OASIS AT A CROSSROADS: AGRICULTURE AND GROUNDWATER IN LIWA, UNITED ARAB EMIRATES

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1 Introduction

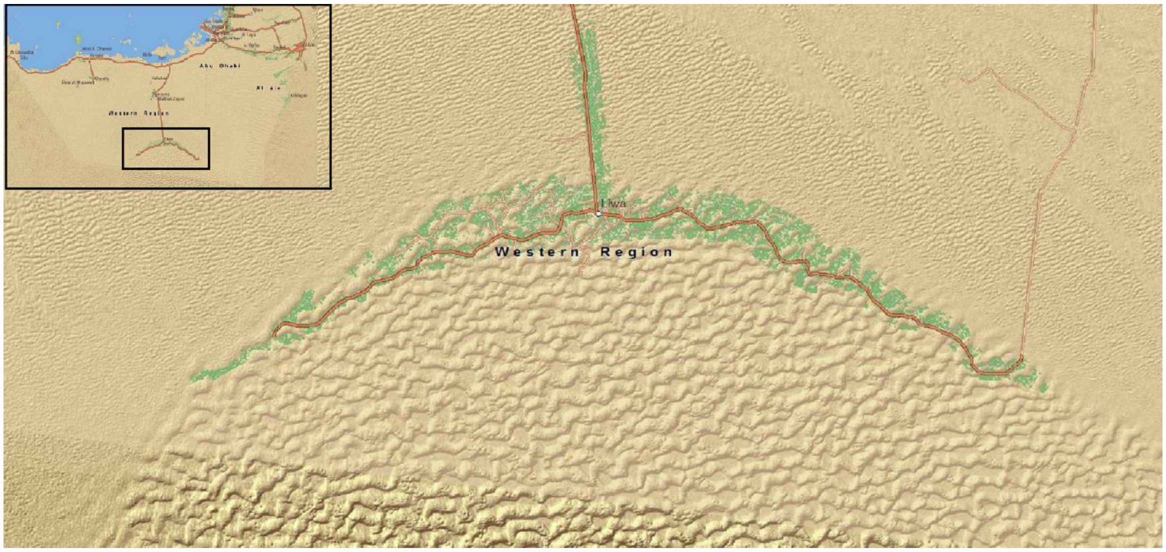
The Liwa Oasis is an excellent case study to examine groundwater utilization patterns in the United Arab Emirates. Liwa is a crescent-shaped oasis that sits atop a freshwater mound on the edge of the Empty Quarter and is one of the Emirate of Abu Dhabi's two high-quality and shallow aquifer systems. The surrounding area is the critical agricultural land of Abu Dhabi's Western Region. However, intensive agriculture and desert greening forestry programs have put enormous strains on the aquifer system. Balancing the need for local food production, economic development and socio-cultural continuity with the incredibly fragile natural resource environment in the area necessitates careful planning and governance to ensure the protection, productivity and longevity of Liwa's groundwater resources.

This report is meant to complement the Water and Groundwater in Abu Dhabi – Resources and Management IWMI Project Report (hereafter Fragaszy and McDonnell, 2016)) which takes stock of the overarching water resource baseline and UAE federal and Abu Dhabi Emirate-level groundwater policies and governance mechanisms. By providing an integrated case study of groundwater utilization in the Emirate, this report aims to accomplish the following goals:

I. Review the baseline physical parameters of local groundwater resources;
II. Describe modern agricultural production and forestry systems;
III. Discuss institutional and agricultural management challenges and planned reforms;
IV. Evaluate the impacts of groundwater utilization on the aquifer system.

For the purposes of this report, the "Liwa area" refers to the region highlighted in Figure 1. The primary farm visits undertaken during the course of the research all occurred within this delimited area. Reference is also made to the Western Region and Al-Ain regions of Abu Dhabi Emirate which are shown in full in Figure 1(b) of the Abu Dhabi report (McDonnell and Fragaszy, 2016).

Figure 1. Map of Liwa irrigated areas (farms, forests and amenity plantings)



Source: EAD Enviroportal; area highlighted within Google Maps image.

1.1 Methodology

The primary information presented in this report was obtained from field visits to 20 farms and discussions with the managers and workers on those farms conducted over a period of 3 working days in November 2014 and 5 days in March 2016. Further detail on the characteristics of the farms visited and other interviews conducted is shown in Appendix 2. The interview questionnaire used during the farm visits is shown in Appendix 3 and was used as a guide since not all interviewees were able to answer all questions due to time or information constraints. With farm managers and workers English or Arabic versions of the questionnaire were used, and on visits to 2 farms a farm manager accompanied the author and translated questions into Urdu and Bengali for farm workers. In addition, group meetings and individual interviews were held with farm owners, government officials from the Abu Dhabi Farmers' Services Centre (FSC) and, Abu Dhabi Food Control Authority (ADFCA) in the Liwa area and Abu Dhabi as well as the Environment Agency – Abu Dhabi (EAD) and Khalifa Fund for Enterprise Development in Abu Dhabi[1]. Background information on the FSC, ADFCA and EAD is provided in section 3.6 of the Abu Dhabi report (McDonnell and Fragaszy, 2016). Further detail on interviewees is provided in Appendix 2.

Requests for anonymity have been respected and as such interview citations describe only the agencies for which individuals work; further information on their roles overall is provided in Appendix 2. Also, EAD, ADFCA and FSC all provided unpublished information and data for utilization in this

[1] The Khalifa Fund for Enterprise Development (Khalifa Fund) is a government-linked organization which provides funding and business development and training support for small and medium-sized enterprises in the UAE. It is a vehicle to promote entrepreneurship in the UAE and especially targets sectors of interest to government development plans. The *Zaarie* program for development of hydroponics, greenhouses and aquaculture is one of its funding vehicles and is described in more depth in Section 3.2

report and the author has respected their requests for data characterization. Aside from this field and stakeholder assessment, the report relies on official government statistics and reports as well as review of secondary sources.

2 Liwa's groundwater resources baseline

In order to assess groundwater utilization and sustainability in the study area, a basic description of the baseline physical groundwater resource system is necessary. The groundwater resources of Abu Dhabi have been examined in depth through multi-year hydrogeological studies and monitoring activities conducted by the United States Geological Survey and the UAE's National Drilling Company (USGS, 1998) as well as GTZ and the EAD (GTZ, 2005). This report's summary descriptions of Liwa's groundwater resources rely on review of those baseline works, national planning documents derived using their data (e.g., EAD, 2009), information from the aquifer storage and recovery project (e.g. Menche, 2010). Section VI provides the most current information on groundwater status from the EAD, the primary government entity tasked with monitoring and regulating groundwater usage, and describes the impact of irrigated agriculture and forestry on the groundwater resource system.

2.1 Climate and precipitation

Liwa has a hot and arid climate with mean annual precipitation falling well under 100mm, mean average maximum temperatures over 40 degrees between May and September and potential evapotranspiration of over 2m per year according to the National Centre for Meteorology and Seismology 10-year running averages for Medina Zayed and Liwa (Mazairaa) stations (NCMS, 2015). Surface water resources are negligible and limited to the immediate aftermath of precipitation events.

The spatial and temporal variability of rainfall is very high as is common in desert environments. Precipitation in Abu Dhabi's Western Region has high intra-annual variability, occurring most frequently and strongly during the winter months of December through April and primarily as a result of cloud band migration from East Africa via well-defined upper troughs in the mid-latitudes (Brook, 2006). Inter-annual variability in precipitation is over 70% and some years have no measurable precipitation at all (ibid.). In Liwa the infrequent precipitation events are currently inadequate to support crop growth on their own without supplemental groundwater-dependent irrigation. The important exception to this rule is the date palm which historically could be largely self-sustaining as explored further in Section III**.**

2.2 Surface morphology

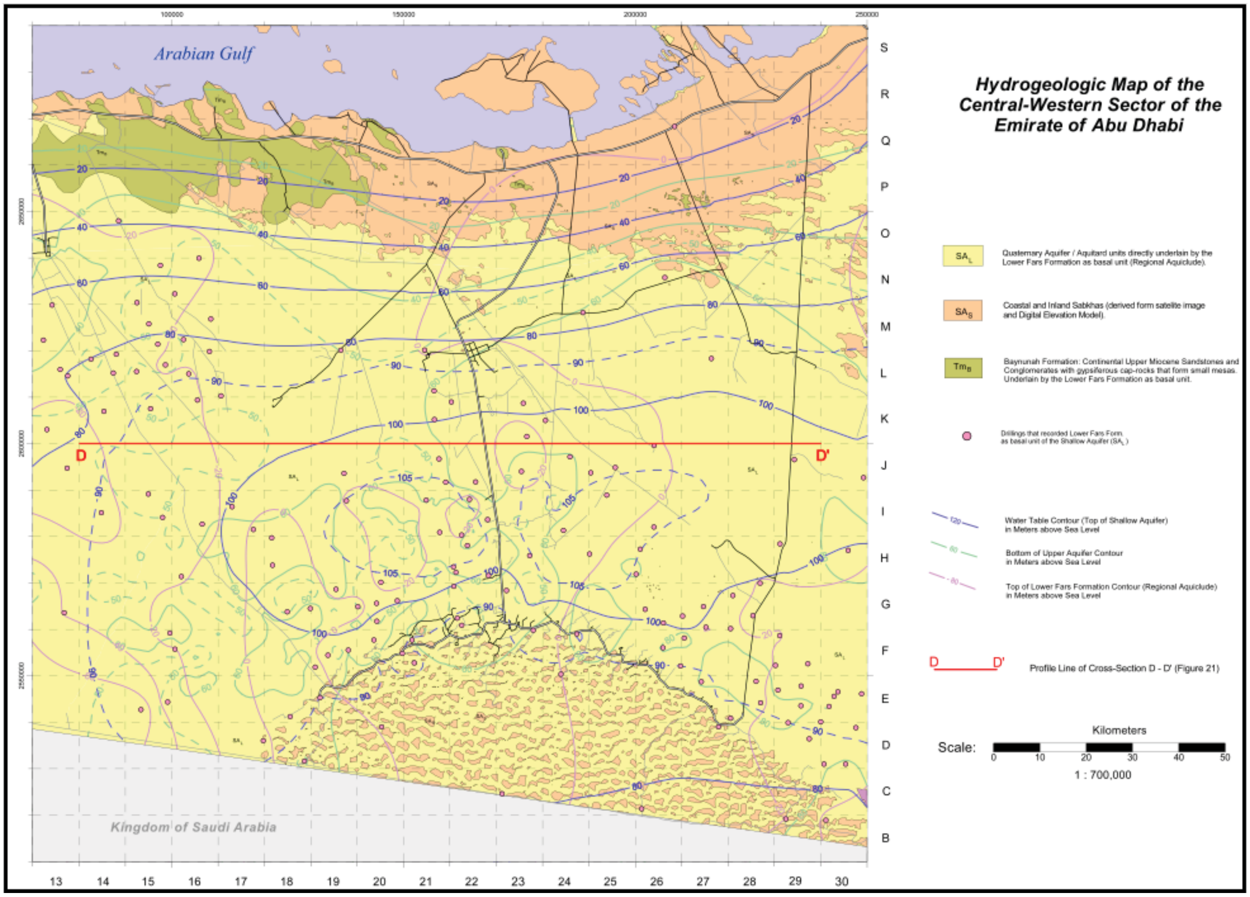
The study area's surface is predominated by Holocene era 30-40m high aeolian sand dune structures separated by nearly flat inter-dunal *sabkhat* (plural of *sabkha)* or fluvial deposit gravel plains (Stokes and Bray, 2005). The Liwa Oasis is bounded to the South by large barchan dune complexes frequently over 100m high and to the East by the gradual incline towards Oman's Hajjar Mountain massif that supports Abu Dhabi's other productive aquifer system in Al-Ain. To the West of Liwa is the Empty Quarter's sand sea and to the North, the Quaternary morphological structures run gradually towards the coastal *sabkhat* and tidal flats before meeting the shallow Persian Gulf (USGS, 1996).

2.3 Hydrogeology

In the Liwa area, groundwater is encountered in both shallow and deep aquifer systems, but it is the shallow unconsolidated aquifer system which is most important in terms of both storage and utilization (Rizk and AlSharhan, 2003). Therefore, unless otherwise qualified, groundwater described in this report refers only to that derived from the shallow upper aquifer. The hydrogeological map in Figure 2 below indicates the depth of the groundwater table and bottom of the productive unconsolidated aquifer and denotes the region of the cross-section shown below in Figure 3. Unfortunately, much of the data related to groundwater in the bedrock aquifers is described in petroleum exploration studies and therefore not publicly available. Also, oil and gas-related groundwater production activities are not under the purview of the EAD or ADFCA and ADNOC subsidiaries do not share information with those agencies at present (Interviews D; F, 2016).

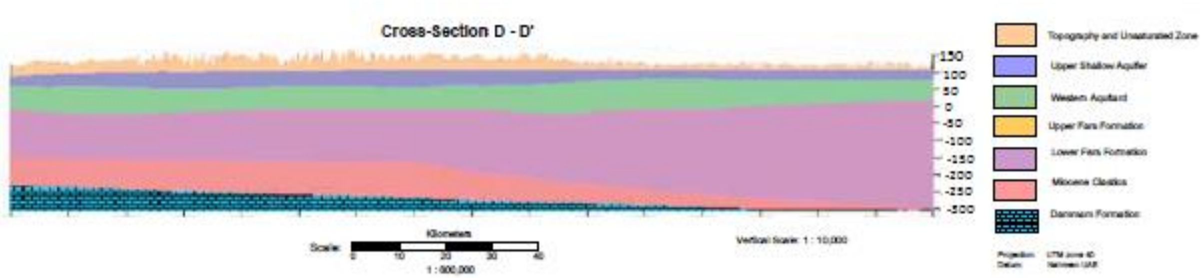
To date, groundwater exploitation potential in the Western Region has not been examined beyond the deep Umm Ar-Radhuma formation, the Paleocene limestone carbonate aquifer which underlies much of the Northeastern Arabian Peninsula and is highly productive in parts of Saudi Arabia, Qatar, Bahrain, Iraq, Kuwait and Oman (UN-ESCWA and BGR, 2013). However, in the UAE the aquifer is only exploited for irrigation water in highly limited areas south of Al-Ain. Few exploration wells in the Western Region have reached the formation which occurs over 700m below the surface, and those which did had very low yields and produced only hyper-saline water with TDS over 185,000 mg/l (Brock, 2006).

Figure 2. Hydrogeologic map of central Abu Dhabi



Source: GTZ, 2005.

Figure 3. Hydrogeologic cross-section of central Adu Dhabi



Source: GTZ, 2005.

Likewise, the Dammam aquifer is relatively unexplored in the Western Region in relation to groundwater production because it is highly saline. In the Liwa area the marine limestone carbonate aquifer is first reached approximately 250m below sea level, about 350m below the ground surface, and has a total thickness of nearly 320m, the thickest for the formation in the UAE. It is separated from the Umm Ar-Radhuma by the Rus formations which are evaporitic, highly saline, non-water bearing and serve as a confining unit (EAD, 2009). While the Dammam aquifer is productive in the Al-Ain area where several large well fields tap it, it is not exploited in the Western Region where it is more saline reflecting longer residence time along flow-gradients. The thin Miocene clastic sandstone formation underlies the Lower Fars in the Western Region. It is highly saline in the Liwa area. It is used in the Liwa area as a recipient of brine injection from oil and gas-related activities.

The Lower Fars serves as an aquiclude between the shallow unconsolidated and semi-consolidated Quaternary aquifer and the deeper bedrock aquifers described above. The Fars formation consists primarily of mudstone, dolomites and evaporates. While groundwater in the formation has relatively low salinity, the formation serves as a confining unit and is not developed for groundwater supply.

These bedrock aquifers have not been developed for irrigation supply due primarily to their high salinity. However, they are used in oil and gas production activities. The table below (AlSharhan et al., 2001) shows the utilization of the various units in relation to oil and gas production activities. The volume of abstraction from these saline aquifers is significant. Including water taken from the Late Cretaceous aquifer of the Simsima formation as well as those identified in the table below, abstraction is about 875,000 m^3/day (AlSharhan et al., 2001). The water is abstracted and re-injected into the Lower Cretaceous Aquifers to maintain pressure in the oil-bearing formations. Also, certain bedrock aquifers such as the Miocene are receptacles for excess production water injection.

Table 1. Aquifers underlying Liwa

Hydrogeologic unit	Thickness (m)	Nature	Lithology	Salinity (mg/l)	Importance and use
Lower Fars	160	Confining unit	Evaporite and clastic	5,000	Prevents vertical flow
Miocene	100	Aquifer	Sandstone	100,000	Receives injected brines
Dammam	265	Aquifer	Limestone	70,000	Source of water for injection into deeper reservoirs
Rus	215	Confining unit	Anhydrite/limestone	Very high	Prevents vertical flow
Umm er Radhuma	415	Aquifer	Limestone	160,000	Source of water for injection into deeper reservoirs

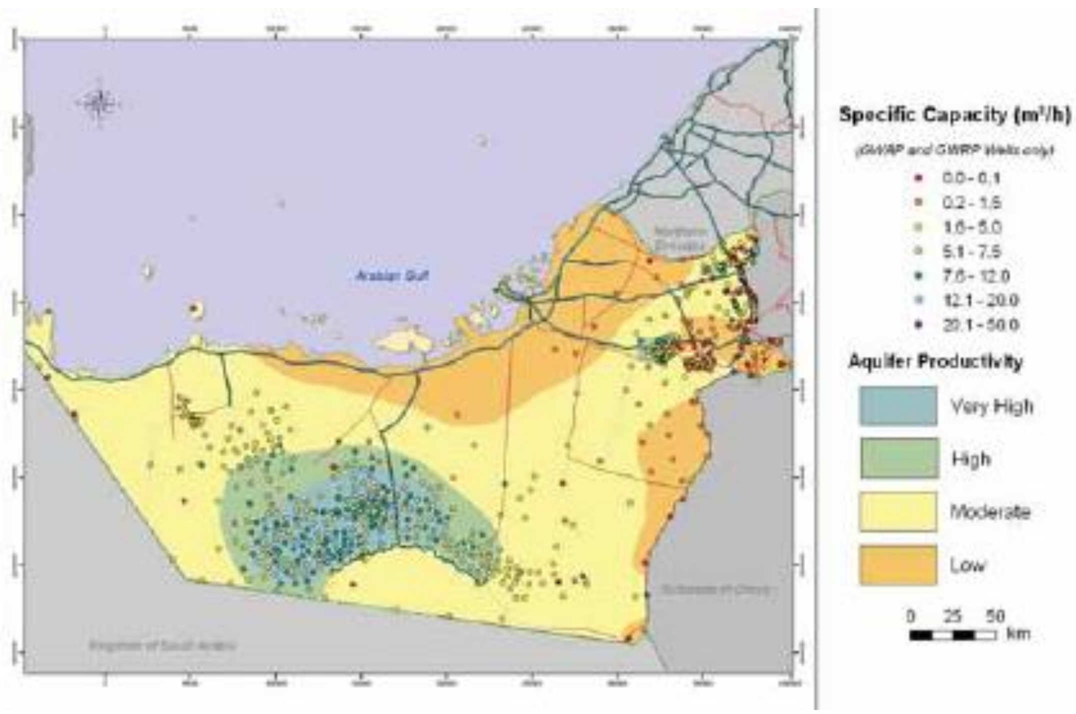
Source: Alsharhan et al., 2001.

2.4 Quaternary shallow aquifer – the Liwa freshwater lens

The shallow aquifer is made up of unconsolidated sands and is relatively clay- and silt- free in its upper zones leading to moderate permeability and high porosity and transmissivity. With depth, aquifer porosity and productivity reduce to the extent that it acts as an aquitard between the upper zone and the basal complex, the Miocene Age Lower Fars formation which underlies the entire study area (GTZ, 2005). Few groundwater wells have penetrated the Lower Fars formations in the Western Region and EAD maps show that no water production wells over 150m deep are located in the Liwa area precluding active abstraction from the Lower Fars since it is typically greater than 150m from surface depth in the Liwa area (Menche, 2010; EAD, 2013). Several EAD monitoring wells in the region reach depths of 200m or more in the region and so active monitoring of the Fars aquifer is ongoing although additional information about its evolution in recent periods was not available (EAD, 2016b).

Though the shallow sand dune aquifer system is present throughout most of Abu Dhabi, the saturated thickness of the freshwater zone, relatively shallow depth to groundwater and high productivity in the Liwa area combine to make it a hydrologically unique region in the context of the Western Region (EAD, 2009). Well productivity as measured by specific capacity is illustrated in Figure 4 (GTZ, 2005) which highlights the unique nature of the Liwa aquifer in Abu Dhabi overall.

Figure 4. Groundwater well specific capacity in Liwa area

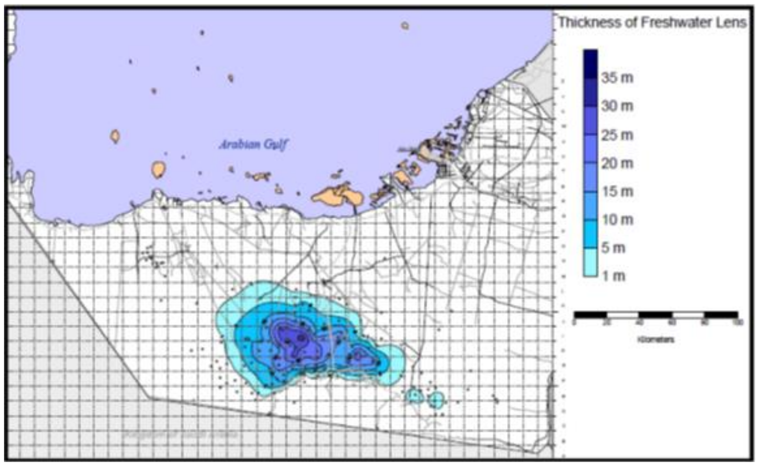


Source: GTZ, 2005.

The Liwa lens of fresh groundwater with less than 1,500 mg/l TDS extends over an area of approximately 2,500km2 and has an average saturated thickness of approximately 25m – and a maximum extent of about 50m (USGS, 1998) as shown in Figure 5. As observed, the thickness of the freshwater lens overlaps to a large extent with aquifer productivity as wells' specific capacity is related to the loosely-bound sand and silt features of the local lithology (EAD, 2016b).

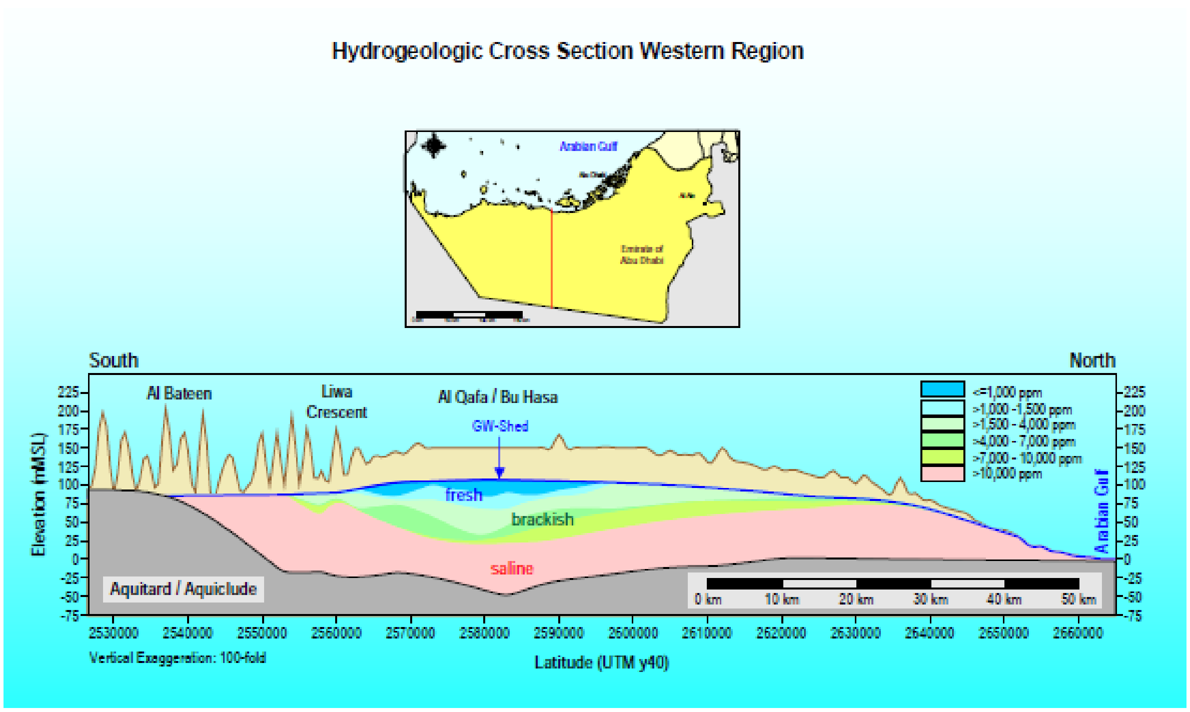
The freshwater layer blends into a brackish zone with TDS between 1,500-15,000 mg/l which extends on average a further 70m into the aquifer. The saline zone of TDS>15,000 mg/l extends to the bottom zone of the aquitard (GTZ, 2005) and in areas down the flow-gradient from the Liwa freshwater lens, such as discharge zones near the coast, can reach salinities of over 200,000 mg/l (AlSharhan et al., 2001). These characteristics are shown in Figure 6 which depicts a South to North cross-section of the shallow aquifer with specific lenses of the aquifer defined by depth and salinity (Rizk and AlSharhan, 2003).

Figure 5. Thickness of groundwater lens in Liwa



Source: Brock, 2006.

Figure 6. Hydrological cross-section focus on groundwater salinity



Source: Rizk and AlSharhan, 2003.

Estimates of drainable freshwater reserves in the Western Region vary only slightly; the USGS study (1998) provides a figure of approximately 14 Bm^3 while GTZ (2005) gave a slightly lower figure of 12.5

Bm^3. Accessible freshwater represents less than 2.5% of the total drainable shallow aquifer storage in the Western Region (GTZ 2005). A further 38 Bm^3 of drainable groundwater with TDS<15,000 mg/l are present under the Liwa lens (USGS. 1998). In total, the Western Region has approximately 550 Bm^3 of drainable groundwater with over 80% of it being saline with TDS>10,000 mg/l.

The freshwater lens of the shallow aquifer was recharged largely during the Holocene wet period that lasted from 9,000 to 6,000 years before present as evidenced by isotope hydrology studies (Wood and Imes, 1995). Isotopic tracer studies show that the source of recharge during the Holocene era was precipitation of Indian Ocean origin and indicate strong summer monsoonal circulation (Wood et al., 2003). The monsoon still reaches the Dhofar Mountains and Salalah in southern Oman annually and connected cyclonic events reach as far north and west as Muscat. In Liwa, up-flow from underlying aquifers is highly limited and the lack of adjacent aquifer systems suggests that most solutes in the Liwa aquifer system have atmospheric origins (Wood et al., 2003)

Modern recharge to the shallow aquifer in the Liwa region is effectively zero – though intense precipitation can induce flow into the unsaturated zone of the upper aquifer as evidenced by tritium content and groundwater fluxes in test wells (AlSharhan et al., 2003) - and so for all intents and purposes, all groundwater abstracted in the study area can be considered fossil water that is non-renewable. Modern groundwater recharge does occur in the eastern region of Abu Dhabi, particularly in the wadi systems near Al-Ain, although it is estimated to be only 24 Mm^3 per annum (Brook, 2006).

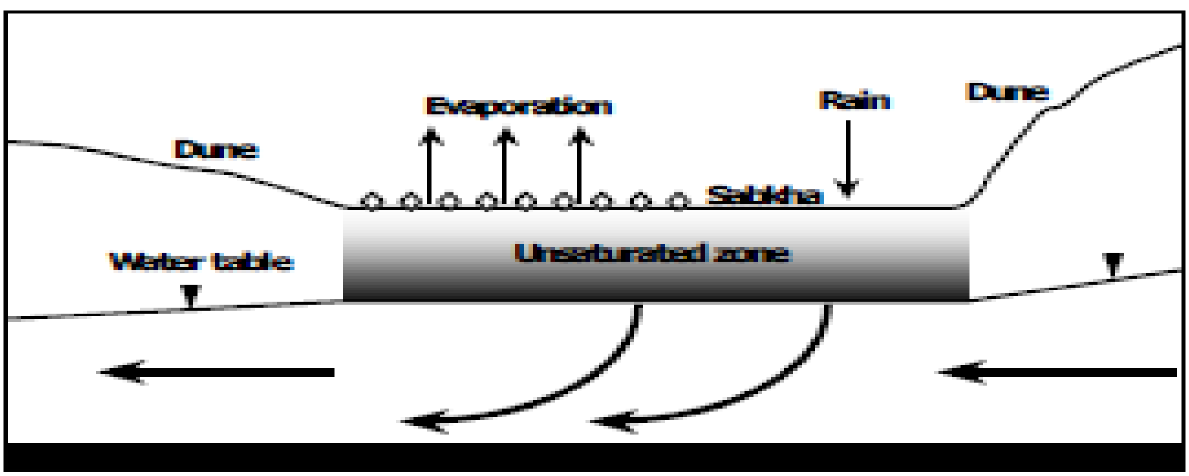
2.5 Groundwater quality and salinity in Liwa

Dangerously high nitrates levels (mg/l > 50) are primarily responsible for the groundwater phase-out of municipal supplies. High nitrates levels occur naturally in Abu Dhabi's soil and groundwater due to the low level of plant uptake and accumulation of precipitation-derived evaporites (Wood et al., 2003). This issue of a high natural baseline can become a localized problem even in regions underlain by the Liwa freshwater lens because excessive irrigation mobilizes nitrates in the sandy soil and transports them to the shallow aquifer (EAD, 2009). Inorganic fertilizer application exacerbates mobilization of naturally-occurring nitrogen and both have combined to cause widespread nitrogen spikes in the shallow aquifer as shown in Figure 8 of the Abu Dhabi report (McDonnell and Fragaszy, 2016). Aside from direct human health problems, high nitrogen concentrations affect livestock rearing and could impact aquifer storage and recovery projects in the Liwa area (EAD, 2009).

Oil and gas-related activities at the Bu Hasa, Asab, and Shah fields, the locations of which are shown in Figure 9 of the Abu Dhabi report (McDonnell and Fragaszy, 2016), are a concern for groundwater quality in the shallow aquifer. Indeed, over 600,000 barrels per day (bbl/day) are produced at the Bu Hasa field, one of the first giant oilfields to enter production in the UAE, and as recently as 2001 hyper-saline (100,000-150,000TDS) production water contaminated with hydrocarbons was released into unlined ponds on the land surface at a rate of 2,000bbl/day, approximately 318 m^3. This impacted the shallow aquifer nearby raising TDS from 500 to 1,000ppm by 1985 and then 4,500ppm by 1996 which impacted agricultural usage at the time (Alsharhan et al., 2001). Unfortunately, the extent and continuity of such activities is difficult to monitor and gauge effectively.

In the Liwa area groundwater salinity varies with depth in the shallow aquifer as a function of recharge timing and meteoric precipitation evaporation processes. The shallow aquifer was recharged primarily during the Pleistocene humid period which lasted from 32,000 to 26,000 years before present and then in the Holocene era from 9,000 to 5,000 before present. Following the Pleistocene period, Liwa's climate alternated between hyper- to semi-arid (<50mm/year to <250mm/year) resulting in highly limited groundwater recharge and concentration of salts in shallow soil layers due to the evaporation of precipitation and groundwater discharge to the *sabkha* surface. During the Holocene humid period from 9,000 to 6,000 years before present, increased precipitation mobilized these accumulated salts during recharge events as evidenced by significant solute masses in the groundwater without direct evidence of evaporation on the groundwater's isotopic composition (Wood, 2011). Therefore, precipitation in the Holocene era led to the formation of the topmost freshwater lens and mobilized these salts which reached the deeper groundwater of the Pleistocene era (Wood et al., 2003). This process is illustrated generally in Figure 7 below which shows groundwater recharge processes in the dune and *sabkha* environment of the Liwa region (Wood et al., 2003).

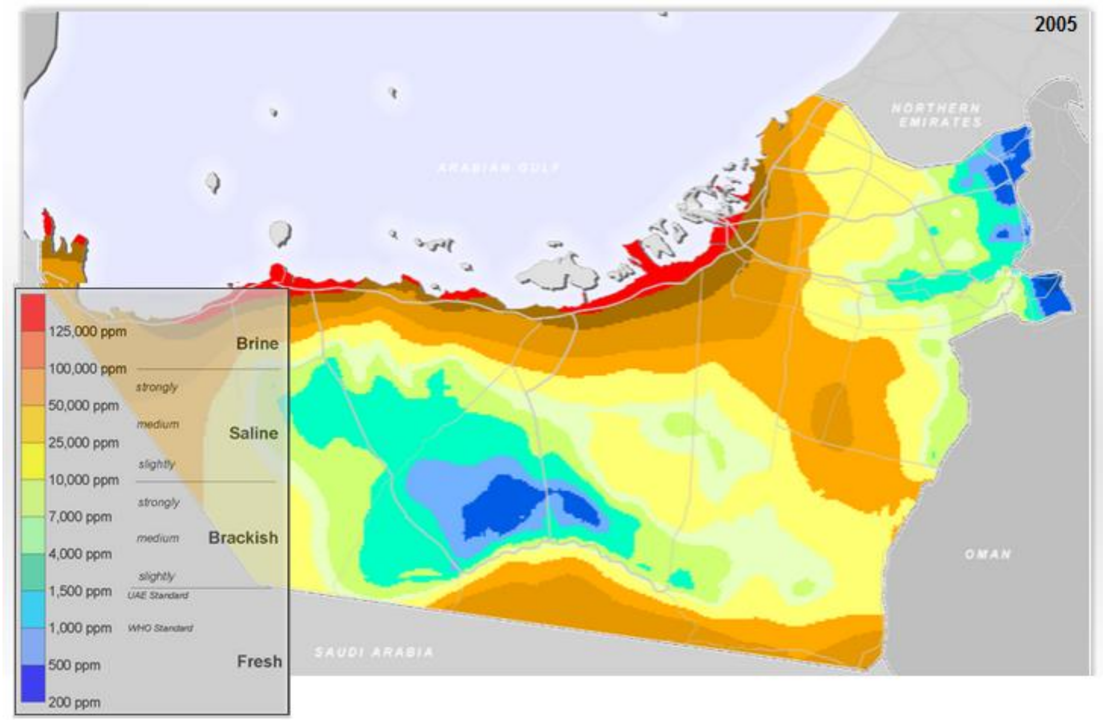
Figure 7. Groundwater recharge processes in Liwa



Source: Wood et al., 2003.

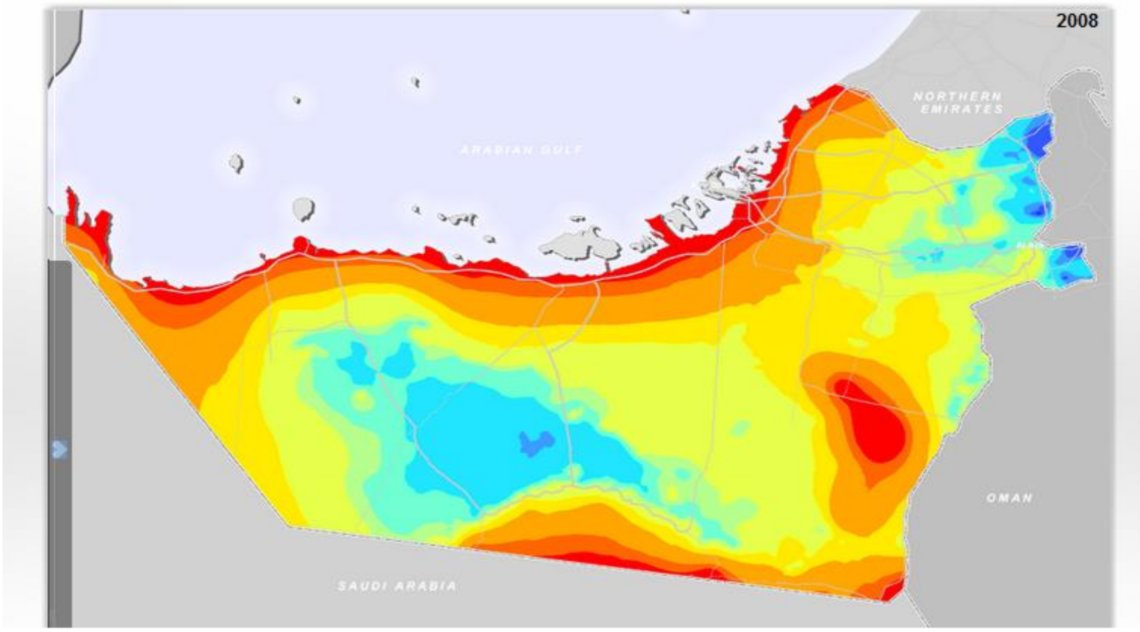
Currently salinity is the main control on groundwater utilization for agriculture and forestry. Therefore, depletion of the freshwater lens or the creation of overlapping cones of depression due to poorly spaced wells causes upwelling of more saline groundwater is a major challenge. Groundwater salinity rise and associated soil salinization is the primary cause of farmland abandonment in Abu Dhabi (ICBA, 2014). Groundwater salinity, as defined by the salinity in the upper horizons of the shallow aquifer, is shown in Figures 8 and 9 below which highlight the increasing salinization of the shallow aquifer between 2005 and 2008 (Environmental Atlas of Abu Dhabi, 2015). The decrease in the area of the lowest TDS groundwater in 2008 compared to 2005 highlights the rapid depletion of the freshwater lens in the Liwa area.

Figure 8. Groundwater salinity in Abu Dhabi (2005)



Source: Environmental Atlas of Abu Dhabi, 2015.

Figure 9. Groundwater salinity in Abu Dhabi (2008)



Source: Environmental Atlas of Abu Dhabi, 2015.

However, it is important to note that local patterns of abstraction can greatly alter the rather homogeneous pictures shown in Figures 8 and 9. As discussed further in Section VI, frequently groundwater from wells on opposite ends of a farm – at times less than 200 m apart – can vary hugely in salinity due to different depths to groundwater and rapid changes in groundwater horizons (Interviews B, 2016). These massive variations in salinity across a small area pose major challenges to groundwater management and agricultural systems in the region.

Groundwater salinity was the primary factor of concern related to groundwater according to all farm owners and managers contacted during this study (Interviews B-C, 2016). Some older farms, those established in the 1980s, have witnessed groundwater salinity increase three times or more which necessitates either abandonment of all cultivation except date palms or the utilization of small-scale reverse osmosis (RO) systems (Interviews A-B, 2016). Forestry is similarly impacted by salinity rises with few species able to tolerate or thrive when provided with the brackish water primarily used for forest plantations.

3 Agricultural production systems in the Liwa Oasis

3.1 Historical agricultural production in Liwa

The Liwa Oasis appears to have supported small communities at the edge of the Empty Quarter for millennia. Archaeological finds suggest habitation on the eastern and northern edges of the oasis in the region's Late Stone Age period 7,000 to 6,000 years before present coinciding with a more humid climatic period in the region (Adams, 1991; Harris, 1998). Whether that habitation continued unbroken until the Islamic period is unclear as the trail of direct evidence is thin until the late 16th and early 17th century when elements of the Bani Yas confederation occupied Liwa on a permanent basis (Hellyer, 2012). However, elsewhere in the Western Region and in Al-Ain the record of habitation continues in the intervening period with firm evidence of established communities interspersed in the interim (Heard-Bey, 2005).

Liwa provided the vital agricultural base for the semi-nomadic Bani Yas community and acted as a stepping-stone for the settlement of the island of Abu Dhabi. Until the beginning of the oil era, though, only a small number of people - in 1968 only slightly more than 300 families - stayed in Liwa on a year-round basis (Wilkinson, 2009). However, Liwa's date-palm cultivations can be considered the socio-economic centre of the Western Region society and the key pillar of the local populace's livelihood mainstays, the others being camel herding which occurred throughout the sparsely vegetated Western Region as well as pearl-diving which became a vastly more important economic activity from the early-1800s onwards (ibid).

However, the amount of fresh water that can be abstracted locally from Liwa's sand-dune aquifer before inducing more saline inflow into wells limited the extent of historical cultivations, as did the accessibility of fresh water prior to the introduction of motorized pumps. Wells historically were used for potable and irrigable water until the salinity increased, and then they were left for several hours or days to recover. Therefore, each settlement within the valleys of the Liwa crescent was typically a small village with fewer than 20 houses built onto the south-facing sides of the dunes. This explains the absence of large permanent settlements even though some of the inter-dunal gravel plains were of similar size to the villages in Al-Ain (Heard-Bey, 1974).

While the Liwa oases could not sustain the population of the Western Region, they did provide adequate food, water and feed during the summer harvest period when camel meat and milk was less abundant. Dates are calorie, nutrient and fibre rich, and when combined with high-protein foods such as fish or milk products provide a simple but nutritionally adequate diet (Heard-Bey, 1974). Also, date palms provided the structural framework for local houses, fences and wind breaks as well as the materials for fishing implements and a variety of household objects (FAO, 2015). As late as the 1970s Arish buildings – those reliant on palm materials – made up over 80% of the buildings in the UAE (ibid.).

After the date palm is established, it requires little active attention other than during pollination and harvest periods. For the first few months after a seedling is planted – typically a cutting from an established palm – it requires irrigation until the roots reach the groundwater table. After about three years female plants produce fruit and can continue to do so for over 100 years. Date gardens in Liwa typically include only one or two male plants and so pollination is a manual and labour-intensive process in the spring. Otherwise, the main labour requirement occurs during the summer harvest period when the population of the Western Region typically converged on Liwa. Because of the annual cycle, extended family groups were able to participate in the three overlapping pillars of the economy by utilizing family or hired labour to tend date cultivations the majority of the year except for harvest time when the vast majority of the dates were consumed as the dietary staple (FAO, 2015; Stevens, 1970).

3.2 Agriculture and land tenure in the post-oil economy

The oil-based economy of the last half-century completely upturned these traditional agricultural and nomadic cycles. Upon the establishment of the United Arab Emirates in 1971, all land in Abu Dhabi not explicitly held by a citizen in legal fact became state property (AlShamry, 1994). Thus in political terms distribution of land was an avenue to gain support for the nascent ruling group, ground former nomads within the country and induce a sense of citizenship. In socio-economic terms, land distribution, agricultural preparation and groundwater supply provision for citizens was a tool to realize Sheikh Zayed's vision of an agricultural society emerging in the UAE as well as to help narrow the rapidly-widening food import gap for the growing populace (Lambert, 2013).

Modern agricultural development in Liwa can be divided into two periods: from 1980 to approximately 2006 and then 2010 onwards with a transition period between 2006-2010 when the creation of the Environmental Agency – Abu Dhabi (EAD) and Abu Dhabi Food Control Authority (ADFCA) and initiation of agricultural policy reforms shifted a broad set of incentives to re-structure agricultural production in Abu Dhabi.

The Project of Economic and Social Development (1981-1985) and Ministerial Decree No. 511/7 of 1983 underpinned the rapid expansion of agricultural area in Abu Dhabi. Under these plans, the state increased spending on agriculture by about 220% and policies were created to encourage expansion of farmed area by distributing to UAE citizens plots of 5-10 hectares in the early 1980s and then 2-4 hectares in the late 1980s onwards for which the state provided the following initial services (AlShamry, 1994; Shihab, 2001; EAD, 2009):

1. Land leveled and prepared for cultivation;
2. One well drilled per hectare and associated technical services such as installation of water pumps;
3. Interest-free loans to purchase pumps, mechanical equipment, fencing, hire labour, etc.

Once established, farmers received a variety of other subsidies or supports including the following:

1. Subsidies for and/or provision of production inputs such as seeds, machinery, insecticides;
2. Price supports and guaranteed purchase of outputs by government-owned firms and marketing boards;
3. Favorable or free electricity rates.

By 1990 farmland had expanded rapidly because of the guarantee for high profits and nearly 3,400 farms were present in Liwa. In 1986, 126 wells were dug in Abu Dhabi and by 1990 that number had reached 879 per year indicating the scale of expansion (AlShamry, 1994). The guaranteed purchase of farm output by government marketing boards contributed to continued rapid expansion of farmland because of its profitability throughout the 1990s (Shihab, 2001). However, the poor collection, packaging and transport provided resulted in over 50% of vegetable and fruit production (excluding dates) to spoil and be classified as wastage (AlShamry, 1994). In the mid-2000s the guaranteed purchase of vegetables and fruit was stopped and subsidies reduced leading to a rapid decline in vegetable cultivation (FSC, 2014).

Simultaneously, in the mid-2000s land allocation was slowed due to shifting focuses in agricultural policies reflecting the new leadership after the death of Sheikh Zayed. Deteriorating groundwater status and farmland abandonment due to soil and groundwater salinization played some role in this shift (Interviews A; C-D, 2016). New areas have been opened to cultivation in the last 10 years but land allocation now occurs with greater consideration of groundwater quality and availability than in the past (Interviews D, 2014). Farmland is still distributed to citizens and prepared for them upon request to the Municipality[2] - or at times provided on a rental basis from municipalities – but it is a more arduous process now and occurs with far less frequency and with greater oversight than in the past (ibid.). Although statistics were not available on the number of land requests and approvals, anecdotal information does highlight that the process has become more selective: Khalifah Fund recipients who receive institutional support for petitions to be provided farmland from municipalities are not guaranteed success (Interviews B; G, 2016). This illustrates the reticence of the state to continue land allocation expansion. Arable land stock is therefore fixed by the state and cultivable area in Liwa is limited in practice by the lack of distribution of new land titles and the low level of rental available from municipalities. From 2005 to 2013 the number of farms in the Western Region increased from about 7,400 to 8,600 with much of the increase in Medina Zayed and Ghayathi (SCAD, 2015; Interviews A, 2016).

Land can be bought and sold by citizens but such transactions are relatively infrequent due to the cultural prestige and lucrative nature of farm ownership in Abu Dhabi (Interviews C, 2016). Renting of farmland by owners in the Western Region is technically illegal since land titles are specified for farming by the designated owner only according to information provided by the Western Region integrated government services agency, TAMM (Interviews H, 2016). However, farm managers in Liwa reported it is a relatively common practice with established clearing prices of 40,000-50,000 AED[3]/year for ~2 hectares of prepared open field farms and ~150,000AED/year for farms with greenhouses (Interviews B, 2016). Numerous advertisements on UAE online sales platforms show farmland for rent in the Liwa area with similar prices and photos showing the farm with map locations so enforcement of these rental restrictions seems to be somewhat lax.

[2] The process of land granting remains opaque. Land requests from individuals can be denied by the Municipality and groundwater sustainability is part of the basis for land grant decision-making. Land title information is not easily accessible and for land sale records an offocial letter from the Municipality is required. The number of farms is marked as stable in statistics for the past few years (2012 and after). Before 2012 the number of farms is not broken down by region in official statistics. The exactitude of numbers is not accurate as farm numbers also include abandoned farms.

[3] The Emirati dirham (AED) is pegged to the US dollar at an exchange rate of 3.68 AED=$1.

The rental system is informal but regulated by contracts – which are not likely to be legally enforceable - between the citizen farm owner and the renters. Renters are primarily foreign investors who may or may not be resident in the UAE but who can make the transaction through relatives or agents in the country. A small number of UAE citizens also rent additional farmland to expand their farm area and achieve greater economies of scale. Interviewees report that land quality – hardness, stoniness and salinity – is a greater determinant of rental prices than groundwater salinity indicating low levels of perception of its importance to agricultural productivity overall (Interviews B; H, 2016). Without long-term security of legal contractual arrangements, renters cultivate land very intensively focusing on short-term profits over long-term sustainability; this mind-set differs from farm owners who of course aim to maximize profits but are also concerned with groundwater salinity rise and groundwater table drawdown because of their combined effects on crop productivity and electricity consumption (Interviews B, 2016).

As a result of this history of land distribution and land tenure characteristics, the vast majority of farms in the Liwa area are small-scale. Less than 3% of cultivated area is in farms greater than 5 hectares, and about 40% of cultivated area is in farms less than 3 hectares as shown in Table 5 in Appendix 1. The large number of small farm owners, the vast majority of whom do not live in Liwa, produces a whole host of challenges to improving on-farm groundwater management explored in depth in Section V.

3.3 Cropping patterns

From the minute cultivated area in the pre-oil era, farmed areas and forest plantations have expanded enormously in Abu Dhabi overall as shown in the Abu Dhabi report (Figure 21 in McDonnell and Fragaszy, 2016). In 1987, farm area in the Liwa region was approximately 1,000 hectares and by 2002 it peaked at about 21,000 hectares, over 2/3 of farmland in the Western Region, which in turn made up about 40% of Abu Dhabi’s total farmland (ERWDA, 2004; Brook, 2006). Agricultural area contracted in the mid-2000s as groundwater table declines and rising groundwater and soil salinity impacted an increasing number of farms, particularly in Al-Ain, but also the Liwa region causing thousands of farms to be abandoned (ICBA, 2014). For the crop year 2010/2011, the last year for which detailed agricultural statistics are available from ADFCA, about 6,150 working farms and forest sections in the Liwa region occupied over 15,000 hectares, 80% of the Western Region’s total (ADFCA, 2011).

Within Liwa’s irrigated area of about 15,000 hectares, only about 10,000 are actively cultivated: date palm plantations cover over 6,500 hectares, fields crops - primarily alfalfa and Rhodes grass - a further 1,700 hectares, forests nearly 1,000 hectares and the remaining area is used for vegetables, greenhouses and other fruits (ADFCA 2011, author’s calculations). The crop season for vegetables is from mid-September through the beginning of May which permits near year-round cultivation of vegetables. The remaining area is left fallow (~4,000 hectares), used for buildings or is otherwise unutilized as shown in Table 6 in Appendix 1 with all areas shown in *dunum.*[4] Over 90% of greenhouses in the Western Region are in Liwa which represents about 1/3 of the total in Abu Dhabi, and about 0.4% of agricultural land is cultivated within greenhouses (SCAD, 2013). Liwa's role in livestock systems is far less prominent than in irrigated agriculture, though, with its herds representing about 1/3 of the Western Region's total (ADFCA, 2011).

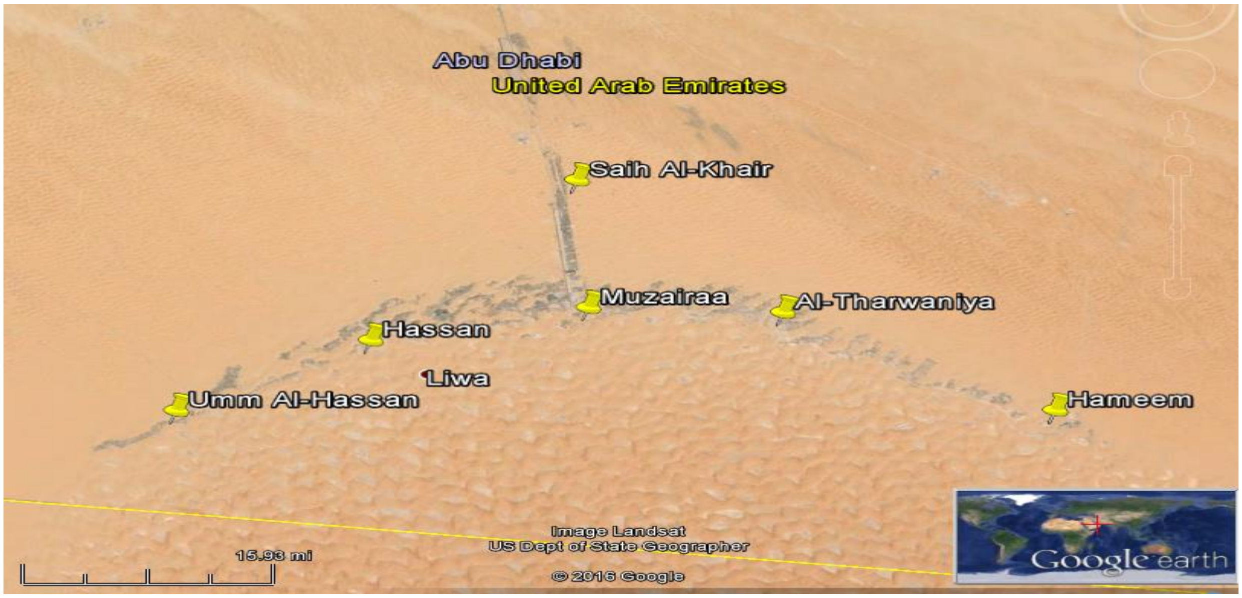
Unless limited by groundwater salinity, virtually all farms have about 10% of their area devoted to field crops, primarily alfalfa or Rhodes grass, and at least some area devoted to date palms. Otherwise, farm cultivations tend to be mixed with the exception of the numerous farms in areas with salty groundwater which solely have date palms (Interviews A-B, 2016). Fodder crops are grown for sheep, goats and especially camel-rearing which are perceived as more culturally prestigious than other types of farming. Therefore, despite the heavily subsidized fodder sale program run by the FSC and regulations against extensive fodder cropping, fodder crops continue to be cultivated widely and some farms still devote their entire area to them (Interviews A-C, 2-16).

Liwa and Al-Ain - which has nearly two and a half times as many productive date palms as Liwa - are the centres of UAE date production, which overall consistently provides over 5% of the world's date exports (FAO, 2015). Over 1.2 million productive date palms are irrigated in Liwa, and in fact, the high salinity of groundwater in much of the region precludes virtually all crops except for dates. Some varieties are grown in areas with salinity over 15,000TDS and they are still productive if managed well (Interviews B-C, 2016). Also, subsidy structures linked to reducing fodder crop cultivation are tied to farmers switching to date palms which has led to a rapid expansion in their cultivated area in the last five years as explored further in Section IV (Interviews A-C; E-F, 2016).

The specific areas mentioned in Tables 4-9 are inclusive of the study area and are shown approximately in the map below. Table 9 in Appendix 1 shows the number of wells in each region and Table 9 in Appendix 1 shows the number and area of farms in the region per salinity class.

[4] *Dunum* is an Ottoman land measurement which in the UAE is equal to 0.1 hectare.

Figure 10. Map of FSC Centres



Source: Composite image from http://www.adfsc.ae/en/pages/ourcenters.aspx and Google Earth.

These cultivated area and farm region salinity class statistics highlight the different cropping patterns predominating each area in Liwa as a function of groundwater salinity. This is most evident in Saih Al-Khair which has among the lowest average well depth and no marketing farms falling within Salinity Class B; it also has over 2/3 of the Western Region's vegetable crop area and a large proportion of the greenhouses. Groundwater salinity acts as a control on vegetable cultivation in Liwa, which is generally far more profitable than other crop types since the elimination of Rhodes purchase subsidies in 2010 (Interviews A-C, 2016). Consequently, areas with less saline water have higher proportions of vegetable cultivation since vegetable cultivation in areas with saltier water is reliant on small-scale reverse osmosis systems or otherwise is less productive. Overall cultivated area in vegetables has decreased since the early 2000s though market share of locally-produced vegetables has increased markedly because of improved produce quality, improved marketing and increasingly intensive cultivation through greenhouses and more recently hydroponics (Interviews A-C, 2016).

3.4 Groundwater abstraction for irrigation

Groundwater supplies virtually all irrigation water in Liwa and all abstraction comes from privately owned and controlled wells (Interviews A, 2016). Statistics shown in Table 9 indicate that in 2011 there were ~13,500 working wells and a further 3,000 that had been abandoned, although statistics do not elucidate the cause. However, EAD officials reported figures of approximately 35,000 wells (many of which are not in use) in Liwa as of 2007 which seems consistent with cultivated area statistics and the presence of multiple abandoned wells on several farms visited during the survey and the presence of at least one working well per irrigated hectare.

Unfortunately, the most recent irrigation abstraction statistics shown in Figures 16 and 33 of the Abu Dhabi report (McDonnell and Fragaszy, 2016) are based on data over five years old, not disaggregated by locale and made by estimation since wells are not metered. Abstraction estimates are based on surveys of farm workers' practices, pump capacities and crop area (SCAD, 2013; Interviews A; D, 2016). Thus, they are very much "ballpark" estimations rather than precise figures.

In addition to these limiting factors, available statistics date from pre-2011 when Rhodes Grass cultivation accounted for approximately 60% of irrigation water demands in Abu Dhabi overall (EAD, 2014). Therefore, groundwater abstraction in Liwa has likely dropped considerably from these published statistics in line with reductions in fodder crop growth as well as due to campaigns to distribute efficient irrigation equipment and others aimed at educating farmers and farm workers (ADFCA, 2015). ADFCA recently concluded a 2-year farm survey program and EAD is currently undertaking a large-scale well-survey and monitoring program; therefore updated and more comprehensive statistics are likely to be published in the near future.

Well-metering, while under strong consideration for widespread implementation by the ADFCA and EAD, faces major challenges described in Section V. However, the 2010 figure of ~1.8 Bm^3 abstracted within Abu Dhabi for agriculture annually, with a further 400 million cubic meters for forestry and amenities, indicates the brisk pace at which the fresh and brackish aquifer reserves are being depleted (EAD, 2013). Given that total abstractable reserves of fresh and brackish water with TDS under 15,000 mg/l in the study region are approximately 50 Bm^3, this is a critical sustainability issue. 2010 baseline figures for the whole Emirate of Abu Dhabi indicate that under the current abstraction regime, fresh and brackish groundwater resources will be exhausted in fewer than 55 years (EAD, 2014). However, that eye-catching figure lumps all groundwater and abstraction in the Emirate together which is somewhat misleading because current abstraction rates in Al-Ain far outstrip that in the rest of Abu Dhabi.

3.5 Liwa irrigation compared to the rest of Abu Dhabi Emirate

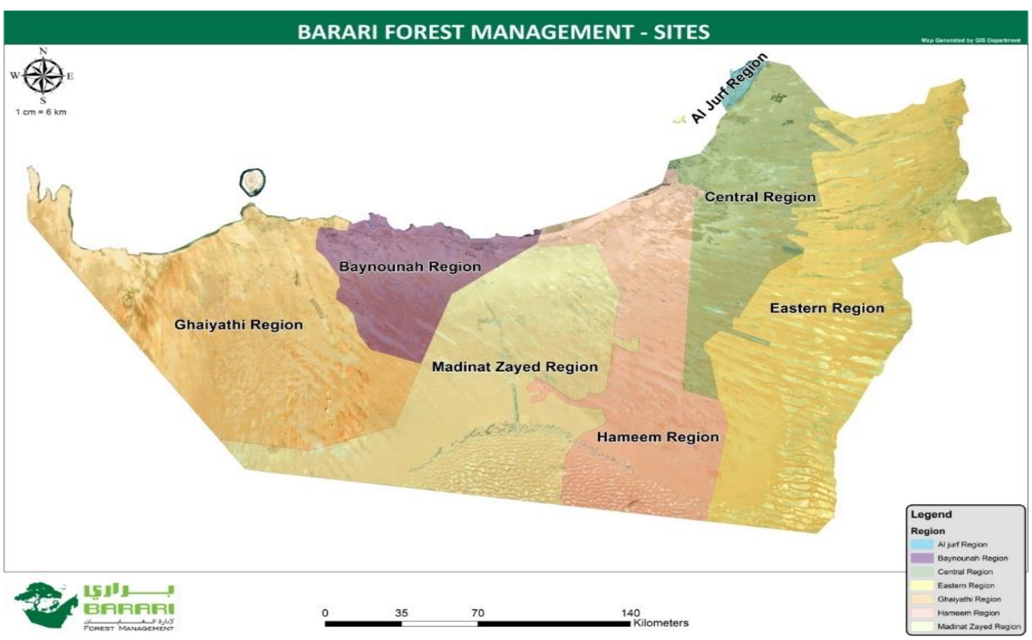
As mentioned above, Liwa is virtually entirely reliant on groundwater abstraction from private wells. No farms in the Liwa area are connected to the ADFCA-controlled well-fields described in the Abu Dhabi report (McDonnell and Fragaszy, 2016). Tables 4 and 5 in the Abu Dhabi report (McDonnell and Fragaszy, 2016) highlight the vast difference in consumption patterns between farms in the different regions. While extensive description of the project methodology was not made available, the data is broken down by farm cultivation types and the author was told that best efforts were made to ensure the direct comparability of regions by controlling for factors such as farm size, cultivation types, etc. Unfortunately, data provided for the Western Region are not classified further by area and so they include farms in Liwa and also farms beyond the immediate study area (Interviews F, 2016).

The results of this project demonstrate very clearly that water management differs significantly between regions: farms in Abu Dhabi utilized the least amount of water per unit area for all farm types followed closely by Ali-Ain. Farms in the Western Region used significantly more water per unit area for all farm types. Not surprisingly, within the same region, farms which had ADFCA-controlled water supply had substantially lower water consumption overall compared to farms with private wells in this study, in some case less than 10% for similar cultivations for similar cultivated area within the same region. While any more detailed conclusions require access to more of the project information and data, this initial comparison is invaluable to highlight the different consumption patterns per region as a baseline to discuss water management challenges which are discussed further in the Abu Dhabi report (McDonnell and Fragaszy, 2016) in Section 2.3.1 and Section V below.

3.6 Forestry

The vast majority of Abu Dhabi's forest plantations are managed by the private sector firm, Barari Forest Management under contract from the EAD. The small remaining areas not under Barari oversight are in private residences or controlled by Municipalities until the end of 2016 when the latter will be transferred to Barari and it will manage 95% of all forests (Interviews D, 2016). In Barari's classification, the Liwa area falls under the Medina Zayed and Hameem sections shown in Figure 10. However, given that the majority of the Hameem region's cultivations are along the roads leading to Abu Dhabi to the East of Liwa, this report focuses primarily on the Medina Zayed section in which the majority of forests are on the northern edge of the Liwa freshwater aquifer as shown in Figure 5.

Figure 11. Abu Dhabi forest regions - Barari



Source: Barari, 2015.

In the Medina Zayed section nearly 1.8 million trees are planted on an area of almost 10,000 hectares and utilize 1,122 wells. This represents the 'desert greening' project launched by Sheikh Zayed with the idea to transform the desert into greenscape. Around and in the cities it is also aimed to reduce sand and dust in the air and alongside roads to reduce sand overtaking roads. This is slightly under

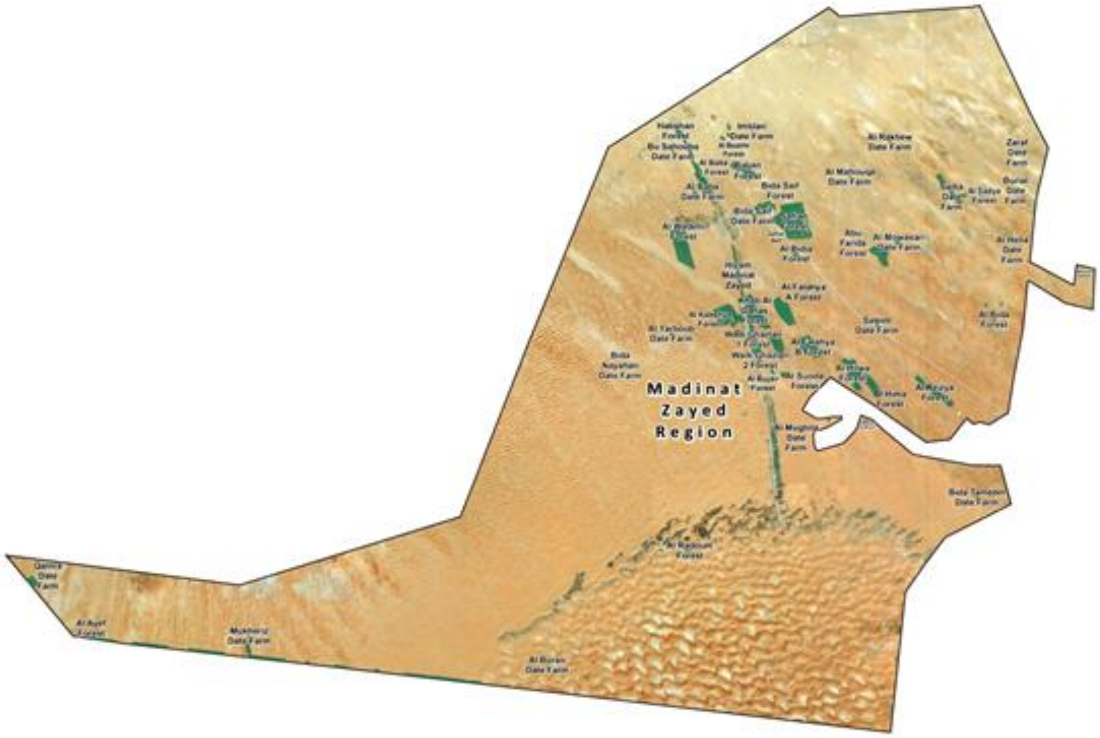
10% of the total in Abu Dhabi and includes both forestry and date palm plantations which hold over 43,000 date palms. Barari (2015) estimates water consumption by multiplying dripper yield per tree per hour by the number of hours irrigation takes place, but unfortunately the provided report did not contain any statistics on estimated consumption in the forestry sector. However, Barari is currently implementing a monitoring plan which includes a well census, installation of meters at bulk supply-fields areas, pumping tests on wells at sites, and calculations of final consumption at the individual forest level. This will permit Barari to assess losses in transmission and estimate abstraction in a far more accurate manner (Barari, 2015). In any case, the 'desert greening' project is known to be damaging for groundwater resources but remains politically sensitive as it was a core feature of the late king's agenda.

A recent figure for total water usage in forestry for Abu Dhabi was approximately 360 Mm^3/year as of 2010 (Government of Abu Dhabi, 2013), but interviews with EAD officials provided a newer figure of 214 Mm^3/year of which 9% are treated wastewater (TWW), 9% desalinated water, and 82% groundwater. An EAD-commissioned groundwater valuation study estimated that average consumption for forested areas in the Western Region was 156 m^3/dunum per year (EAD, 2016b). Using this rough figure and planted area statistics, one can estimate that in Medina Zayed, approximately 15.5 Mm^3 of groundwater are used per year in forests which is within the expected range given consumption statistics and its proportion of the total planted area.

In the Medina Zayed section Barari reports water shortages due to groundwater table drawdown in numerous areas including at least one forest section close to Saih Al-Khair. Like in agriculture forestry sections are also impacted by salinity. Wells in the Medina Zayed area have an average salinity of about 7,500TDS with individual forestry wells in various areas ranging from about 1,000TDS to over 25,000TDS. Because of the high TDS trees are often stunted and do not achieve a full canopy or expected biomass (Barari, 2009). Aside from groundwater salinity in irrigation causing trouble, forests in *sabkha* areas can be under through from groundwater table reaching trees' root zones. Precipitation events cause rapid groundwater table rises which can kill entire forests because of upwelling saline water (Interviews D, 2016).

Forest plantations were initially planned with little consideration of groundwater resources and they have caused significant drawdown in certain areas. Indeed, in several cases they are the cause of groundwater "red-zones", areas of drawdown greater than 1.5m/year. In theory these areas should not be able to have well rehabilitation or new wells. In these cases EAD can recommend clearing, or "de-commissioning" forests in certain areas but ultimately it's a political decision and no officials are quick to dismantle what is still seen as a key component of Sheikh Zayed's legacy in terms of desert greening.

Figure 12. Forest areas in Liwa



Source: Barari, 2015.

The current primary avenue to improve groundwater sustainability in the forest sector is to increase the utilization of TWW. For example, the recent completion of the Ruwais water treatment plant has led to the provision of 15,000 m^3/day of treated wastewater which is now being used for forests in the Ghayathi area. One longstanding plan is to build a pipeline from the Wathba treatment plant in Abu Dhabi to forested areas in the Centre and Eastern regions to provide nearly 300,000 m^3/day which are currently being discharged into the sea. However, this plan has been stalled for several years due to the estimated cost of ~AED1.5 billion (Interviews D, 2016).

In addition, Barari and EAD are undertaking long-term studies on trees' irrigation needs. The current irrigation guidelines are in major need of updating since they date from 1984 and consist of one simple rule of thumb: apply 36 litres per tree every other day in the summer and twice a week in the winter through watering cycles of four hours. New research is focusing on the true crop water demands of the three primary cultivated species - *Prosopis cineraria*, *Acacia tortilis* and *Salvadora persica* - which make up 85% of forest plantings in Abu Dhabi. This research is concluding in the near future and will likely result in new irrigation guidelines (Barari, 2015; Interviews D, 2016).

Lastly, EAD are promoting the increase of indigenous species in forested areas because they better tolerate heat and salinity and have lower irrigation requirements than non-native species. However, replacement of existing stands can only occur when trees die and so this is a slow process (Interviews D, 2016).

4 Agricultural market factors in Liwa

Addressing the economic role and market structure of agriculture in Abu Dhabi is highly important to understanding the context of and obstacles to efficient agricultural water management. In 2012 Abu Dhabi's entire agriculture sector – including forestry and fisheries – was valued at $1.45 billion, less than 1% of Abu Dhabi's GDP. In the UAE the agriculture sector employs about 5% of the workforce, but in Liwa over 70% of the population is employed in the agriculture sector (Oxford Business Group, 2014; FAO, 2015).

However, the terms employment and population must be understood in the UAE context: the vast majority of farm workers are foreign labourers primarily from South Asia paid the minimum guaranteed salary of approximately 800AED/month (Interviews A-C, 2016). Farm managers are usually trained agricultural engineers from Egypt, Jordan, Palestine and Pakistan. All farms are owned by UAE citizens but a negligible proportion of farm owners are involved in farm management on a daily basis. The vast majority of farms are owned by citizens who live and are employed elsewhere, most frequently in the capital and Al-Ain. Local stakeholders in Liwa said that only a small minority of farm owners rely on farm earnings for the majority of their income and these are older farm owners who are retired (Arthur and Al-Qaydi, 2010; Interviews A-C, 2016).

4.1 Direct agricultural subsidies

Agricultural subsidies and groundwater governance and abstraction are intimately tied in the UAE. They must be considered within the geopolitical realities of food security in the Gulf States and also the political context of government legitimation in the UAE. These two broad issues merit a brief mention though they are beyond the scope of this report because they shape the ideologies and structural framework of the water and agriculture sectors.

Food security in the Gulf States has always been a salient political issue, and its relevance and visibility increased dramatically during the period of rapid food price rises in 2008 and 2011 (Woertz, 2013). The UAE continues to import over 95% of its food by volume and virtually all of its wheat, the largest source of caloric intake in the country (National Bureau of Statistics, 2013). Saudi Arabia's precipitous depletion of groundwater reserves for wheat-growth illustrates clearly that food autarky is an unrealistic goal in the Arabian Peninsula; indeed, Abu Dhabi's food security remains linked with global market mechanisms (Fragaszy, 2015). However, the discourse of food security demands permeates UAE government publications and neatly combines with increased market and cultural interest in locally-grown agricultural products, especially vegetables, to shape the future direction of agricultural production in Liwa and Abu Dhabi more generally (FSC, 2014).

Politically Abu Dhabi is considered a "distributive state," one in which the ruling bargain entails that citizens, and to a lesser extent expatriates, enjoy the benefits of oil wealth directly (Krane, 2010). In practice, this means that citizens enjoy a wide range of cradle-to-grave welfare benefits and government policies act to distribute wealth accordingly. Direct agricultural subsidies fall into this category of policies, and more than one senior government official described subsidy programs overall as social policies rather than agricultural policies hinting that their ultimate intent is to maintain social stability first and foremost rather than incentivize the most economically productive, efficient and sustainable farming methods and their primary objective (Interviews D-F, 2016).

The primary and most important subsidy for farm owners is connected to the foregoing of large-scale fodder crop cultivation and the increase of date palm cultivation. These subsidies are connected to water usage rationalization since fodder crops accounted for the majority of irrigation abstraction prior to 2010 and date palms are highly salt-tolerant. FSC and ADFCA officials reported that subsidy structures depend on a farm owner's independent income: all farm owners receive 90,000AED/year if they do not grow Rhodes grass or alfalfa on more than 10% of their farmland and also do not have over 120,000AED/year of real-estate income. Roughly 2/3 of farm-owners in Abu Dhabi receive this subsidy. An additional 10,000AED/year are provided to all farm owners who have 60 or more date palms on their farm (Interviews D-F, 2016). Given that there are about 7,100 farms in Liwa and roughly 60% of farm-owners receive this subsidy, a back-of-the-envelope calculation on the annual value of this subsidy based on approximately 7,100 farms in Liwa shows that its annual value reaches over AED380 million, a substantial sum.

In order for this transition from growing fodder crops to succeed, the ADFCA simultaneously initiated the above-mentioned subsidy and launched major importation programs to provide fodder and feed stocks to farmers at subsidized rates tiered for the scale of their livestock holdings: fodder is available at 300AED per ton up to 10 tons per month, 500AED per ton per month up to 20 tons and 1,600AED (cost-reflective price) per ton if over 20 tons per month as of 2013 (ADFCA, 2013). Concentrated feed pellets are provided at subsidized rates depending on the scale of the farm as well. Also, at various times farmers have been able to receive free date palms, which for Khlas dates, a popular variety in the UAE, would cost farmers approximately 100AED for shoots or 700-1,000AED for several year-old palms, although specifics on the extent and timing of these programs was not clear (Interviews A; D-F, 2016).

Figure 13. Fodders bales at an FSC distribution centre in Liwa

Source: Authors.

The case of Rhodes Grass cultivation in the UAE highlights perfectly the role subsidies, especially price supports, have played in determining patterns of agricultural production. Prior to 2010, the government purchased Rhodes Grass at a price of AED 1,650/fresh ton from UAE farmers. Three fresh tons are required to make one ton of dry forage, which was then sold to livestock farmers at a price of 300AED (EAD, 2009). Rhodes Grass is a highly water-intensive crop that grows in areas with average precipitation over 600mm/year and has irrigation requirements of up to 48,000 m^3/ha/year (El-Keblawy and Ibrahim, 2006). The program, aside from incentivizing the growth of a highly water-intensive crop, was subject to wide abuses in which livestock owners bought subsidized Rhodes Grass and subsequently exported it (Joseph-Facun, 2010). Between 2005 and 2010 field crops, predominantly Rhodes Grass, was cultivated in an area ranging from 22,000 to 34,000 hectares annually in the UAE. By 2012 field crops were grown on only 4,500 hectares in the UAE; the cultivation of Rhodes Grass dropped by approximately 90% and that of alfalfa by approximately 75% between 2010 and 2012 (National Bureau of Statistics, 2011; 2013).

FSC - which is responsible for monitoring and regulating farm activities - also provides a wide range of farm-management services for farm owners whether or not they are members of the FSC or part of its marketing network. For instance, in 2016 FSC will be treating all farms for dust mites since there is a major infestation. FSC also provides initial well assessments and associated well technical services to all farms and distributed drip irrigation equipment to all farms for free. FSC input shops also provide insecticides and fertilizers which are sourced from the private sector and then sold at reduced prices for members. Lastly, they provide farm extension services and technical training on a no-cost basis in most cases (Interviews E, 2016).

4.2 Indirect subsidies

In addition to formal, direct agricultural subsidies, a range of indirect subsidies also exist. Of these, the most important subsidies are connected to water and electricity rates and also provision of financing. Direct oil and gas products and electricity subsidies absorbed about 6% of UAE government expenditure in 2013. That figure has dropped since 2013 due to a series of fuel and electricity subsidy reforms (Brookings Institute, 2016). Reforms in water subsidies have been slower to follow and less deep, but Abu Dhabi recently issued a new water and electricity tariff structure shown in Table 2 below which is the first major step in the subsidy rationalization agenda of the Abu Dhabi government (RSB, 2015; Brookings Institute, 2016).

Table 2. Water and electricity tariffs

Customer type	Pre-2015 water tariff (AED/1,000L)	Current water tariff (AED/1,000L)	Pre-2015 electricity tariff (fils/kWh)	New electricity tariff (fils/kWh)
Government	2.2	Cost reflective tariff (10.55)	15	Cost reflective tariff (29.7)
Commercial	2.2	4	15	16
Agriculture (including ranches)	2.2	2.2	3	3
Fisheries and livestock (feedlot)	2.2	4	3	16
Industrial	2.2	4	15	16, off-peak 30, summer-peak

Source: RSB, 2015.

It should be noted that agricultural water tariffs shown here only apply when water deliveries occur from desalination plants and not when water is sourced from groundwater abstraction since groundwater is free when farm owners abstract from their own wells. To the interviewees' knowledge, no Liwa farmers pay for irrigation water at present. The implications of government-supplied agricultural water hinted at in Section 2.3.1 of the Abu Dhabi report (McDonnell and Fragaszy, 2016) are explored in more detail in Section V. The government water tariff of 10.55 AED/m^3 is cost-reflective and this highlights the major subsidies inherent in the Abu Dhabi water sector for nearly all consumers including agricultural users.

Likewise, the cost of electricity for agricultural users is approximately 10% of the actual cost of production and transmission for the electricity they consume. This highlights a substantial indirect subsidy for agricultural activities. This is especially pertinent since farm managers stated that farm owners are most concerned about electricity consumption in terms of on-farm resource management because it has the greatest impact on the farm's bottom line (Interviews B, 2016).

Investment in the agriculture sector is sourced largely from government-owned banks and funds since returns on investment are dependent on subsidy structures which are prone to change and otherwise farming is largely unattractive to the private sector with the exception of large commercial ventures which constitute a tiny minority of agricultural production overall (Government of Abu Dhabi, 2009). Unfortunately, few statistics are publicly available on agricultural investment, though interviews and additional characterization helped to fill some gaps. Official government statistics (SCAD, 2015) from Table 3 below indicate a peak of AED46.5 million in 2005 dropping to AED4.9 million in 2014 but they do not indicate the source of funds and certainly exclude the private sector as evident by the loan forgiveness indicated. Particularly notable is the focus of loan activities in the Al-Ain area and also the sharp drop-off between 2010 and 2014.

Table 3. Loans provided to Abu Dhabi farmers per region ('000 of AED)

Region	2005	2010	2013	2014
Total*	**46,509**	**26,719**	**4,346**	**4,912**
Abu Dhabi and Al Gharbia	5,689	4,967	179.1	830.9
Al Ain	40,820	21,752	4,167	4,081

Note (*): farmers pay only 50% of the value of the loan.
Source: SCAD, 2015.

Before the introduction of motorized pumps, Al-Ain, as its name suggests, had perennial fresh groundwater springs which supported permanent residency and cultivation. As a result, agriculture expansion in Abu Dhabi first occurred in Al-Ain and it remains the centre of agricultural production in the UAE although severe groundwater table drawdown and salinity rise are major constraints for short-, medium- and long-term sustainability there.

The second feature, the drop in funding reported from 2013 and 2014 compared to 2010, may be a result of shifting agricultural finance channels rather than an outright decrease in capital investment: instead of funding through government-owned banks, a much greater proportion of funding may be directed through specific government-linked funds and government agencies. For instance, FSC provides loans to farmers directly in some cases. Also, the Khalifah Fund, a government-linked but financially independent entity, has disbursed approximately AED100 million through its *Zaarie* program which began significant funding activities in 2012. In addition to these channels, farmers can also apply to the Crown Prince's Court of Abu Dhabi for financial subsidies or grants of up to 100,000 AED/year to improve operations. They're case-dependent but focused on existing farms whereas Khalifah Fund was more geared towards farms starting from scratch (Interviews G, 2016).

In any case, loans from government banks, government agencies and government-linked entities such as the Khalifah Fund have highly preferential repayment terms. The statistics in Table 3 indicate that 50% of a loan's principal is forgiven and other sources show that government loans to farmers are soft loans without interest. FSC loans to farmers within its marketing network are partially repaid in-kind over several agricultural seasons (Interviews B; G, 2016). Likewise, the Khalifah Fund loans are also without interest and have 5 to 7-year repayment windows.

These generous terms and the significant investments made believe the fact that the majority of farms in Liwa are still very small-scale, low-tech and low-capital operations. The Khalifa Fund's program represents a significant investment in agricultural productivity and water demand management savings, but it focuses solely on vegetables and aquaculture which represent a tiny proportion of cultivation and water usage in Liwa. The challenge of addressing water demand on the more than 7,000 working farms in Liwa is far beyond the capacity of one such program. Indeed, interviews with farm managers and workers suggest that guaranteed profits for farm-owners, whether from subsidies or via guaranteed purchase from government-owned firms in the case of dates, provide disincentives to investment in agricultural equipment and human resources for all but the most enterprising farmers (Interviews A-C; F, 2016).

4.3 Government marketing roles

A constellation of government agencies and government-owned or government-linked firms continue to play a central role in the agriculture sector in Abu Dhabi, especially in terms of marketing produce and facilitating subsidy programs.

The FSC plays a marketing function for approximately 1,500 farms, of which about 400 are in the Liwa area. These farms have contractual arrangements with the FSC and make up its supply network for the sale of local produce, primarily vegetables and meat, as well as a small amount of fresh dates. FSC supplies large retail chains like Carrefour and Lulu as well as small grocers and runs its own outlets. Farms which have this type of relationship with the FSC benefit from increased frequency of extension and technical services and are also under increased oversight in terms of farm operations (Interviews A, 2016).

The FSC provides farmers a minimum guaranteed purchase price which is an estimate of farmer costs plus a guaranteed profit margin determined for each farm-owner based on his/her farm characteristics. FSC picks up the produce weekly during crops seasons, packs, grades, transports and sells it to retailers. If the end-client purchase price is lower than the minimum guaranteed price, the FSC takes the loss, and if the end-client purchase price exceeds the minimum guaranteed price, the FSC provides the excess to the farmer. This system significantly reduces risks for producers, streamlines incomes, and eliminates the necessity for farm owners to find buyers (Interviews A; E, 2016).

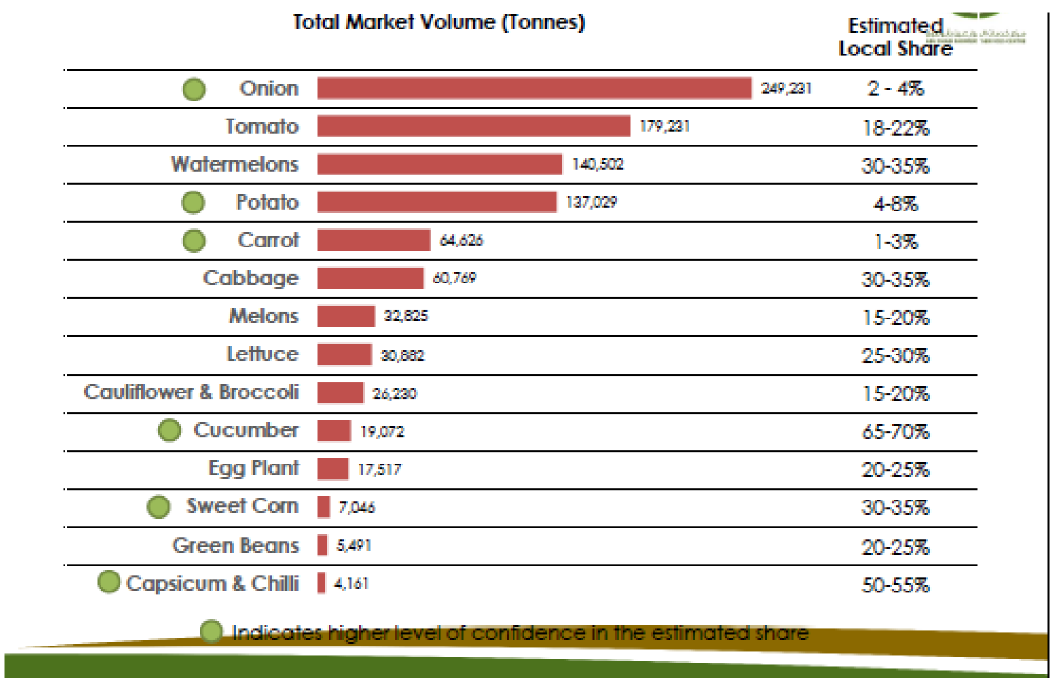
Al-Dahra Holding, a subsidiary of the government-affiliated Al-Ain Holding, is an agribusiness conglomerate with farmland and agricultural production in the UAE and abroad. The company has played a major role in the fodder import and subsidized provision program. Al-Dahra is the primary provider of fodder crops and livestock feed in Abu Dhabi and has executed the ADFCA mandate to reduce locally-produced fodder and feed and replace it with foreign-sourced crops (Al-Dahra, 2016).

It primarily supplies fodder to the UAE local market through farm operations or agribusiness assets it owns abroad as well as through contract deliveries.

Al-Foah Dates Company is a government-owned firm established in 2005 to improve the operations and profitability of the UAE date sector. It is the primary purchaser of dates in the UAE and in 2014 purchased dates from over 18,000 farmers in the UAE and made payments of over AED700 million to farmers (Al-Foah, 2014). Like with the FSC, payments are made throughout the season to ease farmers' cash flow and also to separate the product collection and payment processes. Payments to farmers are based on grading with raw date prices ranging from AED3/kg to over AED30/kg for the best grades of premium varieties (Al-Foah, 2014; Interviews E, 2016).

Farmers do not have an obligation to market crops through these outlets but, especially for date palms, the large majority do because doing so reduces transaction costs of finding buyers, transporting and marketing crops. Also, the government-owned firms and agencies have mandates to ensure prices paid to farmers meet minimum costs plus profit margins. With this marketing infrastructure and price support as well as improved control over pesticide and insecticide usage in local vegetable farms, the market-share of locally-grown crops has increased in recent years though has not approached the FSC's goal of achieving 40% self-sufficiency in vegetables (Interviews A-C; E, 2016).

Figure 14. FSC market share in fruits and vegetables



Source: FSC, 2014.

Overall market-share of locally-grown vegetables is estimated to be 16% in terms of total volume with specific crops reaching over 50% and total value over AED2.1 billion in 2014 (Emirates News

Agency, 2015). This proportion is rising because FSC-network farms are becoming increasingly productive with the expansion of greenhouse and hydroponic cultivation especially in key crops (Interviews B, 2016). In addition, increasingly stringent pesticide and chemical reporting requirements for imports have reduced some competition recently, particularly from South Asia, from where a number of large shipments have been refused entry following chemical tests revealing residue of banned products in the UAE (Times of India, 2016). This sets off periodic rapid price rises and increases the profitability of local farm produce.

5 Agriculture and water management challenges

During the course of the survey farms were visited ranging from those recently established to some dating from the 1980s. In addition, several of the officials interviewed in Liwa have been working in the area for over 20 years. The farm visits and interviews with key stakeholders identified a number of challenges to agricultural and irrigation management at the farm level in Liwa. Several of these have been alluded to in previous sections and in this section more details are presented along with their implications for water management. The challenges identified here are connected to agricultural human resource, perceptual, institutional and structural issues. In addition, this section provides the most recent information from EAD about aquifer status and drawdown in recent years.

Connected to all three sets of issues is the critical topic of irrigation efficiency. While irrigation demand management is addressed in Section 6, the topic of irrigation efficiency cannot be addressed in isolation because in many ways it represents the sum of the challenges discussed below. Unfortunately, the lack of survey studies and groundwater monitoring preclude rigorous assessment of irrigation water application in the Liwa region. At present, before the results of the ADFCA and EAD’s crop calculator project are published, the best avenue to discuss crop water needs and general irrigation efficiency in Liwa, then, is to compare consumption on the farm and cultivated area scales in Liwa with consumption in other regions.

That comparison is shown in Tables 4 and 5 of McDonnell and Fragaszy (2016) and illustrates that Western Region date palm farms included in the study – primarily but not solely in Liwa – on average use 3.28 times as much water per irrigated donum as Al-Ain farms of the same type and 4.73 times as much as Abu Dhabi farms. Likewise, Western Region farms use 1.53 times and 1.97 times as much water per cultivated donum in mixed farms (dates and vegetables or other mixed cultivations) in Al-Ain and Abu Dhabi, respectively, and 1.48 and 4.26 times as much water per cultivated donum in date and fodder mixed farms as Al-Ain and Abu Dhabi farms respectively (ADFCA, 2016b). While such comparisons ignore issues such as quality of irrigation water, which differs significantly in salinity content both within and between regions, they are useful to highlight the fact that farms in Liwa utilize vastly greater sums of water for the same cultivations in the same irrigated areas as similar farms in other parts of the Emirate and therefore it is quite likely that great improvements in irrigation efficiency are possible.

5.1 Human resources challenges

Challenge 1 - unskilled labour: The majority of farms visited during the survey did not have a farm manager with training in irrigation management, agricultural engineering or a similar field. Interviews confirmed that this is the norm, and in fact the proportion of farms with trained managers is likely very small, much lower than the survey indicates because the visits to a large extent were conducted with FSC staff on their typical rounds. FSC staff visit farms with which they have marketing contracts more regularly than other farms and therefore these farms tend to be better-managed as the owners delegate much authority to FSC and trained managers who are present. Interviews suggest that particularly on farms with no vegetables (only date palms, date palms and fodder crops, or date palms and some livestock), the presence of trained managers is very rare while for farms that have vegetables trained managers are more common (Interviews A-B, 2016).

Impact – unskilled labour: The impacts of unskilled labour on farm and groundwater management are numerous and grievous. First and foremost, unskilled labourers frequently have no previous experience in farming at all, and if they do, it is typically from areas with vastly different climates. Upon arrival in the UAE they usually have no training in using irrigation equipment, identifying over- or under-irrigation and tending crops. Farm labourers typically do not know how to use or maintain drip irrigation systems, and in multiple farms visited, the drip component had been removed completely from the lines because labourers thought the crops needed more water than was provided given the hot and arid climate or because they had clogged and the labourers did not know how to repair them. On other farms, drip irrigation systems had not been installed at all and the equipment was lying in a corner of the farm (Interviews A-B, 2016).

Lack of experience in tending plants is also a major issue especially for date palm production since date palms require very specific care at certain times of the year in order to be productive and provide high-quality fruits, reduce pest infestation, reduce irrigation water needs, etc. Aside from crop management, unskilled labourers are not experienced in well usage and identification of well problems and so FSC are frequently called to investigate well problems only once they have become very bad, often with severe leakage as a result. As a result of these types of issues, crops are frequently majorly over-irrigated, not tended properly, and not harvested at the peak team (Interviews A-B; E-F, 2016).

Case study 1: One farm visited in the Saih Al-Khair area exemplifies the whole set of problems resulting from untrained farm workers. The farm was rented from the Emirati owner by an Egyptian investor who planted alfalfa on the entire 2-hectare area which was under the supervision of 5 unskilled labourers paid the minimum guaranteed wage. The drippers in the irrigation system - which usually would provide 8l/hour/dripper - were removed. Water volume supplied was therefore dependent entirely on pressure in the system which, given the visible and extensive pooling of water on the ground surface, can be surmised was quite high. The farm labourers said that they irrigated at this rate for 3 hours in the morning and 3 hours in the evening. According to the FSC staff present this is vast over-watering since even if the equipment were working properly, the alfalfa would require

30 minutes (4 litres per plant) in the morning and evening only at that time of year. Also, the plants were not being harvested on time – they had passed the ideal flowering stage and therefore would have reduced protein content (Interviews A-B, 2016).

Challenge 2 - lack of farm workers: It is common for multiple farms to be under the supervision of a single labourer, especially when the farms have only date palms. Since farms with only date palms are primarily in areas with high salinity (over 5,000TDS), poor irrigation practices have especially dire consequences in terms of soil salinization and aquifer degradation. While this problem was more common in the past than present according to interviews, it is still frequent for one labourer to be responsible for irrigation on 2 or 3 farms of 2 hectares each which is entirely inadequate (Interviews A, 2016).

Impacts - lack of farm workers: A lack of farm workers in a given area leads to under-tending plants and over-irrigation. One farm labourer cannot properly prune, cut and oversee pollination of date palms on multiple hectares which, as mentioned above, leads to sub-optimal output of crops in terms of quantity and quality, especially for date. In terms of irrigation management, lack of farm workers leads to severe over-irrigation because well pumps are left on while the labourer completes a variety of farm tasks or is unable to maintain irrigation systems in ideal working order (Interviews A-B, 2016).

Case study 2: One farm worker in the Umm Al-Hassan area reported being solely responsible for three farms. He reported that each morning he turned on the well pump and checked irrigation lines on farm one, then walked to and repeated the steps at farms two and three before returning to turn off the pump at farm one, then two and three. He said it took a few hours for him to complete his circuit, which some parts of the year he had to repeat in the evening as well. Therefore, the pumps at each farm were running for several hours while he made his rounds leading to major over-irrigation (Interviews A-B, 2016).

Challenge 3 – high turnover of farm labourers and language barriers: In addition to having inadequate hands in the field and untrained farm workers, farm owners typically only retain the same labourer(s) for a period of several years and then must bring in new staff. This is a common issue in the UAE in all sectors, but for agriculture it compounds the problems mentioned above. A connected problem is the language barrier – the vast majority of farm labourers are from South Asia and speak neither Arabic nor English on arrival in the UAE whereas the vast majority of FSC staff, farm owners, and farm-managers speak Arabic and also English (Interviews A-B, 2016).

Impacts – high turnover of farm labourers and language barriers: High turnover of farm workers means that even when training programs designed to teach unskilled labourers irrigation and crop management are successful, they must be repeated very frequently as farm workers change after a short time. In many cases the more experienced workers do not overlap for a long time period with new entrants to the UAE and therefore don’t have the chance to pass on their newly-learned skills to the next set of workers on a given farm or in a given *mahdhar* (farm area) where they work.

Communication barriers are a substantial challenge to overcome; FSC staff typically pick up basic words in Hindi, Urdu and Bengali, and labourers eventually learn basic Arabic and English terms, but the learning curve is steep and communication challenges preclude in-depth discussion on a variety of topics. The EAD and ADFCA conduct training programs and produce leaflets in all of the above-mentioned languages but the staff who have the most frequent contact with farm workers often rely on farm managers and more experienced workers to communicate complex and detailed information, and in the absence of such individuals on a farm, communication is highly limited. Interviewees reported that the language barrier was a source of significant trouble in relation to irrigation management since ongoing maintenance and oversight of irrigation systems is key to ensure their optimal functionality (Interviews A-B; D-F, 2016).

Case Study 3: One farm visited in Muzairaa was run by four labourers of whom one from Bangladesh had several years of experience. The three more recently-arrived labourers were from Pakistan and did not speak English or Arabic and so the more-experienced labourer was unable to communicate and teach the new arrivals properly and they could not understand FSC staff either. This has led to major problems in terms of farm and irrigation management and the drip systems are no longer properly maintained as a result.

5.2 Perceptual challenges

Challenge 1 – groundwater drawdown and salinity rise is inevitable: Perhaps the most pernicious challenge facing agricultural and irrigation management in Liwa is the perception that rapid groundwater drawdown and salinity rise are inevitable. It is fundamentally true that utilization of groundwater in Liwa will cause drawdown and increase salinity because there is no active recharge. However, discussions with farm owners (and farm managers' about farm owners' opinions) during the course of the survey revealed the generalizable attitude that little could be done to manage the issue effectively (Interviews B-C, 2016).

While by and large they said that awareness of the problem of groundwater drawdown and salinity rise is increasing quickly, and discussions of "sustainability" in various forms permeate the public discourse on water management, they perceive few actions which could be taken to alter the current trajectory fundamentally. They added that the resistance to well-metering and water charges, which were proffered as avenues to reduce over-irrigation, will be very difficult to overcome, and they do not believe there is adequate political will and resource availability to ensure enforcement if such measures were put in place (Interviews A-C; D-F, 2016).

One FSC officer interviewed who has worked in the Liwa area since the late 1990s provided the following general context of groundwater abstraction in the area: when he arrived and began working in Liwa, well depths were maximum of 24-37 meters. Now maximum well depths depending on area range from 61-122 meters. In general, though, few farm owners, managers or workers measure groundwater usage in Liwa or know the static water level within the wells. Farm managers tend to characterize groundwater table drops by the time between well deepening and increases in electricity consumption (Interviews A, 2016).

Challenge 2 – government has the duty to ensure irrigation water availability: This perception was held by all farm-owners and managers met with during the survey. The basis of this attitude is clear and can be summed up as one individual described it: “the government provided us farmland and so has the responsibility to ensure we can farm on it” (Interviews A-C, 2016).

In contrast, government officials’ views on this issue are mixed and dependent on the specific agency and role in which interviewees worked. Some individuals said the government had a duty to provide irrigation water in the absence of adequate groundwater reserves whereas others said the duty of the government was limited to providing the enabling environment to access groundwater when and where it was available in adequate quantities and within quality constraints. This divide indicates one of two things: either there is not a clear and well-understood government-wide mandate in relation to provision of water for irrigation, or the institutional overlaps in groundwater management and irrigation water provision provide conflicting mandates between institutions (Interviews A-C; E-F, 2016).

It is typical for farms to have multiple wells which tap very different horizons in the aquifer. Two farms visited in the Hassan area date from the 1980s and the managers at both have been present since the late 1990s. They have witnessed significant groundwater table declines and increasing salinity levels. Older wells dug in the 1990s are shallower (about 30m) and have salinity of approximately 4,500TDS which is used for vegetables that are tolerant of saline water. Newer wells located on the opposite end of the property - approximately 300m from the older wells and further from the sand dunes into the valley – are about 70m deep and have been dug since 2006. They produce water with salinity of approximately 9,000TDS and so can only be used for date palms. Likewise, a farm manager in the Muzairaa area said he had to replace two 5-year old wells in 2014 and the new wells reached almost 110 meters whereas the old wells were 80-90 meters previously (Interviews A-B, 2016).

Challenge 3 – reluctance and difficulty challenging the status quo: This issue is particularly important in terms of groundwater regulation and well monitoring. In the UAE, social stability is a paramount policy goal and while criticizing the government openly is infrequent and frowned upon, government officials are highly reluctant to take any action or pass new measures which may provoke social backlash. Such backlash and resistance to new regulatory measures frequently occurs primarily beyond the pale and reach of technical agencies such as the ADFCA and the EAD. Thus even small steps are institutionally difficult to make for fear it will lead to retrenchment (Interviews D-F, 2016).

Also, information campaigns explaining new policy directions are perceived by many government stakeholders as somewhat vague in that they do not outline clearly the ultimate objective of reforms for fear of immediate rejection. At times this leads to confusion from farm-owners and even FSC officials in Liwa who have trouble discerning clear policy directions from the regulating agencies, EAD and ADFCA (ibid.).

In practice, government officials described the conundrum in this way: increased monitoring and metering of abstraction could begin but as soon as one well-connected and powerful individual gets upset and begins airing grievances, the entire program may be in jeopardy. So explaining and exploring the issue at length publicly as well as building consensus and resolve at the highest level of government is necessary before embarking on new policy directions, but at times it can forestall meaningful action interminably (ibid.).

However, some farm managers of course do monitor groundwater usage and could provide a baseline measure of good performance in the region. One farm manager in Saih al-Khair area who manages two 2ha farms with hydroponics, greenhouses, open field cultivation and fish ponds stated that he estimates his own usage is approximately 190-300 m^3 per day depending on the specific crop rotation and season. He estimates this via the dripper specifications and timing of irrigation, which he ensures is exact, and also flow rates from the well for fish ponds. At this level of consumption, his maximum consumption per dunum approaches the average consumption per dunum of farms in Al-Ain which is especially notable given that his farm has several fish ponds as well which are especially high consumers of water in such an arid environment. At another farm in the Muzairaa area, meters had been installed on at least one of the wells and the FSC officer records readings on each visit – this is because the particular farm has had to deepen the wells several times in past years and has particularly fast groundwater table declines so FSC monitor usage and report to ADFCA because it is anomalous (Interviews B, 2016).

Challenge 4 – groundwater is considered only when it becomes a limiting factor: At present, farm-owners consider groundwater a secondary concern in terms of farm resource management. Electricity is the primary consideration since it is expensive, and groundwater enters into the equation only through the lens of electricity consumption and crop potential: when groundwater tables drop, pumping costs rise and when salinity rises either farmers must utilize small-scale RO systems (or spend more on RO operational costs) or change their cropping patterns. The main exception to this general rule is that farm owners and managers described the fact that their neighbours' abstraction impacted their own groundwater table and water quality as a reason to focus on water resources (Interviews A-C, 2016).

Almost all farm managers discussed salinity rise as occurring on farms in the past few years, although the pace varied drastically from one farm to another. One farm manager in Muzairaa said that at his farm salinity has increased from 2,500TDS to 3,000TDS in about two years although the groundwater table has not dropped whereas another farm manager also in the Muzairaa area said the salinity on his farm his increased from 2,000TDS to 7,000TDS in a five-year period. A 25-year old farm in Tharwaniya area has witnessed more than tripled in salinity; when the farm first began operations salinity was about 7,000TDS and now it is over 22,000TDS. About six years ago an RO system and greenhouse were installed so he could grow vegetables and not just date palms which he switched too after the water became to saline for fodder crops. In the Saih Al-Khair area, which has the freshest groundwater on average, salinity levels have increased as well: one farm which was established about six years ago had groundwater initially of 1,000TDS which has now increased to about 2,000TDS when it was last measured in the fall of 2015 (Interviews B, 2016). Discussions with farm managers indicate that farm-owners begin to consider changing practices or crop cultivations primarily when they are reaching the natural limit of particular crops in terms of salinity and that groundwater level is not considered at all since well deepening is always an option and is not expensive (ibid.).

5.3 Institutional challenges

Challenge 1 - lack of strong regulatory enforcement mechanisms and uneven implementation of enforcement: With the exception of substantial fines for illegal groundwater sales, which all stakeholders said have been enforced quite strongly in recent years, groundwater and agricultural regulations are difficult to enforce because of the lack of strong enforcement mechanisms as well as the lack of resources and will to enforce existing regulations (Interviews A-C; D-F, 2016).

Currently the main enforcement mechanism for agricultural practices is the removal of subsidies and for well operations it is fines. But since about 1/3 of farms do not receive the primary direct subsidies, this mechanism doesn't cover all farms. Also, the process for removal of subsidies is lengthy and unevenly enforced according to government stakeholders. In terms of well operation, government stakeholders said that even with relatively low fines, few have been handed down in actuality. In terms of regulatory enforcement, one FSC official summed up the difficulty in this way: "here there isn't such a thing as 'illegal' for a local who has good connections" (Interviews A-C; E-F, 2016).

This difficulty enforcing regulation is partially the result of divided institutional responsibilities and capacity on the ground. For example, FSC officers told me that if they notice a well pump has greater capacity than the well's license, they must inform the farm owner and also ADFCA. But no one had ever heard of fines being implemented for agricultural well misuse in this way. If an FSC officer sees a farm with all Rhodes Grass, he should report it to FSC and ADFCA and then the farm-owner will receive a letter saying he has two weeks to fix it. After that time period FSC will return and if it hasn't been cut out, the farmer will lose his subsidy and FSC will have its staff come cut the fields. But again this is rare and multiple farms were passed during the course of the survey which had only fodder crops. Likewise, while not directly regulated in enforceable terms, if drippers on an irrigation system are broken or unused, FSC staff contact the owner and then follow up. But there isn't a mechanism to ensure that they're used properly and so compliance primarily comes down to the farm labourers (Interviews A-B, 2016).

Challenge 2 – Regulatory agencies have little presence on the ground: The FSC executes policy which is set by the ADFCA and EAD and it does not enforce regulation. Rather, in terms of regulatory enforcement the role of the FSC is to report to the other agencies and at times enforce the decision they make such as cutting fodder crops on farms as noted above. But it is the agency with the greatest physical presence in Liwa and other farming areas and it has the most direct relationship with farmers.

When asked with which agencies farm managers and workers interact, they unanimously state the FSC, ADFCA and EAD in that order. Farm workers and managers who noted any interaction with EAD (a small minority) said it was solely during the process of well installation. No farm workers or managers have experienced regulatory inspections of their well utilization to their knowledge. Some farm managers indicated they have trouble contacting EAD officials and said that even for well issues which EAD is supposed to cover, they rarely get feedback and want a closer relationship with EAD (Interviews B, 2016).

ADFCA is involved in the well licensing process as well and several farm workers said they had been visited by ADFCA staff who checked their operations, especially in relation to RO systems. While to some extent farm workers and managers may not know the institutional affiliation of those who visit them since the organizations work in concert - in regards to new/replacement well licensing all are involved at separate stages - the trend is clear that regulatory enforcement officials are rarely seen at the farm level and farm managers and workers said by and large the ADFCA and EAD are far from farmers (Interviews A-B, 2016).

Challenge 3 - Illegal wells: No estimate of the number of unlicensed, illegal wells is available, nor is there an estimate of the number of wells which operate beyond their license limitations, for instance through the installation of a pump with greater capacity than the license permits. FSC said while they thought the problem of illegal wells was not particularly widespread, it was known and indeed during the survey several active wells were seen which were most likely illegal because they were located adjacent to a farm property but not within its boundaries. Also, one farm visited that was under 4 hectares had at least one unlicensed well because there were 5 operational wells on the property and by law farms are allowed one well per hectare. FSC officials said there was frequently no punishment for the digging or utilization of non-licensed wells (Interviews A-B, 2016).

Challenge 4 - Unlicensed wells: Licensing of wells only began after 2006 and so any well which predates that and has not required major fixing is not within EAD's existing database. While EAD is currently undertaking a well census to address this issue in particular and geo-tag wells, it is a major effort which will take substantial resources over a three-year period (Interviews D, 2016).

Challenge 5 - Dealing with RO discharge water: FSC officials estimate that approximately 1% of farmers in the Liwa area utilize small-scale RO systems although there are not official statistics on their utilization. During the survey every farm visited which had an RO system had either greenhouses or hydroponic cultivations and also were overseen by trained farm managers (Interviews A-B, 2016).

However, farmers currently face major challenges dealing with discharge brine water. Three of four farm managers met during this survey simply discharge the brine water onto the land some short distance away from their farm. FSC officials confirmed this is the normal practice and also said that it is not infrequent for brine to be discharged directly into unused wells. By law RO brine discharge cannot be put into sewer lines. The fourth manager, a particularly enterprising man, connected his brine discharge to aquaculture ponds mixed with well-water of 2,000TDS and will soon begin raising shrimp using the brine discharge with a smaller proportion of mixing. Productive usage of brine water is the exception and not the norm and so managing brine discharge is a current policy priority for EAD as discussed in the Abu Dhabi report (McDonnell and Fragaszy, 2016; Interviews A-C; D, 2016).

5.4 Agriculture sector structural challenges

Challenge 1 - absentee owners: Virtually all farms are owned by individuals for whom farming is a secondary source of income. The large majority of farm-owners do not live in the Liwa area and do not visit the farm on a regular basis; only one farm manager met during the survey reported speaking with the farm-owner more than once a week. Several of the farm workers and managers reported speaking to the owner more than once per month and all others less than once per month unless a major problem arose (Interviews A-C, 2016).

According to the survey and existing reports, farm operation is frequently not a major concern to the absentee owners and therefore is up to the initiative of the farm manager or workers. In the large majority of cases, especially for farms with only date palms, the only people working on the farm are labourers who, as mentioned previously, are paid just the guaranteed minimum wage of approximately 800AED/month and have few or no incentives to implement good practices if they even know them. Therefore, lack of oversight compounds the workers' lack of skills significantly (Arthur and Al-Qaydi, 2010; Interviews A-C, 2016).

Challenge 2 - small-scale farms: The majority of farms are between 2 and 4 hectares and this size range of farms constitutes the vast majority of cultivated area. Economies of scale are difficult to achieve in the region because land tenure patterns effectively preclude the agglomeration of larger holdings. At such small scales, the financial and human capital available and reasonable to expect farm-owners to utilize is limited. Coupled with absentee ownership, this means that any initiatives related to groundwater management must reach a large number of dispersed farm-owners who already have very little contact with the workers on their farms, vastly increasing the resources required for and difficulty of training and sensibilization programs (Interviews A; E, 2016).

Challenge 3 – renting farmland: While illegal and punishable by fine, renting of farmland occurs. Rent-holders do not have legal security of contracts and therefore do not incur the risk of investing in farm improvements. Also, renters have no incentives to maintain sustainable practices and farm workers on rented farms emphasized the renters' insistence on immediate returns to a greater degree than workers for the farm-owners. Because the scale of land renting is not known and no self-professed land renters were met during the course of the survey, the ultimate implications of renting practices on water management are unclear. However, the survey indicates that farmland rental in the least bad scenario incentivizes unsustainable land and water management in the search for short-term profits since security of contract is absent and renters are not assured of tenure beyond the immediate crop season (Interviews B; H, 2016).

Challenge 4 - Lack of groundwater charges and water valuation: As the points raised in Section 3.6.4 of the Abu Dhabi report (McDonnell and Fragaszy, 2016) indicate, groundwater valuation is an emergent topic of policy relevance. However, what is clear from the farm survey is that while direct market signals for water valuation are not present, there are indirect signals to which farm-owners pay attention. For example, one FSC official said that he has seen a substantial increase in the number of farm-owners building greenhouses as their well salinity increases (Interviews B; D, 2016).

Farm managers and workers said that the farm owners see greenhouses as a viable way to increase water productivity and especially importantly to slow the increase in groundwater salinity which they know to be a direct by-product of groundwater over-abstraction. So the direct use value of water is not considered in farm irrigation management, but the use value of saline versus fresh water is considered. Further research in this area is absolutely critical to understand how farm-owners do and could value water resources (ibid.).

The table below summarizes the agricultural and irrigation management challenges and impacts described in this section.

Table 4 - Summary of agricultural and water management challenges

	Challenges	Impacts
Human Resources	Unskilled labour	Poor irrigation practices; behaviour change for labourers difficult
	Lack of farm workers	Inadequate labour to manage farm activities effectively
	High turnover of farm labourers and language barriers	Labourer behaviour change and training difficult
Perceptual	Groundwater drawdown and salinity rise as inevitable	Apathy; disincentivizes and limits behaviour change for farm owners
	Government duty to ensure irrigation water availability	Confusion over agricultural water supply mandate especially where GW is low quality / low availability
	Reluctance and difficulty challenging the status quo	Disincentivizes introduction of new policy / regulatory enforcement mechanisms; makes enforcement politically difficult
	Groundwater considered only when a limiting factor	Apathy ; disincentivizes and limits behaviour change for farm owners and farm managers
Institutional	Weak regulatory mechanisms and uneven enforcement	Little incentive for farm owners to change practices
	Regulatory agencies have little presence on the ground	Difficulty enforcing existing regulations and monitoring violations
	Illegal wells	Increases difficulty of monitoring & measuring abstraction; shows lack of commitment to regulatory enforcement
	Unlicensed wells	Increases difficulty of monitoring & measuring abstraction
	Dealing with RO discharge water	Shallow groundwater and soil salinization
Structural	absentee owners	Poor farm oversight
	small-scale farms	Increases difficulty of regulatory enforcement and training and behaviour

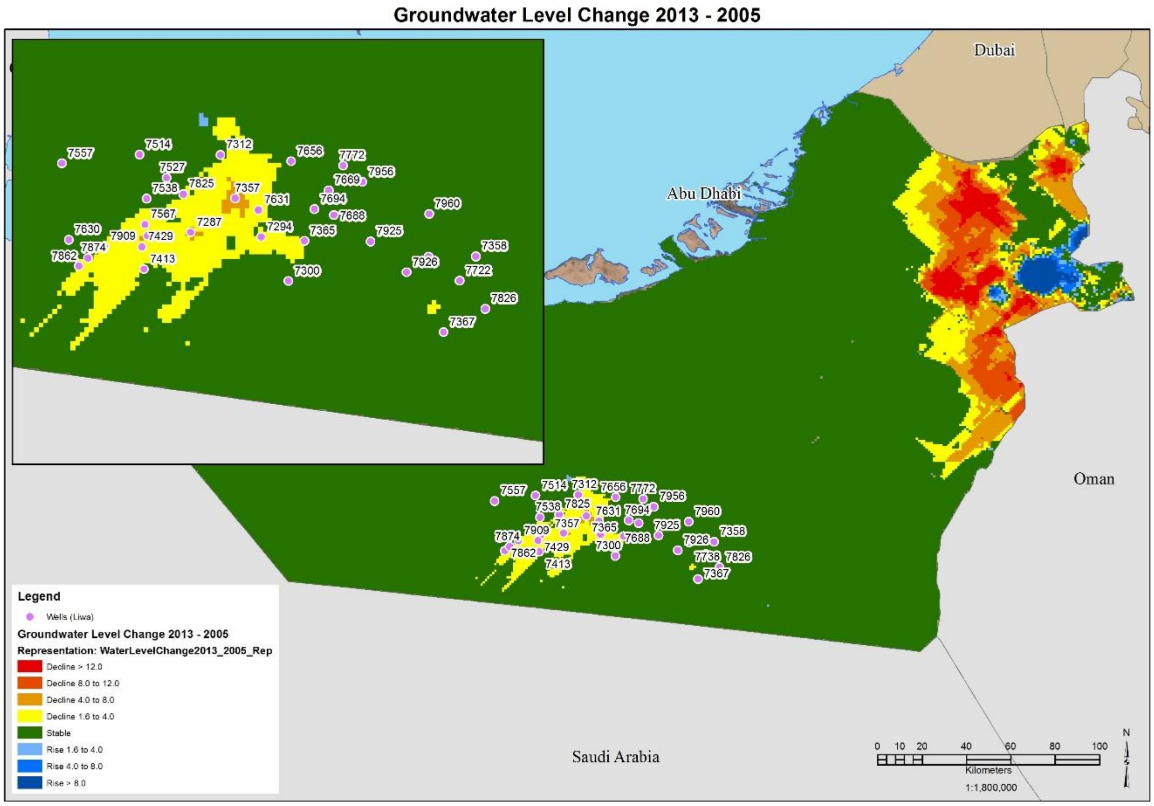
Challenges		Impacts
		change programs for farm owners and labourers; unable to achieve economies of scale
	renting farmland	Increases difficulty of regulatory enforcement ; incentivizes poor long-term farm and GW management practices
	Lack of groundwater charges and water valuation	Disincentives careful irrigation management and consideration of GW as a valued resource

5.5 Recent EAD information on groundwater in Liwa

The EAD mandate includes monitoring groundwater and licensing wells in accordance with groundwater quality and availability. In regulatory terms, these themes focus primarily on salinity, groundwater table drawdown and remaining saturated thickness of aquifer lenses. Indeed, the policies connected to well-licensing are currently linked to levels of groundwater drawdown as described further in Section 3.6.4 of the Abu Dhabi report (McDonnell and Fragaszy, 2016). The most recent available information on groundwater salinity is unfortunately over five years old and is discussed in Section II. EAD officials confirmed they are finalizing updates on groundwater salinity mapping in the near future.

In terms of groundwater table drawdown, the EAD provided data to construct the following image which shows total drawdown between 2005 and 2013 as well as the location of the monitoring well network in the Liwa area.

Figure 15. Groundwater level change 2005-2013

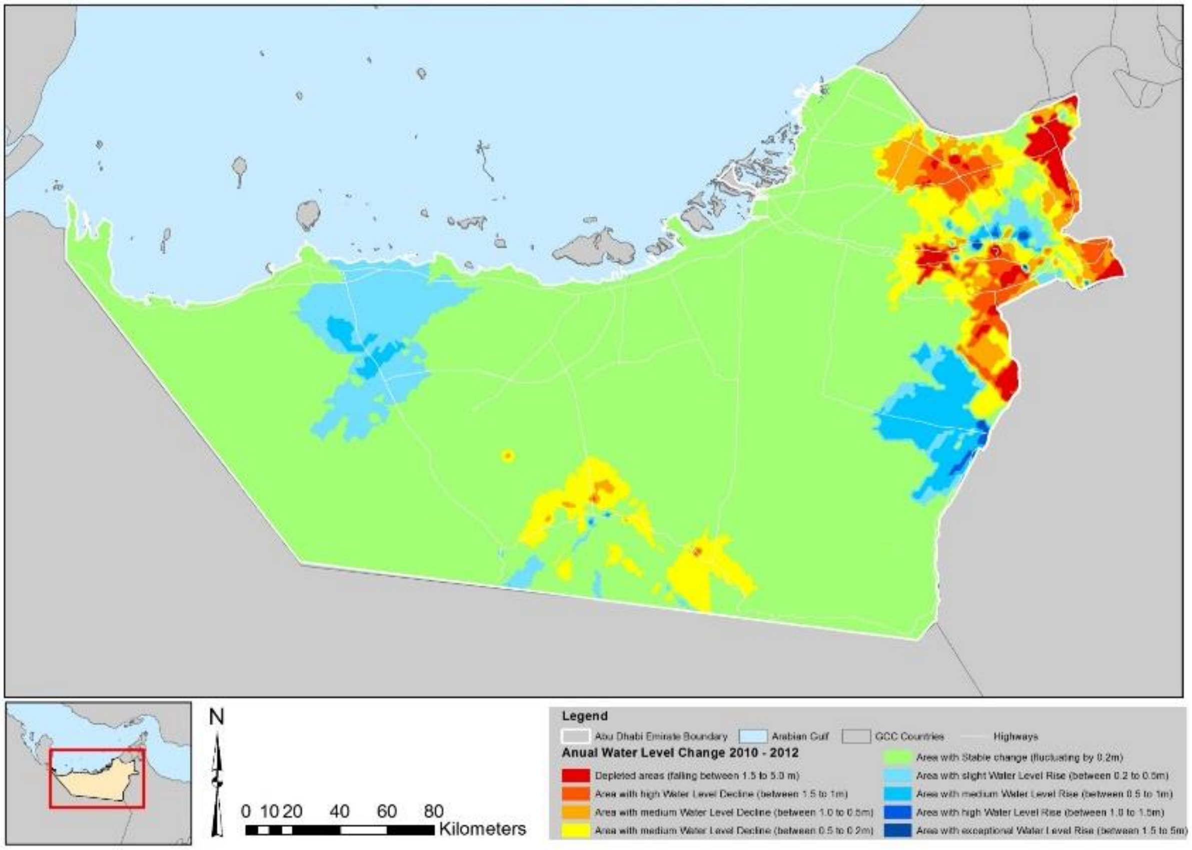


Source: EAD, 2016b, 2016c.

Focusing just on Liwa, the primary point to note is that drawdown has occurred most rapidly – between four to eight meters in the 2005 to 2013 period - in the Muzairaa area. In the northern and western areas of Liwa drawdown has reached one to four meters in the period in Saih Al-Khair, Hassan and Umm Al-Hassan. The eastern areas of the Liwa Crescent were largely stable. The small area of groundwater rise in the area of focus is a forestry section which likely draws groundwater from an adjacent area and so over-irrigation has contributed to groundwater rises, a trend which can be seen in other parts of the map such as the major rise in Al-Ain city.

Examining shorter periods of time provides additional information of relevance. Figure 12 shows drawdown between 2010 and 2012 at a finer scale than Figure x above. With less severe definitions of groundwater drawdown (with drawdown noted at 0.2m rather than 1.6), it is possible to notice pockets of severe drawdown surrounded by more gradual declines such as in the Muzairaa and Saih Al-Khair areas.

Figure 16. Groundwater level change 2010-2012



Source: EAD, 2016c.

One important point to note is that these average fields may obscure more drastic localized changes. Because farm areas are highly concentrated, as can be seen in Figure 1, and prior to 2006 well spacing did not consider potential overlapping cones of depression, well drawdown is highly uneven as suggested by farm managers' comments.

6 Towards the future

This section describes potential long-term plans to improve sustainability in the groundwater sector through both water supply- and demand-side opportunities. Additionally, there is a brief discussion of long-term frameworks of relevance for future water resource management planning in relation to agriculture.

The primary policy initiatives related to these measures are described in depth in Section 3.6.4 of the Abu Dhabi report (McDonnell and Fragaszy, 2016). Central to all of the plans described here are two main themes: improved monitoring of abstraction, especially the potential to meter abstraction, and increasing control of abstraction whether through red-zoning to eliminate abstraction completely in at-risk areas, groundwater valuation and tariffs to charge for abstraction, or abstraction limits on metered wells. However the goal is achieved, the ongoing well census and crop calculator play a vital role in linking together these various themes.

6.1 Irrigation demand management

Aside from top-down regulatory efforts to control abstraction, groundwater demand-management can take many forms in the Liwa region. The EAD, ADFCA and FSC are currently tackling the issue through several ongoing programs. First and foremost, the FSC in 2012 was granted administration of an AED100 million fund to disburse over five years with the aim of supporting the revitalization and improvement of irrigation infrastructure on existing farms. The fund has been used to provide farms with drip irrigation systems and support the expansion of greenhouse and hydroponic cultivation. While greenhouses and hydroponics are not directly subsidized, farmers are able to take soft loans to cover 50% of their installation costs. Participating farmers also receive technical training, improved seeds and other extension services (ADFCA, 2015).

6.1.1 Increasing irrigation efficiency

Utilizing drip systems and greenhouses increases irrigation efficiency by reducing evaporation and deep percolation of irrigation water. According to ADFCA statistics, highly wasteful practices such as ditch and furrow flooding irrigation have been virtually eliminated from the Liwa area where over 99% of irrigated area is served by drip systems (ADFCA, 2010). However, this survey and other field studies show that even in areas with drip systems there can be significant water wastage due to equipment deterioration and poor practices by farm-workers. (Arthur and Al-Qaydi, 2010**;** Interviews B, 2016)

Over-irrigation is problematic for three reasons: it exacerbates groundwater over-abstraction and leads to soil salinization and groundwater salinity rise. UAE soils in many areas are highly susceptible to salinization and the exceedingly high evaporation rates, approximately 2,100mm/year in the central areas of the country, exacerbates the problem (Rizk, 1999). Soil salinization has been the primary cause of agricultural land abandonment in Abu Dhabi and the big decline in agricultural area since the 1990s (ICBA, 2014). When over-irrigation occurs, return-flows to the aquifer lead to salt and nitrogen mobilization in the soil column. Due to evaporate concentration and low uptake, Liwa area soils have high natural baseline salt and nitrate levels and in some areas high boron, all of which can lead to groundwater aquifer degradation (Moreland et al., 2007).

Expanding the proportion of greenhouse cultivation is a top priority of the ADFCA because of their potential to reduce agricultural water demand and their crop output's competitive placement in the UAE market even without extensive input subsidies and purchase price guarantees (ADFCA, 2010; Arthur and Al-Qaydi, 2010). Greenhouse cultivation typically results in water savings of 50-90% when compared directly to open-field cultivation and when they utilize sub-surface or hydroponic systems the benefits can be compounded (Czyzyk, et. al., 2014). Anecdotal reports suggest that in Liwa, hydroponic systems can reduce water consumption compared to greenhouses by at least 50 percent (Interviews B, 2016)

Although the effect of irrigation efficiency gains on overall groundwater abstraction was not explored directly in the study, some general observations can be made (Interviews A-C, 2016). As farmers build greenhouse or hydroponics infrastructure, they typically hire experienced farm managers who are able to improve overall agricultural practices and intensify existing cultivation patterns. Also, newly-hired farm managers may introduce new types of cultivation, or aquaculture, which by their nature are high-consumers of water. Therefore, some of the efficiency gains may be ploughed into increasing output and value of production. However, due to the tightly controlled nature of land ownership described in Section 3.2, outright expansion of cultivated area as a result of irrigation efficiency gains is not an immediate concern. In any case, well-ownership is tied to land area and so if a farmer were able to expand into a new area, he also would be entitled to new wells. Therefore, irrigation efficiency gains may not be used to expand cultivated area but may be used to intensify cultivation or permit the cultivation of higher-value products.

The EAD and ADFCA have also begun research on the viability of sub-surface irrigation systems in Abu Dhabi although they were not encountered during the field survey. Review studies show that subsurface irrigation can have a variety of advantages over drip irrigation systems, particularly in sandy soils like those found in the UAE, including significant crop yield increases, water savings typically higher than 50% compared to drip systems, reduced risk of aquifer contamination, reduced risk of pathogenic contamination when using TWW, reduced application of fertilizers and pesticides, reduced weed growth, and reduced electricity usage since pressure requirements in subsurface systems are lower than drip system (Camp, 1998; Sinobas and Rodriguez, 2012). Of course, the major barrier to sub-surface irrigation as well as greenhouse and hydroponic cultivation is the high capital requirement and the high technical competence required to operate them effectively.

6.1.2 Hydroponics

One of the most potentially important shifts in agricultural production systems in Liwa is the recent increase in hydroponic utilization. The technology is still nascent in the area to be sure, and public statistics do not count usage yet highlighting that fact. However, the output increases and simultaneous extreme reduction in irrigation water requirements place hydroponic cultivation at the fore of ADFCA and FSC planning in terms of implementing the irrigation water demand management agenda (Interviews F-G, 2016).

In Liwa the FSC plays a close oversight and at times management role in hydroponic farming with specific staff recruited for extension to hydroponic farms (Interviews A, 2016). Farms utilizing hydroponics visited during the survey all focused on cultivation of key vegetables for which bulk markets are secured and profitable most of the year, especially cucumbers and tomatoes. Farm managers stressed that hydroponics have proven their value in terms of return on investment and whether that holds true for the funding agencies is currently under review by the Khalifa Fund (Interviews B; G, 2016).

At present hydroponic development is funded by a mix of financial support from the ADFCA for farmers who sign production agreements with the FSC – up to 50% of project financing in the form of interest-free loans which at times can be repaid in-kind - and from entities such as the Khalifa Fund as well as the Crown Prince's Court. In all such cases of public financing, farm-owners are required to put up their own capital as well, usually between 10-20% of the total cost. Frequently this comes from government-owned banks (Interviews A; G, 2016). At present there are 85 Khalifa Fund projects related to hydroponics, all of which have oversight from the FSC (Interviews E, 2016).

Hydroponic development faces a number of challenges in the area, though. Aside from the funding avenues mentioned above, which come attached with a range of incentives described in Section IV but also strings – increased oversight, fixed-term contracts and bureaucratic hurdles – access to finance is a limiting factor (Interviews B; C, 2016). Also, there are currently only a small number of firms which supply the needed materials. Human resource constraints are critical with farm-owners describing difficulties identifying and hiring trained managers and organizing training for other staff (Interviews C, 2016). Lastly, irrigation or plant-medium water for use in hydroponics must be very low-salinity. For Liwa groundwater to be used in hydroponic cultivation, desalination is required even in areas atop the freshwater lens leading to greatly increased chances of groundwater contamination from brine discharge and otherwise generally increased management difficulties.

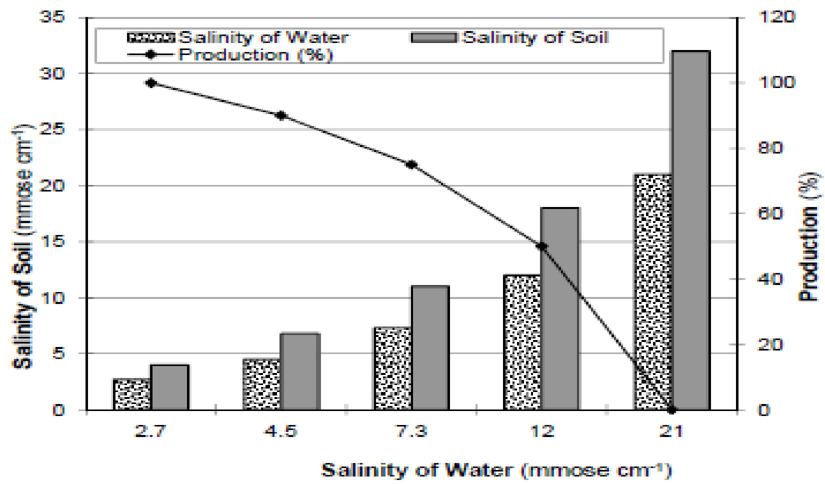
6.1.3 Arid-land and saline-tolerant plants

Aside from improving irrigation efficiency for currently-grown crops, The EAD and ADFCA have also partnered with research universities and institutes such as ICBA to spearhead research on the best-adapted varieties and salinity limits for crops grown in the UAE. Many of these projects are conducted on active commercial farms in Abu Dhabi. Given that date palms account for approximately 1/3 of irrigation water and fodder crops, at least prior to the reduction of Rhodes Grass cultivation, utilized about 60% of irrigation water, much of this research focus has focused on date palm and fodder crops, though efforts are being undertaken on a wide range of crops overall (Green et al., 2014; ICBA, 2014).

A final component of the EAD and ADFCA's irrigation demand-management agenda is to expand the utilization of highly brackish and saline groundwater for the cultivation of economically viable salt-tolerant crops and halophytes. Utilizing significant quantities of this poor-quality water in the Liwa area could be viable in the long-term as long as potential soil salinization and shallow aquifer impacts could be managed effectively. As shown in Section II, groundwater from deeper zones of the Liwa aquifer is often highly saline with TDS well over 15,000mg/l. Research has shown the feasibility of irrigating salt-tolerant and halophyte crops in the region, with salt-tolerant fodder and field crops showing the greatest promise for the Liwa area (ICBA, 2014).

However, irrigating to attain crop yield maximums without over-irrigating is exacting because crop production declines significantly with relatively little under-watering while the impact of over-watering has a much less steep impact curve. Also, some crops take relatively long periods to recover from even short episodes of under-irrigation (Green et al., 2014; Ismail et. al, 2014). A similar relationship for salinity - that of slightly decreasing yields due to increasing soil and irrigation water salinity until an inflection point is reached – are illustrated in Figure 14 below from a review study on date palm cultivation.

Figure 17. Date palm production under various irrigation water salinity scenarios



Source: Ismail et al., 2014.

Therefore, for all of these potential measures and most importantly implementation of the crop calculator-determined abstraction limitations, human resource capacity is a critical limitation to overcome. Without far greater oversight of farm management than presently occurs, especially on the majority of farms which have only date palm cultivations and/or solely employ untrained labourers, it is difficult to envision efficient irrigation practices being implemented on a consistent basis.

6.2 Irrigation supply augmentation

6.2.1 Treated wastewater

A promising supply-side avenue to mitigate groundwater over-abstraction is the utilization of TWW for irrigation. TWW currently makes up about 10% of the total water supply in the UAE and is used primarily for amenity plantings and green spaces in cities and to a lesser extent in forestry (Mulla, 2011). TWW is an excellent candidate for blending or replacing groundwater in agriculture, though, particularly because of its extremely low salinity due to its origin as desalinated water. But TWW currently falls under a restricted use classification and so its use is currently highly limited in agriculture (Akhand, 2014). Also, farm-owners, even those who work within the ADFCA and EAD, are highly reticent to use TWW on their farms and so long-term informational campaigns would be necessary to ensure the utilization of TWW even if it were available on a large scale (Interviews D-E, 2016).

The short-term viability of using TWW to reduce pressure on groundwater resources in Liwa faces several key challenges. First of all, demand for TWW already exceeds supply. Total water consumption for amenity plantings is approximately double the volume of available TWW at the moment (Mulla, 2011). While initiatives are being implemented to increase the proportion of native species in amenity plantings and thus reduce water consumption, current estimates show amenity water usage will increase greatly in the next decade (Government of Abu Dhabi, 2013). Whether willingness to pay for water-hungry amenity plantings will change with the new tariff structure that requires municipalities to pay a cost-reflective tariff for all water used remains to be seen (RSB, 2015).

Another challenge is that existing distribution networks are inadequate to utilize all the treated effluent that is currently produced (Akhand, 2014). This problem is being addressed through such investments as the STEP project outlined in the Abu Dhabi report (McDonnell and Fragaszy, 2016) and also the construction of several wastewater treatment plants in the city of Abu Dhabi (Dawoud, 2012). Still, TRANSCO currently has no plan to build new distribution pipelines to Liwa which would be needed were large-scale utilization of TWW for agriculture to be implemented in Liwa (TRANSCO, 2014). However, plans do exist to bring TWW to the expansive Nahda farms area outside the city of Abu Dhabi. Given that the Nahda farms are currently supplied with groundwater pumped from the Liwa area, eliminating that need will reduce pressure on Liwa groundwater resources (Dawoud, 2012). Also, the EAD has planned to connect the Wathba treatment plant which discharges about 300,000 m^3/day to irrigated areas between Abu Dhabi and Dubai as well as Al-Ain.

Therefore, the main role of TWW in alleviating pressure on Liwa's groundwater resources in the near future will most likely be via the reduction of abstraction for amenity and forestry plantings. Presently about 5% of groundwater abstraction is used for amenities and a further 15% is for forestry plantings, and replacing groundwater with TWW for those uses in the Western Region of Abu Dhabi would contribute significantly to improving groundwater sustainability overall, though perhaps with less of a direct impact in Liwa than the Western Region and Abu Dhabi more generally.

Likewise, if realized, production water utilization would initially be for forest plantations in the early stages. As such, it too would alleviate pressure on groundwater supplies by reducing abstraction for forestry plantings.

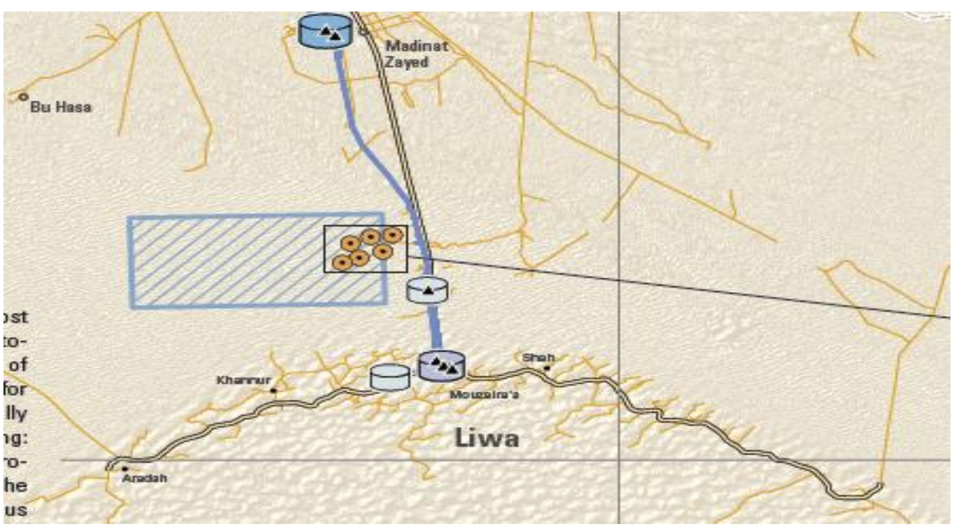
6.2.2 Aquifer storage and recovery

Finally, TWW, treated production water and also desalinated seawater could contribute to groundwater resources management in the Liwa area through their use in aquifer storage and recovery (ASR) programs. ADWEA is currently completing work on the largest ASR program in the Middle East. The project is designed to expand Abu Dhabi's emergency municipal water storage capacity to 90 days (assuming a greatly-reduced per capita consumption ration) from the current reserve of about 3 days by inducing recharge into the shallow Liwa aquifer using desalinated water and later abstracting the groundwater should the need arise (Koffler, 2012).

Understanding the logic of the ASR program's potential uses beyond a simple emergency reserve requires a brief comment on desalination in Abu Dhabi, a topic beyond the scope of this report but which has been written about extensively elsewhere (e.g., ADWEC, 2008; Fath et al., 2013). All potable water consumed in Abu Dhabi comes from desalinated seawater which is produced almost entirely using multi-stage flash distillation processes in electricity and water co-generation plants. Seasonal water and electricity demand fluctuations can be met through gas-fired plants adjusting their outputs of each, though there are limitations to plant flexibility which lead to significant inefficiencies. During the winter, electricity needs require running desalination units in excess of water needs, and during the summer both electricity and water demands peak simultaneously leading to efficiency losses in electric generation capacity of gas-fired plants (Dawoud, 2009).

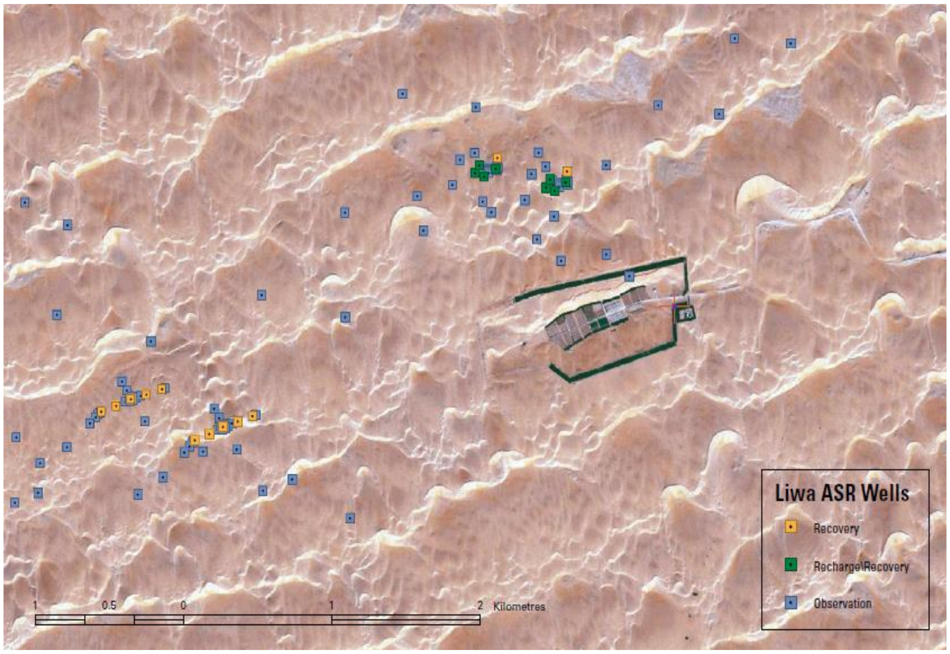
The Liwa ASR project has strategic water security components but in the future could also be used to help rationalize water production output in Abu Dhabi or as a model for similar programs from different water sources. Its limited storage capacity of approximately 25 Mm^3 of abstractable water indicates that this type of project has limited scope to address agricultural demand, but it is seen throughout the Middle East and indeed arid regions globally as a test case for the method of storing potable water (Koffler, 2012). The project site was chosen partially based on the absence of agricultural impacts on the shallow aquifer (Menche, 2010). Figures 14 and 15 below show the injection, recovery and observation wells in addition to the infiltration basins that make up the ASR project.

Figure 18. Liwa ASR location



Source: Environmental Atlas of Abu Dhabi Emirate, 2015.

Figure 19. Liwa ASR wells



Source: Environmental Atlas of Abu Dhabi Emirate, 2015.

Therefore, the Liwa ASR project itself, an AED2.2 billion program, will not directly reduce pressure on groundwater resources for agriculture as per design specifications, but long term could potentially be utilized to balance seasonal municipal supply and demand (Koffler, 2012; Cariou, 2014). That method of utilization could have implications for groundwater abstraction indirectly by reducing demand for groundwater irrigation of amenity and forestry plantings. Also, in the long-term, this type of injection or infiltration and recovery method could be replicated to utilize treated municipal, industrial or even oil-associated process water and natural bio- and geo-remediation processes to induce recharge that meets irrigation water standards. This is currently not planned, but the Liwa ASR project brings these ideas into the realm of possibility.

6.3 Going forward

Government officials by and large presented two possible frameworks for long-term management of groundwater abstraction in order to improve sustainability: government command and control well-fields with clear abstraction limits and quantified allocation to individual farms or the enforcement of private well abstraction limits and the enactment of water charges. Nearly all officials indicated the importance of subsidy rationalization in both cases in order to incentivize efficient groundwater consumption on the farm. These frameworks must be described within the context of two major non-technical and non-political factors to sustainable groundwater management: financial and human resource constraints.

6.3.1 Beyond technical and policy constraints

It is clear that major financial and human resource constraints must be overcome in order for any new infrastructure, regulatory and subsidy framework to succeed in the implementation of a groundwater sustainability agenda.

In the absence of strong private-sector involvement in agricultural financing and in the absence of a dedicated agricultural bank or other centralized funding vehicle, farm-owners rely on a mix of government agencies as well as pseudo-public institutions and patronage networks for access to capital and land. While substantial financial resources are available for farm-owners, they are scattered and not always linked directly to water sustainability objectives. The lack of available information and statistics on agricultural investment in Abu Dhabi overall is indicative of the immaturity and fragmented nature of the agricultural finance sector in the Emirate.

In order to meet stated food security objectives in terms of vegetable production, major increases in agricultural productivity and efficiency are needed. The success and spread of greenhouse and hydroponic cultivation thus far offer the best route to meet that goal. However, hydroponic farms are incredibly capital-intensive with units costing about 250,000 AED to set up - as compared to 30,000-50,000 AED for greenhouses (Interviews E, 2016). In addition to set-up costs, hydroponic farms in the UAE typically require RO units as well which increase expenses and management difficulties since brine discharge is a critical problem at present. Meeting the capital requirements of a major leap forward in agricultural production will require much more concerted coordination between the funding entities involved, much of which would be facilitated by the establishment of an agricultural bank or dedicated funding vehicle to oversee and consolidate such efforts.

Whether or not capital-intensive production methods constitute a major component of future agricultural production, human capital constraints will continue to plague groundwater sustainability agendas if not addressed in a comprehensive manner. The challenges at the base of the agricultural production pyramid – on-farm labour and its oversight – are among the most entrenched in the sector and will likely prove by far the most difficult to overcome on a wide scale. While individuals interviewed during the course of the research described changing attitudes, mentalities and perceptions of sustainability in relation to groundwater, farm owners' lack of direct involvement with farm activities currently precludes such changes having impacts on the ground. Likewise, in the absence of incentives for farm workers to implement best practices themselves, it is unrealistic to expect vastly improved outcomes. New policy and regulatory frameworks connected with irrigation therefore must connect directly with farm-owner outreach, communication and participation efforts on an unprecedented scale.

6.3.2 Subsidy rationalization

Agriculture subsidies have changed substantially in the last decade – from elimination of guaranteed purchase of vegetable produce in the 2000s to a complete reversal of substantial subsidies related to fodder crop cultivation and introduction of subsidized, imported fodder. These changes have altered crop patterns drastically: in areas with marginal water quality that was adequate for Rhodes Grass, date palm cultivations were incentivized and became the main replacement. This primary avenue of water demand management - reducing area of water-intensive crops in favour of low-irrigation and saline-tolerant crops – was realized almost entirely utilizing blanket subsidy structures.

Eligibility for significant agricultural subsidies currently hinges only on avoiding the most water-intensive crops and now the majority of palm plantations started as a result of this subsidy have reached maturity. As clearly shown by the levels of over-irrigation in date palms as well as other crops, irrigation efficiency in Liwa could be the next target of subsidies to improve water management in agriculture. New legislation permitting the regulation of abstraction volumes could be tied to alterations in the subsidy structure to permit flexible regulatory action via the reduction of subsidies rather than the implementation of fines. This shift from reliance on punitive action to tiered elimination of benefits may be useful in behaviour-change campaigns.

Whatever new direction water management legislation takes, rationalization of subsidy structures is likely to be a key component. Realizing the shift from agricultural subsidies forming part of a social policy of wealth distribution to the tune of over $100 million per year in Liwa alone rather than a concerted program to maximize the productivity, profitability and efficiency of farming is key to advance the long-term sustainability of agriculture in Liwa.

6.3.3 Metered, costed, enforced

One of the two frequently-mentioned avenues to reduce water consumption long-term is the realization of well-metering and abstraction limits on the farm level. To facilitate abstraction limits, officials suggested that tiered pricing could be employed (Interviews D-F, 2016).

The positive feature of this framework, fully metered and costed groundwater abstraction, is that existing infrastructure can be utilized to maximum effect with metering as the primary new infrastructure requirement. While new regulatory and water pricing mechanisms would be needed to ensure cooperation with abstraction limits, the baseline information exists to begin exploring this possibility via the groundwater valuation study and also the crop calculator project described in more depth in the Abu Dhabi report (McDonnell and Fragaszy, 2016) in Section 3.6.4.

As discussed in the Abu Dhabi report (McDonnell and Fragaszy, 2016), water markets and pricing have an exceedingly long history in the Arab world and have until the recent past been used effectively to allocate common-pool groundwater resources effectively in the *aflaj* systems of Al-Ain among other areas. However, privately accessible groundwater resources are not easily accommodated within such market structures. Modern groundwater rights as practiced in the UAE – as opposed to in law whereby in theory all underground resources are property of the state – currently incentivize rapid abstraction and preclude active pricing. However, one can imagine a situation in which subsidy structures geared to decline over time help farmers transition to the type of efficient irrigation necessary to stay within regulated limits as determined by well meters and the crop water calculator tools being finalized now.

The negative feature of this option is the very high regulatory enforcement burden. Enforcement of existing legislation is weak and as discussed above, the regulatory agencies have little presence on the ground in farm areas. Beginning active monitoring and oversight of well activities necessary to ensure wide-spread compliance to such major new initiatives would be difficult with present human capacity in the agencies.

6.3.4 Supply command and control

The second option mentioned to realize long-term sustainability in the agriculture sector is the wholesale revision of farming irrigation supply along the lines of the ADFCA-controlled irrigation networks that currently serve over 7,000 farms in the Emirate. In the Liwa area these would most likely take the form of well-fields with distribution networks to farm areas as shown in Figure 19 of the Abu Dhabi report (McDonnell and Fragaszy, 2016).

The positive feature of this is that government-controlled well-fields could be developed to consider hydrological characteristics of the region rather than focusing abstraction in narrow areas within farms. Well-fields could be created within each *mahdhar*, or between a collection of several of them, and be spaced appropriately in contrast to the current system in which wells are frequently adjacent to one another and exacerbate local drawdown and cones of depression. Abstraction volumes would be under the control of government agencies and therefore be a direct tool of sustainability policy. In this system, water markets would be far more feasible than if private wells were retained. Indeed, the fixed volumetric supply would in many ways be analogous to *aflaj* systems and therefore have a strong historical precedent with allocation of fixed rights which could be traded within a market structure.

The negatives of this option are twofold: first, it entails a complete upending of existing groundwater governance practice in the region and secondly it would require the creation of a vast amount of irrigation infrastructure in an area where much already exists. The political dimension of shifting from individual control to government-controlled well-fields would be a significant barrier just as the cost of constructing the needed wells and pipelines may be prohibitive.

7 Conclusion

The Liwa freshwater aquifer is a critical resource in the context of the UAE, one of the most water-scarce nations on earth. It holds over 80% of Abu Dhabi's remaining fresh groundwater and is the focal point of the Emirate's second-largest cultivated region. In the near future with the completion of the ASR project the aquifer will also be the Emirate's strategic freshwater reserve should desalination plants along the Gulf coast be disrupted. If current groundwater abstraction rates are projected into the future, the fresh and slightly brackish zones of the Emirate's aquifers will be exhausted in less than 55 years, and the major driver of abstraction is agricultural irrigation. As such, devising sustainable groundwater management strategies for the agricultural sector is a pressing priority for the government which must be balanced with food security, social and economic agendas.

Major institutional reforms in the structure of groundwater and agricultural governance since the mid-2000s have provided the institutional framework necessary to drive the groundwater sustainability agenda within government. Also, the basic research on groundwater resources in Liwa conducted over the last twenty years has provided a solid foundation on which to base future groundwater sustainability strategies although actual monitoring of current abstraction is a major weakness in such endeavours. In a break from past practices, demand-management is at the front and centre of initiatives to improve groundwater sustainability, though a variety of supply-side options do exist and should be explored based on their potential to reuse water resources that are currently under- or un-utilized for irrigation purposes.

However, reform in agricultural water management faces major obstacles identified in this report; human resource, perceptual, institutional and structural challenges in the agriculture sector must be addressed for on-farm groundwater management to align with sustainability priorities. Also, monitoring of groundwater abstraction for irrigation is currently highly limited because of the lack of meters. Current programs and policy initiatives launched by the EAD, ADFCA and FSC described in the report and the Abu Dhabi Report (McDonnell and Fragaszy, 2016) show the range of current and future planned interventions taken to address these challenges and limitations. The recently-implemented subsidy changes related to field and fodder crops also represents a significant step towards rationalizing water consumption.

Indeed, the removal of subsidies that incentivized wasteful irrigation practices coupled with extensive support to farmers to implement novel technologies and methods that improve irrigation efficiency have already begun reducing groundwater abstraction within the agricultural sector overall. Prior to the oil era, development of water resources for irrigation was technologically constrained, and in the modern era new technological and management innovations will be required to ensure agricultural production can be accomplished in a sustainable manner. The efficiency improvements will be costly, and an immense array of novel tactics will be necessary to meet sustainability objectives, but the ultimate objective of preserving the integrity of the UAE's largest freshwater resources is an invaluable end.

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Appendix 1: Data tables

Table 5 Farm number and area in Liwa

Region	<20 Number	<20 Area	20-29 Number	20-29 Area	30-39 Number	30-39 Area	40-49 Number	40-49 Area	50-59 Number	50-59 Area	>60 Number	>60] area	Total Number	Total Area
Tharwaniya	830	7223	450	10254	127	4247	499	20440	13	710	12	1096	1,931	43,970
Hamim	260	2293	392	8040	45	1640	169	6782	3	166	1	69	870	18,990
Hassan	136	1303	152	3470	824	18532	148	4974	3	155	6	438	1,269	28,872
Muzairaa	619	5119	426	9522	164	5201	396	15840	7	371	12	843	1,624	36,896
Seih Al Khair	8	68	8	160	9	284	486	19093	0	0	13	1401	524	21,006
Um Al Hassan	29	352	779	17307	11	411	64	2565	2	164	0	0	885	20,799
liwa total	1882	16358	2207	48753		30315	1762	69694	28	1566	44	3847	7,103	170,533
Total W region	2,479	24,346	2,342	51,278	1,199	30,966	2,471	97,890	30	1,676	51	4,302	8,572	210,45

Source: National Bureau of Statistics, 2011

Table 6 Farm and cultivated area breakdown

Area	Number of farms	fruit area (primarily date palm)	Field crop area	vegetables area	fallow area	forest area	greenhouse number	building number	Unused area	total area
Al Tharwaniya	1,931	20,227	5,802	0	3,992	3,501	181	925	9,825	44,453
Hamim	870	8,068	600	260	7,275	984	58	565	1,974	19,784
Hassan	1,269	8,087	6,106	152	6,738	695	80	865	1,755	24,477
Muzairaa	1,624	16,049	542	362	11,995	1,230	323	807	4,956	36,265
Seih Al Khair	524	9,138	3,800	2,222	1,216	1,152	441	275	2,799	21,044
Um Al Hassan	885	6,140	525	436	11,537	720	10	285	771	20,425
Liwa total	7,103	67,709	17,375	3432	42,753	8,282	1093	3722	22,080	166,446
Western Region total	8,572	78,282	29,072	3,482	55,902	10,860	1,096	4,370	27,395	210,458

Source: National Bureau of Statistics, 2013

Table 7 Livestock holdings

Livestock	Holdings	total	goats & sheep	cattle	camels
Muzairaa	541	92,520	88,293	198	4,029
Al Tharwanea	290	39,938	33,048	20	6,870
Hussan	220	28,606	25,047	56	3,503
Western Region Total	3,678	461,159	391,766	1,104	68,289
Liwa total	1,051	161,064	146,388		14,402

Source: National Bureau of Statistics, 2013

Table 8 Date palm cultivations

Area	Productive Number	Productive Area	Unproductive number	Unproductive area	Total number	Total area
Al Tharwaniya	276,000	17,100	50,020	2,910	326,000	20,010
Hamim	145,991	4,672	120,950	3,337	266,941	8,008
Hassan	241,992	7,985	1,054	31,690	241,992	7,985
Muzairaa	308,102	11,075	132,840	4,821	440,942	15,896
Seih Al Khair	170,100	6,804	45,125	1,805	215,225	8,609
Um Al Hassan	104,503	3,870	56,270	2,085	160,773	5,955
Liwa Total	1,246,688	51,506	406,259	46,648	1,651,873	66,463
Western Region Total	1,238,346	58,877	508,681	17,611	1,747,027	76,480

Source: National Bureau of Statistics, 2013

Table 9 Well number and depth

Area	total wells	working wells	avg well depth (feet)
Al Tharwaniya	3,897	3,297	280
Hamim	2,041	1,608	280
Hassan	3,076	2,494	240
Muzairaa	4,228	2,919	280
Seih Al Khair	1,407	1,303	250
Um Al Hassan	2,151	1,774	245
Liwa region total	16,800	13,395	
Western Region Total	20,223	15,954	

Source: National Bureau of Statistics, 2011a

Table 10 Farm area by salinity class

Area	Salinity A (number of farms)	Salinity A area	Salinity B (number of farms)	salinity B area	Total number	Total area
Al Tharwaniya	55	2,088	781	22,821	836	24,909
Hamim	26	923	481	11,239	507	12,162
Hassan	223	5,311	293	6,924	516	12,235
Muzairaa	222	8,241	344	8,392	566	16,633
Seih Al Khair	307	11,907	0	0	307	11,907
Um Al Hassan	132	3,612	563	13,368	695	16,980
Liwa region total	965	32,082	2462	62,744	3427	94,826
Wester Region Total	1,104	35,190	3,228	83,732	4,332	118,923

Source: National Bureau of Statistics, 2011a.

Appendix 2: Farm survey and interview characteristics

Farm characteristics:

- 20 farms visited, all between 2 – 4 hectares
- 11 farms had some vegetable cultivation
- 12 farms had fodder crops, of which 3 grew solely fodder crops, and of which 2 had over 10% of cultivated area devoted to fodder crops as determined by visual assessment
- 6 farms were predominantly devoted to date palms (all farms had some number of date palms)
- 4 farms had fish ponds
- 5 farms had livestock, of which 3 had almost exclusively livestock (sheep, goats, camels)
- 8 farms had trained farm managers (all farms with RO units, all farms with hydroponics and all farms with fish ponds as well as several farms with greenhouses)

- 4 farms had RO units
- 4 farms had hydroponic houses
- 6 farms had greenhouses

Interview characteristics – Liwa:

- 1 group meeting with FSC officials
- 2 group meetings with FSC officials and farm-owners
- 9 individual interviews with Liwa area FSC staff (4 extension officers, 3 heads of technical services, 1 center director, 1 commercial manager)
- 1 individual interview with ADFCA staff (well management and hydrology)
- Total of 10 farm-owners
- Total of 8 farm managers
- Total of 13 farm workers

Interview characteristics – Abu Dhabi:

- 6 interviews with EAD officials (1 policy advisor, 1 technical advisor, 1 groundwater monitoring officer, 1 forestry manager, 2 communications and public relations officers)
- 4 interviews with FSC officials (1 director, 1 senior consultant, 1 commercial manager, 1 irrigation specialist)
- 2 interviews with ADFCA officials (1 director, 1 program manager)
- 1 interview with Khalifa Fund loan officer

Appendix 3: Farm survey questionnaire

Farm characteristics:

What are you growing/what livestock do you raise?

How many hectares is the farm?

Is there any rotation of crops?

Water use:

What water do you use for irrigation?

For how long do you irrigate per day?

Has the water become saltier over time? Has it changed in any other way?

Has the groundwater level dropped?

Do you count how much water you use? If so, how?

Institutional support and control:

What support do you have from the government? (subsidies)

What agencies do you interact with and in what way?

Is your water use overseen by government agencies?

Are your agricultural practices overseen by government agencies?

How does the farm-owner oversee operations?

Other:

What are your biggest water-related challenges?

What are your biggest other challenges?

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