majority of the interviewed SMEs further highlighted the need for a holistic integrative approach to water and agriculture in order to develop sustainable solutions. They also emphasized the current issues related to a lack of policy implementation and enforcement mechanisms that create a barrier to successful policy implementation.

The key findings in this chapter combined with the findings from the previous chapters have been used as the basis for developing the Agriculture-Water Policy Framework expounded in Chapter 7.

Chapter 7. Agriculture-Water Policy Framework

7.1 Introduction

This chapter proposes an Agriculture-Water Policy Framework (AWPF) that aims to address the identified gaps showcased in the previous chapters in order to develop a long-term strategic perspective on agricultural development for ADE. The proposed AWPF has been created to provide a clear understanding of the situation and the consequences of different policy options to inform decisions. It is structured following guidelines for best practice global frameworks promoted by international agencies, as well as a selection of frameworks that are developed at a local level. These frameworks mainly focus on a cross-sectoral integration approach to enable the development of a comprehensive sustainable agriculture-water framework.

The chapter consists of the framework development background, the framework objectives and structure, and its implementation in the ADE context, which weave in the discussion and recommendations based on the findings and output from the previous chapters. It also presents a policy scenario analysis for palm tree and vegetable cultivation and their link to food self-sufficiency and the impact on water demand. Furthermore, it demonstrates validation of the ADE AWPF in order to ensure that this framework is reasonable and provides a practical solution for the ADE government to sustain agricultural development.

7.2 Background

The global frameworks reviewed in Section 2.5.5 (IWRM, WFD and APAF) were selected in this study as best practice frameworks to provide the basis for the development of the AWPF for ADE. Further selected conceptual frameworks developed at a local level that were reviewed in Section 2.5.5 were also used to help develop the AWPF. Although the focus of each of these frameworks is slightly different, they are all aimed at achieving sustainable development of agriculture and water. The learning and knowledge obtained from the review of these frameworks were used to develop the AWPF.

The IWRM framework (Section 2.5.5.1) focuses on bringing together different stakeholders (water, agriculture, environment, food security, etc.), including decision- and policy-makers, planners, relevant scientists and professionals, and users, for the holistic sustainable management of water resources. It provides high-level principles and a set of process steps that can be used to develop a customized national and/or regional framework. These principles are focused on integrating the knowledge, information and participation of stakeholders to enable identifying of current gaps, setting of objectives, management of planning and monitoring of implementation that provides feedback for any necessary changes (Figure 2.4).

The WFD is connected to the Common Agriculture Policy (CAP), as noted in Section 2.5.5.2. The WFD–CAP connection focuses on farmers to secure food production and sustain natural resources while making provision for climate change adaptation. The WFD as a single institutional framework has the political will to manage water resources across EU countries, while also ensuring monitoring and data collection programmes. Through the WFD, the EU also mandated IWRM as part of its framework. The CAP created measures for farmers in order to optimize EU spending in the agriculture sector, protect agricultural production from international high prices and avoid overproduction, as well as environmental protection measures that are directly linked to subsidies provided to farmers. Similar to the IWRM planning cycle, WFD also provides a high-level planning cycle process that focuses on developing management plans, assessing their effectiveness and managing the agreed plan implementation (Figure 2.5).

The APAF provides theoretical steps that can promote clear thinking (Section 2.5.5.3) in order to reduce trade-offs between objectives and eliminate misunderstandings between stakeholders and policy-makers. It consists of four main interlinked components (objectives, strategies, policies and constraints) that can provide a systematic approach in the decision-making process.

The main principles and insights obtained from these reviewed frameworks were used as the basis to develop the AWPF for ADE. The components that were selected from these approaches in order to develop the AWPF are as follows:

- Integrating all relevant stakeholders and obtaining their input.
- Generation of knowledge (building capacity) by integrating expertise and databases.
- Setting management cycle steps from setting objectives to implementation and monitoring plans.

The framework management cycle process for these three frameworks was used as the basis for the development of the AWPF in this study. Further steps were added to make it more comprehensive and easier to follow.

7.3 Agriculture-Water Policy Framework Objectives

As explained in Section 4.5, in the last few decades the government has invested large amounts to meet self-sufficiency targets by increasing domestic agricultural production. ADFSC incentivizes farmers through subsidies, training, loans and guaranteed sale of their farm produce to increase their production, which has been successful. This has been limited to a few crops during winter (short season), provided a limited economic return and still met a small percentage (27%) of the market demand for those crops (Sections 4.6 and 4.7). At the same time, increasing agricultural development influenced the water resources, threatening the sustainability of future agricultural development.

The current basis of agricultural strategy and policy relied on the country's economic strength to subsidize both agriculture and water sectors while treating groundwater depletion as an externality. As the government recently realized the high risk to the country's strategic reserves, it anticipated the need to change the current management approach towards a more integrated approach (McDonnell and Fragaszy, 2016). Also the interview results show that the majority of SMEs are in agreement (Section 6.3.2). Therefore, the proposed AWPF overarching objectives are the following:

- Create a balance between meeting water demand in agriculture and preserving the groundwater while meeting social, environmental and economic needs.
- Rationalize agricultural policy-making.
- Rationalize the utilization of limited water resources.
- Establish short- and long-term sustainable water resources plans in the agriculture sector taking into account climate change and environmental impact.
- Align agricultural targets with food security targets.
- Reduce wastage (water, food, etc.) and preserve natural resources.
- Optimize water use and allocation of water resources.

7.4 ADE AWPF Structure and Implementation Process

The ADE AWPF consists of seven primary steps that are interlinked in an iterative sequential process, shown in Figure 7.1. These steps are: 1) establish ADE agriculture-water governance, 2) identify gaps and define scope, 3) develop agriculture objectives and associated strategies and policies, 4) issue final list of agreed policies, 5) enact policy implementation, communication and enforcement mechanism, 6) implement policy monitoring and auditing, and 7) develop reports on lessons learnt and recommendations. The descriptions and discussion of each of the framework steps are explained in the following subsections.

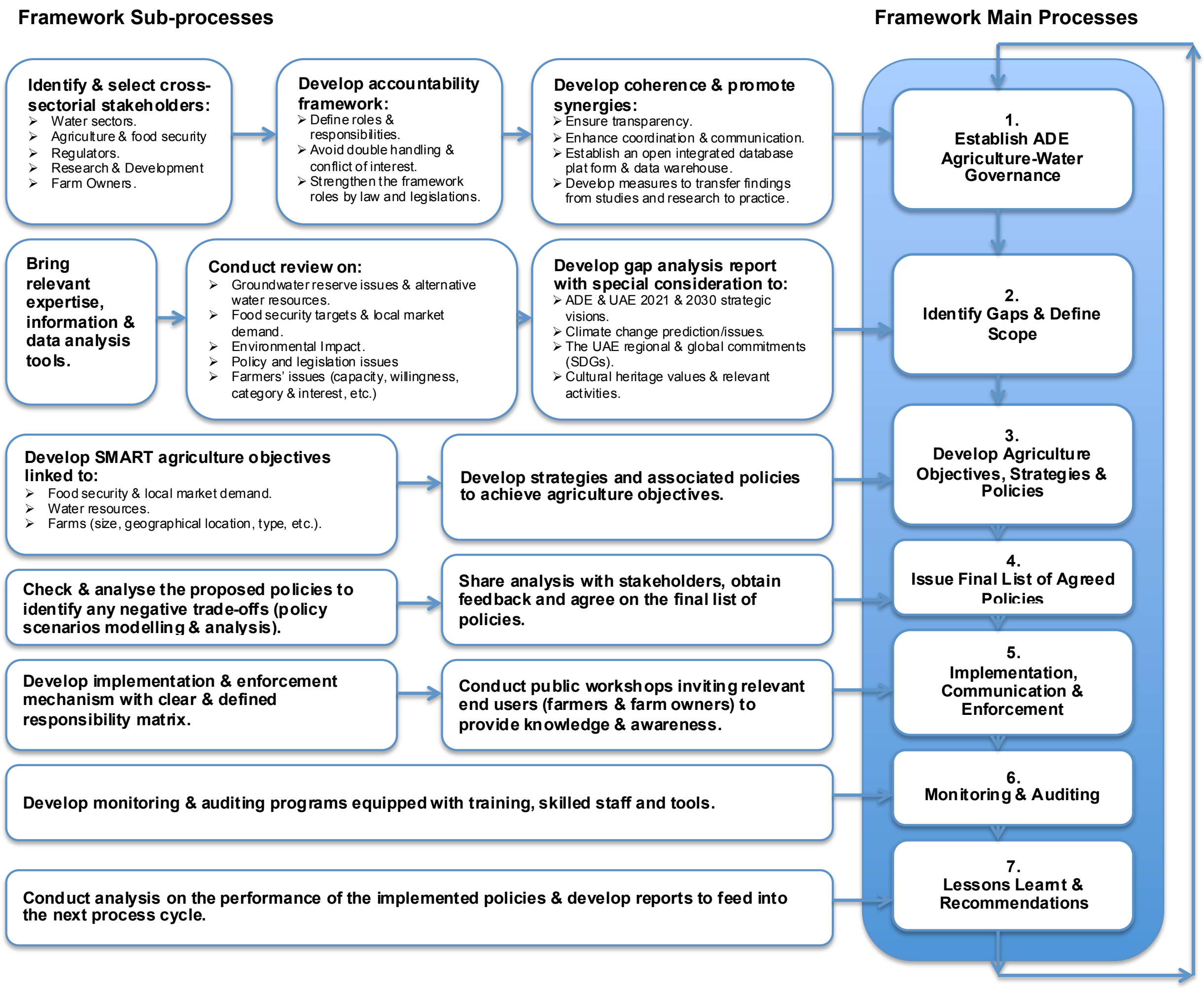

Figure 7.1 Agriculture-Water Policy Framework for ADE.

7.4.1 ADE Agriculture-Water Governance

The review of the current water and agriculture structure presented in Section 6.2 shows that there is a shared interest in water use across the entities, where duplicated roles and conflicts of mandates occur. Therefore, it is suggested that ADE agriculture-water governance should be established as the first step of the framework, as shown in Figure 7.1.

ADE agriculture-water governance is proposed to be developed in three main stages. The first is to identify and select cross-sectoral stakeholders from various relevant systems. These stakeholders can come from five main groups, as shown in Figure 7.2.

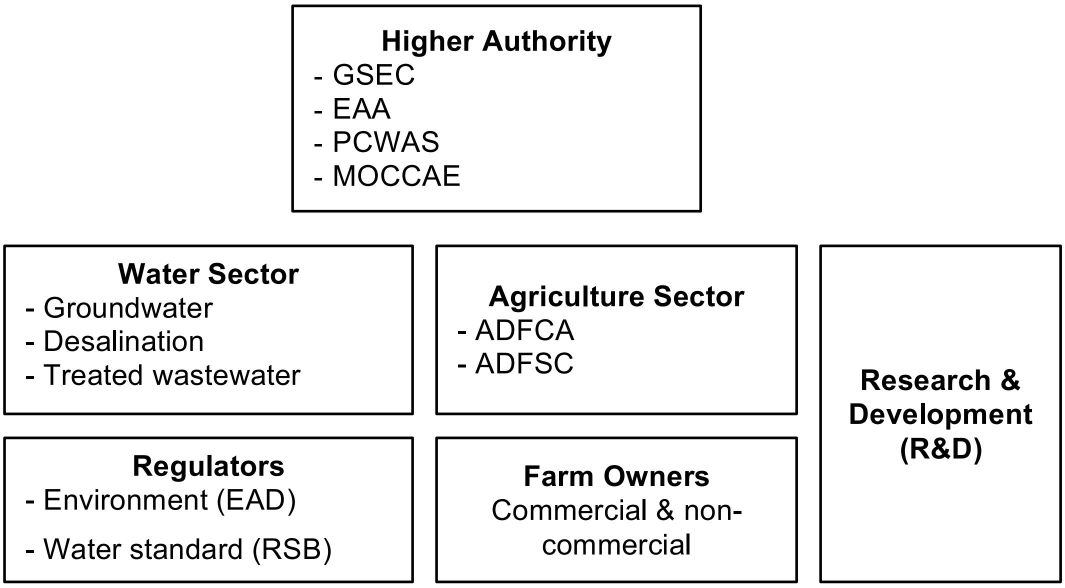

Figure 7.2 ADE agriculture-water governance key stakeholders.

The higher authority consists of entities/committees under EC, such as GSEC, EAA, PCWAS and MOCCAE, which already exist, as presented in Table 6.1. These bodies have the authority to administer the development of water and agriculture policies, as well as other policies and strategies including food security. Similarly, the agriculture sector as an existing structure consists of ADFCA and ADFSC. However, it is suggested that the water sector be managed by one entity (group) to operate, maintain, supply and manage all water resources (groundwater, desalination, treated wastewater), including groundwater, which is currently managed by four different parties (ADFCA, EAD, ADM and farmers).

EAD and RSB fall under the regulator group, where EAD remains responsible for safeguarding the environment from any negative impact that could result from regulation of drilling and groundwater abstraction, and RSB is responsible for water quality standards. However, the absence of environmental assessment and regulation of small-scale brackish desalination (including brine discharge) becomes critical and contributes to groundwater and soil contamination (Section 4.5.4). Therefore, this scope needs to be added (activated) to the EAD's roles.

The R&D and other relevant studies, as explained in Sections 2.5.2 and 6.2, are mostly done by ADFCA, AGEDI, ICBA and FSCAD, where there is no defined mechanism on how the research findings can be used in practice. Therefore, such a mechanism is to be established along with an open database platform to integrate all scattered data and information in one central database.

In this structure, the farm owners' group is also to be included, which can be done through a farmers' association – which is to be established – or delegated farm owners. In order to obtain farmers' views and gain their commitment to ensure successful policy implementation, it is suggested that the farmers' group needs to be actively involved as part of the strategy and policy development process. This way they will be part of the solution rather than part of the problem, as proposed by the AFL interviewed SMEs (Section 6). This will improve their understanding of the real situation, the negative impact of high agricultural water use and how their farm produce can be sustainably linked to food security.

Secondly, to develop an accountability framework where the boundaries between the role of stakeholders and their responsibilities are to be defined, and to facilitate a feedback loop for ensuring coordination and integration of knowledge, expertise and information, the development of an interconnection and communication mechanism is needed. Furthermore, it is also required to enhance and strengthen the framework roles by law and legislation.

Finally, developing coherence and promoting synergies can be achieved by enhancing transparency, ensuring coordination and improving communication between the entities. This will help to avoid any fragmentation in effort, double handling and conflicts of interest. All of these were highlighted during the semi-structured interviews (Sections 6.3.2.6 and 6.3.3.3) as the main barriers to successful policy implementation.

Developing coherence can also be done by establishing an open and integrated database platform and data warehouse in order to build up an accurate and accessible database that can be updated in a timely manner. This will facilitate bringing the largely scattered data, knowledge, information and databases from the various entities (14) together to feed into a centralized database that can be accessible to all users, especially decision- and policy-makers. Furthermore, to make the best use of research and studies, there is a need to develop measures to transfer the findings of studies to practice. Research and development, technology generation and their applications have to focus strongly on the government's objectives of optimizing resources, conservation and preservation of groundwater and maintaining agricultural sustainability.

As noted in Section 4.1, in ADE there is a gap in the current water use and groundwater abstraction rate data, especially at the farm level. At least one SME from each group interviewed highlighted the critical need to address the knowledge gap and database integration across the sectors, which prevent a clear understanding of the current situation (Section 6.4.3.1). They further emphasized that this gap could be the reason behind the high agricultural water use and the main barrier to successful policy implementation. They also indicated that the efforts of professionals and experts are fragmented across the sectors (Section 6.3.2.6). Therefore, to allow systematic and empirical assessment of the current agriculture and food security policies and their implications, ADE needs to integrate all data pools together and bring professionals and experts from different disciplines to build an integrated, comprehensive and accurate database.

The current efforts of ADFCA, ADFSC, EAD, ICBA and MOCCAE can be further developed to be part of the integrated database. These entities have developed demonstration plants and conducted on-farm research and studies on cultivating different crops/species using innovative technologies with efficient water use and improved crop productivity. Relevant examples of these research initiatives and demonstration plants are the production of vegetables and fish using aquaponic systems (Section 2.5.2), the cultivation of vegetables in hydroponic systems and greenhouses, and fish farming using saline and hypersaline groundwater. Currently, there are some successful attempts at cultivating halophytes in different parts of the country, such as quinoa and salicornia which contain high levels of proteins, based on saline and hyper-saline irrigation water (Section 2.5.3.3). These methods need to be further developed, promoted and widely implemented as part of the overall strategy.

7.4.2 Identify Gaps and Define Scope

The second step in the proposed AWPF is to conduct a review and gap analysis exercise (as followed in the IWRM cycle in Section 2.5.5.1 and 2.5.5.6) in order to identify gaps and define the required scope. It is suggested to bring relevant expertise, information and data analysis tools to help conduct a systematic assessment of the implications of the existing agriculture targets, policies and farmers' practices on water resources, food security and environment. The gap analysis reports to be developed with special consideration to the country's strategic vision, SDGs regional and international commitments, climate change predictions (Section 2.2.3), and cultural heritage values and preservation activities. Pinpointing any negative consequences found from the review, and figuring out how to minimize them when developing new policies, is one of the main outputs of this process. It may lead to adjustment of the current policies or the development of new policies.

At this stage sufficient information on the current policies, demand, supply, resources and national and international markets is strongly required in order to draw an accurate picture of the results and consequences. The information from the recent governmental reports could be used to conduct the review and identify the gap. This study provides comprehensive empirical and quantitative findings that can also serve as the input dataset in this process.

This study shows that ADE is facing a decrease in groundwater availability, which has already created a shortage in meeting agricultural water demands and is being gradually replaced by seawater desalination. If the current unsustainable groundwater abstraction rate

(Section 4.3) does not improve, the agriculture sector's development could be at risk in the future. This shows the urgent need to preserve and protect the groundwater as well as identify the sustainable abstraction rate.

The study also shows the inefficiencies of agricultural water use in current farming practices, for instance in the cultivation of intensive water use crops, including Rhodes grass, alfalfa and seasonal vegetables (e.g. onion, sweet melon, bean, tomato and cabbage). These seasonal vegetables are mainly cultivated by open field farming, which exhibits high water use, low crop yield and low water productivity (Section 5.4.5). The greenhouse farming technique, on the other hand, shows far better performance, with low water use and high productivity compared to open field farming. However, only 7% of farms used this technique, by which they mainly cultivated cucumbers.

Furthermore, palm trees are cultivated largely for their cultural heritage link rather than their economic value. They show poor management with high water use, low crop yield and poor water productivity, in addition to the excessive supply of dates that has reached 4.4 times the required demand, with a high percentage used as animal feed due to the poor quality and low export ratio (Section 4.6). Other than date palms, only a few vegetables can contribute to food self-sufficiency, with a small accumulated percentage (27%) of the five main vegetable crops mainly during the winter season (Section 4.6).

7.4.3 Develop Agricultural Objectives, Associated Strategies and Policies

As demonstrated in Section 6.3.2, there is no evidence of an integrated agriculture strategy that is linked to food security and water resources. The majority of the interviewed SMEs significantly highlighted the issue of developing existing agriculture policies in isolation from water use policies. They emphasized the urgent need for an integrated approach that can link policies, expertise, data and information scattered across various sectors. Based on the output of the review and gap analysis process explained in the previous step (second step of the framework), the framework suggests developing SMART (Specific, Measurable, Available at acceptable cost, Relevant and Time bounded) agriculture objectives. The agriculture objectives can be based on efficiency, equity and security (Pearson, Gotsch and Bahri, 2004). Example of agriculture objectives can be food security, affordability, sustainability of natural resources used, water conservation, improving agricultural productivity, providing employment, reducing food import dependency and so on. These objectives should be quantifiable and measurable (as noted in the implementation of APAF). At the early stage of developing agriculture objectives, the link should be established with water resources, climate change and other resources required (such as arable land, infrastructure, finance, etc.).

The literature review and the findings of the research objectives explained and discussed in previous chapters helped to identify two main goals for ADE's quest to preserve groundwater and ensure sustainable agricultural production: water conservation and food self-sufficiency. The suggested objectives and associated strategies and policies are explained in detail in the following subsections.

7.4.3.1 Suggested Objectives to Achieve Water Conservation

In order to achieve the water conservation goal, mainly aiming to preserve the groundwater, objectives WC1 and WC2 are suggested, as follows (Table 7.1).

Objective WC1: Reduce groundwater abstraction rate to equal to or less than 130 Mm^3/year.

In order to preserve the non-renewable groundwater, limit the abstraction rate to the renewable groundwater, which is estimated to be 130 Mm^3/year in Sections 1.1 and 4.4.2. This limit would maintain sustainable groundwater abstraction.

Objective WC2: Increase utilization of treated wastewater to reach 100%.

Currently, only 1% of the total treated wastewater produced is used in agriculture (ADFCA treated wastewater pilot on 143 farms), as shown in Section 4.3. Half of the remaining quantity is used for amenities and the other half is discharged to the sea. If the discharged quantity were redirected for use in agricultural production, 160 Mm^3/year of the existing water used would be saved. This rate is higher than the renewable groundwater abstraction rate (130 Mm^3/year).

Treated wastewater can be used to produce vegetables in greenhouses and other efficient water use techniques such as hydroponic, aquaponic and so on. This will help increase treated wastewater utilization (WC2) and contribute to food self-sufficiency for selected vegetable crops that demonstrate high water productivity, as stated by a number of studies in Section 2.5.3.2.

7.4.3.2 Suggested Objectives to Achieve Food Self-Sufficiency

To increase food self-sufficiency, the following objectives can be presented (as optional objectives) and further evaluated (Table 7.1 and Section 7.5). Objectives FS1 and FS3 are presented for the current ADE situation (self-sufficiency ratio, water use and crop yield rate) to help conduct a comparison with alternative scenario objectives such as FS2 and FS4.

Objective FS1: 441% of palm date self-sufficiency (current situation).

Objective FS1 is aimed at developing a scenario for maintaining the current self-sufficiency production of 441% palm dates, which is 4.4 times the total required quantity (see Section 4.6), and applying the current yield rate of 18 kg/tree (Section 5.4), which is lower than the FAO estimated rate of 24 kg/tree for the UAE (FAO, 2007) and much lower than the minimum rate (32 kg/tree) indicated by the ADE government, as noted in Section 4.6. It also applies the current water use (Section 5.4), which is almost double the FAO recommended rate (22,754 versus 14,700 m^3/ha).

Objective FS2: 100% of palm date self-sufficiency.

The target of FS2 is to meet the total required quantity (multiplying the quantity of required supply per individual per year by the total population; Section 4.6). The yield capacity per tree is to apply the government's average recommended yield (32 kg/tree) and FAO's recommended water use (14,700 m^3/ha).

Objective FS3: 27% of total vegetable self-sufficiency.

This objective represents the current contribution ratio of total vegetables to the local market (self-sufficiency) and applying the current water use per crop obtained from Sections 4.6 and 5.4, respectively.

Objective FS4: 91% of cucumbers cultivated in greenhouses.

Section 5.5.4 shows that cucumbers have by far the highest water productivity and the highest yield rate among all cultivated crops. Therefore, for comparison purposes they are selected to be maintained at the same current ratio and the same average water use is applied (Section 5.4).

Objective FS5: Rely on 100% food imports for vegetables.

Applying this objective relies completely on vegetable imports, and will result in saving all the water used in objective FS3. This may be a feasible solution if a full economic study is done to compare the feasibility between local production and imports, where the full water cost is included (accounting for water scarcity measures).

Table 7.1 Suggested objectives for water conservation and food self-sufficiency goals.

Main Goals	Objectives	Remarks
Water conservation	**WC1:** Reduce groundwater abstraction rate to 130 Mm^3/year	Maintain sustainable groundwater abstraction rate
	WC2: Increase utilization of treated wastewater to 100%	Increase treated wastewater utilization in agricultural production
Food self-sufficiency	**FS1:** 441% of palm date self-sufficiency	Maintain the current pattern
	FS2: 100% of palm date self-sufficiency	Meet the required quantity, increase crop yield rate and follow FAO recommended water use
	FS3: 27% of total vegetable self-sufficiency	Maintain the current pattern
	FS4: 91% of cucumbers cultivated in greenhouses	Maintain the current pattern of cucumber production and eliminate the cultivation of open field vegetables
	FS5: 100% food imports for vegetables	Focus only on vegetable imports and eliminate domestic production

7.4.3.3 Strategies and Associated Policies

Subsequent to the development of the objectives pointed out in the previous section, a set of strategies and policies should be created to help achieve these objectives (as noted in Section 2.5.5.1 and 2.5.5.4). Details of strategies and associated policies are listed in Table 7.2.

Table 7.2 List of objectives and associated strategies and policies.

Objective	Strategy	Examples of Relevant Policies
WC1	Decrease groundwater demand	*1.* Restrict drilling of new wells *2.* Install meters in all wells *3.* Define volumetric limit for groundwater abstraction *4.* Apply tariff for groundwater use *5.* Ban the operation of wells in areas where water table is deep *6.* Enforce well permit process and penalize non-compliance *7.* Enforce Rhodes grass phase-out *8.* Phase out other fodder crops (e.g. alfalfa and panicum)
	Improve agricultural water use efficiency	*1.* Restrict cultivation of intensive water use crops *2.* Identify list of allowed crops that have high tolerance and less water use to be cultivated in ADE *3.* Define water use baseline for various selected crops *4.* Adapt innovative agricultural farming techniques that facilitate efficient water use and high productivity (e.g. greenhouse) *5.* Restrict open field farming *6.* Improve irrigation efficiency
WC2	Increase treated wastewater supply	*1.* Identify list of crops recommended by FAO for safe human use *2.* Provide areas and regions that can benefit from this supply
	Increase farmers' awareness and knowledge	1. Provide practical training for farmers
FS1	Maintain current self-sufficiency targets with current water use pattern	*1.* Allocate alternative water resources (desalination or treated wastewater) to meet shortage in groundwater *2.* Expand farming area
	Maintain current self-sufficiency targets using FAO recommended water use	*1.* Define quantity required to meet defined self-sufficiency target *2.* Set water use limit for farmers
FS2	Focus on high-quality and recommended yield capacity palm trees	*1.* Focus on selected high-quality palm trees with recommended yield capacity *2.* Define best management practices (e.g. irrigation management, pest control, harvesting process, etc.)
FS3	Increase use of greenhouse farming	*1.* Provide support to farmers to build and manage greenhouses *2.* Ensure marketing of farm produce
FS4	Restrict agricultural domestic supply and focus on food imports	1. Set minimum limits for water use in farming 2. Focus on food imports and virtual water trading

For Objective WC1, two strategies are developed. The first is a decrease in groundwater demand, where the policies listed to meet this strategy are all focused on controlling groundwater drilling and abstraction. This initiative has already been launched by EAD in 2016 as part of the well inventory project (Section 1.2.1). This will allow EAD to monitor the abstraction rate and eventually set targets or volumetric measurements for each farm. This project will also allow EAD to collect accurate evidence on current groundwater use, which can be uploaded to the integrated database. The second strategy is improving agricultural water use efficiency, which can be implemented by policies that are focused on the selection of crops, farming techniques and irrigation efficiency.

As Objective WC2 aims to increase treated wastewater utilization, the strategy will be to increase its supply through developing a list of recommended crops, defining the area and regions/farms that will benefit from this supply and providing the required training and education for selected farmers and farm owners.

Objectives FS1–FS4 demonstrate different target options for palm date and vegetable production, where examples of relevant strategies are listed as shown in Table 7.1. Further scenario analysis illustrating food self-sufficiency targets and their impacts on water demand is demonstrated in detail in Section 7.5.

7.4.4 Generate the Final List of Agreed Policies

Quantitative and empirical assessment should be conducted (techno-economic, environmental and social considerations) to assess policy implications as shown in Section 2.5.5 (APAF and WFD). Part of the assessment can be modelling of different scenarios to define policy implications and develop a priority list of preferred policies (Section 2.5.5.5). Policy assessment and evaluation will help to identify the constraints, links and trade-offs between different policies, environmental impacts and opportunities. Details of policy scenario analysis for palm tree and vegetable cultivation are further presented in Section 7.5.

The list of preferred policies with assigned, measured targets and the timeline to be discussed with key stakeholders (Section 7.4.1) to get their consultation and feedback on any negative or positive implications should be subjected to higher authority approval, with an assigned responsibility matrix and timeline. This will lead to issuing the agreed list of policies and responsibility matrix, which defines users, responsible entity and implementation and enforcement mechanisms. In addition to the law, legislation and regulations, budget, timeline required, information, training and public awareness might be needed.

7.4.5 Policy Implementation, Communication and Enforcement

To assess the success of the policy, it is essential to link it with how it is implemented and measured (Van Meter and Van Horn, 1975). The implementation mechanism cannot be developed unless the policy objectives are clearly identified, as suggested, at the early stage of the policy development process. Therefore, during policy design, implementation of the mechanism should be considered (IWRM and WFD) in order to ensure its success.

Policy implementation can consist of a number of mechanisms, including the following:

- Allocating responsibility to the party with the right jurisdiction and required capabilities (sufficient resources and training, information, funding, etc.).
- Ensuring the responsible party understands the policy objectives.
- Facilitating inter-organizational communication.
- Ensuring the communication process with end users is transparent and avoids any misleading and conflicting instructions and messages. Communication with farm owners and farmers can be improved by launching public workshops, using social media (sending notifications and clear messages) and direct out reach targeting specific farms and farm owners. This step is essential to ensure successful implementation.
- Creating an enforcement mechanism and activities.
- Developing a quality assurance mechanism.

Implementation and enforcement mechanisms were highlighted as a suggestion to elevate critical water issues and main barriers to the successful implementation of policies, as demonstrated in Sections 6.3.2.7 and 6.3.3.3. For policy enforcement it is also important to strengthen the institutions' role and empower their authority in managing water use in agriculture, which was emphasized by different institutions' representatives and is also underlined as a barrier to successful policy implementation, as shown in Section 6.3.3.3.

7.4.6 Monitoring and Auditing

Policy monitoring and auditing will require resources (labour, hardware, software), funding, training and time. However, this step is required to keep track of the continuous implementation (as shown in the IWRM cycle) of the policy and generate data and statistics, which will provide the basis for the following step (analysis and reporting), and ultimately to feed back to policy-makers through the policy review process. Maybe at this stage a special focus should be put on water use and its impact on other sectors from different angles.

The policy monitoring and auditing processes are important in order to examine the level of achievement of the policy objectives and the consequences of these policies (Section 2.5.5.2). Those processes are clearly not given the required attention in ADE. This is broadly highlighted by the interviewed SMEs in Section 6.3.3.3. This step will require development of a monitoring and auditing procedure and engaging sufficient staff with enough training provided to them, equipped with electronic devices to enable them to collect the essential information. An example of the monitoring and auditing procedure can be scheduling regular visits (e.g. every three months or before, during and after the season) to various selected farms in order to monitor their performance and record further issues that disable them to follow the issued policies. This will also allow assessing farmers' knowledge, awareness and capacity to meet the required policy objectives. The information collected in this process will then be used as an input to the next step, which is analysis and reporting.

7.4.7 Lessons Learnt and Recommendations

The accumulated data from the monitoring and auditing process will be an input to the policy review that is conducted on a regular basis. In addition to the information and statistics generated from the previous step, statistical data from different sectors, such as water, energy, local, regional and global market conditions and potential future developments, are also required. The assigned party, as mentioned in Section 7.4.1, should assess these databases to improve accuracy and reliability. This is a key factor in the policy analysis process in order to assess the performance of the current policies and whether they are achieving their objectives (IWRM).

The data analysis reports are to be generated based on the monitoring and auditing procedures. This can include the quantity and quality of produced crops, water use per crop, value generated and impact on the local market. Additionally, issues related to farmers' knowledge and capability, coordination or resistance and other relevant challenges can be included. The collective reports will be an input to the next review process.

7.5 Policy Scenario Analysis

In this section, the data analysis and modelling are mainly focused on the impact of the objectives and associated policies on water resources. The discussion explains the data analysis method and provides examples of the scenario analysis output.

Further assessment can be done on the economic, technical, social and environmental domains to create a more in-depth and comprehensive evaluation of the trade-offs of the assigned objectives. However, this requires information on all these areas that is not available to the author at this point in time, therefore it is suggested for future studies.

7.5.1 Data Analysis Background

The key information used in the analysis is self-sufficiency, water consumption and crop and water productivity, all of which are obtained from previous chapters. The food self-sufficiency scenario analysis is conducted on the main ADE agricultural produce that contributes to local market demand. This is established on absolute production versus ADE requirement, as there is no information on the quantity of agricultural produce that is traded across other

Emirates. According to Sections 4.6 and 5.4.1, the main agricultural produce is the palm date and a few selected vegetables (tomato, cucumber, cabbage, eggplant, marrow and corn) that have the highest percentage of contribution to the local market. Table 7.3 presents the calculated self-sufficiency ratios for the selected crops from Section 4.6, with annual water consumption worked out by multiplying the average water consumption per ha (Section 5.4.4) by the total cultivated area (SCAD 2017 report). It also includes the water productivity formulated in Section 5.4.5 for each crop in order to show high- and low-performance crops.

Table 7.3 ADE 2016 cultivated crops self-sufficiency, water consumption and water productivity.

Crop	Self-Sufficiency %	Water Consumption (Mm^3)	Water Productivity	
			kg/m^3	$\$/m^3$
Palm tree	441	550	0.6	1
Vegetables				
Cabbage	170	4.54	3	1
Corn	119	4.17	2	1.8
Cucumber	91	1.5	33.8	23.7
Eggplant	42	1.03	4.4	1.8
Tomato	35	9.3	3.3	2.2
Marrow	19	0.55	5.9	5.3
Bean	8	0.77	0.5	0.7
Onion	7	9.31	0.4	0.3

As a result of assessing food imports, domestic produce and food supply in Section 4.6, the individual calculated quantity (kg/capita/year) per crop is used to calculate the total quantity required. That is worked out by multiplying the total quantity per capita per year by the population of that year for each food item. Then the target quantity is determined based on the defined percentage, followed by calculating the land required (ha) by dividing the target quantity by the production rate (yield/ha) obtained from the SCAD report (2016).

The annual water required is achieved using the average annual water consumption (m^3/ha) for the selected crop found from the survey data analysis (Section 5.4.4), as well as the FAO recommended crop water requirement using the FAO CROBWAT tool (FAO, 2018). This method has been developed and backed up by FAO to be used internationally to support irrigation management planning. ADE meteorological climate data (temperature, humidity, sunshine and wind speed), soil information, selected crops and growth durations are the main input in the model to calculate the crop water requirement.

7.5.2 Scenario Analysis for Palm Trees

The analysis of palm production is conducted to assess the difference between objectives FS3 and FS4: FS3 depending on current self-sufficiency, yield rate and water use pattern (441% self-sufficiency, 18 kg/tree and 22,745 m^3/ha water use); and FS4 based on the suggested pattern (100% self-sufficiency, 32 kg/tree and 14,700 m^3/ha water use).

The two scenarios were run for 2016–2050 based on the required quantity that is contingent on the predicted population. The analysis shows (Figure 7.3) that the saving in water demand is 92% from objectives FS1 to FS2. The latter exercise will help to limit groundwater use (92%) to below 130 Mm^3 (annual groundwater recharge) in order to maintain a sustainable discharge rate, from 55 Mm^3 in 2016 to 106 Mm^3 in 2050 (Figure 7.3).

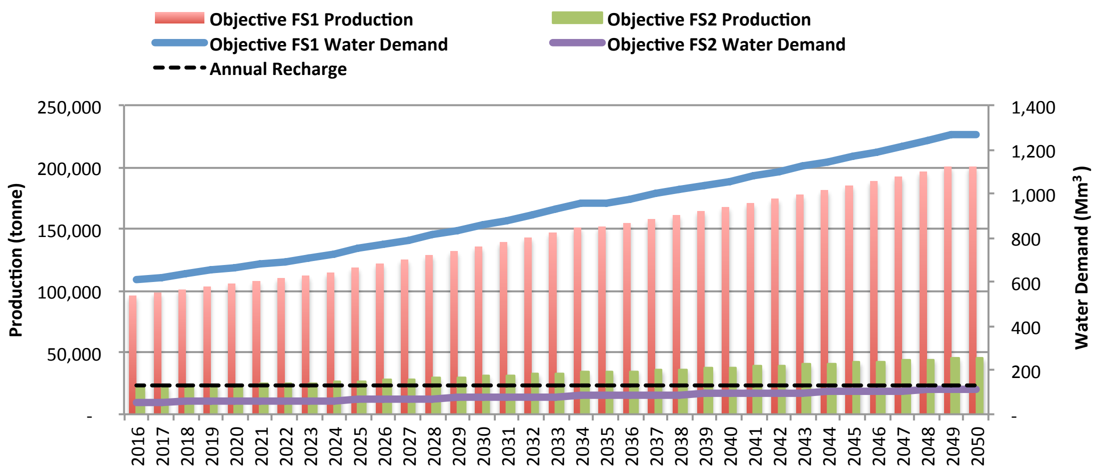

Figure 7.3 Palm production objectives FS1 and FS2 quantity and water demand scenarios.

7.5.3 Scenario Analysis for Vegetables

This assesses the difference between the total water consumption in objective FS3, applying the current vegetable self-sufficiency pattern (27% self-sufficiency of total vegetables and current water use per crop obtained from Sections 4.7 and 5.4.4), and that in objective FS4, which is suggested to focus only on high water productivity crops such as cucumbers cultivated in greenhouses (91% of self-sufficiency). Figure 7.4 shows the saving in total water demand (mainly desalinated water) of 95% between the two objectives.

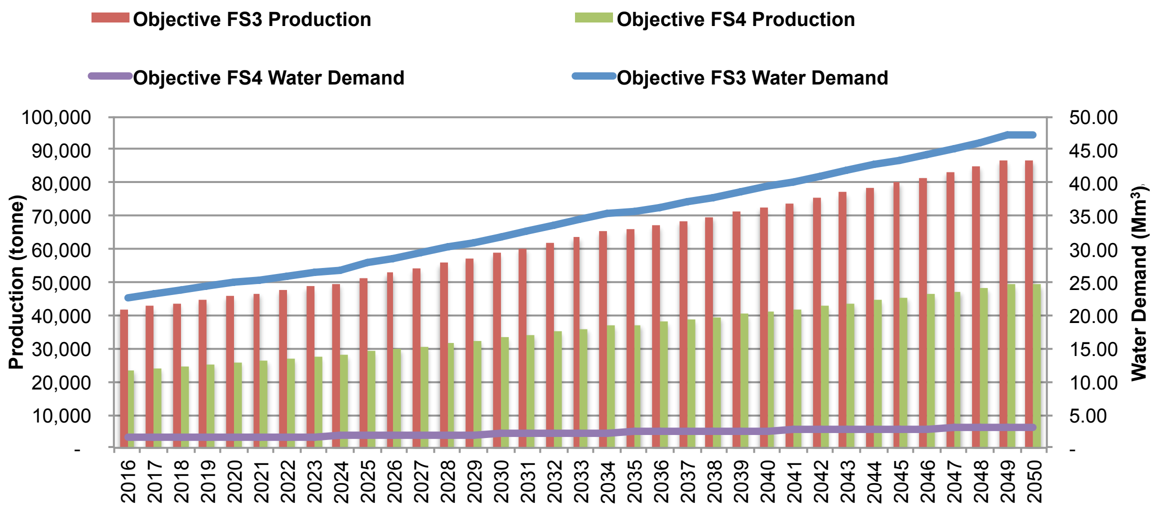

Figure 7.4 Vegetable total water demand for objectives FS3 and FS4.

The water demand for vegetable production can be focused on using treated wastewater, which will generate greater water reuse and save on desalination and groundwater.

7.6 ADE AWPF Validation

As stated in Section 3.5, the validation technique used in this study to check the reliability of the ADE AWPF is member check, where participants' confirmation and views on the researcher's interpretation are obtained and discussed. The following subsections present the details of the validation questionnaire, profile of selected experts, analysis and results.

7.6.1 Validation Questionnaire Development

The survey questionnaire has been used as a research tool to obtain the experts'/participants' feedback on the adequacy and applicability of the framework (Creswell and Poth, 2017). The application of a survey can be conducted by several techniques, such as sending electronically via email or the Internet, sending by post or mail or delivering by hand to the participants and collecting later (Saunders, Lewis and Thornhill, 2012). In this study, the survey was handed over to the participants after 30 minutes' description and interactive discussion on the developed framework provided by the author.

The validation (survey) questionnaire has two main sections, as shown in **Appendix M**. Section A covers participants' background information, such as name, job description, years of experience, qualifications and entity/authority. Section B consists of a set of closed-ended quantitative questions on the general view and impression of the framework. The quantitative data was used in the descriptive data analysis, such as simple counts and frequencies of occurrence for each question.

7.6.2 Selected Experts

A purposive sampling technique was used to select six experts from water- and agriculture-associated entities based on their experience and direct involvement in the management of water and agriculture. As shown in Table 7.4, the selected experts came from a wide range of expertise, professions and designations, with long years of experience that make them conversant and acquainted with the dynamics of water and agriculture.

Table 7.4 Profile of the selected validation experts.

Expert's Code	**Entity**	**Designation**	**Qualifications**	**Years of Experience**
EXP-AO-1	ADFCA	Agriculture Development Director	MSc in Water Resources Management	25
EXP-MO-2	ADFCA	Agriculture Development Manager	PhD in Agriculture and Food Science	5
EXP-SH-3	ADFCA	Agriculture Engineer	BSc in Horticulture	4
EXP-AA-4	ADWEA	Advisor, Business Development (Water & Power)	PhD in Civil Engineering	30
EXP-RP-5	EAD	Advisor, Organizational Development Management	PhD in Zoology and Population Ecology	25
EXP-SP-6	EAD	Senior Advisor, Environmental Policy and Strategy Specialist	PhD in Agriculture and Environmental Science	20

7.6.3 Validation Analysis and Results

The data analysis results of the frequencies of responses from the experts to each question in the survey are shown in Table 7.5.

Table 7.5 Frequencies of responses for each survey question.

Question No.	Question	Variables	Frequency of Responses
1	What is your opinion on the development of this ADE agriculture-water framework?	I agree	6
		I don’t agree	0
		I'm not sure	0
2	What is your view on the framework layout?	It is sufficient	6
		It is not sufficient	0
		I'm not sure	0
3	Do you think that the framework is simple and easy to understand?	Yes	6
		No	0
4	Do you think that the framework is easy to follow with few or no practical difficulties?	Yes	5
		No	1
5	Does the framework address issues related to the sustainability of agricultural production in ADE?	Yes, quite significant	6
		Yes, but not significant	0
		No, not sure if it makes any difference	0
6	Would you agree that the framework is capable of ensuring better allocation of water in the agriculture sector?	Yes, it is capable	5
		No, it is not capable	0
		I'm not sure	1
7	Would you agree that the framework is capable of ensuring sustainable agriculture development?	Yes, it is capable	4
		No, it is not capable	0
		I'm not sure	2
8	In your, opinion are there any further important steps missing in the framework that should be included?	Yes	0
		No	6
9	To implement the framework in ADE, do you think it will require a heavy investment in human resources?	Yes	0
		No	2
		I'm not sure	1
		Any investment is justifiable by the benefits that will be achieved	3
10	To implement the framework in ADE, do you think it will require a heavy investment in training, tools and devices?	Yes	0
		No	3
		I'm not sure	1
		Any investment is justifiable by the benefits that will be achieved	2

In the following subsections, details of the respondents' validation feedback on the framework are provided based on the answers obtained to the survey questions (Table 7.5).

7.6.3.1 General Views and Feedback on ADE AWPF

The answers to Questions 1–4 (Table 7.5) reflect the general views and feedback on the frameworks by the respondents. All of the respondents agree on the development of the framework. EXP-SH-3 stated: "it is very good and highly applicable"; EXP-RP-5 indicated: "just right on time because currently there is a lot of discussion on developing such a framework"; and EXP-SP-6 highlighted the need for ensuring integration with climate change and food security. EXP-AO-1 added: "the government recently initiated a project to develop an agriculture and water framework, and I expect eventually they will produce a framework that is similar to the one produced in this research". They also viewed the developed framework layout as sufficient and covering most areas required, where they further emphasized the need to ensure the engagement of stakeholders as a key factor, as stated by EXP-SP-6 (Questions 1 and 2).

Regarding the respondents' feedback on whether the framework is simple and easy to understand (Question 3), the validation analysis shows that all confirmed that it is simple and easy to understand. Further, in the feedback on whether it is easy to follow with few or no practical difficulties (Question 4), five of six of the validation experts answered "Yes", and one added: "in theory yes, but an integrated approach has long eluded the issue" (EXP-RP-5). Only one respondent out of six answered "No" and added: "I think the framework is not easy to implement due to the current number of stakeholders, the interfaces in their roles and their adaptability to new roles" (EXP-AA-4).

7.6.3.2 Whether ADE AWPF Addresses Issues Related to Sustainability of Agricultural Production

Question 5 (Table 7.5) was directed to the respondents in order to assess if the framework addresses sustainability issues in agricultural production. All respondents answered "Yes" and two added comments: "Yes, but many political issues to overcome" (EXP-RP-5) and "Ensure subsidies are covered" (EXP-SP-6).

7.6.3.3 Whether ADE AWPF Is Capable of Ensuring Better Allocation of Water in Agriculture Sector

To validate if the framework is capable of ensuring a better allocation of water in the agriculture sector, five of six respondents expressed that it is (Question 6) and one answered “I’m not sure”.

7.6.3.4 Whether ADE AWPF Is Capable of Ensuring Sustainable Agricultural Development

The feedback to Question 7 shows that four of six respondents confirmed that the ADE AWPF is capable of ensuring sustainable agricultural production. However, two answered “I’m not sure”. These latter two respondents added comments: “Providing that through the framework, a robust strategy is developed and implemented” (EXP-SP-6) and “It depends on the definition of sustainable agriculture” (EXP-RP-5).

7.6.3.5 Whether There Are Any Missing Important Steps in ADE AWPF

To check whether the framework process and subprocesses are comprehensive enough, all six respondents identified no missing important steps in the framework, where all of them answered “No” to Question 8.

7.6.3.6 Whether Heavy Investment in Human Resources, Training, Tools and Devices Is Needed for ADE AWPF Implementation

Questions 9 and 10 are included in the survey to validate whether the framework implementation will require heavy investment or not, and whether any investment is justifiable by the benefits that will be achieved. The feedback on whether the implementation of the framework will require a heavy investment in human resources (Question 9) shows that two respondents answered “No”. One added: “It needs action not investment” (EXP-SH-3). One out of six answered “I’m not sure” and three answered “Any investment is justifiable”.

The feedback on whether the implantation of the framework will require a heavy investment in training, tools and devices (Question 10) shows that three respondents answered “No”, where one of them added: “Much of what is required is already available. Investment in treated wastewater infrastructure and hydroponics will be the main cost” (EXP-RP-5). One answered “I’m not sure” and two answered “Any investment is justifiable”.

7.7 Chapter Summary

This chapter proposes an Agriculture-Water Policy Framework (AWPF) to help the government have an enhanced policy- and decision-making process in order to sustain agricultural development in ADE. The literature review of agriculture and water frameworks developed at global and local levels (Chapter 2) was used as a basis to help develop the ADE AWPF. Furthermore, findings from the previous data analysis chapters were used in the implementation of the AWPF in ADE. These are data synthesis (Chapter 4), survey data analysis (Chapter 5) and semi-structured interview data (Chapter 6). The outputs of these chapters were utilized to identify the opportunities and challenges in ADE that are required for successful implementation of the proposed framework.

The ADE AWPF consists of seven primary steps that can provide a simple guideline for the decision-making process. The analysis and discussion of the framework implementation in ADE highlighted a number of critical actions, such as establishing agriculture-water governance with defined roles and accountabilities, integrating an open and accessible database platform, conducting policy analysis scenarios, developing implementation and enforcement mechanisms, establishing policy monitoring and auditing, and developing a lessons learnt analysis report to provide feedback for the next cycle.

The validation of the framework shows that the six experts selected from the agriculture- and water-associated entities expressed the majority views that the ADE AWPF is valid, simple and easy to understand and follow with few or no practical difficulties. They also considered that that the framework addresses issues related to sustainability in agriculture, and is capable of leading to better water allocation in the agriculture sector and ensuring sustainable agricultural development. The framework's layout was identified as sufficient and covering all the required important steps, with the majority of experts expressing either that no investment is required or that any investment is justifiable by the benefit that will be achieved.

In the next chapter key findings and conclusions of the entire thesis is presented leading to the research contribution to knowledge, recommendations for policy and decision makers, research limitations and recommendations for further study.

Chapter 8. Conclusions and Recommendations

8.1 Introduction

This thesis has explored the following two key questions:

- How is the growing water demand for agriculture affecting groundwater use and food production in Abu Dhabi?
- To what extent should groundwater be used for domestic agricultural food production under sustainable agricultural water use development and food security goals?

To answer these questions, six objectives were investigated using different research methods. The first three objectives were investigated based on synthesis and dissemination of the available literature and secondary data (Chapter 4). The fourth and fifth objectives were met by conducting a farming perception survey and semi-structured interviews, respectively (see Chapters 5 and 6). The sixth and final objective, AWPF, was developed based on previous chapters and the literature review on global best practices (Chapter 7).

This chapter provides conclusions and reviews the findings of this project, its contribution to knowledge, recommendations for policy and decision makers, limitations and recommendations for further research.

8.2 Research Key Findings and Conclusions

The key findings and conclusions that are drawn from the research objectives are summarized below.

Objective 1: Develop an in-depth understanding of water usage in ADE through critical mapping of water consumption patterns across various sectors.

Although fresh groundwater is limited and receives negligible recharge in ADE, it contributes the largest (63%) share of the total water supplied, whereas the desalination share is 32% and treated wastewater is 5%. Agriculture is the largest water user across the various sectors. It uses 71% of the total groundwater and 52% of the total water supplied. However, as the groundwater reserve is depleted, desalination and treated wastewater supplies have been gradually increased to meet irrigation's increasing demand. The current treated wastewater use in agricultural production is only 1%, which is used to run a pilot-monitoring programme on selected farms. In general, the contribution of treated wastewater has stayed low at 5% for the last 15 years, mainly because of social unacceptability and limited provision of infrastructure.

Given the current dependency on non-renewable groundwater, the government's interventions to increase supply (desalination and treated wastewater) to help meet future demand has not seen successful results. Consequently, it is essential to understand in detail and through empirical study how much water is used in agricultural production, how it is regulated and managed and what are the actions required to enable sustainable agricultural production.

Objective 2: Establish an enhanced knowledge and understanding of groundwater development, usage and associated sustainability issues.

Fresh groundwater is only 3% of the total reserve and occurs in limited areas (such as AA and south of WR) with negligible recharge. The initial policy (desert greening policy) has encouraged agricultural development with more exploitation of groundwater. This has led to a more than 10-fold surge in groundwater abstraction, which exceeds by 20 times its freshwater recharge. This unsustainable abstraction rate has caused a significant decline of the water table (from 1.5 m to 5 m), resulting in the abstraction of brackish and saline water. It is predicted that groundwater sources are going to be completely depleted in the next three decades if the abstraction pattern remains the same.

The majority of wells are located at farms that currently have full operational control by the farm owners. About 76% of farms have between one and three wells, while some (45%) receive supplies from the ADFCA irrigation supply network and a few (11%) own their own small-scale desalination plants. The latter creates an additional concern with groundwater, where farmers discharge the resulting brine to the groundwater aquifer without considering its impact.

Even though entities such as ADFCA, ADFSC and EAD support farmers with funds and drilling permits, they do not provide further managerial and monitoring responsibilities to ensure the sustainable operation and maintenance of wells. As a result, farmers operate their wells for irrigation as they see fit, with no regulatory mechanisms. Furthermore, farmers realize the government's intention to reduce water use, but they are not willing to actively change their pattern of use. This indicates that the government needs to get farmers and farm owners involved in its policy development process.

In addition to the above issues, there is no available information regarding the groundwater abstraction rate and existing practices used by farmers to operate and manage their wells. This situation makes it impossible to employ the right measures needed to ensure sustainable use of wells for agricultural production. This calls for a need to determine the sustainable abstraction rate and groundwater operations currently posing a significant risk to the future use of this resource.

Objective 3: Critically investigate agricultural development and its contribution to food self-sufficiency and the local market.

The drivers behind agricultural development in UAE and ADE are largely related to cultural and social factors (such as honouring the legacy of the country's former president) rather than food security. The government's generous subsidies and free services encouraged the development of farming and farm produce, which is shown in the sharp increase in the total number of farms, farm area and agriculture's contribution to GDP (from 0.7% in 1975 to 3.6% in 1998). However, in the last 15 years the number of farms and farm area have stayed constant, which makes the severe reduction of agriculture's GDP contribution to less than 1% in 2014 unsurprising.

The main cultivated crops are palm trees, vegetables and fodder crops. The palm tree, as the oldest cultivated crop, represents a connection to the heritage legacy, by means of the main source of food in the country. Therefore, the majority (98%) of farmers cultivate palm trees over 72% of the total agriculturally cultivated area. Nevertheless, the crop is poorly managed and is exposed in its high water use (22,745 m^3/ha), consuming 80% of the total agricultural water use with an excessive quantity produced of dates, which is 441% of the required amount. The majority of the dates produced are wasted by way of animal feed (because of their poor quality), whereas only 35% goes to the local market and only 3% is exported. This is alarming given that so much waste goes with the cultivation of palm trees.

Vegetable crops are cultivated by 69% of farms. Over roughly 14% of the cultivated area, they are cultivated mainly by open field farming during the winter season, which makes their supply period short. They also have high water use, which varies from 30,422 m^3/ha (mixed vegetables) to 16,527 m^3/ha (corn). The water consumption rate per crop varies significantly between farmers. This indicates that their estimate of water use per crop is done randomly and with no pursuable baseline. However, cucumbers, refined in greenhouses, demonstrated much lower water use (10,096 m^3/ha), but are cultivated only by 7% of farms. There is also an increasing growth in greenhouse farming, which enables control of temperature, humidity and water use to sustain production all year round, though there are many variables that need to be managed in order to sustain greenhouse productivity and efficiency. The government is currently promoting greenhouse farming, but to date there is not enough data or evidence to confirm how sustainable this is and for what type of crop it is best applicable. Over the last decade, vegetable production has increased, but its contribution to the local market is small (27%), focusing on a few main crops such as cabbage, corn, cucumber, pepper, eggplant and tomato.

Fodder crops (namely Rhodes grass), because of their high water use (23,850 m^3/ha) and low economic value, have been restricted since 2010. Yet there is an indication of them still being cultivated by a high number of farmers (42%) on about 14% of the total cultivated area. This shows a lack of policy implementation and enforcement mechanisms.

It is important to understand the characteristics of crops in terms of actual crop yield rate, water consumption and water productivity, in order to be able to assess the best sustainable approaches for agricultural water policy intervention.

Objective 4: Develop a comprehensive understanding of the current farming practices and their impacts on water resource sustainability.

The findings of the research survey illustrate that about 81% of farmers are not relying on their farm as a main source of income. They use their farm as a source of prestige for the family and a vacation resort. This has an impact on water consumption, as it usually requires landscaping, swimming pools and a family house. Only 19% of farmers developed their farm based on commercial purposes, where they put effort into increasing farm productivity and generating profit.

The produce with the highest crop yield is the cucumber (160,000 kg/ha), which has the highest water productivity too (33.8 kg/m^3 and US $23.7/$m^3$). This could be explained by the method of farming used for cucumbers, namely the greenhouse technique. Other vegetable crops show much lower yields and lower water efficiency. The yield for these crops varies from 9,778 kg/ha (bean) to 65,556 kg/ha (marrow), with water output varying from 0.2 kg/m^3 and US $0.3/$m^3$ (pea) to 5.9 kg/m^3 and US $5.3/$m^3$ (marrow). Palm trees and Rhodes grass also have low crop yields (9,621 and 50,971 kg/ha, respectively) and low water productivity (0.6 kg/m^3 and US $1/$m^3$ for palm trees, and 3.4 kg/m^3 and US $1.4/$m^3$ for Rhodes grass).

To conclude, the majority of the cultivated crops have a poor yield and low water productivity. This shows the inefficient use of water in agriculture, which goes to exacerbate the already unsustainable state of the groundwater and puts more pressure on the demand for desalination. That points to the need to change current farming practices, such as moving away from open field farming to the greenhouse technique, which has a much better performance, as demonstrated in the cultivation of cucumbers. There is also a need to develop standard guidelines for farmers on water use per crop. Furthermore, any major decision and policy intervention addressing water resource issues must consider the cultivation of palm trees, which demonstrates a serious need to improve their management (crop yield, water productivity, etc.).

Objective 5: Critically determine how water use in agriculture is regulated and managed.

The experts interviewed from water- and agriculture-associated entities highlighted the great agricultural water use and its impact on the scarce water resources as the most critical water issue. They also added their concerns on the lack of integration, especially at the planning stage, the absence of an agriculture water strategy and the existing issues related to information and databases, as well as the lack of awareness and education among farmers. Furthermore, they stated there was an absence of agricultural water use policies, and that if such policies did exist, they would not have a clear direction, or implementation and enforcement mechanisms.

To meet the current challenges, the experts emphasized the urgent need to use a holistic approach in managing agricultural development. They stressed the integration of agriculture with water planning and food security strategies to ensure synergy and avoid conflicts between their objectives, as well as reduce the negative impact on water resources.

Objective 6: Develop a systematic and integrated agriculture-water policy framework to aid relevant policy- and decision-makers in ADE.

It is clear from the primary and secondary data analyses that one of the solutions for resolving the agricultural water use challenges in ADE is an integrated framework as a guideline to assist in the decision- and policy-making process. This framework is developed in this study based on the recommended practices obtained from the literature and the key study findings. The implementation of the proposed framework in ADE indicated the need to:

- Re-organize the current structure with a defined demarcation of the roles and responsibilities of each of the assigned stakeholders.
- Establish an open, integrated database platform.
- Create a mechanism to make practical use of the research and study findings.
- Develop measurable agricultural objectives that are directly linked to water and food self-sufficiency.
- Create a mechanism for policy implementation, enforcement, and monitoring and reporting mechanisms.
- Increase utilization of treated wastewater in agricultural production.

Since date palms and vegetables are the two main crops that contribute to food self-sufficiency, they were further considered in designing policy scenario analyses, as part of the framework policy modelling and analysis process. These analyses show that decreasing palm date production from 441% to 100% self-sufficiency would increase the yield rate (from 18 kg/tree to 32 kg/tree) and optimize water use to follow FAO recommendations (14,700 m^3/ha). This would help to save about 92% of total water demand and maintain groundwater use below the sustainable abstraction rate (106 Mm^3/year) in 2050. For vegetable crop cultivation, restricting open field farming and focusing more on the greenhouse farming technique (by using cucumbers as an example) show that more than 95% of total water use can be saved while providing more than 90% self-sufficiency of a selected crop (the example used on the current production ratio of cucumbers).

8.3 Contribution to Knowledge

The main research achievements and contributions are summarized as follows. To the best of the author's knowledge, these contributions have not been covered within previous studies and research, especially in UAE and ADE. The research has achieved the following:

- Produced a review of up-to-date information on food–water context, agriculture and groundwater dilemmas, especially in the GCC countries. It also provides insights into relevant international initiatives developed to overcome food and water challenges. This information provides a useful source of review for interested researchers and industry practitioners.
- Established a detailed background on groundwater and agriculture based on a synthesis of largely fragmented secondary data in ADE. It provides analysis on the historical trend of groundwater abstraction patterns across various sectors, agricultural development, and its production and contribution to food self-sufficiency. The results of this synthesis provide detailed information not only for scholars, but also for relevant government entities.
- Developed an in-depth understanding of current farming practices (i.e. land use, cultivated crops, quantity and value produced, water consumption and water productivity) based on empirical data and statistics, which form an invaluable information source in the policy- and decision-making process.
- Explored and obtained information on farmers' perceptions of ADE's water issues and their willingness to adapt to future policy changes. The findings from this survey are unique in the sense that no such information has been produced for ADE. This makes them highly valuable for policy- and decision-makers at local and national levels, as they provide the necessary information that will help in developing relevant policies and educational programmes for farming practices.
- Conducted an in-depth assessment of current regulation and management governing agricultural water use, which provides deep insights into the level of involvement of

the responsible entities, their knowledge and understanding of the current agricultural water issues, and gaps in the current structure, policy development and implementation.

- Developed a systematic and innovative framework (Agriculture-Water Policy Framework) for addressing unsustainable water use issues. This framework provides detailed guidelines to aid in the decision-making process in sustainable agricultural water strategy development and implementation. It can be used to enable the development of sustainable agriculture not only in ADE, but also in other GCC countries.

8.4 Recommendations for Policy and Decision Makers

The research has demonstrated, among other things, the ineffectiveness of the current management of water use in agriculture sector in ADE. This was evident in the development, implementation and enforcement of the agricultural strategies, objectives and related policies. It also manifested in the accessibility and transparency of data and communications among relevant entities and/or with end users (farmers and farm owners). The research's main recommendations for policy and decision makers towards addressing this ineffectiveness are therefore as follows:

- Change the current approach to managing water and agriculture towards a more holistic and integrated approach thereby eliminating duplications and conflicts of interest between the entities.
- Develop and implement effective strategies with associated policies and governance processes in order to better regulate, in a sustainable manner, the current farming practices and water consumption, and hence mitigate the negative impacts of agriculture and water resources usage in ADE.
- Develop agriculture policies based on clear and measurable targets that are integrated with water resources and food security. Furthermore, establish effective policy implementation, enforcement, monitoring and auditing mechanisms.
- Strengthen institutional roles in managing water use in agriculture.
- Build an open and integrated database platform that provides comprehensive, consistent, up-to-date and accurate data for supporting decision and policy making.
- Regulate groundwater abstraction at farms' level based on established sustainable abstraction rates (i.e. rates less than or equal to the groundwater recharge rates), and through restricting drilling of new wells, especially in areas where groundwater has depleted and deteriorated.

- Improve communication mechanisms with farm owners and farmers regarding the government short and long term strategies, insights of new innovative technologies, issues related to water resources, food security and market demand, etc.
- Pay special attention to raise farm owners' awareness and knowledge on efficient water use techniques, irrigation schedules, high water productivity crops, pest control and other practices relevant to ensuring sustainable farm management.

8.5 Research Limitations

Although the objectives of this research have been met, there are unavoidable limitations. The first is the absence of complete, accurate and precise data on agricultural water use and groundwater abstraction rates.

Secondly, the surveyed farms' crop value produced are calculated based on the average value per tonne provided by the ADFCA statistical report and not on the actual selling price. Therefore, the analysis is based on the assumption that all farms have the same average selling price (value) for each crop per tonne.

Finally, the crop yield and water productivity indicators that are calculated based on the survey data provide empirical statistics on the farms' performance across ADE's three regions, which can be used to evaluate the performance of each cultivated crop. The crop performance assessment presents crude (yet vital) results on how the different farms compare to each other in terms of their farming practices. However, seasonality, climate change, soil type and fertilization used are not considered in this productivity analysis, since it would require more relevant information and a longer time.

8.6 Recommendations for Further Research

In light of the conclusions and key findings presented in Section 8.2, it is acknowledged that further research is recommended.

Further investigation is required in order to link the level of crop performance with different factors, such as farming type (open field, greenhouse, hydroponic, aquaponic, etc.), soil management, irrigation methods and farming methods. In addition, measuring the crop yield response to water and the optimum water requirement is also recommended to draw the line between high and low performance.

The detailed study should be extended to develop actual measurements of the four indicators mentioned for each crop in different locations in ADE, as well as actual measurement of the optimum marketable crop yield per ha and the actual measured crop water consumption (evapotranspiration) in different locations in the country using various measurement devices. It is suggested that information on seasonality, climate change, soil type, fertilization, irrigation practice and farming type should be included. Although this process would take time, effort and considerable budget and expertise, it would add value to setting the baseline for crop water requirements in the country.

Finally, the AWPF presented in this thesis can be considered as a starting step, which in time will require further developments in different aspects such as data analysis tools (for lifecycle analysis, socio-economic analysis, etc.) to develop sound policy scenario analyses. These tools will require an accumulation of different data sources, input from multidisciplinary experts and a smooth implementation process and procedure.

References

Abdelfattah, M. A. (2013) 'Integrated suitability assessment: A way forward for land use planning and sustainable development in Abu Dhabi, United Arab Emirates', *Arid Land Research and Management*, 27(1), pp. 41–64. doi: 10.1080/15324982.2012.722579.

Abdelfattah, M. A. and Kumar, A. T. (2014) 'A web-based GIS enabled soil information system for the United Arab Emirates and its applicability in agricultural land use planning', *Arabian Journal of Geosciences*, 8(3), pp. 1813–1827. doi: 10.1007/s12517-014-1289-y.

Abdelfattah, M. A. and Pain, C. (2012) 'Unifying regional soil maps at different scales to generate a national soil map for the United Arab Emirates applying digital soil mapping techniques', *Journal of Maps*, 8(4), pp. 392–405.

Abu Dhabi Government (2017) *Executive Affairs Authority*. Available at: https://eaa.gov.ae (Accessed: 14 February 2017).

Abu Dhabi Government (2018a) *Executive Council*. Available at: https://www.ecouncil.ae (Accessed: 31 August 2018).

Abu Dhabi Government (2018b) *General Secretariat of the Executive Council (GSEC)*, *Abu Dhabi Digital Government*. Available at: https://www.ecouncil.ae (Accessed: 31 August 2018).

ADFCA (2011a) *Bid to implement better farming practices*, *Abu Dhabi Food Control Authority*. Available at: https://www.adfca.ae (Accessed: 7 November 2017).

ADFCA (2011b) *Code of practice no (11) of 2011 fertilizer*. Abu Dhabi, UAE: Abu Dhabi Food Control Authority.

ADFCA (2011c) *Statistics book 2011*. Abu Dhabi, UAE: Abu Dhabi Food Control Authority.

ADFCA (2012) *Delicious dates: available all year round*. Abu Dhabi, UAE: Abu Dhabi Food Control Authority.

ADFCA (2014) *Agriculture affairs*, *Abu Dhabi Food Control Authority*. Available at: https://www.adfca.ae (Accessed: 22 July 2017).

ADFCA (2015) *About us*, *Abu Dhabi Food Control Authority*. Available at: https://www.adfca.ae (Accessed: 22 July 2017).

ADFSC (2013) *Abu Dhabi Farmers' Service – open-field vegetable production guide*. Abu Dhabi, UAE: Abu Dhabi Farmer Service Centre. Available at: https://www.adfsc.ae/en/SiteAssets/pages/publications/ADFSC%20Eggplant%20%20Production%20Guidelines%20.pdf?TSPD_101_R0=f4dbcd004f2d2d8cf111b58b6ba875eaIR70000000000000001775eccb0ffff00000000000000000000000000005c2b2e4f006eaefe1b (Accessed: 12 April 2019).

Adger, W. N. and Jordan, A. (2009) 'Governing sustainability', *Management of Environmental Quality*, 20(6). doi: 10.1108/meq.2009.08320fae.004.

ADWEA (2013) *About us*, *Abu Dhabi Water & Electricity Authority*. Available at: http://www.adwea.ae (Accessed: 22 July 2017).

ADWEC (2016a) *ADWEC's role*, *Abu Dhabi Water & Electricity Company*. Available at: http://www.adwec.ae/role.html (Accessed: 22 July 2017).

ADWEC (2016b) *Statistical report 1999–2015*. Abu Dhabi, UAE: Abu Dhabi Water & Electricity Company.

AGEDI (2013) *Abu Dhabi Global Environmental Data Initiative (AGEDI)*. Available at: http://bluecarbonportal.org (Accessed: 11 July 2017).

AGEDI (2015a) *Executive briefing: national water-energy nexus and climate change*. Abu Dhabi, UAE: LNRCCP, CCRG/NCAR/SEI. Available at: https://www.energycommunity.org/documents/TechnicalReportUAEWaterEnergyNexus.pdf (Accessed: 12 April 2019).

AGEDI (2015b) *Technical report UAE food security and climate change – AGEDI. LNRCCP. CCRG/NCAR/SEI*. Available at: https://agedi.org/item/technical-report-uae-food-security-and-climate-change (Accessed: 16 April 2017).

AGEDI (2016a) *Executive briefing UAE food security and climate change*. Abu Dhabi Global Environmental Data Initiative.

AGEDI (2016b) *Final technical: regional desalinated and climate change*. Abu Dhabi, UAE: Abu Dhabi Global Environmental Data Initiative.

Al Foah (2016) *SENAAT – General Holding Corporation*. Available at: http://www.senaat.co/al-foah (Accessed: 8 April 2017).

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

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

Ali, M. H. and Talukder, M. S. U. (2008) 'Increasing water productivity in crop production—a synthesis', *Agricultural Water Management*, 95(11), pp. 1201–1213. doi: 10.1016/j.agwat.2008.06.008.

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

Ali Al-Alwai, M. (2014) *Groundwater assessment in Sweihan region, the northeast, United Arab Emirates*. Phd diss. UAEU.

Al Hammadi, M. (2014) *Sustain agriculture sector in Abu Dhabi through smart irrigation system. Abu Dhabi Food Authority*. Available at: https://itunews.itu.int/en/4853-Smart-irrigation-for-sustainable-agriculture-in-Abu-Dhabi.note.aspx (accessed: 14 June 2017).

Al-Jamal, M. S., Sammis, T. W., Ball, S. and Smeal, D. (2000) 'Computing the crop water production function for onion', *Agricultural Water Management*, 46(1), pp. 29–41. doi: 10.1016/S0378-3774(00)00076-7.

Al-Katheeri, E. S. (2008) 'Towards the establishment of water management in Abu Dhabi Emirate', *Water Resources Management*, 22(2), pp. 205–215.

Allan, J. A. (1997) '"Virtual water": a long term solution for water short Middle Eastern economies?' in *Water and Development Session*. *The 1997 British Association Festival of Science*, University of Leeds and School of Oriental and African Studies, University of London London. Available at: http://web.macam.ac.il/~arnon/Int-ME/water/OCC03.PDF (Accessed: 26 November 2017).

Allan, J. A. (2003) 'Virtual water – the water, food, and trade nexus. Useful concept or misleading metaphor?' *Water International*, 28(1), pp. 106–113.

Allen, C. R., Fontaine, J. J., Pope, K. L. and Garmestani, A. S. (2011) 'Adaptive management for a turbulent future', *Journal of Environmental Management*, 92(5), pp. 1339–1345.

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

Alomaran, A. M. and 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 (Sustainable Irrigation and Drainage)*, 168(IV), p. 353. doi: 10.24955/SI120301.

Al Qaydi, S. (2016) 'The status and prospects for agriculture in the United Arab Emirates (UAE) and their potential to contribute to food security', *Journal of Basic and Applied Sciences*, 12, pp. 155–163.

Al-Qurashi, A. D., Ismail, S. M. and Awad, M. A. (2016) 'Effect of water regimes and palm coefficient on growth parameters, date yield and irrigation water use of tissue culture-regenerated "Barhee" date palms grown in a newly established orchard', *Irrigation and Drainage*, 65(4), pp. 491–501. doi: 10.1002/ird.2016.

AlRashed, M. F. (2017) 'Management and security of municipal water at the GCC countries'. *WSTA 12th Gulf Water Conference*, Bahrain, March. Available at: http://www.wstagcc.org/WSTA-12th-Gulf-Water-Conference/2_Mohammad%20Alrashed.pdf (Accessed: 25 November 2017).

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

Al-Said, F. A., Ashfaq, M., Al-Bahri, M. and Khan, I. A. (2012) 'Water productivity of vegetables under modern irrigation methods in Oman', Irrigation and Drainage, 61(4), pp. 477–489.

Al-Subaihi, A. A. (2003) 'Sample size determination. Influencing factors and calculation strategies for survey research', *Saudi Medical Journal*, 24(4), p. 323.

Altheide, D. L. and Johnson, J. M. (1994) 'Criteria for assessing interpretive validity in quantitative research', in Denzin, N. K. and Lincoln, Y. S. (eds.), *Handbook of qualitative reseach*. London: SAGE, pp. 485–499.

Al Wafi, A. and Begmuratov, A. (2017) 'Untapping alternatives for a sustainable future'. *Envirocities eMagazine*. Available at: http://en.envirocitiesmag.com/articles/issue-18/9.pdf (Accessed: 12 April 2019).

Aly, A. A., Al-Omran, A. M. and Khasha, A. A. (2015) 'Water management for cucumber: greenhouse experiment in Saudi Arabia and modelling study using SALTMED model', *Journal of Soil and Water Conservation*, 70(1), pp. 1–11.

Amery, H. A. (2015) *Arab water security: threats and opportunities in the Gulf States*. Cambridge: Cambridge University Press.

Amozurrutia, J. A. and Servos, C. M. (2010) 'Excel spreadsheet as a tool for social narrative analysis', *Quality & Quantity*, 45(4), pp. 953–967. doi: 10.1007/s11135-010-9406-9.

Antonelli, M. and Sartori, M. (2015) 'Unfolding the potential of the Virtual Water concept. What is still under debate?' *Environmental Science & Policy*, 50, pp. 240–251.

Apex, T. (2014) *Which pressure is required for your sprinkler system?*, *TEKNORAPEX*. Available at: https://www.apexhose.com/water-distribution-blog/which-pressure-is-required-for-your-sprinkler-system (Accessed: 21 February 2018).

Arthur, R. and 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), pp. 458–468.

Asano, T. (1985) *Artificial recharge of groundwater*. Boston, MA, USA: Butterworth Publishers..

Attride-Stirling, J. (2001) 'Thematic networks: an analytic tool for qualitative research', *SAGE*, 1(3), pp. 385–405.

Bailey, K. D. (1994) *Methods of social research*. New York: Simon and Schuster.

Bansouleh, F. B. (2009) *Development of a spatial planning support system for agricultural policy formulation related to land and water resources in Borkhar & Meymeh district, Iran*. PhD thesis, Wageningen University

Basch, G., González-Sánchez, E. J., Gómez McPherson, H. and Kassam, A. (2011) 'Opportunities for conservation agriculture in the EU Common Agricultural Policy 2014-2020'. Available at: https://core.ac.uk/download/pdf/36159980.pdf (Accessed: 12 April 2019).

Basheer, A. (2000) 'Greening the great Arabian Desert, the success story of Abu Dhabi'. Available at: http://www.academia.edu/27594998/Greening_the_great_Arabian_Desert_7.doc (Accessed: 21 August 2017).

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R. and Yumkella, K. (2011) 'Considering the energy, water and food nexus: Towards an integrated modelling approach', *Energy Policy*, 39(12), pp. 7896–7906.

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

Belesky, P., Lehane, S., Power, L., Shepherd, B., Cribb, J., Keogh, M., Bell, R. and Falvey, J. L. (2014) *Food and water security: our global challenge landmark study*. Dalkeith, Australia: Future Directions International Research Institute.

Beltrán, J. M. and Koo-Oshima, S. (2004) ‘Water desalination for agriculture applications’, in *Proceedings of the FAO expert consultation on water desalination for agriculture applications*. Rome: FAO. Available at: http://www.fao.org/3/a-a0494e.pdf (Accessed: 12 April 2019).

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

Berkes, F., Colding, J. and Folke, C. (eds.) (2003) *Navigating social-ecological systems: building resilience for complexity and change*. Cambridge: Cambridge University Press.

Bhat, N. R., Lekha, V. S., Suleiman, M. K., Thomas, B., Ali, S. I., George, P. and 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), pp. 448–452. doi: 10.5829/idosi.wjas.2012.8.5.1674.

Binswanger-Mkhize, H. P., Meinzen-Dick, R. S. and Ringler, C. (2012) *Policies, rights, and institutions for sustainable management of land and water resources. Back groundwater chapter for the forthcoming soil, land and water review of the Food and Agriculture Organization.* Washington, DC: FAO. Available at: http://www.fao.org/fileadmin/templates/solaw/files/thematic_reports/TR_09_web.pdf (Accessed: 12 April 2019).

Bizikova, L., Roy, D., Swanson, D., Venema, H. D. and McCandless, M. (2013) *The water-energy-food security nexus: Towards a practical planning and decision-support framework for landscape investment and risk management*. Winnipeg: International Institute for Sustainable Development. Available at: http://www.iisd.org/sites/default/files/pdf/2013/wef_nexus_2013.pdf (Accessed: 2 August 2015).

Bollaci, D., Hawkins, C., Mankin, J. and Wurden, K. (2010) *Sustainable water management*. Master of Public Administration in Environmental Science and Policy Workshop in Applied Earth Systems. Columbia University. Available at: http://mpaenvironment.ei.columbia.edu/files/2014/06/AbuDhabiFinalReport.pdf (Accessed: 12 April 2019).

Braun, V. and Clarke, V. (2006) ‘Using thematic analysis in psychology’, *Qualitative Research in Psychology*, 3(2), pp. 77–101. doi: 10.1191/1478088706qp063oa.

Brook, M. C., Al Houqani, H., Darawsha, T and Achary, M. A. (2006) ‘Groundwater resources: development & management in the Emirate of Abu Dhabi, United Arab Emirates’, in Mohamed, A. M. O. (ed.), *Arid land hydrogeology: In search of a solution to a threatened resource.* Balkema: Taylor and Francis, pp. 15–34.

Bryman, A. (2004) *Social research methods*. 2nd edn. New York: Oxford University Press.

Bryman, A. (2012) *Social research methods*. 4th edn. Oxford: Oxford University Press.

Chao, C. T. and Krueger, R. R. (2007) ‘The date palm (*Phoenix dactylifera L.*): overview of biology, uses, and cultivation’, *HortScience*, 42(5), pp. 1077–1082.

Clapp, J. (2015) *The state of agricultural commodity markets 2015–2016: food self-sufficiency and international trade: a false dichotomy?* Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/3/a-i5222e.pdf (Accessed: 12 April 2019).

Clapp, J. (2017) ‘Food self-sufficiency: making sense of it, and when it makes sense’, *Food Policy*, 66, pp. 88–96.

Cochran, W. G. (1977) *Sampling techniques*. 3rd edn. New York: John Wiley & Sons. Available at: https://archive.org/details/Cochran1977SamplingTechniques_201703/page/n15 (Accessed: 12 April 2019).

Cochran, W. G. (2007) *Sampling techniques*. 3rd edn. Delhi: Wiley India. Available at: https://books.google.ae/books?id=xbNn41DUrNwC (Accessed: 12 April 2019).

Cohen, W. L., Hug, A. W., Taddese, A. and Cook, K. A. (1991) ‘FACTA 1990 conservation and environmental highlights’, *Journal of Soil and Water Conservation*, 46(1), pp. 20–22.

Çolak, Y. B., Yazar, A., Çolak, L., Akça, H. and Duraktekin, G. (2015) ‘Evaluation of crop water stress index (CWSI) for eggplant under varying irrigation regimes using surface and subsurface drip systems’, *Agriculture and Agricultural Science Procedia*, 4, pp. 372–382.

Covalla, E., Williams, J., Williams, and Wingo, A. (2001) *Managing agricultural water impacts*. North Carolina State University. Available at: https://www.wingolog.org/projects/water/water.pdf (Accessed: 29 September 2016).

Creswell, J. W. (2003) *Research designs: qualitative, quantitative and mixed methods approaches*. 2nd edn. Thousand Oaks, CA: SAGE.

Creswell, J. W. (2009) *Research design: qualitative, quantitative, and mixed methods approaches*. 3rd edn. Thousand Oaks, CA: SAGE.

Creswell, J. W. (2014) *Research design: qualitative, quantittative and mixed methods approaches*. 4th edn. Thousand Oaks, CA: SAGE.

Creswell, J. W. and Poth, C. N. (2017) *Qualitative inquiry and research design: choosing among five approaches*. Thousand Oaks, CA: SAGE.

Crosson, P. (1993) ‘Sustainable agriculture: a global perspective’, *Choices*, 8(2), pp. 38–42.

Crotty, M. (1998a) *The foundations of social research: meaning and perspective in the research process*. Thousand Oaks, CA: SAGE.

Crotty, M. (1998b) *The foundations of social research: meaning and perspective in the research process*. Thousand Oaks, CA: SAGE. Dawoud, M. A. (2005) ‘The role of desalination in augmentation of water supply in GCC countries’, *Desalination*, 186(1–3), pp. 187–198. doi: 10.1016/j.desal.2005.03.094.

Dawoud, M. A. and Sallam, O. M. (2012) ‘Sustainable groundwater resources management in arid regions: Abu Dhabi case study’, in *Sustainable Development and Green Environment. Ajman international Environmental Conference*, Ajman, UAE, pp. 30–31. Available at: https://www.researchgate.net/publication/260637853_Sustainable_Groundwater_Resources_Management_in_Arid_Regions_Abu_Dhabi_Case_Study (Accessed: 15 April 2017).

Dawoud, M., Farbridge, R., van Wonderen, J., Brook, M. and Al Houqani, H. (2005) ‘An ArcGIS database for water supply/demand modelling and management in Abu Dhabi Emirate, UAE’, in *5th Gulf Water Conference, Kuwait*. Citeseer. Available at:

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.582.3204&rep=rep1&type=pdf (Accessed: 22 March 2017).

De Fraiture, C. and Wichelns, D. (2010) 'Satisfying future water demands for agriculture', *Agricultural Water Management*, 97(4), pp. 502–511.

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

Dhanisanij. H., Nakhjavani, M. M., Tahiri, A. Z. and Anyoji, H. (2009) 'Assessment of wheat and maize water productivities and production function for cropping system decisions in arid and semiarid regions', *Irrigation and Drainage*, 58. doi: 10.1002/ird.397.

Denzin, N. K. and Lincoln, Y. S. (2005) *The SAGE Handbook of Qualitative Research*. Thousand Oaks, CA: SAGE.

Department of Economic Development (2010) *The reality of agriculture sector in the Emirate of Abu Dhabi*. Abu Dhabi: Department of Economic Development.

Dillman, D. A., Smyth, J. D. and Christian, L. M. (2008) *Internet, mail, and mixed-mode surveys: the tailored design method*. 3rd edn. Hoboken, NJ: John Wiley & Sons.

DMAT (2017) *Municipality System Portal-Emirate of Abu Dhabi*. Available at: https://dmat.abudhabi.ae/en/About/Pages/AboutUs.aspx (Accessed: 1 June 2017).

Domuţa, C. G., Pereș, A. C., Brejea, R. P. and Borza, L. M. (2017) 'Irrigation, a basic technological element, for improving the autumn cabbage yield in Crișurilor Plain, Western Romania', Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 45(2). doi: 10.15835/nbha45210774.

Doyle, J. K. (2005) 'Face-to-face surveys', in Everitt, B. S. and Howells, D. C. (eds.), *Encyclopaedia of statistics in behavioural science*. Chichester: John Wiley & Sons.

EAD (2011) *Environmental atlas of Abu Dhabi Emirate*. Abu Dhabi, UAE: Environment Agency-Abu Dhabi.

EAD (2012a) *Advanced sustainable groundwater management in Abu Dhabi*. Abu Dhabi, UAE: Environment Agency-Abu Dhabi. Available at: https://www.ead.ae/Publications/Advancing%20Sustainable%20Groundwater%20Management%20in%20Abu%20Dhabi/Groundwater-PB-Eng.pdf (Accessed: 12 April 2019).

EAD (2012b) *Annual report 2012*. Abu Dhabi, UAE: Environment Agency-Abu Dhabi. Available at: https://www.ead.ae/Pages/Resources/Publications.aspx (Accessed: 12 April 2019).

EAD (2015a) *Annual report 2015*. Abu Dhabi, UAE: Environment Agency-Abu Dhabi. Available at: https://www.ead.ae/Pages/Resources/Publications.aspx (Accessed: 12 April 2019).

EAD (2015b) *Strategic plan 2016–2020*. Abu Dhabi, UAE: Environment Agency-Abu Dhabi. Available at: https://www.ead.ae/Documents/PDF-Files/EAD_STRATEGY_28%20sep%20spread%20(1).pdf (Accessed: 12 April 2019).

EAD (2017) *Abu Dhabi state of environment report 2017*. Abu Dhabi, UAE: Environment Agency-Abu Dhabi. Available at: https://www.ead.ae/Publications/Abu%20Dhabi%20State%20of%20Environment%20Report%202017/EAD-full-report.pdf (Accessed: 12 April 2019).

EAD and ADFCA (2012) *Advancing sustainable groundwater management in Abu Dhabi*. Annual Policy Brief. Abu Dhabi. UAE: Environment Agency-Abu Dhabi.

Easterby-Smith, M., Thorpe, R. and Jackson, P. (2008) *Management research*. 3rd edn. London: SAGE.

EC (2016) 'Groundwater management law in Abu Dhabi Emirate'. Abu Dhabi, UAE: Executive Council of Abu Dhabi. 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), pp. 3998–4010.

Ellis, F. (1992) *Agricultural policies in developing countries*. New York: Cambridge University Press.

Elmahdy, S. I. and Mohamed, M. M. (2015) 'Groundwater of Abu Dhabi Emirate: a regional assessment by means of remote sensing and geographic information system', *Arabian Journal of Geosciences*, 8(12), pp. 11279–11292. doi: 10.1007/s12517-015-1932-2.

El Masri, S. (2010) *Permanent committee set up on water and agriculture resources*, *Abu Dhabi city guide*. Available at: http://www.abudhabicityguide.com/news/news-details.asp?newsid=3734&newstype=News%20Archive (Accessed: 14 February 2017).

Elo, S. and Kyngäs, H. (2008) 'The qualitative content analysis process', *Journal of Advanced Nursing*, 62(1), pp. 107–115.

Eriksson, M., Jianchu, X., Shrestha, A. B., Vaidya, R. A., Nepal, S. and Sandström, K. (2009) *The changing Himalayas: impact of climate change on water resources and livelihoods in the greater Himalayas.* Patan, Nepal: International Centre for Integrated Mountain Development (ICIMOD).

ERWDA (2002) *2002 Abu Dhabi water resources statistics*,. Available at: https://www.yumpu.com/en/document/view/35881678/2002-abu-dhabi-water-resources-statistics (Accessed: 19 June 2017).

ESCWA (2009) *ESCWA water development report 3: role of desalination in addressing water scarcity*. New York: United Nations. Available at: https://www.unescwa.org/publications/escwa-water-development-report-3-role-desalination-addressing-water-scarcity (Accessed 12 April 2019).

European Commission (2012) *The role of water pricing and water allocation in agriculture in delivering sustainable water use in Europe – final report*. Brussels: European Commission.

Falkenmark, M. and Widstrand, C. (1992) 'Population and water resources: a delicate balance', *Population Bulletin. Population Reference Bureau*, 47(3), pp. 1–36.

FAO (2002) *Date palm cultivation*. Rome: Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/docrep/006/Y4360E/y4360e07.htm (Accessed: 23 December 2017).

FAO (2003) *Review of world water resources by country*. 23. Rome: Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/docrep/005/Y4473E/y4473e06.htm#bm06.1.1 (Accessed 12 April 2019).

FAO (2007) 'Irrigation of date palm and associated crops', in *Irrigation of date palm and associated crops*, Damascus, Syria. Available at: http://www.fao.org/tempref/GI/Reserved/FTP_FaoRne/morelinks/Publications/English/date-Palm-Proceedings.pdf (Accesssed: 12 April 2019).

FAO (2009) 'How to feed the world in 2050?', in *World Summit on Food Security. How to feed the world in 2050 – High-Level Expert Forum*, Rome: Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/wsfs/forum2050/wsfs-forum/en/ (Accessed: 4 February 2018).

FAO (2011a) *Climate change, water and food security*. Rome: Food and Agriculture Organization of the United Nations.

FAO (2011b) *Groundwater management in the Near East region: synthesis report*. Rome: Food and Agriculture Organization of the United Nations. Available at: http://www.groundwatergovernance.org/fileadmin/user_upload/groundwatergovernance/docs/Country_studies/Near_East_Region_Synthesis_Report_Final_Groundwater_Management.pdf (Accessed 12 April 2019).

FAO (2011c) *The state of the world's land and water resources for food and agriculture (SOLW) – managing water at risk*. Rome: Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/docrep/017/i1688e/i1688e.pdf (Accessed: 12 April 2019).

FAO (2012a) *Coping with water scarcity: an action framework for agriculture and food security*. Rome: Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/docrep/016/i3015e/i3015e.pdf (Accessed: 12 April 2019).

FAO (2012b) *Crop yield response to water*. Rome: Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/docrep/016/i2800e/i2800e.pdf (Accessed: 12 April 2019).

FAO (2013) *Good agriculture practices for greenhouse vegetable crops: principles for Mediterranean climate areas*. Rome: Food and Agriculture Organization of the United Nations.

FAO (2014a) *Building a common vision for sustainable food and agriculture: principles and approaches*. Rome: Food and Agriculture Organization of the United Nations.

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

FAO (2015a) *Proposal from the United Arab Emirates: for the designation under the GIAHS program of Al Ain and Liwa historical date palm oases*. Rome: Food and Agriculture Organization of the United Nations.

FAO (2015b) *Towards a water and food secure future: critical perspectives for policy-makers*. Rome: Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/3/a-i4560e.pdf (Accessed: 12 April 2019).

FAO (2018) *CROPWAT*, *land & water*. Available at: http://www.fao.org/land-water/databases-and-software/cropwat/en (Accessed: 10 September 2018).

FAOSTAT (2013) *Database of the Food and Agriculture Organization of the United Nations*. Available at: http://www.fao.org (Accessed: 13 March 2018).

FAOSTAT (2016) *Database of the Food and Agriculture Organization of the United Nations*. Available at: http://www.faostat.fao.org (Accessed: 31 December 2017).

Farrelly & Mitchell (2014) *Opportunities for supply chain consolidation in GCC food sector*. Dublin: Farrelly & Mitchell, Food & Agri-Business Specialists.

Ferreyra, C., de Loë, R. C. and Kreutzwiser, R. D. (2008) 'Imagined communities, contested watersheds: challenges to integrated water resources management in agricultural areas', *Journal of Rural Studies*, pp. 304–321. doi: 10.1016/j.jrurstud.2007.11.001.

Fiaz, S., Noor, M. A. and Aldosri, F. O. (2016) 'Achieving food security in the Kingdom of Saudi Arabia through innovation: potential role of agricultural extension', *Journal of the Saudi Society of Agricultural Sciences*, 17(4), pp. 365–375.

Fipps, G. (1995) *Calculating horsepower requirements and sizing irrigation supply pipelines*. Available at: https://aglifesciences.tamu.edu/baen/wp-content/uploads/sites/24/2017/01/B-6011-Calculating-Horsepower-Requirements-and-Sizing-Irrigation-Supply-Pipelines.pdf (Accessed: 31 March 2017).

Fiscbach, T. (2018) *Advancing food security in the UAE*. Mohammed Bin Rashid School of Government.

Fischer, G., Hizsnyik, E., Prieler, S., van Velthuizen, H. and Wiberg, D. (2012) 'Scarcity and abundance of land resources: competing uses and the shrinking land resource base', in *Worlds within reach: from science to policy* – IIASA 40th anniversary conference, Vienna. Available at: http://pure.iiasa.ac.at/id/eprint/12216 (Accessed: 12 April 2019).

FSCAD (2015) *Food Security Centre-Abu Dhabi.* Available at: http://www.fscad.ae/Arabic/AboutUs/Pages/default.aspx (Accessed: 14 February 2017).

Gallacher, D. J. and Hill, J. P. (2008) 'Intensification of rangeland grazing in an oil-rich state: causes, consequences and possible solutions'. Available at: https://www.researchgate.net/profile/David_Gallacher3/publication/267947074 (Accessed: 22 March 2017).

Geerts, S. and Raes, D. (2009) 'Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas', *Agricultural Water Management*, 96(9), pp. 1275–1284.

Gill, J. and Johnson, P. (2002) *Research methods for managers*. 3rd edn. London: SAGE.

Gilmont, M. (2015) 'Water resource decoupling in the MENA through food trade as a mechanism for circumventing national water scarcity', *Food Security*, 7(6), pp. 1113–1131. doi: 10.1007/s12571-015-0513-2.

Giordano, M. and Villholth, K. G. (2007) *The agricultural groundwater revolution: opportunities and threats to development*. Wallingford: CAB International. Available at: https://cgspace.cgiar.org/handle/10568/36474 (Accessed: 12 April 2019).

Gleick, P. H. (2000) ‘A look at twenty-first century water resources development’, *Water International*, 25(1), pp. 127–138.

Global Water Partnership (2017) *The need for an integrated approach – GWP*. Available at: https://www.gwp.org/en/About/why/the-need-for-an-integrated-approach/ (Accessed: 8 April 2018).

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., and Toulmin C. (2010) ‘Food security: the challenge of feeding 9 billion people’, *Science*, 327(5967), pp. 812–818.

Gollehon, N. and Winston, B. (2013) ‘Groundwater irrigation and water withdrawals: the Ogallala aquifer initiative’, *USDA Economic Series*, 15.

Government of Abu Dhabi (2013) *The water resources management strategy for the Emirate of Abu Dhabi 2014–2018*. Abu Dhabi, UAE: Government of Abu Dhabi. Available at: https://www.ead.ae/Documents/PDF-Files/Executive-Summary-of-The-Water-Resources-Management-Strategy-for-the-Emirate-of-Abu-Dhabi-2014-2018-Eng.pdf (Accessed: 12 April 2019).

Government of Abu Dhabi (2015) *Water resources management strategy for the Emirate of Abu Dhabi 2015–2020*. Strategy and action plan. Abu Dhabi, UAE: Government of Abu Dhabi.

Government of Abu Dhabi (2016) *Preliminary results of the marketing date palm farms*. Abu Dhabi, UAE: SENAAT-General Holding Corporation.

Green, S. R., Cann, I. M., Clothier, B. E., Abdelfattah, M., Dakheel, A., Alyamani, W. and Pangilinan, R. (2014) ‘Water use of date palms growing in the saline desert soils of the United Arab Emirates’, in *29th International Horticultural Congress, 17–22 August 2014*, Brisbane, Australia. Available at: https://www.researchgate.net/publication/267506567_Water_use_of_date_palms_growing_in_the_saline_desert_soils_of_the_United_Arab_Emiratesha (Accessed: 17 May 2017).

Greiner, R. (2004) ‘Systems framework for regional-scale integrated modelling and assessment’, *Mathematics and Computers in Simulation* (MSSANZ/IMACS 14th Biennial Conference on Modelling and Simulation), 64(1), pp. 41–51. doi: 10.1016/S0378-4754(03)00119-8.

HAAD (2016) *Capacity master plan: a healthier Abu Dhabi*. Abu Dhabi, UAE: Health Authority Abu Dhabi.

Haj-Amor, Z., Ritzema, H., Hashemi, H. and Bouri, S. (2018) ‘Surface irrigation performance of date palms under water scarcity in arid irrigated lands’, *Arabian Journal of Geosciences*, 11(2). Available at: https://link.springer.com/article/10.1007/s12517-017-3374-5 (Accessed 12 April 2019).

Hargrove, W. L., Borrok, D. M., Heyman, J. M., Tweedie, C. W. and Ferregut, C. (2013) ‘Water, climate, and social change in a fragile landscape’, *Ecosphere*, 4(2), p. 22. doi: 10.1890/ES12-00269.1.

Hashim M.A.A., Siam N., Al-Dosari A., Asl-Gaadi K.A. and Patil V.C. (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 Sciences, 9(6), pp. 196–206.

Hirich, A. and Choukr-Allah, R. (2017) 'Water and energy use efficiency of greenhouse and net house under desert conditions of UAE: agronomic and economic analysis', in Abdalla, O., Kacimov, A., Chen, M., Al-Maktoumi, A. and Al-Hosnilan Clark, T. (eds.), *Water resources in arid areas: the way forward*. Springer, pp. 481–499. Available at: http://link.springer.com/chapter/10.1007/978-3-319-51856-5_28 (Accessed: 15 August 2017).

HLPE (2015) *Water for food security and nutrition*. Rome: High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Available at: http://www.fao.org/3/a-av045e.pdf (Accessed: 12 April 2019).

HLPE (2016) *Sustainable agricultural development for food security and nutrition: what roles for livestock?* Rome: High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Available at: http://www.fao.org/3/a-i5795e.pdf (Accessed: 12 April 2019).

Hoekstra, A. Y. (2003) 'Virtual water trade', in *Value of water research report series No. 12. Proceedings of the International Expert Meeting on Virtual Water Trade*, Delft, The Netherlands. Available at: https://waterfootprint.org/media/downloads/Report12.pdf (Accessed: 12 April 2019).

Hoekstra, A. and Chapagain, A. (2008) 'The global component of freshwater demand and supply: an assessment of virtual water flows between nations as a result of trade in agricultural and industrial products', *Water International*, 33(1), p. 19. doi: 10.1080/02508060801927812.

Hoff, H. (2011) 'Understanding the nexus. Background paper for the Bonn 2011 Conference: the water, energy and food security nexus', Stockholm: Stockholm Environment Institute.

Horlemann, L. and Neubert, S. (2006) *Virtual water trade: a realistic concept for resolving the water crisis?* Bonn: German Development Institute.

Howari, F. M., Sadooni, F. N. and Goodell, P. C. (2008) 'Assessment of water bodies of United Arab Emirates coastal sabkhas as potential sites for natural salinity gradient solar ponds', *Journal of Energy Engineering*, 134(4), pp. 111–120. doi: 10.1061/(ASCE)0733-9402(2008)134:4(111).

Hsieh, H.-F. and Shannon, S. E. (2005) 'Three approaches to qualitative content analysis', *Qualitative Health Research*, 15(9), pp. 1277–1288.

IAASTD (2009) *Agriculture at a crossroads*. Synthesis report. Washington, DC: International Assessment of Agriculture Knowledge, Science and Technology for Development.

ICBA (2014) *Programs highlights and achievements 2009–2013*. Dubai, UAE: International Centre for Biosaline Agriculture. Available at: http://www.biosaline.org/sites/default/files/publicationpdfenglish/Achievements-Report-rnd3-pages.pdf (Accessed: 12 April 2019).

ICBA (2015) *Innovative agriculture in saline and marginal environments*. Dubai, UAE: International Centre for Biosaline Agriculture. Available at: http://www.biosaline.org/sites/default/files/icba_capability_statement_eng.pdf (Accessed: 31 March 2017).

ICBA (2016) *ICBA annual report 2015*. Dubai, UAE: International Centre for Biosaline Agriculture. Available at:

http://www.biosaline.org/sites/default/files/Annualreportpdf/ar2015_final_english.pdf (Accessed: 31 March 2017).

ICBA (2017) *ICBA at a glance*. Dubai, UAE: International Centre for Biosaline Agriculture. Available at: http://www.biosaline.org/content/icba-glance (Accessed: 28 June 2017).

ICIMOD (2012) *Contribution of Himalayan ecosystems to water, energy, and food security in South Asia: a nexus approach*. Available at: http://www.fao.org/fileadmin/user_upload/mountain_partnership/docs/icimod-contribution_of_himalayan_ecosystems_to_water,_energy,_and_food_security_in_south_asia__a_nexus_appr.pdf (Accessed: 12 April 2019).

IFAD (2015) *Agricultural water management: scaling up note*. Rome: International Fund for Agricultural Development (IFAD). Available at: https://www.ifad.org/documents/10180/8b680fd2-50b8-4a91-bf38-55d3b2bda18e (Accessed: 12 April 2019).

IFREMER (2017) *Water framework directive*. Available at: https://wwz.ifremer.fr/en/Public-policy-support/Water-Biodiversity/Water-Framework-Directive (Accessed: 9 September 2018).

IPCC (2007) AR4 *Climate change 2007: the physical science basis*. Available at: https://www.ipcc.ch/report/ar4/wg1 (Accessed: 12 April 2019).

IPCC (2008) *Water: technical paper of the Intergovernmental Panel on Climate Change*. Geneva: IPCC Secretariat.

IPCC (2013) *Climate change 2013: the physical science basis*. New York: Cambridge University Press.

IPCC (2014) *AR5 Climate change 2014: impacts, adaptation, and vulnerability.* Cambridge: Cambridge University Press. Available at: https://www.ipcc.ch/report/ar5/wg2 (Accessed: 12 April 2019).

Irrigation Research Lab (2007) *Effects of irrigation on the yield and water-use efficiency of Rhodes grass (chloris gayana) in Batinah region*. Oman: Soil and Water Research Center.

Israel, G. D. (1992) *Determining sample size*. University of Florida Cooperative Extension Service, Institute of Food and Agriculture Sciences, EDIS Gainesville. Available at: https://sites.google.com/site/estadisticayunpocomas/tama%C3%B1omuestra.pdf (Accessed: 31 March 2017).

Israel, G. D. (2016) *Sampling the evidence of extension program impact*. Gainesville, FL: University of Florida IFAS Extension. Available at: http://edis.ifas.ufl.edu/pd005 (Accessed: 26 July 2017).

Jimenez, B. and Asano, T. (2004) ‘Acknowledge all approaches: The global outlook on reuse’, *WATER 21*, Dec., pp. 32–37.

Kang, Y., Khan, S. and Ma, X. (2009) ‘Climate change impacts on crop yield, crop water productivity and food security – a review’, *Progress in Natural Science*, 19(12), pp. 1665–1674. doi: 10.1016/j.pnsc.2009.08.001.

Karam, F., Saliba, R., Skaf, S., Breidy, J., Rouphael, Y. and Balendonck, J. (2011) 'Yield and water use of eggplants (*Solanum melongena L.*) under full and deficit irrigation regimes', *Agricultural Water Management*, 98(8), pp. 1307–1316.

Kassie, M., Zikhali, P., Manjur, K. and Edwards, S. (2009) 'Adoption of sustainable agriculture practices: evidence from a semi-arid region of Ethiopia', in *Natural Resources Forum*, 33(3), pp. 189–198.

Kazim, A. (2010) 'Strategy for a sustainable development in the UAE through hydrogen energy', *Renewable Energy*, 35(10), pp. 2257–2269. doi: 10.1016/j.renene.2010.03.013.

Keulertz, M. and Woertz, E. (2015) 'Financial challenges of the nexus: pathways for investment in water, energy and agriculture in the Arab world', *International Journal of Water Resources Development*, 31(3), pp. 312–325.

Kijne, J. W., Barker, R. and Molden, D. J. (2003) *Water productivity in agriculture: limits and opportunities for improvement*. Wallingford: CABI. Available at: https://books.google.ae/books?id=B1kK0yOLBAQC (Accessed 12 April 2019).

Kotilaine, J. T. (2010) 'GCC agriculture', *Economic Research,* 27.

Kreft, S., Harmeling, S., Bals, C., Zacher, W. and van de Sand, K. (2010) *The millennium development goals and climate change: taking stock and looking ahead*. Berlin: Germanwatch.

Lichtfouse, E., Navarrete, M., Debaeke, P., Souchère, V. (2009) 'Agronomy for sustainable agriculture: a review', *Agronomy for Sustainable Development*, 29(1), pp. 1–6. doi: 10.1051/agro:2008054.

Lichtman, M. (2012) *Qualitative research in education: a user's guide*. Thousand Oaks, CA: SAGE.

Lin, P., Khalid, A., Kennedy, S., Sgouridis, S. (2011) 'Sensitivity of CO2 emissions to renewable energy penetration for regions utilizing power and water cogeneration', in Seliger, G., Khraisheh, M. M. K. and Jawahir, I. S. (eds.), *Advances in Sustainable Manufacturing*. Berlin: Springer, pp. 287–292. doi: 10.1007/978-3-7_41.

Lomazzi, M., Borisch, B. and Laaser, U. (2014) 'The Millennium Development Goals: experiences, achievements and what's next', *Global Health Action*, 7(1), p. 23695.

Lorenzoni, I., Benson, D. and Cook, H. (2015) 'Regional rescaling in UK climate adaptation governance: from agency to collaborative control', in Knieling, J. and Klindworth, K. (eds.), *Climate adaptation governance: Theory, concepts and praxis in cities and regions.* Chichester: John Wiley & Sons, pp. 209–221.

Lowndes, V. and Skelcher, C. (1998) 'The dynamics of multi-organizational partnerships: an analysis of changing modes of governance', *Public Administration*, 76, pp. 313–333. doi: 10.1111/1467-9299.00103.

Mahmoud, M. (2016) *Water at the nexus of Gulf security growth challenges*. Washington, DC: Arab Gulf States Institute. Available at: https://agsiw.org/water-nexus-gulf-security-growth-challenges (Accessed 12 April 2019).

Mancosu, N., Snyder, R. L., Kyriakakis, G. and Spano, D. (2015) 'Water scarcity and future challenges for food production. *Water*, 10, pp. 975–992. doi: 10.3390/w7030975.

Margerum, R. D. (1997) 'Integrated approaches to environmental planning and management', *Journal of Planning Literature*, 11(4), pp. 459–475.

Mateo-Sagasta, J. and Burke, J. (2012) *Agriculture and water quality interactions: a global overview*, SOLAW Background Thematic Report—TR08. Rome: FAO.

Mazahrih, N., Al-Wahaibi, H., Al-Farsi, S. and 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), pp. 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, pp. 225–233. doi: 10.1016/j.geoforum.2013.11.009.

McDonnell, R. and Fragaszy, S. (2016) *Groundwater use and policies in Abu Dhabi*. IWMI Project Report 13. Available at: http://gw-mena.iwmi.org/wp-content/uploads/sites/3/2017/04/Rep.13-Groundwater-use-and-policies-in-Abu-Dhabi-Emirate.pdf (Accessed 12 April 2019).

Miles, J. and Gilbert, P. (2005) *A handbook of research methods for clinical and health psychology*. Oxford: Oxford University Press.

Miles, M. B. and Huberman, A. M. (1994) *Qualitative data analysis: an expanded sourcebook*. 2nd edn. London: SAGE.

Ministry of Environment and Water (2014) *UAE state of green economy*. UAE: Ministry of Environment & Water. Available at: http://www.moew.gov.ae/assets/e3bd136a/uae-state-of-green-economy-report-2014.aspx (Accessed: 12 April 2019).

MOCCAE (2016) *UAE Ministry of Climate Change and Environment*. Available at: https://www.moccae.gov.ae/en/about-ministry/about-the-ministry.aspx (Accessed: 22 July 2017).

MOCCAE (2017) *National climate change plan of the United Arab Emirates: 2017–2050*. UAE: Ministry of Climate Change and Environment. Available at: https://www.moccae.gov.ae/assets/30e58e2e/national-climate-change-plan-for-the-united-arab-emirates-2017-2050.aspx (Accessed: 29 March 2018).

MOEW (2010) *United Arab Emirates water conservation strategy*. UAE: Ministry of Environment & Water. Available at: http://extwprlegs1.fao.org/docs/pdf/uae147095.pdf (Accessed: 12 April 2019).

Molden, D., Murray-Rust, H., Sakthivadivel, R. and Makin, I. (2003) 'A water-productivity framework for understanding and action', in Kijne, J. W., Barker, R. and Molden, D. J. (eds.), *Water productivity in agriculture: Limits and opportunities for improvement*. Wallingford: CABI, pp. 1–19. doi: 10.1079/9780851996691.0001

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A. and Kijine, J. (2010) 'Improving agricultural water productivity: between optimism and caution', *Agricultural Water Management*, 97(4), pp. 528–535.

Monke, E. A. and Pearson, S. R. (1989) *The policy analysis matrix for agricultural development*. Ithaca, NY: Cornell University Press.

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

Mousa, H. (2014) *Saudi Arabia grain and feed annual*. Global Agriculture Information Network SA1402. Washington, DC: USDA Foreign Agriculture Service. Available at: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Grain%20and%20Feed%20Annual_Riyadh_Saudi%20Arabia_5-14-2015.pdf (Accessed: 12 April 2019).

Mousa, H. (2016) *Saudi Arabia grain and feed annual*. Global Agriculture Information Network. Washington, DC: USDA Foreign Agriculture Service. Available at: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Grain%20and%20Feed%20Annual_Riyadh_Saudi%20Arabia_5-14-2015.pdf (Accessed: 12 April 2019).

Mujtaba, I. M., Srinivasan, R. and Elbashir, N. O. (2017) *The water-food-energy nexus: processes, technologies, and challenges*. Boca Raton, FL: CRC Press.

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), pp. 181–190. doi: 10.4236/jwarp.2010.22020.

Nafchi, R. A. (2016) 'Comparison of water use efficiency in alfalfa using water and waste water', *Journal of Agricultural Chemistry and Environment*, 5(4), p. 191. doi: 10.4236/jacen.2016.54020.

Nagaz, K., Masmoudi, M. M. and Ben Mechlia, N. (2012) 'Yield response of drip-irrigated onion under full and deficit irrigation with saline water in arid regions of Tunisia', *ISRN Agronomy*, 2012. doi: 10.5402/2012/562315.

Norton, R. D. (2004) *Agricultural development policy: concepts and experiences*. Chichester: John Wiley & Sons.

Obuobie, E., Gachanja, P. M. and Dörr, A. C. (2005) *The role of green water in food trade*. Term paper for the interdisciplinary course, International Doctoral Studies. Bonn: Zentrum für Entwicklungsforschung (ZEF).

OECD (2010) *Sustainable management of water resources in agriculture*. Paris: Organization for Economic Co-operation and Development. Available at: http://www.oecd.org/tad/sustainable-agriculture/49040929.pdf (Accessed: 12 April 2019).

Olsson, P., Folke, C. and Berkes, F. (2004) 'Adaptive comanagement for building resilience in social–ecological systems', *Environmental Management*, 34(1), pp. 75–90.

Ose, S. O. (2016) 'Using Excel and Word to structure quantitative data', *Journal of Applied Social Science*, 10(2), pp. 147–162. doi: 10.1177/1936724416664948.

Ostrom, E. (1990) *Governing the commons: the evolution of institutions for collective action*. Cambridge: Cambridge University Press.

Ouled Belgacem, A. (2017) *United Arab Emirates and ICARDA highlight of 20 years of collaboration and achievements*. Dubai, UAE: ICARDA.

Pandya-Lorch, R., Rosegrant, M. and Pinstrup-Andersen, P. (2001) 'Global food security: a review of the challenges', in Pinstrup-Andersen, P. and Pandya-Lorch, R. (eds.), *The unfinished agenda: perspectives on overcoming hunger, poverty, and environmental degradation*. Washington, DC: IFPRI, p. 314. Available at: http://www.ifpri.org/pubs/books/ufa/ufa_ch02.pdf (Accessed: 26 March 2018).

Patil, V. C., Al-Gaadi, K. A., Madugundu, R., M., Tola, E. H. M., Marey, S., Aldosari, A., Biradar, C. M. and 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), pp. 284–297. doi: 10.1109/JSTARS.2014.2320592.

Payero, J. O., Tarkalson, D. D., Irmak, S., Davison, D. and Petersen, J. L. (2008) 'Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semiarid climate', *Agricultural Water Management*, 95(8), pp. 895–908.

Pearson, S., Gotsch, C. and Bahri, S. (2003) *Applications of the policy analysis matrix in Indonesian agriculture*. Available at: https://web.stanford.edu/group/FRI/indonesia/newregional/newbook.pdf (Accessed: 12 April 2019).

Pearson, S. R., Gotsch, C. and Bahri, S. (2004) *Applications of the policy analysis matrix in Indonesian agriculture*. Jakarta: Yayasan Obor Indonesia.

Pereira, L. S., Oweis, T. and Zairi, A. (2002) 'Irrigation management under water scarcity', *Agricultural Water Management*, 57(3), pp. 175–206. doi: 10.1016/S0378-3774(02)00075-6.

Perry, C. J. (1999) 'The IWMI water resources paradigm – definitions and implications', *Agricultural Water Management*, 40(1), pp. 45–50. doi: 10.1016/S0378-3774(98)00102-4.

Pirani, S. I. and Arafat, H. A. (2016) 'Interplay of food security, agriculture and tourism within GCC countries', *Global Food Security*, 9, pp. 1–9.

Pitman, K., McDonnell, R. and Dawoud, M. (2009) *Abu Dhabi water resources master plan*. Abu Dhabi, UAE: Environment Agency-Abu Dhabi. Available at: https://www.scribd.com/doc/224889521/Abu-Dhabi-Water-Rosources-Master-Plan (Accessed: 12 April 2019).

Platonov, A.; Thenkabail, P.S.; Biradar, C.; Cai, X.; Gumma, M.; Dheeravath, V.; Cohen, Y.; Alchanatis, V.; Goldshlager, N.; Ben-Dor, E.; Vithanage, J.; Manthrithilake, H.; Kendjabaev, 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), pp. 8156–8180. doi: 10.3390/s8128156.

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

Postel, S. (2017) 'Bank it for a dry day', in Postel, S. (ed.), *Replenish: The virtuous cycle of water and prosperity*. Berlin: Springer, pp. 85–105.

Qadir, M., Wichelns, D., Raschid-Sally, L., Minhas, P.S., Drechsel, P., Bahri, A. and McCornick, P. (2007) 'Agricultural use of marginal-quality water: opportunities and challenges', in Molden, D. (ed.), *Water for food, water for life: a comprehensive assessment of water* *management in agriculture*. London: Earthscan and International Water Management Institute, pp. 425–457.

Qadir, M., Sharma, B. R., Bruggeman, A., Choukr-Allah, R. and Karajeh, F. (2007) 'Non-conventional water resources and opportunities for water augmentation to achieve food security in water scarce countries', *Agricultural Water Management*, 87(1), pp. 2–22.

Qadir, M., Wichelns, D., Raschid-Sally, L., McCornick, P.G., Drechsel, P., Bahri, A.,

Minhas, P.S., (2010) 'The challenges of wastewater irrigation in developing countries', *Agricultural Water Management*, 97(4), pp. 561–568.

Qureshi, A. S., McCornick, P. G., Sarwar, A. and Sharma, B. R. (2010) 'Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan', *Water Resources Management*, 24(8), pp. 1551–1569.

Rahil, M. H. and Qanadillo, A. (2015) 'Effects of different irrigation regimes on yield and water use efficiency of cucumber crop', *Agricultural Water Management*, 148, pp. 10–15.

Rasul, G. and Sharma, B. (2015) 'The nexus approach to water-energy-food security – an option for adaptation to climate change', *Climate Policy*, 16(6), pp. 1–21. doi: 10.108114693062.2015.1029865.

Renner, M. and Taylor-Powell, E. (2003) *Analysing qualitative data*. Programme Development & Evaluation, University of Wisconsin-Extension Cooperative Extension. Available at: https://pdfs.semanticscholar.org/8ee4/a0c8532720200bb4359cf5a3741fac60ca74.pdf (Accessed: 22 July 2017).

Rijsberman, F. R. (2006) 'Water scarcity: Fact or fiction?' *Agricultural Water Management*, 80(1), pp. 5–22.

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

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B. H., Liverman, D., Richardson, K., Crutzen, P. and Foley, J. A. (2009) 'A safe operating space for humanity', Nature, 461(7263), pp. 472–475.

Rogers, P. and Hall, A. W. (2003) *Effective water governance*. Stockholm: Global Water Partnership.

RSB (1998) *Law No (2) of 1998 concerning the regulation of the water and electricity sector in the Emirate of Abu Dhabi (as amended)*. Abu Dhabi, UAE: Regulation and Supervision Bureau. Available at: http://rsb.gov.ae/assets/documents/40/law2of1998asamended.pdf (Accessed: 12 April 2019).

RSB (2013) *Supporting the Abu Dhabi economic vision 2030*. Abu Dhabi, UAE: Regulation and Supervision Bureau. Available at: http://rsb.gov.ae/en/publications/detail/supporting-the-abu-dhabi-economic-vision-2030 (Accessed: 7 November 2017).

RSB (2014) *The residential end use of water project – summary report*. Abu Dhabi: Regulation and Supervision Bureau.

Ruttan, V. W. and Hayami, Y. (1984) 'Toward a theory of induced institutional innovation', *Journal of Development Studies*, 20(4), pp. 203–223.

Sadik, A.K., El-Solh, M. and Saab, N. (2014) *Arab environment: food security*. Beirut: Arab Forum for Environment and Development (AFED). Available at: www.afedonline.org/Report2014/English.html (Accessed: 12 April 2019).

Saif, O., Mezher, T. and Arafat, H. (2014) 'Water security in the GCC countries: challenges and opportunities', *Journal of Environmental Studies and Sciences*, 4(4), pp. 329–346. doi: 10.1007/s13412-014-0178-8.

Sathish, S. and Mohamed, M. M. (2018) 'Assessment of aquifer storage and recovery (ASR) feasibility at selected sites in the Emirate of Abu Dhabi, UAE', *Environmental Earth Sciences*, 77(3), p. 112. doi: 10.1007/s12665-018-7251-7.

Saunders, M. L. and Lewis, P. (2009) *Research methods for business students*. 5th edn. Harlow: Pearson Education.

Saunders, M., Lewis, P. and Thornhill, A. (2003) *Research methods for business students*. 3rd edn. Upper Saddle River, NJ: Prentice Hall.

Saunders, M., Lewis, P. and Thornhill, A. (2012) *Research methods for business students*. 6th edn. New York: Pearson.

SCAD (2010) *Statistical yearbook of Abu Dhabi 2009*. Abu Dhabi, UAE: Statistical Centre of Abu Dhabi. Available at: http://www.scad.ae/ar/statistics/Pages/Statistics (Accessed: 12 April 2019).

SCAD (2011a) *Annual bulletin of agricultural statistics 2010*. Abu Dhabi, UAE: Statistical Centre of Abu Dhabi.

SCAD (2011b) *Statistical yearbook of Abu Dhabi 2011*. Abu Dhabi, UAE: Statistical Centre of Abu Dhabi. Available at: https://www.scad.gov.abudhabi/en/Pages/ThemePublication.aspx?PID=7&ThemeID=1 (Accessed: 12 April 2019).

SCAD (2012) *Statistical yearbook of Abu Dhabi 2012*. Abu Dhabi, UAE: Statistical Centre of Abu Dhabi. Available at: https://www.scad.gov.abudhabi/en/Pages/ThemePublication.aspx?PID=7&ThemeID=1 (Accessed 12 April 2019).

SCAD (2013) *Statistical yearbook of Abu Dhabi 2013*. Abu Dhabi, UAE: Statistical Centre of Abu Dhabi. Available at: http://www.scad.ae/ar/statistics/Pages/Statistics (Accessed: 12 April 2019).

SCAD (2014) *Food Balance Sheet of the Emirate of Abu Dhabi 2014.* Abu Dhabi, UAE: Statistical Centre of Abu Dhabi

SCAD (2015) *Abu Dhabi over a half century*. Abu Dhabi, UAE: Statistical Centre of Abu Dhabi.

SCAD (2016) *Statistical year book of Abu Dhabi 2016*. Abu Dhabi, UAE: Statistical Centre of Abu Dhabi. Available at: https://www.scad.ae/en/Pages/ThemePublication.aspx?PID=7&ThemeID=1 (Accessed: 30 March 2017).

SCAD (2017a) *Agriculture land uses*. Abu Dhabi, UAE. Available at: https://www.scad.ae/Release%20Documents/Agricultural%20Land%20Uses%20-%202016-%20EN-QR.pdf (Accessed: 12 April 2019).

SCAD (2017b) *Statistical yearbook of Abu Dhabi 2016.* Abu Dhabi, UAE: Statistical Centre of Abu Dhabi. Available at: https://www.scad.gov.abudhabi/en/Pages/ThemePublication.aspx?PID=7&ThemeID=1 (Accessed 12 April 2019).

Schmidhuber, J. and Tubiello, F. N. (2007) 'Global food security under climate change', *Proceedings of the National Academy of Sciences of the United States of America*, 104(50), pp. 19703–19708.

Seckler, D. W. (1998) *World water demand and supply, 1990 to 2025: Scenarios and issues*. Colombo, Sri Lanka: IWMI.

Seo, K. and Rodriguez, N. (2012) 'Land grab, food security and climate change: a vicious circle in the Global South', in Chhetri, N. (ed.), *Human and Social Dimensions of Climate Change*. London: InTech.

Sgouridis, S., Griffiths, S., Kennedy, S., Khalid, A. and Zurita, N. (2013) 'A sustainable energy transition strategy for the United Arab Emirates: evaluation of options using an integrated energy model', Energy Strategy Reviews, 2(1), pp. 8–18. doi: 10.1016/j.esr.2013.03.002.

Sgouridis, S., Abdullah, A., Griffiths, S., Saygin, D., Wagner, N., Gielen, D., Reinisch, H. and McQueen, D. (2016) 'Re-mapping the UAE's energy transition: an economy-wide assessment of renewable energy options and their policy implications', Renewable and Sustainable Energy Reviews, 55, pp. 1166–1180. doi: 10.1016/j.rser.2015.05.039.

Shah, T. (2014) *Groundwater governance and irrigated agriculture*. Stockholm: Global Water Partnership (GWP). Available at: https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/gwp_tec_19_web.pdf (Accessed: 2 December 2017).

Shahid, S. A., Abdelfattah, M. A., Othman, Y., Kumar, A., Taha, F. K., Kelley, J. A. and Wilson, M. A. (2013) 'Innovative thinking for sustainable use of terrestrial resources in Abu Dhabi Emirate through scientific soil inventory and policy development', in Shahid, S., Taha, F. and Abdelfattah, M. (eds.), Developments in soil classification, land use planning and policy implications. Dordrecht: Springer, pp. 3–49. doi: 10.1007/978-94-007-5332-7_1

Shahin, S. M. R. and Salem, M. A. (2014) 'Review future concerns on irrigation requirements of date palm tree in United Arab Emirates (UAE): call for quick actions', in *The Fifth International Date Palm Conference*. College of Food and Agriculture, UAE University.

Sharaiha, R. K. and Ziadat, F. M. (2008) 'Alternative cropping systems to control soil erosion in the arid to semi-arid areas of Jordan', *Arid Land Research and Management*, 22(1), p. 16. doi: 10.1080/15324980701784266.

Sharan, G., Jethava, K. and Shamante, A. (2005) *Greenhouse cultivation in a hot arid area*. Colombo, Sri Lanka: IWMI.

Sharifi, M. A. and Rodriguez, E. (2002) 'Design and development of a planning support system for policy formulation in water resources rehabilitation: the case of of Alca´zar De San Juan District in Aquifer 23, La Mancha, Spain', *Journal of Hydroinformatics*, 4(3), pp. 157–175.

Shihab, M. (2001) 'Economic development in the UAE', in Al Abed, I. and Hellyer, P. (eds.), *United Arab Emirates: a new perspective*, London: Trident, pp. 249–59.

Shrestha, A. B. and Aryal, R. (2011) 'Climate change in Nepal and its impact on Himalayan glaciers', *Regional Environmental Change*, 11(1), pp. 65–77.

Siebert, S., Burke, J., Faures, J., Frenken, K., Hoogeveen, J., Döll, P. and Portmann, F. T. (2010) 'Groundwater use for irrigation–a global inventory', Hydrology and Earth System Sciences, 14(10), pp. 1863–1880. doi: 10.5194/hess-14-1863-2010.

Siegel, F. R. (2008) *Demands of expanding populations and development planning: clean air, safe water, fertile soils*. Berlin: Springer Science & Business Media.

Smith, M. Cross, K., Paden, M. and Laban, P. (eds) (2016) *Managing groundwater sustainably*. Gland, Switzerland: IUCN.

Sommariva, C. (2010) *Desalination and advanced water treatment: economics and financing*. Hopkinton, MA: Balaban Desalination Publications.

Spandre, R. (2009) 'Artificial groundwater recharge', *Groundwater*, 3, p. 53.

Srinivasan, J. T. and Reddy, V. R. (2009) 'Impact of irrigation water quality on human health: a case study in India', *Ecological Economics*, 68(11), pp. 2800–2807.

Tashakkori, A. and Teddlie, C. (1998) *Mixed methodology: combining qualitative and quantitative approaches*. Thousand Oaks, CA: SAGE.

Taylor, S. J., Bogdan, R. and DeVault, M. (1998) *Introduction to qualitative research methods: a guidebook and resource*. 3rd edn. New York: John Wiley & Sons.

UAE Government (2018) *The UAE's response to climate change*. Available at: https://government.ae/en/information-and-services/environment-and-energy/climate-change/theuaesresponsetoclimatechange (Accessed: 24 July 2018).

UNDP (2006) *Human development report 2006: beyond scarcity power, poverty and the global water crisis*. New York: United Nations Development Programme. Available at: http://www.undp.org/content/dam/undp/library/corporate/HDR/2006%20Global%20HDR/HDR-2006-Beyond%20scarcity-Power-poverty-and-the-global-water-crisis.pdf (Accessed: 12 April 2019).

UNDP (2016) *Arab human development report 2016: youth and prospects for human development in a changing reality*. New York: United Nations. Available at: https://reliefweb.int/sites/reliefweb.int/files/resources/AHDR2016En.pdf (Accessed: 12 April 2019).

UN-Water (2012) *The United Nations world water development report 4: managing water under uncertainty and risk*. Paris: UNESCO. Available at: http://www.unesco.org (Accessed: 7 June 2017).

UN-Water (2015) *The United Nations world water development report 2015: water for a sustainable world*. Paris, France: UNESCO.

UPC (2010) *Estidama*: *a comprehensive guide of procedures for implementing Estidama in the Municipality of Abu Dhabi City*. Abu Dhabi, UAE: Urban Planning. Available at: http://www.adm.gov.ae/uploads/New%20Folder/Estidama_Brochure_en.pdf (Accessed: 29 May 2017).

UPC (2017) *Abu Dhabi Urban Planning Council announces the Estidama Pearl Rating System training program*. Available at: https://www.upc.gov.ae:443/en/en/Estidama/Media Center/Press Releases/Abu Dhabi Urban Planning Council Announces the Estidama Pearl Rating System Training Programme (Accessed: 29 May 2017).

Van der Gun, J. A. M. (2007) ‘Sharing groundwater information, knowledge and experience on a worldwide scale’, in Giordano, M. and Villholth, K. G. (eds.), *The Agricultural Ground Water Revolution: Opportunities and Threats to Development*. Wallingford: CABI, pp. 362–392.

Van Koppen, B. and Shah, T. (2007) ‘IWRM challenges in developing countries: lessons from India and elsewhere’, *Water Policy Briefing, International Water Management Institute*, 24, pp. 1–8.

Van Meter, D. S. and Van Horn, C. E. (1975) ‘The policy implementation process: a conceptual framework’, *Administration & Society*, 6(4), pp. 445–488.

Vraneski, A. and Allan, T. (2001) 'The Middle East water question: hydropolitics and the global economy', *Arab Studies Journal*, 9/10(2/1), pp. 160–164. Available at: http://www.jstor.org/stable/pdf/27933822.pdf (Accessed: 26 November 2015).

Wade, N. M. (1999) ‘Energy and cost allocation in dual-purpose power and desalination plants’, *Desalination*, 123(2), pp. 115–125. doi: 10.1016/S0011-9164(99)00065-X.

Wahb-Allah, M. A. and Al-Omran, A. M. (2012) ‘Effect of water quality and deficit irrigation on tomato growth, yield and water use efficiency at different developmental stages’, *Journal of Agriculture & Environmental Science*, 11(2), pp. 80–110.

Wang, J., Huang, J., Blanke, A., Huang, Q. and Rozelle, S. (2007) ‘The development, challenges and management of groundwater in rural China’, in Giordano, M. and Villholth, K. G. (eds.), *The agricultural groundwater revolution: opportunities and threats to development*, Wallingford: CABI, pp. 37–62.

Webb, P. J. and Iskandarani, M. (1998) *Water insecurity and the poor: issues and research needs*. ZEF Discussion Papers on Development Policy. Bonn: Zentrum für Entwicklungsforschung/Center for Development Research.

WHO (2006) *Guidelines for the safe use of wastewater, excreta and grey water*. Geneva: World Health Organization.

Wichelns, D. (2015) ‘Achieving water and food security in 2050: outlook, policies, and investments’, *Agriculture*, 5(2), pp. 188–220.

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

Woertz, E. (2013) *Oil for food: the global food crisis and the Middle East*. Oxford: Oxford University Press. Available at: https://global.oup.com/academic/product/oil-for-food-9780199659487?cc=us&lang=en& (Accessed: 12 April 2019).

World Bank (2005) *A water sector assessment report on the countries of the Cooperation Council of the Arab States of the Gulf*. 32539-MNA. Washington, DC: World Bank. Available at: http://documents.worldbank.org/curated/en/415761468052156362/A-water-sector-assessment-report-on-the-countries-of-the-Cooperation-Council-of-the-Arab-States-of-the-Gulf (Accessed: 12 April 2019).

World Bank (2007) *Making the most of scarcity: accountability for better water management in the Middle East and North Africa*. Washington, DC: World Bank. Available at: https://openknowledge.worldbank.org/handle/10986/6845 (Accessed: 25 November 2017).

World Bank (2008) *Agriculture water management policy*. Washington, DC: World Bank Group. Available at: http://siteresources.worldbank.org/INTGENAGRLIVSOUBOOK/Resources/AWM_Note_3_Policy_Jan08.pdf (Accessed: 12 April 2019).

World Bank and UN (2016) *SDGs in action 2016*: *outcome report*. Washington, DC: World Bank.

World Economic Forum (2011) *Water security: the water-food-energy-climate nexus. The World Economic Forum Water Initiative*. Washington, DC: World Economic Forum.

Yang, H., Reichert, P., Abbaspour, K. C. and Aehnder, A. JB. (2003) ‘A water resources threshold and its implications for food security’, *Environmental Science and Technology*, 37(14), pp. 3048–3054.

Yang, H., Du, T., Qiu, R. and Chen, J. (2017) ‘Improved water use efficiency and fruit quality of greenhouse crops under regulated deficit irrigation in northwest China’, *Agricultural Water Management*, 179, pp. 193–204. doi: 10.1016/j.agwat.2016.05.029.

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

Appendices

Appendix A: Farmer Perception Survey Questionnaire

Introduction:

This survey is being undertaken as part of my PhD research with Brunel University, London. The objective of this survey is to assess farmers' perceptions and awareness on water related issues in Abu Dhabi Emirate. I will appreciate it if you could spend a short time to answer the following questions to the best of your knowledge and ability. Any information obtained in connection with this study will remain strictly confidential and also will not be identified with you.

Date:

Section 1: Demographic Information

1.1 Farm Location

☐ Abu Dhabi Region
☐ Al Ain Region
☐ Al Western Region

1.2. Farm Area (Hectare)

☐ < 2 ☐ 3-3.9 ☐ 5-5.9
☐ 2-2.9 ☐ 4-4.9 ☐ 6+

1.3. Farm Ownership Type

☐ Single owner ☐ Joint Ownership
☐ Inheritors

1.4. Farm Owner Gender

☐ Female ☐ Both
☐ Male

1.*5*. Farm Owner Age Range

☐ 20-29 ☐ 40-49 ☐ 60-69
☐ 30-39 ☐ 50-59 ☐ 70+

1.*6*. Who Is Managing the Farm?

☐ Farm Owner ☐ Farm Tenant

☐ Farm Owner Representative

Section 2: Water Sources

Groundwater

2.1. How many wells do you have?
If you have wells please fill in the table below:

Wells	Depth (ft)	No. of working hours per day	Pump capacity (horsepower)	Water salinity (TDS)
1				
2				

Government Collective Irrigation Network

2.2. Do you have municipality supply connection?
- ☐ Yes
- ☐ No

If you have municipality supply connection please fill in the table below:

Connection	Size (inch)	No. of times of supply per week	No. of hours of supply each time	Water salinity (TDS)	Source of water
1					
2					

Desalination plant

2.3. Do you have a desalination plant?
- ☐ Yes
- ☐ No

If you have a desalination plant, please fill in the table below:

Desalination daily production in gallons	
Number of working hours per day	
How are you disposing of the brine?	

Section 3: Purpose & Main Objectives

3.1. What is your main purpose of having and running your farm?

- ☐ Commercial
- ☐ Personal

3.2. Does this farm generate profit for you?

- ☐ Yes

☐ No

Section 4: Farm Practice and Productivity

4.1. Fertilizer Type

☐ Organic
☐ Inorganic
☐ Organic & Inorganic

4.2. Productivity

Crop	No. of ha/trees	Quantity (tonne)/ ha/season	No. of cycles /year	Pump capacity (horse power)	Duration of irrigation/ day/ha (min)	Water consumption/ha/ day	Type of farming (greenhouse or open area)	Type of irrigation (drip, flood or sprinkler)
Beans								
Cabbages								
Cucumbers								
Red dry onions								
Tomatoes								
Corn								
Rhodes grass								
edMix svegetable								
Marrows								
Palm trees								

4.3. How do you sell the farm produce?

☐ Direct to local market. ☐ I don’t sell
☐ Through farmer centre
☐ Through private distributor
☐ Directly to customers
☐ Directly to Al Foah

4.4. Who chooses the type of crop to plant? Why?

☐ Farm owner. Why?

☐ Farmer centre. Why?

☐ Other persons/entity/agency, etc. (please specify…)

4.5. Are you going to continue with the existing plan?

☐ Yes
☐ No

4.6. If no, what is your future plan?

Section 5: Farmers' awareness

5.1. Do you receive drinking water supply?

☐ No
☐ Yes

5.2. If yes, what are your views on the drinking water tariff introduced this year?

☐ I agree
☐ I don't agree
☐ I don't know

5.3. In your opinion why has this tariff been introduced?

☐ Reduce water consumption
☐ Share water cost with the government
☐ I don't know

5.4. Do you think there is a drinking water issue in Abu Dhabi?

☐ No
☐ Yes
☐ I don't know

5.5. Were you using drinking water for irrigation?

☐ No
☐ Yes

5.6. Has the new tariff affected your operations? If yes, which ones, why and how they have been affected?

- ☐ No
- ☐ Yes

If yes which area and how?

5.7. Do you know about groundwater depletion?

- ☐ No
- ☐ Yes

5.8. Have you noticed any deterioration of the groundwater quality?

- ☐ No
- ☐ Yes
- ☐ Only in some wells
- ☐ I don't know

5.9. What are your views if the farmer centre were to take measures to control groundwater pumping?

- ☐ I agree
- ☐ I don't agree
- ☐ I don't have productive wells

5.10. If the groundwater becomes unusable, what would you do?

- ☐ Switch to desalination
- ☐ Decrease farming area
- ☐ Other (please specify)

5.11. Do you think that what you are producing is valuable for Abu Dhabi?

- ☐ No
- ☐ Indirectly valuable
- ☐ Yes

If yes, why?

5.12. What is your view if the farmer centre were to reduce or stop subsidies for farmers?

- ☐ I agree
- ☐ I don't agree

5.13. Do you think other farmers (your neighbours) are doing the same practice as you do?

- ☐ Yes
- ☐ No
- ☐ Sort of
- ☐ I don't know

5.14. Please add below any comments or suggestions in relation to water, farm production and practices:

Appendix B: Semi-structured Interview Questionnaire

1. What are the most critical water issues in Abu Dhabi?
2. Why do you think all these issues occurred in Abu Dhabi?
3. What are your suggestions to make the situation better?
4. What are the current policies that relate to/may affect agricultural water use?
5. What are the water use policies that are under development or discussion?
6. How usually are policies developed and cascaded for implementation?
7. What are the barriers that prevent successful implementation of these policies?
8. What is your view on the continuous development of the agriculture sector?
9. Is it feasible to increase the local food supply to reach 40%?
10. Are you aware about groundwater deterioration in quantity and quality?
11. What are the alternative water resources to reach a 40% increase in local food supply?
12. Is this alternative water resource feasible to support the 40% increase? Why?
13. What is your view on the importance of communication and coordination between related organizations to help improve understanding of the issues and ensure the development of better decisions?
14. What is the current level of communications by Abu Dhabi water- and agriculture-associated entities?
15. To what extent do you agree or disagree with the statement: “all future water use for agriculture/forestry should derive from seawater desalination”?
16. Is this an active policy discussion? Who participated and what were the results?
17. To what extent do you agree or disagree with the statement: “all future water use for agriculture/forestry should derive from groundwater”?
18. If groundwater were considered off limits in favour of conservation, would you support a halting or reduction of local food production due to the costs and environmental complications of desalination?
19. Has this discussion been done? With whom? What was the result?
20. What is your view on the development of forestry in Abu Dhabi?

Appendix C: Brunel University Ethical Approval Letter

College of Engineering, Design and Physical Sciences Research Ethics Committee
Brunel University London
Kingston Lane
Uxbridge
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United Kingdom

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16 May 2016

LETTER OF APPROVAL

Applicant: Miss Ameena Al Tenaiji

Project Title: Water and Energy Nexus

Reference: 2532-LR-May/2016- 3019-2

Dear Miss Ameena Al Tenaiji

The Research Ethics Committee has considered the above application recently submitted by you.

The Chair, acting under delegated authority has agreed that there is no objection on ethical grounds to the proposed study. Approval is given on the understanding that the conditions of approval set out below are followed:

- The agreed protocol must be followed. Any changes to the protocol will require prior approval from the Committee by way of an application for an amendment.

Please note that:

- Research Participant Information Sheets and (where relevant) flyers, posters, and consent forms should include a clear statement that research ethics approval has been obtained from the relevant Research Ethics Committee.
- The Research Participant Information Sheets should include a clear statement that queries should be directed, in the first instance, to the Supervisor (where relevant), or the researcher. Complaints, on the other hand, should be directed, in the first instance, to the Chair of the relevant Research Ethics Committee.
- Approval to proceed with the study is granted subject to receipt by the Committee of satisfactory responses to any conditions that may appear above, in addition to any subsequent changes to the protocol.
- The Research Ethics Committee reserves the right to sample and review documentation, including raw data, relevant to the study.
- You may not undertake any research activity if you are not a registered student of Brunel University or if you cease to become registered, including abeyance or temporary withdrawal. As a deregistered student you would not be insured to undertake research activity. Research activity includes the recruitment of participants, undertaking consent procedures and collection of data. Breach of this requirement constitutes research misconduct and is a disciplinary offence.

Professor Hua Zhao

Chair

College of Engineering, Design and Physical Sciences Research Ethics Committee
Brunel University London

Appendix D: Summary of the Survey Descriptive Data

Parameter	Number of Farms				Descriptive Statistics				
	AD	AA	WR	Total	**N**	**Min**	**Max**	**Mean**	**Std. Deviation**
Farm size distribution									
<2	4	0	3	7					
2–2.9	110	19	14	143					
3–3.9	0	124	2	126					
4–4.9	0	6	61	67					
5–5.9	0	0	0	0					
>6	1	0	0	1					
Total	115	149	80	344	344	1	6	2.750	0.810
Ownership type									
Single owner	97	135	74	306					
Inheritor	15	8	5	28					
Joint ownership	1	6	1	8					
Total	113	149	80	342	342	1	3	1.13	0.399
Farm owner gender									
Female	19	13	16	48					
Male	80	122	57	259					
Both	9	8	2	19					
Total	108	143	75	326	326	1	3	1.190	0.445
Farm owner age distribution									
20–29	0	0	0	0					
30–39	3	1	0	4					
40–49	13	18	3	34					
50–59	46	66	22	134					
60–69	34	53	47	134					
70+	5	3	3	11					
Total	101	141	75	317	317	2	6	4.360	0.769
Farm manager									
Farm owner	26	12	13	51					
Representative	83	133	66	282					
Tenant	4	4	1	9					
	113	149	80	342	342	1	3	1.880	0.401
Farming intent									
Commercial	33	16	16	65					
Personal	82	131	64	277					
Total	115	147	80	342	342	1	3	2.510	0.795
Irrigation methods									
Drip irrigation				326					
Flood irrigation				14					
Sprinkler				4					
Total				344					
Fertilizer type									
Organic	68	104	60	232					
Inorganic	1	2	4	7					
Both	45	41	15	101					
Total	114	147	79	340	340	1	3	1.610	0.913

Appendix E: Detailed Information on Farm Wells across ADE's three regions

Information on Farm Wells	AD	AA	WR	Total
Total no. of wells	57	302	160	519
No. of farms' own wells	32	149	80	261
Total no. of sampled farms	115	149	80	344
% of farms' own wells of total sampled farms	28%	100%	100%	76%
Sd. deviation: 0.966				
Depth (m)				
10–50	5	0	28	33
51–100	4	42	130	176
101–150	27	39	0	66
151–200	21	78	0	99
201–250	0	45	0	45
251–300	0	23	0	23
301–350	0	63	1	64
351–400	0	12	0	12
651–700	0	0	1	1
Missing	0	0	0	0
Total	57	302	160	519
Working hours per day				
2–5	14	44	0	58
6–10	34	174	103	311
11–15	7	53	57	117
16–24	0	21	0	21
Missing	2	10	0	12
Total	55	292	160	507
Pump capacity (hp)				
1.5	1	0	0	1
7	10	0	28	38
7.5	2	4	47	53
10	42	117	84	243
12	0	2	0	2
15	0	46	1	47
20	0	73	0	73
25	0	48	0	48
Missing	2	12	0	14
Total	55	290	160	505
Salinity (ppm)				
2,000–5,000	1	134	79	214
6,000–10,000	15	74	58	147
10,500–15,000	25	68	23	116
16,000–20,000	4	12	0	16
25,000–27,000	4	3	0	7
Missing	8	11	0	19
Total	49	291	160	500

Appendix F: Detail on Surveyed Farms' Produce

Crop	No. of farms	% of farms	Cultiva -ted area (ha)	% of total cultivated area	Total product -ion (tonnes)	% of total production	Value per tonne ($) (SCAD, 2017)	Calculated value (using SCAD rate, $)	% of total value
Palm tree*	***336***	***98***	***354.36***	72	***3,292***	***30***	1,680	***5,530,652***	***52***
Fodder crops	***166***	***48***	***66***	13.40	***2,980***	***27***		***1,197,511***	***11***
Rhodes	144	42	50.1	10.20	2,509	23	406	1,018,654	10
Alfalfa	24	7	13.5	2.70	414	3.70	406	168,084	1.60
Panicum	7	2	2.4	0.50	57	0.50	189	10,773	0.10
Vegetables	***236***	***69***	***68.2***	13.90	***4,820***	***43***		***3,917,516***	***37***
Corn	46	13	14.1	2.90	223	2.00	1,049	233,927	2.20
Tomato	41	12	11	2.20	506	4.60	652	329,912	3.10
Mixed vegetable	40	12	9.2	1.90	252	2.30	1,664	419,328	3.90
Marrow	27	8	6.9	1.40	449	4.00	918	412,182	3.90
Cucumber	25	7	13.9	2.80	2,916	26	702	2,309,472	22
Eggplant	19	6	4.4	0.89	216	1.95	423	91,368	0.90
Cabbage	18	5	4.6	0.93	211	1.90	351	74,061	0.70
Bean	9	3	1.6	0.33	16	0.10	1,329	21,264	0.20
Onion	8	2	1.5	0.30	16	0.14	757	12,112	0.10
Pea	1	0.30	0.5	0.10	2	0.02	1,329	2,658	0.00
Sweet melon	2	0.60	0.5	0.10	13	0.12	864	11,232	0.10
Turf grass	***7***	***2***	***3.6***	***0.70***	***36,000***		***1.62***	***58,320***	***0.54***
Total			**492.16**		**11,092**	**100**		**10,703,999**	**100.00**

Appendix G: Cultivated Area Percentage per Crop across ADE's Three Regions

Crop	Region		
	AD	**AA**	**WR**
Palm tree	***26%***	***44%***	***31%***
Fodder crops	***29%***	***49%***	***22%***
Rhodes	34%	39%	27%
Alfalfa	7%	90%	3%
Panicum	54%	29%	17%
Vegetables	***50%***	***27%***	***23%***
Corn	77%	6%	18%
Tomato	25%	47%	27%
Mixed vegetables	50%	35%	15%
Marrow	49%	32%	19%
Cucumber	58%	27%	14%
Eggplant	50%	16%	34%
Cabbage	17%	4%	78%
Bean	50%	19%	31%
Onion	20%	67%	13%
Pea	0%	100%	0%
Sweet melon	40%	60%	0%
Turf grass	***36%***	***64%***	***0%***
Total	30%	42%	28%

Appendix H: Cultivated Area per Crop in This Study and ADE 2016

Crop	This Study			ADE 2016		
	Cultivated Area (ha)	% of Total Farm Area (1,058.27 ha)	% of Cultivated Crop Area to Total Cultivated Area	Cultivated Area (ha)	% of Total Farm Area (74,986.8 ha)	% of Cultivated Crop Area to Total Cultivated Area
Palm tree	***354.36***	***33***	***72***	***30,000***	***40***	***79***
Fodder crops	***66***	***6***	***13***	***6,021***	***8***	***16***
Rhodes	50.1		10	5,773.70		15
Alfalfa	13.5		3	247.09		1
Panicum	2.4		0.50			
Vegetables	***68.2***	***6***	***13.86***	***1,935***	***3***	***5***
Corn	14.1		2.87	84		0.20
Tomato	11		2.24	370		1.00
Mixed vegetables	9.2		1.87	176		0.50
Marrow	6.9		1.40	101		0.30
Cucumber	13.9		2.83	429		1.10
Eggplant	4.4		0.89	91		0.20
Cabbage	4.6		0.93	193		0.50
Bean	1.6		0.33	38		0.10
Onion	1.5		0.30	131		0.30
Pea	0.5		0.10			
Sweet melon	0.5		0.10	70		0.20
Others				252		0.70
Turf grass	***3.6***	***0.3***	***1***			
Grand Total	**492.16**	***47***	**100**	**37,956**	***51***	**100**

** Others: potato, sweet and hot pepper, cauliflower, pumpkin, carrot and beet* (SCAD, 2017)

Appendix I: Water Consumption per Cultivated Crop

Cultivated Crop	Average Daily Water Consumption per Hectare (m^3/ha/day)	Average Annual Water Consumption (m^3/ha/year)	Total Water Consumption (m^3/year)	% of total water consumption
Palm tree	41	14,663	8,161,136	79.90
Fodder crops				
Rhodes	66.47	10,882	921,771	9.00
Alfalfa	62.89	11,747	185,212	1.81
Panicum	29.9	8,501	11,734	0.11
Vegetable				
Corn	77.8	16,882	148,738	1.46
Tomato	95.36	23,978	179,240	1.75
Mixed vegetables	125	26,265	183,887	1.80
Marrow	82.11	17,244	95,511	0.94
Cucumber	50.7	10,096	91,114	0.89
Eggplant	78.5	18,377	70,300	0.69
Cabbage	97.2	20,729	74,221	0.73
Bean	124.5	26,146	33,892	0.33
Onion	89.12	18,716	44,991	0.44
Pea	112	8,880	8,880	0.09
Sweet melon	88	18,500	3,700	0.04
Turf grass	58	15,051		
Grand Total			**10,214,328**	**100**

Appendix J: Annual Water Use Rate Descriptive and Test of Normality Data

Crop	Descriptive data								Test of Normality *					
									Kolmogorov-Smirnova			Shapiro-Wilk		
	N	Mean	Median	Min	Max	SD	Skewness	Kurtosis	Statistic	df	Sig.	Statistic	df	Sig.
Onion	8	29,970	29,600	10,360	44,399	13,627	-0.187	-1.574	0.230	8	0.200	0.881	8	0.193
Sweet Melon	3	27,133	22,200	14,800	44,400	15,404	1.293		0.292	3		0.923	3	0.463
Mixed Vegetables	38	30,422	22,200	925	88,799	21,079	0.926	0.341	0.204	38	0.000	0.907	38	0.004
Bean	9	26,146	22,200	7,400	66,599	16,646	2.017	5.267	0.307	9	0.015	0.774	9	0.010
Tomato	41	23,978	17,720	1,772	79,741	19,039	1.864	3.237	0.227	41	0.000	0.771	41	0.000
Rhodes	141	23,850	18,966	2,529	113,799	18,758	2.235	6.818	0.228	141	0.000	0.788	141	0.000
Alfalfa	24	22,774	19,028	3,383	50,744	15,112	0.580	-0.882	0.179	24	0.045	0.906	24	0.029
Palm Tree	337	22,745	20,297	3,460	101,486	13,116	1.355	3.890	0.115	337	0.000	0.914	377	0.000
Cabbage	18	20,422	18,686	4,933	44,399	11,215	0.545	-0.699	0.186	18	0.100	0.922	18	0.140
Egg Plant	21	18,911	14,800	7,400	44,400	10,902	1.183	1.064	0.218	21	0.010	0.854	21	0.005
Marrow	27	17,720	12,686	3,700	85,627	15,830	3.239	13.253	0.24	27	0.000	0.663	27	0.000
Corn	46	16,527	12,686	1,269	50,742	12,801	1.243	0.842	0.197	46	0.000	0.857	46	0.000
Turf Grass	5	15,051	7,249	1,812	42,814	16,862	1.516	1.926	0.278	5	0.200	0.834	5	0.149
Cucumber	25	10,096	8,880	1,691	38,057	8,172	1.901	4.880	0.185	25	0.028	0.818	25	0.000
Panicum	7	12,096	12,862	3,215	19,293	5,457	-0.047	-0.801	0.175	7	0.200	0.923	7	0.494

** Test of normality (Razali NM, Wah YB. Power comparisons of Shapiro–Wilk, Kolmogorov– Smirnov, Lilliefors and Anderson–Darling tests. J Stat Modell Anal 2011;2(1):21–33*

Appendix K: Productivity Data in This Study and Other Relevant Studies

Crop	This Study				Other studies				Reference	Location and methods of data collection
	kg/ha	m^3/ha	kg/m^3	\$/m^3	kg/ha	m^3/ha	kg/m^3	\$/m^3		
Palm tree	9,621	22,745	0.59	0.99	3,000				(Al Said *et al.*, 2007)	Oman, Survey data
						20,000			(Pitman, McDonnell and Dawoud, 2009)	UAE, Estimated
						3,600-10,800			(Green *et al.*, 2014)	UAE (Dubai), measured
					2,700	15,000-20,740	0.2-0.26		(FAO, 2007)	UAE, Estimated
					4,800	14,700			(FAO, 2007)	UAE, Recommended
						24,914			(Bhat *et al.*, 2012)	Kuwait, measured
						24,000			(Haj-Amor *et al.*, 2018)	Tunisia, measured
					4,272	21,950-29,700	0.15-0.21		(FAO, 2007)	Oman, Estimated
					8,380-11,750	9,320-16,080	0.71-0.89		(FAO, 2007)	Oman, measured
							0.57-1.56	0.60-1.64	(Al-Mulla and Al-Gheilani, 2018)	Oman, Estimated
Fodder Crops										
Rhodes	50,971	23,850	3.4	1.4	40,000	53,640	0.7	0.45	(Al-Said *et al.*, 2012)	Oman, measured
						20,000			(Pitman, McDonnell and Dawoud, 2009)	UAE, Estimated
						13,000			(MOEW, 2010)	UAE, Estimated
					16,693	18,219	0.8		(Hashim M. A.A *et al.*, 2012)	Saudi Arabia, measured
					15,140-60,390	22,053-163,294	0.44-0.69		(Patil *et al.*, 2015)	Saudi Arabia, measured
					7,000-12000				Al Said *et al.*, 2007)	Oman, Survey data
					5,000-25,000	15,126-47,269	0.47-0.85		(Mazahrih *et al.*, 2016)	Oman, measured
Alfalfa	25,750	22,774	2.2	0.9	21,000-35,100	15,140-60,390	0.38-0.43		(Patil *et al.*, 2015)	Saudi Arabia, measured and modeled
					9,607-18,964	9,780			Yan Li, 2017	China, measured
					36,000				(Al Said *et al.*, 2007)	Oman, Survey data
					17,734	18,219	0.84		(Hashim M. A.A *et al.*, 2012)	Saudi Arabia, measured
					15,074	17,333	0.87		(Nafchi, 2016)	California, USA., measured
					3,852-18,271	5,520-25,780	0.70-0.71		(Al-Gaadi, Madugundu and Tola, 2017)	Saudi Arabia, measured
Panicum	29,286	12,096	2.2	0.4	19,981	12,975	1.54-2.47		(Hashim M. A.A *et al.*, 2012)	Saudi Arabia, measured
Vegetables										
Corn	15,576	16,527	1.8	1.9	10,930-11,190	9,892-21,580	0.51-1.11		(Patil *et al.*, 2015)	Saudi Arabia, measured and modeled
					4,000				(Al Said *et al.*, 2007)	Oman, Survey data
					4,048	45,260	0.79		(Hashim M. A.A *et al.*, 2012)	Saudi Arabia, measured
Tomato	44,390	23,978	3	2	80,100	8,050	11.9	0.71	(Al-Said *et al.*, 2012)	Oman, measured
					8,000-38000				(Al Said *et al.*, 2007)	Oman, Survey data
								0.00-1.281	(Speelman, 2009)	South Africa, computed
					60,000-120,000		1.3-3.5		(Algharibi *et al.*, 2013)	Oman, Estimated
					54,900-66,500	2,740-6,820	2.64		(Algharibi *et al.*, 2013)	Oman, Simulated
Marrow	65,556	17,720	6	5						
Cucumber	160,000	10,096	33.8	23.6	24,000-38000				(Al Said *et al.*, 2007)	Oman, Survey data
							14.4-48.3		(ADFCA, 2016)	Abu Dhabi, measured
					100,000-300,000				(*Nutritional recommendations for cucumber*, 2014)	Estimated world wide average yield
					70,000-99,000	1,090-3,550	27.9-64.2		(Aly, Al-Omran and Khasha, 2015)	Saudi Arabia, measured
							81		(FAO, 2013)	Netherland, Secondary data
					91,000-150000	1,470-3,550	42.25-61.5		(Alomaran and Luki, 2012)	Saudi Arabia, measured
Eggplant	45,238	18,377	3.21	1.35	7,000				(Al Said *et al.*, 2007)	Oman, Survey data
					8,335	58,080	1.43		(Hashim M. A.A *et al.*, 2012)	Saudi Arabia, measured
					12,390-33,700		0.27-0.56		(Karam *et al.*, 2011)	Lebanon, measured
					40,900-78,700		12.2-21.9		(Çolak *et al.*, 2015).	Turkey, Field experiments
Cabbage	43,056	20,422	2.98	1.044	49,300	14,400	7.8	0.81	(Al-Said *et al.*, 2012)	Oman, measured
								0.003-1.66	(Speelman, 2009)	South Africa, computed
					53,256	4,375-5,826	4.7-11.6		(DOMUŢA *et al.*, 2017)	Romania, measured
Beans	9,778	26,146	0.51	0.67	3,007	30,300	1		(Hashim M. A.A *et al.*, 2012)	Saudi Arabia, measured
								0.003-3.08	(Speelman, 2009)	South Africa, computed
Onion	10,125	29,970	0.4	0.31	3,000-18,000				(Al Said *et al.*, 2007)	Oman, Survey data
								0.00-1.494	(Speelman, 2009)	South Africa, computed
Peas	10,000	44,400	0.2	0.29				0.00-.0417	(Speelman, 2009)	South Africa, computed
Sweet Melon	24,667	12,333	1.14	0.98	23,800	4,970	5.7	0.67	(Al-Said *et al.*, 2012)	Oman, measured
					14,000				(Al Said *et al.*, 2007)	Oman, Survey data

Appendix L: List of References on Crop Yield Response to Water

Crop	Reference	Location and Methods of Data Collection
Palm tree	R1: FAO (2007)	Saudi Arabia, experiment
	R2: Al-Qurashi, Ismail and Awad (2016)	Saudi Arabia, measured
Fodder crops		
Rhodes grass	R1: Irrigation Research Lab (2007)	Oman, experiment
	R2: Mazahrih *et al.* (2016)	Oman, measured
Alfalfa	R1: Nafchi (2016)	Iran, measured
Vegetables		
Corn	R1: Payero *et al.* (2008)	Nebraska, USA, experiment
	R2: Dehghanisanij *et al.* (2009)	Iran, experiment
Tomato	R1: Algharibi *et al.* (2013)	Oman, experiment
	R2: Wahb-Allah and Al-Omran (2012)	Saudi Arabia, experiment
Cucumber	R1: Aly, Al-Omran and Khasha (2015)	Saudi Arabia, measured
	R2: Alomaran and Luki (2012)	Saudi Arabia, measured
	R3: Rahil and Qanadillo (2015)	Palestine, measured
Eggplant	R1: Çolak *et al.* (2015)	Turkey, measured
	R2: Karam *et al.* (2011)	Lebanon, measured
Onion	R1: Al-Jamal *et al.* (2000)	New Mexico, measured
	R2: Al-Jamal *et al.* (2000)	New Mexico, measured
	R3: Nagaz, Masmoudi and Ben Mechlia (2012)	Tunisia, measured

Appendix M: ADE Agriculture-Water Policy Framework Validation Questionnaire

Introduction

This questionnaire is developed to validate the Agriculture-Water Policy Framework developed for Abu Dhabi Emirate (ADE) based on the PhD research findings. The aim of this validation is to assess experts' views and opinions to determine the appropriateness and acceptability for use by decision and policy makers to ensure sustainable agriculture water management. It is also intended to assess and validate the practicality and adequacy of the framework in addressing the current main management issues in ADE.

Section A: Background of participants

Kindly provide the following information:

Name:……………………………………………………………………………………

Job Designations:……………………..

Years of Experience:……………...

Qualifications:……………………………………………………………………………

Entity/Authority:…………………………………………………………………………

Section B: General view and impression on the Agriculture-Water Policy Framework

Please tick ✔ as appropriate and add comments if any:

1. What is your opinion on the development of this ADE agriculture-water framework?
   - ☐ I agree
   - ☐ I don't agree
   - ☐ I'm not sure

   Add comments if any

2. What is your view on the framework layout?
   - ☐ It is sufficient
   - ☐ It is not sufficient
   - ☐ I'm not sure

   Add comments if any:

3. Do you think that the framework is simple and easy to understand?
   ☐ Yes

   ☐ No

   If you answer no please provide explanation:

4. Do you think that the framework is easy to follow with little or no practical difficulties?
   ☐ Yes

   ☐ No

   Add comments if any:

5. Does the framework address issues related to the sustainability of agriculture production in ADE?
   ☐ Yes, quite significant

   ☐ Yes, but not significant

   ☐ No, not sure if it makes any difference

   Add comment if any:

6. Would you agree that the framework is capable of ensuring better allocation of water in the agriculture sector?
   ☐ Yes, it is capable

   ☐ No, it is not capable

   ☐ I'm not sure

   If your answer is no, please explain:

7. Would you agree that the framework is capable of ensuring sustainable agriculture development?
   ☐ Yes, it is capable

   ☐ No, it is not capable

   ☐ I'm not sure

   If your answer is no, please explain:

8. In your, opinion is there any further important steps missing in the framework that should be included?
   ☐ No

   ☐ Yes

If you answer yes, please provide more explanation:

9. To implement the framework in ADE, do you think it will require heavy investment in human resources?
   - ☐ Yes
   - ☐ No
   - ☐ I’m not sure
   - ☐ Any investment is justifiable by the benefits that will be achieved

   Any comments if any:

10. To implement the framework in ADE, do you think it will require heavy investment in training, tools and devices?
    - ☐ Yes
    - ☐ No
    - ☐ I’m not sure
    - ☐ Any investment is justifiable by the benefits that will be achieved

    Any comments if any: