AGEDI
مبادرة أبوظبي العالمية للبيانات البيئية
Abu Dhabi Global Environmental Data Initiative

an initiative of UNEP

هيئة البيئة - أبوظبي
Environment Agency - ABU DHABI

AGEDI | THE ABU DHABI GLOBAL ENVIRONMENTAL DATA INITIATIVE
CLIMATE CHANGE PROGRAMME

WATER RESOURCES: AL AIN WATER RESOURCES

- Atmospheric Modelling
- Arabian Gulf Modelling
- Terrestrial Ecosystems
- Marine Ecosystems
- Transboundary Groundwater
- Water Resource Management
- Al Ain Water Resources
- Coastal Vulnerability Index
- Desalinated Water Supply
- Food Security
- Public Health Benefits of GHG Mitigation
- Sea Level Rise

Full Technical Report

AGEDI.org

The authors of this report are Francisco Flores (co-Principal Investigator) and Stephanie Galaitsi from the Stockholm Environment Institute – US Center and David Yates (co-Principal Investigator) from the National Center for Atmospheric Research.

Suggested Citation:

AGEDI. 2015. Technical Report: Al Ain Water Resource Management & Climate Change. LNRCCP. CCRG/NCAR/SEI

Acknowledgments

Many individuals provided invaluable support, guidance, and input to the Al Ain Water Resources & Climate Change project.

The authors would like to express their sincere and heartfelt gratitude to them for taking time to review our reports, provide comments, feedback, data as well as for the opportunity to present multiple deliverables within the course of the project. These individuals include but are not limited to the below list:

Anil Kumar, Environment Agency – Abu Dhabi (EAD)
Anuja Vijayan, Environment Agency – Abu Dhabi (EAD)
Dr. Fred Launay, Environment Agency - Abu Dhabi (EAD)
Kamal Alhashmi, Environment Agency – Abu Dhabi (EAD)
Majdy Al Alawneh, Environment Agency - Abu Dhabi (EAD)
Dr. Mohamed Dawoud, Environment Agency – Abu Dhabi (EAD)
Eng. Moustafa Lofty, Environment Agency – Abu Dhabi (EAD)
Dr. Richard Perry, Environment Agency – Abu Dhabi (EAD)
Sai Ravi Krishna, Environment Agency – Abu Dhabi (EAD)
Dr. Simon Pearson, Environment Agency – Abu Dhabi (EAD)
Dr. Khalil Ammar, International Center for Biosaline Agriculture (ICBA)

We are additionally thankful the participation, time and effort that multiple stakeholders across the region who participated in the multitude of meetings and dialogue. The authors would like to especially thank the following stakeholders for their particularly involved participation: the Al Ain Municipality team, the EAD experts team, Naoko Kubo and Tomoo Machiba – Ministry of Climate Change and Environment (MOCCAE) and Carl Nettleton – Open Oceans Global, and the United States Geological Services (USGS) team.

About this Final Technical Report

In October 2013, the Environment Agency of Abu Dhabi launched the "Local, National, and Regional Climate Change (LNRCC) Programme to build upon, expand, and deepen understanding of vulnerability to the impacts of climate change as well as to identify practical adaptive responses at local (Abu Dhabi), national (UAE), and regional (Arabian Peninsula) levels. The design of the Programme was stakeholder-driven, incorporating the perspectives of over 100 local, national, and regional stakeholders in shaping 12 research sub-projects across 5 strategic themes. The “Al Ain water resources” sub-project within this Programme focuses on analyzing vulnerability and building resilience for coping with climate change impacts on its water resources in the Al Ain region of Abu Dhabi.

The purpose of this "Final Technical Report" is to offer a comprehensive discussion of what has been learned in carrying out the research activities involved in the study. In short, this report seeks to provide the reader with a comprehensive overview of the results of the assessment, supported by a discussion of the input data, methodology, modelling tools and other issues that can support future research and policymaking regarding managing water resources in the Al Ain region under climate change.

Table of Contents

List of Figures

List of Tables

List of Acronyms

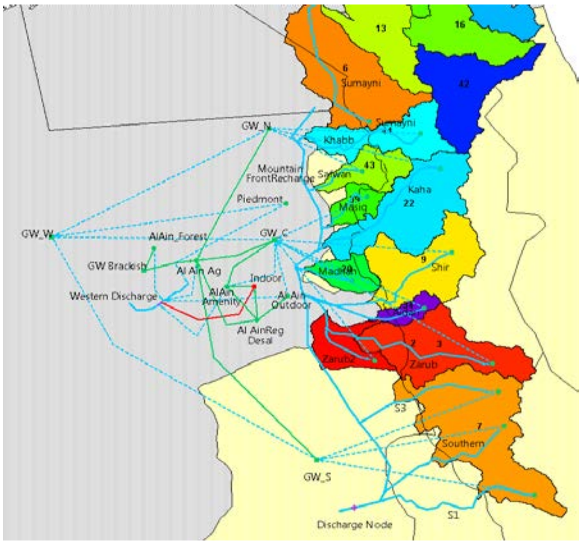
AGEDI	Abu Dhabi Global Environmental Data Initiative
BAU	Business-as-usual
BCM	billion cubic meters
CCRG	Climate Change Research Group
CO2	Carbon dioxide
DSS	Decision Support System
EAD	Environment Agency of Abu Dhabi
FAO	Food and Agricultural Organization of the United Nations
GCC	Gulf Cooperation Council
GCM	Global Climate Model
GW	Groundwater
GWh	Gigawatt-hour (billion watt-hours)
HU	Heat Units
IPCC	Intergovernmental Panel on Climate Change
LNRCCP	Local, National, and Regional Climate Change Programme
lpcpd	liters per capita per day
M^3	cubic meters
MAF	Ministry of Agriculture and Fisheries
MED	Multi effect distillation
MGD	million gallons per day
MCM	million cubic meters
MMT	millions of metric tonnes
MODFLOW	MODular Three-Dimensional Finite-Difference Groundwater FLOW model
MSF	Multi-stage flash
MWh	Megawatt-hour (million watt-hours)
NCAR	National Center for Atmospheric Research
PGM	Plant Growth Model
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RO	Reverse osmosis
SEI-US	Stockholm Environment Institute – US Center
UAE	United Arab Emirates
UN-ESCWA	United National Economic and Social Commission for Western Asia
US	United States
WEAP	Water Evaluation and Planning model
WWTP	Wastewater Treatment Plant
Yr	year

Executive summary

The Al Ain region has become the agricultural center of the United Arab Emirates. Using a water and agricultural systems modeling approach, this study captures the interactions between water supply and demand and agricultural production to explore how future climate and other changes might impact this historically important region. The region relies on brackish and fresh groundwater, desalinated water, and reuse to supply an array of growing water uses. Despite being inland and far from the coast, Al Ain receives imported desalinated water to support a growing population. The energy inputs for desalination are one order of magnitude greater than the energy required for either groundwater pumping or transmitting water from surface rivers or reservoirs. Hence, water and energy are linked to a much greater degree in the UAE than in other countries where the climatic context reflects more precipitation and more abundant water resources. In the future, individual municipalities are expected to increase their desalination capacity to meet the demands of a growing population and economic development, suggesting that reliance on desalination is as much of an energy challenge as it is a water challenge.

The overall goal of the sub-project was to better understand the water resources of the Al Ain region in the face of climate change and other drives such agricultural water development strategies, and socioeconomic development. The major research questions underlying the methodological approach were twofold. First, how will climate change affect the water resources of the Al Ain Region that support direct human use and uses for a forestry sector and an agriculture sector that have grown considerably over the past few decades supported primarily with fossil groundwater? Second, what water management strategies could be explored - as measured in water savings associated with various scenarios - that aim to promote efficiency and conserve natural resources under climate change?

Figure ES-1. Schematic representation of the Al Ain region showing Wadis, groundwater systems and demand elements



To conduct an analysis of the Al Ain water resource situation an analytical framework capable of accounting for the water and agriculture systems of the region in an integrated manner was developed. The Water Evaluation And Planning (WEAP) system was used for this analysis. WEAP is an integrated modeling tool that can represent supply/demand (see Figure ES-1) and can track water resource stocks and flows associated with extraction, production, and consumption, including seawater desalination, groundwater pumping, and the transmission of water. A modeling development period using historic data from 2005 – 2015 was used for model setup and configuration. Once the Al Ain WEAP model was calibrated and validated against the historic period, it was used to project forward into the 21st century under different assumptions of resource use and climate. A future planning period of 2015 through 2060 was considered in the analysis (see Table ES-1 for an overview of the methodology implemented).

Table ES-1: Methodology implemented

Step 1: Identify the model scope and extent for the Al Ain Region. Collect available data.	Step 2: Build the water supply, demand and groundwater models in WEAP	Step 3: Develop the WEAP Application the Al Ain domain. (supply, demand, GW).	Step 4: Develop a detailed agricultural demand and production model for primary Ag crops.	Step 5: Calibrate and Validate the WEAP Al Ain model: Model is run for a historic period (2005-2015) to establish baseline conditions based on observed data.	Step 6. Develop future scenarios, including Business as Usual and Policy scenarios that reflect current conditions and possible future conditions and policy actions.

The validated water and agriculture systems model was used to analyze the impact of a policies to promote the resilience of the water system in the Al Ain region in the face of climate change. The scenario framework consisted of three scenarios. Two scenarios were described as Business-as-Usual (BAU) scenarios; one BAU scenario with climate change; the other without climate change. A Business-As-Usual (BAU) scenario assumes that the historic climate repeats itself into the future and the CO2 concentrations remain at 2015 concentration level estimates (i.e. 415 PPM). A second Business-As-Usual also assumes the same level of resource use and activity, but applies the impacts of climate change based on the Intergovernmental Panel on Climate Change Representative Concentration Pathway (RCP) 8.5 as was simulated in the Regional Atmospheric Modeling project and represents a roughly 2.5°C increased in temperature and a 7% increase in annual rainfall by 2060. This scenario also includes CO_2 fertilization effects on the water and agricultural systems in the region, with the scenario referenced as BAU-RCP85 in the report. A pair of policy scenarios

Table ES-2: Policy scenarios analyzed

Policy Scenario	Policy Objective
FallowFF	Reduction in water use by the Forestry and Fodder sectors that use subsidized fossil groundwater well below market value. The water subsequently saved in the forestry and fodder sector is used to irrigate higher value crops in the agricultural sector (date palm, vegetable and fruit production).
GWStabilize	Maintaining groundwater levels in a near steady-state condition over a prolonged period of time by finding the level of imported desalinated water and amenity and outdoor water use that allows groundwater levels to keep a constant elevation.

were then developed, which was used to illustrate the kind of analysis that is possible within the WEAP Al Ain modeling framework, as outlined in Table ES-2.

One policy scenario (*FallowFF*) focused on Al Ain's fossil groundwater system and assumes that forestry and fodder production activities decline linearly from their current levels, which are assumed to exist in 2015 and are fully fallowed by 2060 (see Table ES-2). Then, using a substitution-of-service assumption, we estimate the total water savings over the 45-year period as forestry and fodder production are phased out. We then assume that this volume of water is available for the higher valued agriculture products (date palms, vegetables, and fruits) and we iteratively run the WEAP Al Ain model to find the additional agricultural area that could be put under production using the equivalent amount of water saved by not irrigating the forest and fodder sectors. We report the additional area that could be used in hectares and the additional agricultural production in terms of metric tonnes of output.

A second policy scenario (*GWStabilize)* explored the sustainability of Al Ain's regional alluvial aquifer, which represents the historic water supply and is the only renewable water source in the UAE. This policy scenario explores the evolution of Al Ain's alluvial aquifer over the coming decades, within the context of regional population and socio-economic growth and water demand and changes in climate. This regional alluvial aquifer has shown considerable heterogeneity in terms of groundwater levels, with some regions exhibiting dramatic drawdown of groundwater levels, while others have revealed local phenomena, such as elevated groundwater levels, which have caused local problems to infrastructure. The *GWStabilize* scenario explores water management strategies that seek to stabilize the groundwater aquifer.

The main results of the climate change and policy scenarios are as briefly described in the bullets below. Major highlights of the study are outlined in Table ES-3. As the WEAP model built for the Al Ain region are available online at the AGEDI Inspector portal, interested stakeholders will have the ability to explore additional adaptation scenarios and other water resource management questions.

- *Water consumption:* If practices and methods of irrigation remain the same, climate change will cause annual increases in water use for the forestry, amenity, and outdoor water use sectors. The increase is on the order of 5% by 2060, as warming conditions create slightly greater demand for water. However, agriculture uses do not increase due to efficiencies from CO_2 fertilization effects, which lead to more production over a shorter growing season. The new water use in the region by 2060 is about 1.35 BCM in the BAU and BAU-RCP8.5 scenario.

- *Groundwater levels:* Wetter conditions in Al Ain region could help support recharge of the alluvial aquifers. The precipitation in the BAU-RCP8.5 scenario assumes an annual increase in precipitation of more than 10%, producing a near doubling of annual average recharge, increasing from 58 MCM to about 100 MCM. While apparently large, this still represents a small fraction of the overall water used in the region, which we estimate at over 1,000 MCM. Currently, more than 200 MCM of desalinated water are imported into Al Ain region.

- *FallowFF Policy scenario:* The fallowing of forests and fodder results in about 10 BCM of water savings over the full 45-year analysis period. The total area in production of higher valued agricultural commodities, including date palm, vegetables, and other crops can grow by 2 times over the 45-year period due to a compensatory increase of 10 BCM of water equaling the reduction in water use for the forest and fodder sectors.

- *GWStabilize Policy Scenario:* The *GWStabilize* scenario uses the analytical framework to explore 'win-win' outcomes in terms of stabilizing the local groundwater system by conjunctively using it along with desalinated water. Although the future use of this groundwater system would be relatively small (e.g. 8 MCM to 10 MCM annually), its use can reduce desalinated mports and circumvent problems of locally elevated groundwater,

Table ES-3: Policy scenarios: Summary of Results

Policy Scenario	Results
BAU-RCP8.5	Outdoor water consumption increases in 5% by 2060 however, agriculture uses do not increase due to efficiencies from CO2 fertilization effects and shorter growing seasons. Water use in the region by 2060 is about 1.35 BCM. Annual increase in precipitation of more than 10%, doubling the annual average recharge, from 58 MCM to about 100 MCM.
FallowFF	This scenario shows how the fallowing of forestry and fodder production could save 10 BCM of water over the 45-year analysis period. Production of higher valued agricultural commodities, including date palm, vegetables, and other crops could double with this water due to the compensatory increase of 10 BCM of equivalent water reduced by fallowing forest and fodder. Agricultural production grows from 9 MMT in the BAU-RCP8.5 scenario to 13.7 MMT or a 55% increase.
GWStabilize	This scenario demonstrates how the alluvial groundwater system could be sustainably managed by conjunctively using it along with desalinated water. However, these renewable groundwater sources would remain a relatively small portion of overall use (e.g. 8 MCM to 10 MCM annually). Strategic groundwater use could reduce desalinated imports and circumvent problems of locally elevated groundwater, which could be exacerbated under a future climate with wetter conditions and thus greater groundwater recharge.

which could be exacerbated under a future climate with wetter conditions and thus greater groundwater recharge. Care would need to be taken to ensure the stability and sustainability of the groundwater, and thus a corresponding monitoring program would be helpful to manage these shared resources.

1. Introduction and Background

The UAE recognizes water resource management as a serious emerging challenge to country's long-term sustainable development. At the national level, domestic, agricultural, and industrial water consumption have increased at annual rates roughly consistent with the rapid population growth rate, suggesting that little conservation or efficiency improvement is occurring. These consumption growth rates vary by Emirate due to differences in economic development, the types of water uses, the size of each Emirate, and population growth rates. Nevertheless, improvement of water-resource management across all the emirates is urgently needed to achieve water conservation, maintenance of better quality water, and restoration of deteriorating aquifer systems (Rizk and Alsharhan, 2003). High efficiency irrigation technologies, groundwater-recharge dams, salt-tolerant crops, increased public awareness, and the strengthening of institutional capacity have all been cited as urgent national priorities to help ensure that water demand growth rates decline in the future. This LNRCC sub-project examines the water resources of the eastern region of the Abu Dhabi Emirate- Al Ain, which has historical significance as one of the traditional communities of the region, the birthplace of Sheikh Zayed bin Sultan Al Nahyan, the first president of the United Arab Emirates, and a region with the highest proportion of Emirati nationals (30.8%).

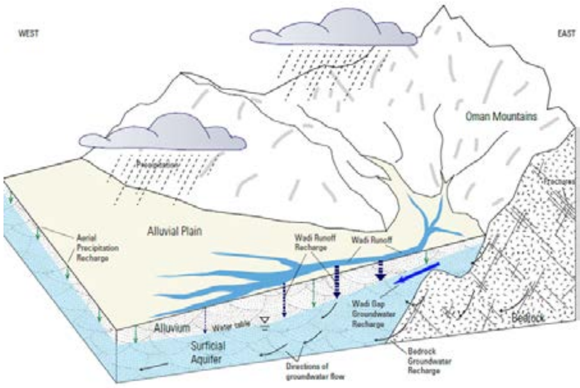
Figure 1-1: map of the United Arab Emirates, including the region of Al Ain, defined by the bounding box included on the map

Al Ain is the 2nd largest city of Abu Dhabi Emirate with a current population of roughly 700,000 people. It is located about 150 kilometers east of the capital Abu Dhabi. The name Al Ain means 'The Spring', and the region is referred to as the Garden City due to its relative greenery (Figure 1-1). Al Ain's historical oases supplied water via underground irrigation systems known as "aflaj" (singular falaj) that brings water from boreholes that tap into the shallow alluvial aquifers, to water farms and palm trees. Falaj irrigation is an ancient system dating back thousands of years and was used widely in the region, including Oman, the UAE, China, Iran and other countries.

Due to the importance of the Al Ain region, the study explored current conditions of water use and its future prospects in the face of climate change and increasing population pressures. Prior to rapid population growth, the local population relied on the falaj system, which represents the only renewable water resource in the region. The introduction of drilling rigs and mechanical groundwater pumps has allowed the exploitation of the regional groundwater on a completely different scale than had been previously realized. There is intensive water uses in the region, bringing into question the viability of sustaining the greening-of-the-desert policy, whereby large tracts of trees are maintained via irrigation from brackish groundwater supplies through deep wells and pumping.

Groundwater used in the agriculture and forestry sectors is derived primary from mined, brackish groundwater deposits developed thousands of years ago during a different regional climate regime. These deep groundwater sources are scattered throughout the UAE including near and around the Oman Mountains and in the desert plain regions to the west. During this period, the region was climatically 'wet' with several perennially flowing surface wadis. The contributions from this paleo rainfall and paleo wadi flow likely played a major role in creating secondary permeability, flushing out soluble matter from the soil matrix, which allows for a relative increase in groundwater storage in certain locations west of the Oman Mountains (Figure 1-2).

Figure 1-2: A schematic representation of recharge mechanisms which occur throughout the Oman Mountain and the Al Ain Region of Abu Dhabi (image courtesy of US Geological Survey).



There are several groundwater recharge mechanisms in the Al Ain region. The main ones are: (1) infiltration of periodic surface flow along wadis that drain the Oman Mountains, (2) subsurface flow from lateral flow in alluvial channels at the mouths of the drainage basins (gaps) along the mountain front, and (3) lateral flow through fractured bedrock along the mountain front (Mohammad, 2014, Imes et al. 1993, Bright et al. 1996). The mechanisms of recharge to the surficial aquifer are depicted in the graphic in Figure 1-2, where wadi runoff recharge and aerial precipitation recharge on the piedmont plain (Ostercamp et al. 1995; Silva 1999). This report focuses on the local alluvial groundwater system.

Modern day recharge of these deeper, brackish aquifers is practically non-existent and water that is extracted from them is essentially mined. The estimate of the total volume of brackish, fossil groundwater in the Abu Dhabi Emirate is around 200 Billion Cubic Meters (BCM), with a high variability of its quality form location to location. To put that volume into perspective, the current estimate of annual water use in the UAE is about 4.5 BCM in 2010, of which more than 60% is for outdoor uses associated with agriculture, forestry, and amenity activities. In some regions, intensive groundwater use has caused groundwater levels to decline as much as 60 meters to 80 meters, such as is observed in Al Hamaranyah and Jabal Al Heben in the Northern Emirates due to intensive agriculture activities.

The second groundwater source consists of more recent local sources derived from near-surface alluvial aquifers that extend westward from near the Oman Mountains near Al Ain, into the eastern deserts of the UAE. These are the only identified renewable groundwater supplies in the UAE, and are primarily derived from poorly consolidated Quaternary piedmont deposits and underlying clastic rocks of Miocene to Pleistocene age (Woodward and Menges, 1992). The response time of these alluvial aquifers to current recharge events are weeks to months, and is a key focus of the analysis done in this report.

In this arid climate, annual potential evapotranspiration is significantly greater than rainfall, and most rain that infiltrates is evaporated or transpired from the shallow subsurface. However, during infrequent but more intense storm events, infiltration rates can exceed evaporation rates, enabling aquifer recharge in the piedmont plain to the west of the mountains. Estimates of the annual, natural recharge volume in the Al Ain region are highly uncertain given the complexity of the geology and the erratic nature of rainfall. A recent estimate of the annual natural flow of the steady-state, pre-development condition of the alluvial aquifers ranges between about 50 and 100 MCM or less than 3% of the current total annual water use in the UAE (Bright and Eggleston 2016). We estimate that annual water use in the Al Ain Region is about 1,000 MCM, so renewable resources represent less than 10% of the total water used in region. Other reports suggest that more than 220 MCM of desalinated water are imported into the Al Ain region to support the water demands of a growing population. Interestingly, it is likely that these substantial water imports into the regional are causing local, elevated groundwater issues within the municipal boundaries of Al Ain (Gulf News, 2010). Most of the forest and agriculture uses are supported by the brackish, fossil groundwater and generally do not use the alluvial, renewable groundwater source.

Desalinated water accounts for an increasing share of water supply. In the UAE, large desalination plants are combined with power plants for electricity generation to meet on-site requirements and to satisfy national electricity needs. All three major types of desalination technology currently used for desalination – Reverse Osmosis (RO), Multi-Stage Flash (MSF), and Multi-Effect Distillation (MED) – consume significant levels of electricity and lead to corresponding levels of greenhouse gas emissions. There are more than 50 desalination plants in the UAE with a total capacity of more than 2200 million m^3/year. It is estimated that about 200 MCM are of desalinated water are delivered annually to the Al Ain region, primarily for municipal uses but also some amenity and agricultural applications. Individual municipalities, with the aid of the Federal Government, plan to increase their desalination capacity soon for some urban centers, mainly in Abu Dhabi, Dubai and Sharjah, to meet the demands of growing population and economic development. This suggests that reliance on desalination is as much of an energy challenge as it is a water challenge.

The challenge of effective water resource and agricultural management at national and local levels is already difficult and will be exacerbated by climate change. The Emirates lie within an arid-semi-arid zone with high climatic variability typical of arid regions, and climate change is expected to directly increase this variability. Rainfall is erratic and irregular in time and space and already insufficient to supply the needs of agriculture, industrial development, and a growing population. The average annual rainfall in the UAE varies from less than 60 mm around the Liwa area in the interior of southern desert to about 160 mm in the mountainous areas of northern and eastern parts of the country, including the area near Al Ain, where surface runoff is captured in small dams to support groundwater recharge (Murad et al., 2007). Climate change is likely to alter patterns and cycles of water supply, with profound implications for water resource management.

In the UAE, several trends suggest the importance of addressing water and agricultural management in the Al Ain region in holistic manner. First, climate change has already begun to affect rainfall and temperature patterns across the region, and while the country is characterized as a typically warm, arid region, future warming and changing rainfall, wind, humidity, cloud cover, and CO_2 concentrations could change patterns of water and agricultural production (Xue and Elthair, 2015). The outputs of LNRCCP sub-project #1 (Regional Atmospheric Modeling) have shown that these changes are expected to intensify in the coming years.[1] Second, socioeconomic growth trends indicate that the population in the country's arid environment is likely to continue to increase and will require additional resource capacity to satisfy increasing water demands, with interest in increasing food security through increased local food production.

The rest of this Final Technical report is organized around several core sections that build upon the context described above. The report also builds on the methodological discussion addressed in the Preliminary Findings and the draft outputs presented in Draft Visualizations and Draft Technical reports previously developed and distributed to partners and stakeholders for feedback. For additional details, the reader is kindly referred to those documents. The next section starts with a review of key background issues, followed by a discussion of technical approach, data inputs, and model structure for the water and agricultural model (Section 3). Section 4 describes the policy scenario framework used to analyze the impact of alternative development strategies, followed by a discussion of results of the analysis of the Baseline (Section 5) and policy scenarios (Section 6). Conclusions and recommendations for further research are offered in Section 7.

2. Study Objective and Background Information

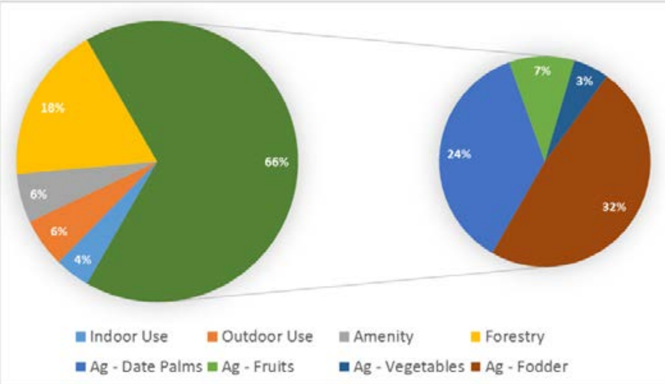
The overall goal of the sub-project is to better understand Al Ain's water and agricultural management challenges in the face of climate change and socioeconomic development. The major research questions underlying the methodological approach were twofold. First, how will climate change affect the water resources of the Al Ain Region that support direct human use and uses for a forestry sector and an agriculture sector that have grown considerably over the past few decades supported primarily with fossil groundwater? These sectors have an important cultural legacy and heritage, particularly surrounding the production of date palms - the region's important and productive agricultural commodity - and other agricultural products, such as water intensive fruit and vegetable production, and the production of fodder used to support a relatively large livestock sector. Second, what water management strategies could be explored - as measured in water savings associated with various scenarios - that aim to promote efficiency and conserve natural resources under climate change?

[1] For location-specific information about climate change in the UAE, please see the Regional Atmospheric Modeling Inspector available at www.ccr-group.org/atmospheric

2.1.Historic Water Use in the Al Ain Region

We have estimated the current annual water use for each of the primary water uses in the Al Ain region, which are summarized in Table 2-1 and Figure 2-1. These estimates are based on data from the MOEW (2010) and estimates of activities around the year 2010. The table shows the total number of hectares under irrigation for the study region and the portion of water used for each activity. The region's water demand is driven by population and rising socio-economic growth resulting in higher per-capita water demand in the domestic sector, and more intensive use of water in other sectors, including amenity and agriculture uses. The domestic policy of *greening the desert,* by the late Sheik Zayed, has led to considerable groundwater use for what is known as the 'forestry' sector. More than 300,000 ha are estimated to be under forestry irrigation in the UAE, using about 2,000 m^3/year/hectare (MOEW 2010).

Figure 2-1: Representation of various water uses in the Al Ain region by portion. The total annual water use is about 1,000 MCM



Most of the forestry sector water use occurs in the Abu Dhabi Emirate and we have assumed that the forestry sector within and around the Al Ain region that is considered in this study occupies 44,000 hectares. Amenity uses of water include municipal landscapes, parks, and other public spaces that are largely managed by municipalities. A large portion of amenity water is supplied through municipal water re-use, although demand is also met by desalinized water and some by groundwater. Table 2-1 summarizes the Al Ain region's current population served and their indoor and outdoor use, an estimate of area and water use per unit for the amenity and forestry sector, and an estimate of agricultural demands in the region. We have aggregated the agricultural water uses into four broad commodities, including Date Palms, fruits, vegetables, and animal fodder or switch grass and estimate the amount of each activity irrigated in hectares and their average annual use activity in units of m^3 per hectare. When all these uses are combined, we estimate that the region around Al Ain uses about 1,250 MCM of water annually, with most this water use attributed to the agricultural and forestry sectors.

Table 2-1: Estimate of annual water use in the Al Ain Region by activity for the year 2010.

Sector	Activity	Source	Unit	Demand per Activity	Unit	Annual Use (MCM)
Indoor Use	700,000	United Nations, Department of Economic and Social Affairs, Population Division. 2015.	people	73 (200)*	M^3/cap (lpcpd)	53
Outdoor Use	7,000	UAE Water Conservation Strategy. 2010.	ha	7,500 (195)*	M^3/ha (lpcpd)	53
Amenity	12,000	Assume 1% of Study area is irrigated for Amenity uses.	ha	5,500	M^3/ha	66
Forestry	44,000	Environment Agency Abu Dhabi. 2015.	ha	1,800	M^3/ha	80
Agriculture - Date Palms	17,000	UAE Water Conservation Strategy. 2010[&].	ha	17,000	M^3/ha	290
Agriculture - Fruits	10,000	UAE Water Conservation Strategy. 2010[&].	ha	4,200	M^3/ha	42
Agriculture - Vegetables	8,400	UAE Water Conservation Strategy. 2010[&].	ha	3,400	M^3/ha	30
Agriculture - Fodder	22,800	UAE Water Conservation Strategy. 2010[&].	ha	15,700	M^3/ha	360
Total					---	**970**

** UAE average daily usage of water in liters per capita per day (lpcpd) is 365 According to United Arab Emirates Water Conservation Strategy (2010). We implemented 200 lpcpd for indoor use and 165 lpcpd for outdoor use with a total of 295 lpcpd. &: Based on an estimated number of farms in the Abu Dhabi Emirate with an average cropped area per farm of 5.65 ha*

2.2. The Historic Water Supply in the Al Ain Region

Water supplied for the above uses is from brackish, fossil groundwater, fresh groundwater, desalinated water and reclaimed water. Historically, all water uses have been met, although there is reliance on water transfers from other regions, most notably desalinated water from the east coast region via pipeline to Al Ain. Brackish groundwater is the major supply source for agriculture and forestry, with groundwater supplementing small amounts of municipal and industrial water supplies, but meeting only 2% of those demands. Desalinated water is used primarily to meet domestic and industrial demand, with estimates of about 220 MCM imported to the region. According to official 2009 data from Abu Dhabi Water and Electricity Authority (ADWEA) desalinated water – about 85 MCM a year –is used for agriculture in the Abu Dhabi Emirate. If we assume that the Al Ain region represents 60% of this use, then more than 50 MCM of desalinized water is used in the agricultural sector annually in the Al Ain region.

2.3. The Historic Agricultural Sector in the Al Ain Region

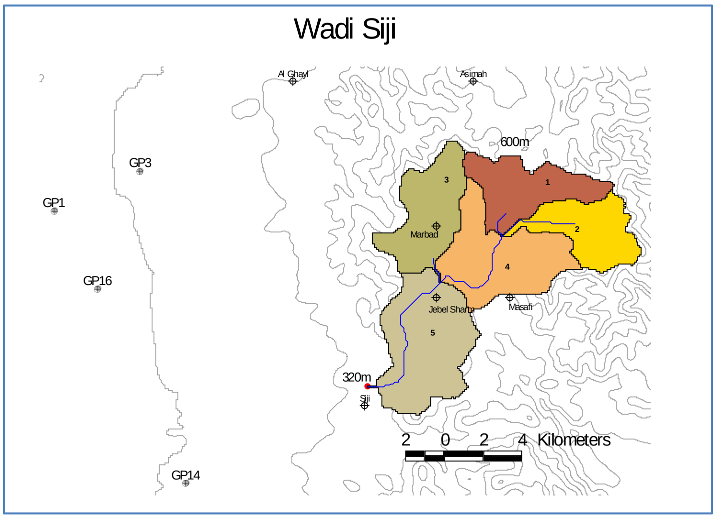
The Al Ain region represents the historical heritage of the United Arab Emirates, where traditional agriculture was limited to date groves in oasis areas fed by springs, falaj systems and shallow wells. The culture was built around the rearing of camels, sheep and goats on rangeland to support a relatively small, indigenous population. Those traditional ways of life changed dramatically with the discovery of oil and the adoption of a policy to "green the desert." Thus, with an unlimited and free access to fresh and brackish groundwater reserves, farmed area increased from 3,000 hectares in 1968 to over 100,000 hectares by 2008. The desert greening policy resulted in more than 300,000 hectares of irrigated 'forests', primarily near transportation corridors. The agriculture sector has been developed around tree crops, primarily date palms, with vegetables and fruit also grown. The UAE currently grows about 160 varieties of dates, and 55 species have been initially identified, with estimates of more than 40 million date palm trees producing nearly 80,000 tons of dates per year (Sheikh Mohammed Centre, 2016). Fodder to support livestock supplemented rather than displaced livestock. Indeed, between the 1980 and 2008, the number of livestock increased from about 0.5 million to 3.3 million, with forage crops to support the livestock industry accounting for 39% of farmed area in 2008 and accounted for 45% of total agricultural water use.

The period of rapid agricultural expansion appears to have ended. Cultivated areas are shrinking by about 4,000 hectares per year likely due to changes in the Federal and Emirate policies on agricultural subsidies, shortages of good groundwater quality, and increasing production costs. Recognizing its unique culture importance in the UAE, we single out the production of date palms in the UAE. The estimate of date production in the UAE is about 760,000 metric tonnes. We estimate that about 33% of the total production is within and around the Al Ain region, and thus Date production has been around 250,000 metric tonnes in the recent period (2010 to 2015; UAEU 2014).

2.4. Understanding Groundwater Recharge in the Al Ain Region

To understand groundwater recharge and wadi response to rainfall, several wadis in the Al Ain Region have been studied in recognition of their water resource significance, and thus have observational records in terms of both meteorology and hydrogeology. This section explores recharge mechanisms based on observational evidence to understand some of the hydrologic and aquifer dynamics. These analyses are useful in understanding the nature of aquifer recharge, such as the differences between low and high frequency rainfall events and their associated intensities. The high frequency events correspond to large-scale, frontal weather systems that occur during the winter months in the UAE, when evapotranspiration rates are relatively lower. Likewise, winter rainfall occurs during favorable antecedent soil moisture conditions, which may lead to greater fractions of rainfall becoming recharge. Hence, five days of consecutive 20 mm rainfall during the winter could yield more

Figure 2-2: Boundary and sub-watersheds of Wadi Siji, as derived from the 90-meter resolution digital elevation model data (total area ~103 km²). Contour intervals are 100 meters, and markers indicate locations of gauging stations and groundwater monitoring wells (GWR4 and GP15 are between and just to the west of GP14 and GP16 and are not shown)



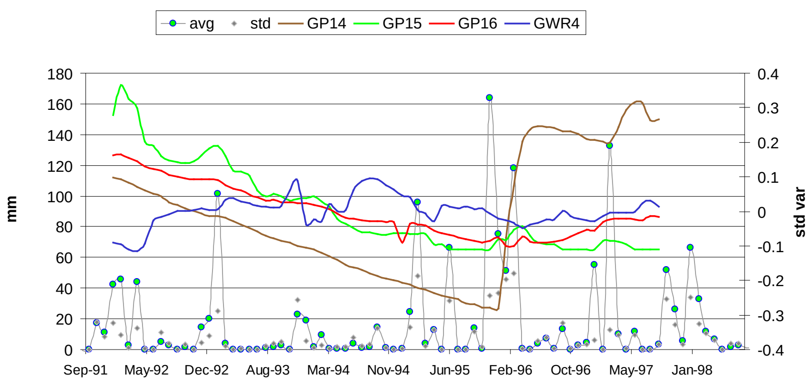
recharge than would a day of 50 mm rainfall followed by a dry day and then another day of 50 mm of summer rainfall.

One wadi system that has been studied is wadi Siji that is in the central portion of the Dubai Emirate. Figure 2-2 is the outcome of a GIS based watershed and stream identification analysis using a 90-meter resolution digital elevation data, suggesting a catchment area of approximately 100 km^2. Although outside our immediate study domain, this watershed and the surrounding area have several weather stations that have recorded rainfall for many years (Marbad, Jebel Sharm, Masafi and Siji), and the main stream near the catchment outlet (to the southwest) has a stage recording station. There are also groundwater well monitoring stations near this watershed and to the west, by which groundwater response to precipitation events can be analyzed.

Groundwater level data from the Ministry of Agriculture and Fisheries (MAF) show a variety of responses to the high rainfall events, with an example from 1995-1996 (Figure 2-3). Also plotted is the average precipitation from the 4 stations near and around wadi Siji and their standard deviation. This winter was especially wet, with widespread flooding in many areas of the UAE, with groundwater monitoring wells showing strong evidence of the sensitivity of the alluvial aquifer systems in and around the Oman Mountains to strong, sustained rainfall events.

From 1990 to 1995, nearly all of the groundwater-monitoring wells near Wadi Siji exhibited a long-term, declining trend, with the exception of GWR4 (Figure 2-3). Note that there were no data available on groundwater extractions near these wells, so the role of groundwater pumping on well levels was not considered. Within this period of record, the monitoring wells in the western desert (GP15, GP16 and GWR4) exhibit periods of groundwater level increases associated with seemingly smaller rainfall episodes. For example, the winter of 1992/93 had significant rainfall and the groundwater levels in these wells appeared to respond positively to this rainfall. However, GP14 showed little response to these events, and the discharge records of wadi Siji during this period showed only small amounts of discharge as a result of these rainfall episodes. This suggests that the rainfall was spatially variable, and was not great enough to contribute to discharge from wadi Siji, but likely contributed to wadi discharge in other nearby stream systems, which led to the response of the down-gradient well levels.

Figure 2-3: Standardized change in groundwater levels near Wadi Siji (right axis) and precipitation amount and standard deviation in mm (left axis).



The previous Figure 2-2 shows that GP14 is located near the boundary of the wadi, while the other monitoring wells are further west. Note the rapid response of GP14 in January 1996, after 3 significant flood flows that likely produced significant transmission losses along the channel. In 1995, there was a period of 13 out of 15 days that reported measurable precipitation. In 1997, the March precipitation occurred over a 5-day period.

The alluvial aquifers are highly braided, with corresponding fingerlike extensions of high and low permeabilities and transmissivities. For example, it appears quite likely that GWR4 is in an area of higher transmissivity and therefore experiences more significant response to greater rainfall events, suggesting different precipitation regimes can lead to different groundwater responses. The significant rainfall that occurred during the winter months of 1995 and 1996 reversed the long-term declining trend exhibited in most of these monitoring wells. The reversal was most dramatic in GP14.

Rainfall observations in the mountainous regions show that the winter precipitation of 1995/96 was unusually significant and appears to have led to a rapid response of the near-surface aquifers in this area. Peak and total volume discharge of Wadi Siji was significant during the winter of 95/96, with large volume floods occurring in December, January and March. GP14 appears to have a strong hydraulic connection to wadi discharge, while GWR4 and GP16 also appears to respond positively to these rainfall episodes, with an approximately 4- to 6-month lag while GP15 exhibits little response to these rainfall events and subsequent wadi flows. The rapid response time of the aquifers certainly suggests that the primary recharge mechanism is due to percolation from the wadi bed during times of high flow. The response of the down-gradient wells to the 1995/96 precipitation events suggests that particularly wet winters are the ones that lead to significant recharge of the larger aquifer systems. Well-level and precipitation records also suggest that smaller precipitation sequences lead to aquifer recharge, but are perhaps not as widespread or prolific as larger events, and are confined to more local aquifers.

Interestingly, in July of 1996, the Siji stream gauging station recorded large flood peaks on both July 24th and July 27th (see Figure 2-4). Corresponding precipitation data does not support this strong outflow and total volume data are not in the current data holdings, so confirmation of these floods events would need further study. Jebel Shaam showed strong precipitation for these events (nearly 60mm), while precipitation for the other stations on these dates was much smaller. Also, a groundwater response to this July 1996 recorded flood peak in Wadi Siji does not appear in the well level data of GP14, as can be seen in Figure 2-2. The role of this July event on recharge is difficult to deduce. Additionally, the flood peak estimates of some of the winter peaks are well over 200 m^3/sec, and the July peak is nearly 600 m^3/sec, although these peak discharge estimates seem quite high (Figure 2-4).

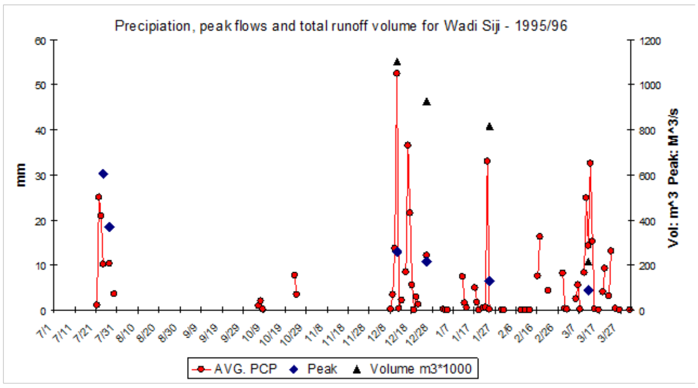
3. Analytical framework for supply and demand in Al Ain Region

Addressing the goal and research questions required an analytical framework capable of accounting for the water and agriculture systems of the region in an integrated manner. The Water Evaluation And Planning (WEAP)[2] system was used for this analysis and is an integrated modeling tool that can track water resource stocks and flows associated with extraction, production, and consumption, including seawater desalination, groundwater pumping, and the transmission of water.

The development of a valid and credible water and agriculture systems model for the Al Ain region is the final component of the analytical approach. The following steps were followed.

- *Step 1:* Develop the WEAP model: Developing the water system model in WEAP required a comprehensive estimate of the water supply/demand characteristics of the Al Ain Region in the UAE. Once the baseline data were established, such as the regional population, the per-capita indoor water demand, the extent of outdoor irrigation for amenity, garden, and agricultural uses, the water supply sources including fresh and brackish groundwater, desalinization and technologies used, etc. were configured into the model to facilitate mass balance calculations on a daily time step.
- *Step 2.* Build the groundwater model: The groundwater model included a representation of the alluvial groundwater systems of Al Ain, using of WEAP's catchment objects to provide the recharge mechanism via the wadi and mountain front recharge, and then using of Darcy's law to simulate the flux of water through the near-surficial alluvial aquifer of the Al Ain region.
- *Step 3.* Calibrate the groundwater model: After building the groundwater model, we had to calibrate it according to pre-development, steady-state conditions that maintained a level groundwater table across the representative area, from the eastern region of Al Ain, westward towards the Arabian Gulf. Parameters of the model, such as the hydraulic conductivity, porosity, representative lengths, wadi recharge, etc., were modified until steady-state conditions were reached. Once steady state conditions were established, the model could be used to explore current and future use conditions.

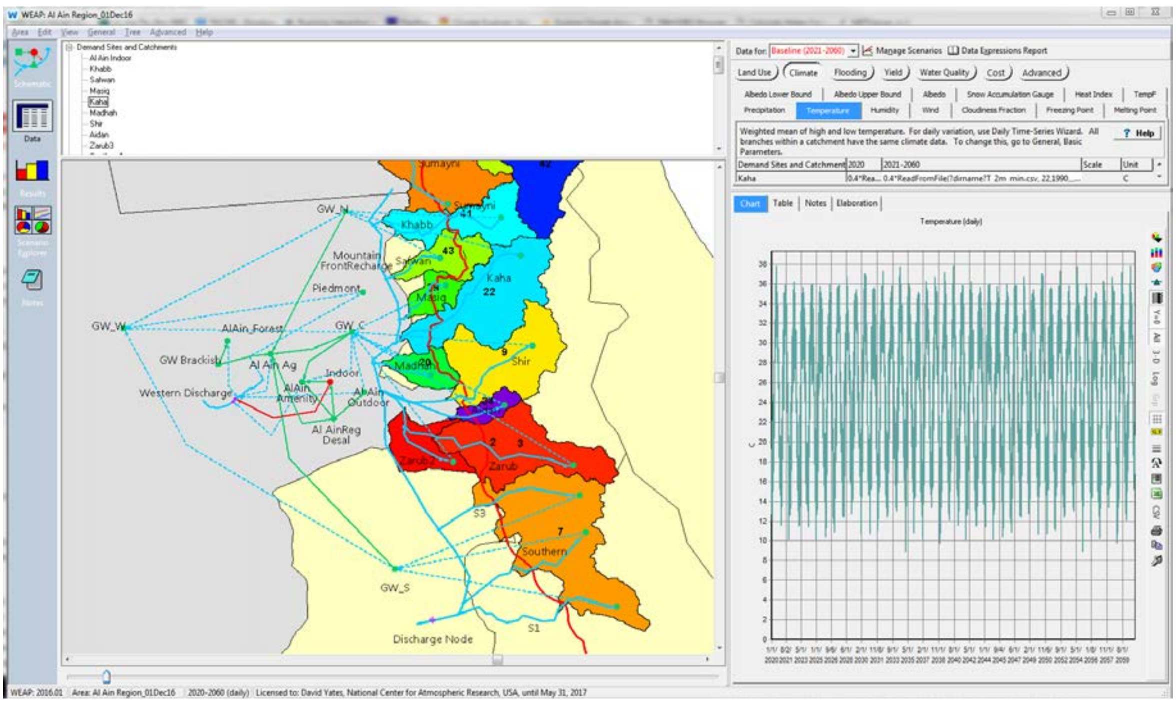
Figure 2-4: Plot of average daily precipitation from 4 meteorological stations near Wadi Siji (red dots), observed peak discharge (blue diamond) and total flood volume (black triangle) from flood stage recording devices within the Wadi Siji flood plain, from July 1995 through March 1996



[2] Information about the WEAP model can be found at http://www.weap21.org

- *Step 4.* Development of a detailed agricultural demand and production model. Making use of WEAP Plant Growth Model (PGM), we have developed a detailed model of the primary crops in production in the region (date palms, fodder, vegetables, and fruits). This model can be used to explore the demand for groundwater and the production of agricultural outputs under current and future climate conditions, including the effects of CO_2 fertilization.
- *Step 5*. Calibrate the WEAP model: Once the water supply and demand models were developed, they were run for the historic period 2005 to 2015 to establish baseline conditions based on observed data with regards to water supply and use. This can be considered a calibration phase.
- *Step 6.* Develop a Business-as-Usual (BAU) scenarios that reflect current conditions that continue into the future, but that consider changes in future climate. In addition, we have developed a future policy scenario that assumes a reduction in the forestry and fodder areas, and an increase in land under agricultural cultivation for higher valued crops such date palms and vegetables.

Figure 3-1: The WEAP-Al Ain model and its geographic scope.



A model development period using historic data from 2005 – 2015 was used for model setup and configuration. Once the Al Ain WEAP model was calibrated and validated against the historic period, it was used to project forward into the 21st century under different assumptions of resource use and climate. A future planning period of 2015 through 2060 was considered in the analysis. The overall extent of the model domain is shown in Figure 3-1.

The Al Ain Region water and agriculture systems model identifies the main wadis that serve as recharge basins to the eastern surficial aquifers. The model captures system characteristics like agricultural areas, populations, water demand for human consumption and irrigated amenity areas, wastewater treatment plant capacities, desalinated water production capacities, irrigation demands, and groundwater availability/recharge. The model was developed on a daily time step to examine water supply and demand balances in the Al Ain region, and encompasses and area of approximately 14,000 km^2 from the western boundary of the Oman Mountains near Al Ain, which extends westward towards the central desert of the Abu Dhabi Emirate. The area of the Oman Mountains included in the model and which contain active wadis is about 3,600 km^2. An illustrative, schematic view of the model is shown in Figure 3-1. The schematic demonstrates the aggregated nature of the Al Ain model's representation of water supply (green lines) and demands (red and green dots). A final version of the Al Ain water system model, after receiving and incorporating all stakeholder feedback, will be available for download.

3.1.Data input sources and assumptions

This section provides an overview of the data sources, key underlying assumptions, structure, and validation of the water and agriculture system model. The water and agriculture systems model uses a host of data assumptions that influence water supply and demand. These data assumptions have been carefully assessed and incorporated into a working version of the water system model which adequately simulates historical conditions. After a review and vetting process by stakeholders of the current version of the model, a final version will be developed that incorporates all feedback.

The representation of water supply and demand characteristics within the water system model was as "granular" as possible. While there was ample local data to construct a modestly granular water system model, there was not enough detailed data to develop a highly granular water system model. This has consequences for the level of detail that can be analyzed during the policy scenario analysis. That is, the water system model can analyze high-level (i.e., sectoral level) policy scenarios and offer first-order indications of alternative development pathways. However, the model cannot analyze the interactions between water supply/demand policies at lower levels of disaggregation (e.g., level of enterprises, households, precincts).

The water system model built in WEAP is fundamentally data-driven. Hence, there is a large amount of data that was needed to build the model. The data collection effort has benefitted from collaboration across relevant UAE institutions which have granted access to necessary data. As of this writing, this process has been satisfactorily completed.

There were several differing types of modeling assumptions that were incorporated into the water system model. Background for each of the major assumptions is provided in the subsections below regarding water supply, water demand, and wastewater treatment.

3.2.Model structure

The WEAP software was used to build a water system model for the Al Ain UAE. WEAP provides an sector-specific integrated approach to water resources planning by linking quantification of water availability and water allocation routines, hydrologic processes, system operations and end-use quantifications within a single analytical platform (Yates et al. 2005). The modeling software incorporates the multiple dimensions critical to water resources management, including surface water and ground water hydrology, water quality, water demands, population growth, reuse, system losses and consumption. WEAP represents water supply and demand centers in a spatial way because its focus is the flow of water from

The structure of the water system model accounts for the locations of all water supply sources and the magnitude of current and future demand for water. The spatial coverage encompasses the eastern region of the Abu Dhabi Emirate, which includes Al Ain and the wadis of the Oman Mountains, reflecting the shared aquifers between the UAE and Oman, where there is some renewable fresh groundwater. The nomenclature of water system components, as illustrated in the WEAP modeling figures, is outlined below:

- Green squares represent both alluvial and fossil groundwater aquifers- Three aquifer objects are used to represent the active alluvial aquifer, including a GW_North (N), GW_Central (C), and GW_South (S). These three aquifers receive influx from the wadis system and mountain front recharge, and flux this water westward, towards a groundwater object that is assumed to be in steady state identified as GW_West (W). A fossil groundwater aquifer represents the brackish supply and is assumed to contain 50 BCM at the start of the simulation in 2015 (MOEW 2010).
- Red dots represent indoor water consumption per capita; A single indoor water use is assumed to represents the Al Ain municipality demands.
- Maroon dots represent wastewater treatment facilities; A single wastewater plant treats effluent and supplies reuse water amenity watering (Mohamed 2014).
- Green dots represent catchment water demands associated with different types of land covers that require irrigation; 15 catchment objects are used to represent the wadis of the Oman Mountains, comprising roughly 4,000 km^2. This object is also used to represent agriculture, amenity, and outdoor irrigation and water demands.
- Green diamonds represent desalination plants; A single desalination supply is assumed, with estimates of more than 200 MCM of water imported annually (Mohamed 2014).
- Green lines represent water transmission flow; A set of transmission links define how water is allocated among the various supplies and uses. For example, amenity uses can receive reclaimed water, desalinated water, or freshwater in that order of priority.
- Red lines represent water return flow; Return flow water is water that is passed back to the environment or recharges to an aquifer.

- Dashed blue lines represent connections of hydrologic processes, including the transmission of recharge water to the alluvial aquifer or the flux of water from the alluvial aquifer to the steady-state aquifer.

The Al Ain region is divided into an eastern region that includes the major wadis of the Oman Mountains and a western region that includes the demand centers of the city of Al Ain and surrounding region. Demands include indoor, outdoor and amenity uses. The model uses a single demand object to represent the forestry uses and assumes 44,000 hectares under plantation requiring about 2,000 m^3/hectare per year that is served solely from fossil, brackish groundwater. A single demand object is also used to represent amenity water use, where we assume that 12,000 hectares are under active irrigation, using about 7,500 m^3/hectare.

3.3. Modeling Water Demands in WEAP Al Ain Model

Water demands include indoor and outdoor municipal use, amenity water use, forestry, and irrigated agriculture. WEAP's catchment object was used to represent "Outdoor water use" corresponding to irrigation for private outdoor household demand. "Amenity water use" corresponds to irrigation for public forests and amenity use (i.e., recreational or green areas such as public parks, green areas along road ways and freeways, turfs mainly representing golf courses, and trees in urban areas). "Agricultural water use" corresponds to land area used for crop cultivation (i.e., date palm plantations, fodder, agricultural vegetables crops, and other agricultural crops).

3.3.1. Municipal Water Demands

Municipal water demand (i.e., drinking, process, industrial, and other indoor water uses) was estimated as a single demand in the water system model. Municipal water demand was calculated as a product of population which was assumed to grow over time, consistent with the central estimate from UNDESA (UNDESA, 2015) and a water use per capita value of 115 m^3/year. Each demand site in the UAE assumes that the indoor per-capita water demand is constant throughout the year and over the entire planning horizon in the absence of water efficiency and conservation measures. Municipal demands in the WEAP Al Ain model are broken into an indoor and an outdoor use. Indoor use is simply computed from per-capita demand, estimated at 200 l/day and an outdoor demand, which is based on assumed outdoor activity in hectares multiplied by a daily irrigation demand that we estimate at 7,500 m^3/hectare (see earlier Table 2-1).

3.3.2. Agriculture systems of the Al Ain Region

Recently, the WEAP software was updated with new algorithms that simulate the effects of climate change and elevated atmospheric CO_2 concentrations on cultivated plant's water use and crop yields. This new modeling tool in WEAP is the Plant Growth Model (PGM) that simulates the following processes (SEI 2015):

- Reduction in stomatal conductance caused by elevated CO_2
- Increase in radiation use efficiency caused by elevated CO_2 (fertilization effect)

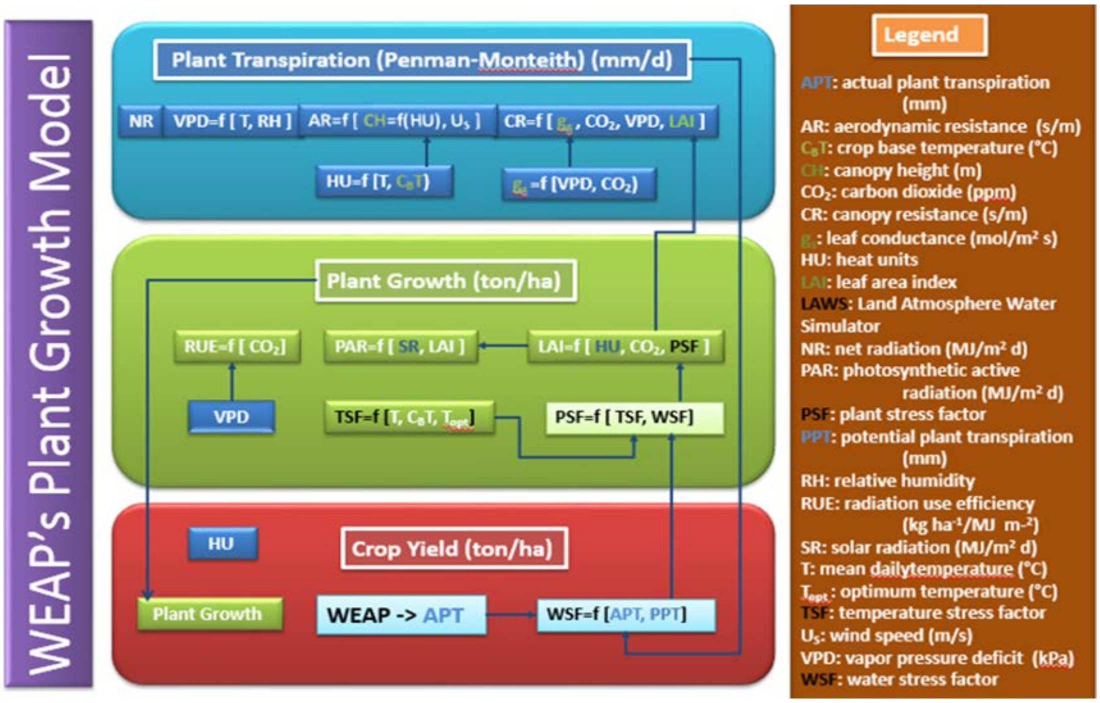
- Increase in leaf area caused by elevated CO_2
- Increases in evaporation and transpiration caused by elevated temperature
- Increase or decrease in temperature stress caused by elevated temperature
- Acceleration in the accumulation of degree day heat units which accelerates crop maturation
- Decrease the length of the growing season caused by elevated temperature
- Reduction in stomatal conductance and radiation use efficiency caused by elevated vapor pressure deficit

The PGM model allows cultivated and non-cultivated vegetation to grow and determine water use under this new meteorological conditions through the implementation of specific crop parameters that characterize each crop. Figure 3-2 shows the components of the PGM, which was implemented in the Al Ain WEAP model to represent properly the irrigation demands and agricultural production of the Al Ain region. The primary crops included in the Al Ain WEAP model include date palms, fodder, vegetables and fruits, and whose primary parameters are presented in Table 3-1.

Table 3-1: Plant growth model's main parameters used in the development of the Al Ain WEAP model.

Parameter	Units	Baseline			
		DatePalms	Fodder	Veg(Tomato)	Others(Melon)
Years of Comparison	NA	1990-2010			
CO2 Concentration	ppm	352-387			
Crop Base Temperature	°C	13	12	10	16
Optimal Crop Temperature	°C	32	30	30	35
Potential Heat Units	HU	5000	5585	2220	1510
Leaf Area Index (from 330 to 660 ppm CO2)	NA	5	2.5 - 2.9	3 - 3.5	3 - 3.5
Stomatal Conductance (from 330 to 660 ppm CO2)	m/s	0.0071 - 0.0049	0.005 - 0.0025	0.008 - 0.0054	0.006 - 0.004
Radiation Use Efficiency (from 330 to 660 ppm CO2)	g/MJ	12 - 14.4	21 - 25.2	30 - 39	30 - 36
Management Allowed Depleation	%	0.75	0.95	0.5	0.5

Figure 3-2: The Plant Growth Model



3.4. Modeling Water Supplies in the WEAP Al Ain Model

3.4.1. The Groundwater System in the Al Ain Region

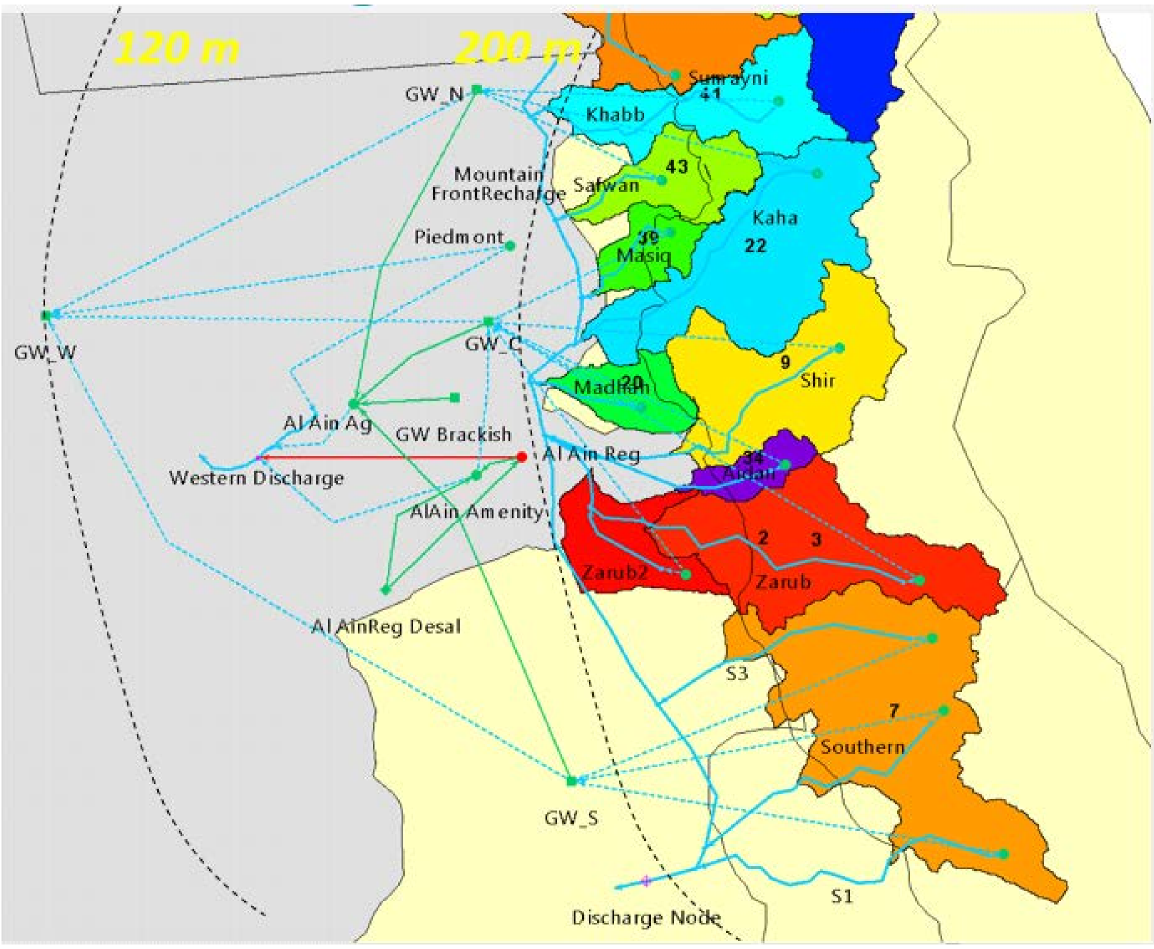
The presence of renewable, fresh groundwater is limited in the region. Groundwater flux from Oman Mountains is defined by the topographic gradients of the area and the wadi channels, depicted in Figure 1-2. The characteristics of these wadis are steep and active after heavy rainfall, but as the flux of water crosses the Emirati borders the flow velocities decrease as the water spreads across the flatter topography of the piedmont plain.

The contributions from this paleo rainfall and paleo wadi flow likely played a major role in creating secondary permeability, flushing out soluble matter from the soil matrix. This allows for a relative increase in groundwater storage in certain locations west of the Al Hajar Mountains (Brook 2006). In this arid climate, annual potential evapotranspiration is significantly greater than rainfall, and most rain that infiltrates is evaporated or transpired from the shallow subsurface. However, during infrequent but more intense storm events, infiltration rates can exceed evaporation rates so that some recharge to the aquifer occurs in the piedmont plain to the west of the mountains (Ostercamp et al. 1995; Silva 1999).

Unconsolidated alluvial deposits of varying age comprise the surficial unconfined aquifers of Abu Dhabi Emirate, the top of which defines the active water table. According to GTZ (2005), the "shallow aquifer comprises all permeable layers that are hydraulically connected and exhibit a hydraulic head that is defined by the water table for any given point." The average thickness of the Quaternary alluvium in the study area is about 30 m, the specific yield is estimated to be about 10-15%, and the average transmissivity of the surficial aquifer is about 270 m^2/d (Symonds et al. 2005). Aquifer transmissivity in the north is larger than in the Al Ain area near Jabal Hafit (Brights et al. 1996). A representation of the Al Ain water system model showing the linkages among the modeled elements appears in Figure 3-3.

The ability of the Al Ain region WEAP model to capture the dynamics of the alluvial groundwater system was done by simulating the pre-development, steady-state conditions, before modern pumping began. The model was calibrated using manual calibration techniques, with the goal of establishing a set of realistic model parameters that simulate the steady-state elevations on the eastern boundary and a constant flux boundary on the western boundary of the modeled domain. The three alluvial aquifers depicted in Figure 3-3 are the GW_N, GW_C and GW_S. Each of these groundwater systems are

Figure 3-3. Zooming in on the WEAP-Al Ain model showing Wadis, groundwater systems and demand elements, including the 200m estimated groundwater elevation on the eastern boundary, and the constant head boundary of 120 meters on the western boundary.



hydrologically connected to each of the 15 wadis, which pass their flux to these three groundwater objects. The physical parameters of each groundwater object are summarized in Table 3-2.

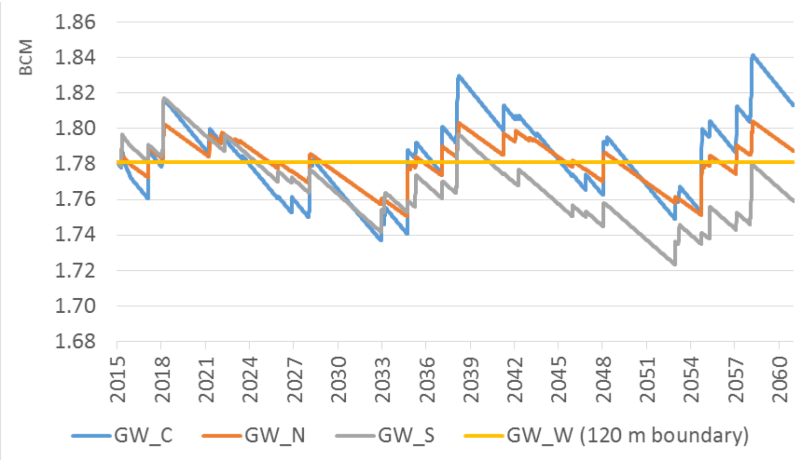
Table 3-2: Summary of groundwater parameters for the three modeled alluvial groundwater objects used in the WEAP Al Ain model.

Groundwater System	Conductivity (m/d)	Represented Length (km)	Reference Height (m)	Initial Storage Fraction	Specific Yield	Storage at Equilibrium (MCM)
GW_N	4	90	280	0.95	0.2	2000
GW_C	4	75	280	0.95	0.2	2000
GW_S	4	120	280	0.95	0.2	2000

A collection of 15 WEAP catchment objects represent the eastern wadis of the Oman Mountains (i.e., Sumanyi, Kaha, Shir, etc.), in the eastern region of the UAE that includes the region bordered by Oman. Together, these wadis encompass about 4,000 km^2 of the Al Hajar Mountain range in and around Oman. This is the one region where natural groundwater recharge is generated through rainfall via near-surface alluvial aquifers that extend westward from near the Oman Mountains into the eastern deserts of the UAE. These fresh groundwater resources are found in the eastern area of the Abu Dhabi Emirate, the region near and around Al Ain, which was once a much more active fluvial system. In many locations, aerial photographs reveal evidence of strong outflow through the wadi gaps onto the western plains. During this period, the region was climatically 'wet' with several perennially flowing surface wadis.

Groundwater flows from the alluvial aquifers to the western constant flux boundary are calculated using Darcy's Law, where $Q = K\,A\,I$ and the hydraulic gradient (I = ΔH/ΔL) in the study area is calculated using head contours presented in USGS (2016). The model assumes a variable boundary that starts at 200m for each of the alluvial aquifers, and a constant head boundary of 120 meters on the western edge. Parameters of the model, such as the hydraulic conductivity, porosity, representative lengths, wadi recharge, etc., were modified until steady-state conditions were reached. Once steady state conditions were established, the model could be used to explore current and future use conditions. Figure 3-4 shows the final calibrated groundwater storage trace for the three alluvial aquifers (GW_N, GW_C, and GW_S) and the groundwater object that serves as the constant head boundary on the western flank of the domain, GW_W.

Figure 3-4: WEAP simulated storage of the three alluvial aquifers (GW_N, GW_C, and GW_S) and the constant boundary groundwater (GW_W).



The results demonstrate the annual variability of the simulated groundwater storage as depicted by the WEAP model, with a storage variance of about 240 MM3. The recharge mechanisms included here are, 1) the infiltration of periodic surface flow along wadis that drain the Oman Mountains, and 2) subsurface flow from lateral flow in alluvial channels at the mouths of the drainage basins (gaps) along the mountain front. The WEAP steady-state simulation suggests an annual recharge from periodic infiltration of about 36 MM3 and from sub-surface, lateral flow from the alluvial aquifers of about 24 MM3 for a total annual recharge of about 60 MCM per year. This recharge represents a small percentage of overall water demand for the country and the region (USGS 2016).

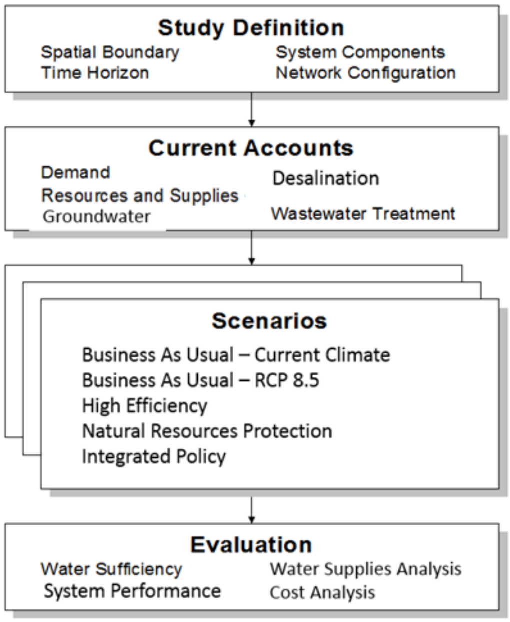
3.4.2. Representing Wastewater treatment and reuse in the model

The Al Ain region includes the collection of waste water effluent for reuse in outdoor amenity and garden watering. This supply serves the municipal water demand sites discussed in the previous subsection. It was assumed that 75% of the treated waste water in the region is reused as a non-potable supply for outdoor irrigation (Mohamad 2014). It was further assumed that of the total water supplied to the indoor demand sites, 15% is consumed and or lost from the system. The remaining 85% is returned to waste water treatment systems and used in amenity watering of public parks and landscapes. Some of this water is treated in wastewater treatment plants which have been assumed to have daily treatment capacities to treat wastewater coming from the different demand sites with a corresponding cost for this treatment. Any wastewater quantity above the treatment capacity threshold flows untreated into wadis in the model.

3.4.3. Desalinization Imports

Municipal and industrial uses in Al Ain are largely supported through desalination, with the total annual volume of desalinated water distributed in Al Ain estimated to be about 220 MCM (Mohammad, 2014). Almost 50% of this water is distributed for domestic use; while the other 50% is distributed for commercial, industrial, and some agricultural use. Some portion of this water, accounted for in the overall water budget, will enter the surficial aquifer and serve as recharge. There is some evidence to suggest that this water has caused elevated groundwater levels in some area around Al Ain (Dawoud 2010; Baker and Gabr, 2010).

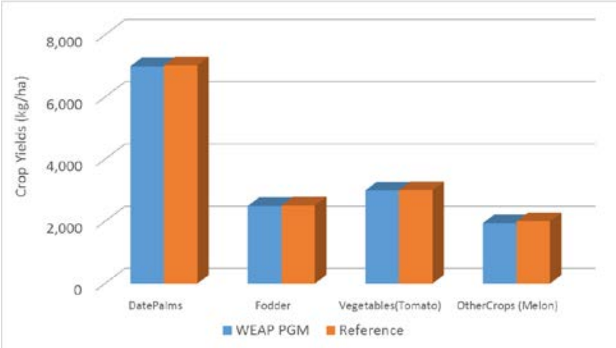
Figure 3-5: The WEAP analysis and scenario development process.



3.5.Model calibration

Calibrating the water system model consisted of several key steps, as illustrated in Figure 3-5. First, as outlined in the previous section, the calibration process begins with a schematic representation of the water supply-demand system (i.e., "Study Definition" in Figure 3-5). This is intended to visually indicate all the system's physical determinant components: demand sites, wastewater treatment plants, groundwater access sites and links to transport the water between these areas. Secondly, once the components have been represented physically, they have been populated with some of the acquired local UAE and Al Ain specific data around the period 2005-2015 (i.e., "Current Accounts" in Figure 3-5) and structured with the remaining local data to ensure that system constraints are adequately represented. Lastly, the water system model was compared to historical conditions to asses if it could reproduce the physical reality as closely as possible.

Figure 3-6: WEAP PGM crop yields for date palms, fodder, vegetables and other crops in the Al Ain region for the corresponding period of 1990-2010.



The results of the calibration indicate that the water system model adequately reproduces historical conditions for water supply and demand. Calibration of the Al Ain agricultural sector in terms of crop yields replicates historic average yields. The simulated yields from the PGM model were analyzed against reference crop estimates as dry matter weight and are presented in Figure 3-6. The calibration period was from 1990-2010 and PGM replicates very closely those crop yields as shown in Figure 3-6.

Table 3-3: Reference crop yields as dry matter used for calibration in PGM. Reference data came from difference sources

	Avg Yield	Yield (Commercial Yield)	Moisture Content	Yield (Dry Matter)
Crop	**kg/tree**	**kg/ha**	**%**	**kg/ha**
Date Palms	60[a]	9,360	25	**7,020**
Fodder	NA	4,180[b]	40	**2,508**
Vegetables (Tomato)	NA	60,000[c]	95	**3,000**
Other Crops (Melon)	NA	20,000[d]	90	**2,000**

a: spacing between trees 8*8 m thus, 156 trees/ha; https://www.netafim.com/crop/dates/best-practice
b: SWAP model UC Davis; http://www.sciencepub.org/nature/0204/10-haiqingwu.pdf
c: FAO 66 Crop yield response to water; Leoni, 2002.
d: 400 45 lb cartons/ac = 20,175 kg/ha; Cantaloupe/Honey Crop Guide

Reference data used to calibrate the models came from the FAO and other various sources. These sources are identified in Table 3-3. Most of them correspond to regional conditions in the UAE and from other global sources due to the lack of local data (see previous Tables 3-1 and 3-2).

- Regarding groundwater supply, about 2,200 MCM of groundwater was abstracted annually in the UAE, to meet water demand during the 2010-2012 period, per local observed data.
- Regarding desalinated water supply, we estimate about 1,500 MCM of fresh water was produced from saline and brackish sources in the UAE during the 2010-2012 period, per local observed data.
- Regarding treated wastewater effluent, the data sources accessed were not able to offer an observed estimate of reuse volume.

In conclusion, comparing the water system model to historical conditions shows that the model can reproduce the physical reality of water supply and demand adequately. For this reason, it was considered a valid modeling framework to use in the exploration of future development scenarios.

4. The Policy Scenario Framework

The validated water system model for Al Ain region enabled analyzing the impact of potential policy scenarios that could promote the resilience of water and agriculture systems in the region in the face of climate change. Establishing a plausible policy scenario framework is fundamental for using the coupled model to explore challenges and opportunities for transitioning to more climate-resilient development paths. As described in the sub-sections that follow, this scenario framework is based on a set of underlying premises and demonstrates the modeling framework's ability to explore possible outcomes, such as the level of water use, the sustainability of groundwater systems, the measure of desalinated water needs, the amount of energy used in the water supply, etc. Two Business-as-Usual scenarios extend the past water supply and use patterns into the future; and a policy scenario assumes the gradual reduction in forestry and agricultural production in fodder in favor of date palm production and other high value crops (fruits and vegetables) that are consistent with the objective of trying to meet greater food requirements from local sources. A brief overview of these scenarios is provided below.

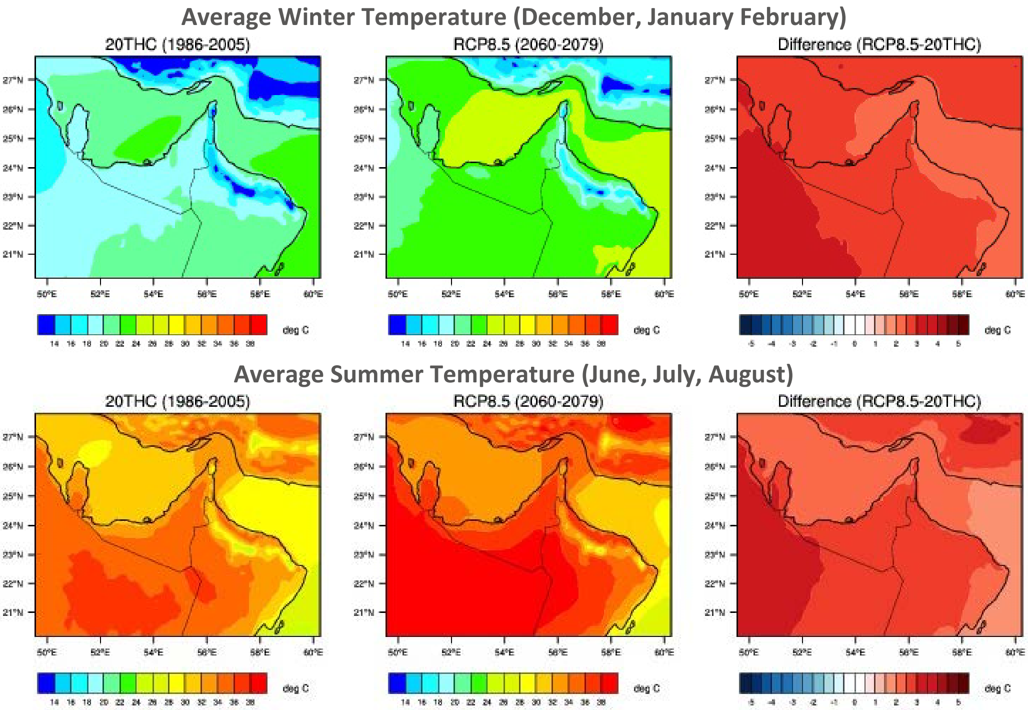
A Business-As-Usual (BAU) scenario assumes that the historic climate repeats itself into the future and the CO_2 concentrations remain at 2015 levels (415 PPM). A second Business-As-Usual also assumes the same level of resource use and activity, but applies the impacts of climate change based on the Intergovernmental Panel on Climate Change Representative Concentration Pathway (RCP) 8.5 as was simulated in the Regional Atmospheric Modeling project and represents a roughly 2.5°C increased in temperature and a 7% increase in annual rainfall by 2060. This scenario also includes CO_2 fertilization effects on the water and agricultural systems in the region (BAU-RCP85). Comparing the BAU-RCP8.5 and BAU scenarios reveals the impact of climate alone. In contrast, comparing the individual policy scenario to the BAU-RCP8.5 scenario reveals policy-only impacts relative to the same resource and environmental indicators where the climate change role has been eliminated.

4.1. Future Climate: Climate Change Projections based on Regional Climate Modeling Sub-Project Results

As part of a separate LNRCCP sub-project[3] regional atmospheric modeling for the Arabian Peninsula region was undertaken under conditions of climate change. Some of the outputs of this research were incorporated into the analytical framework to capture the impact of climate change on the supply and demand for water and energy resources. Two greenhouse

[3] Sub-project #1; Yates, et al., 2015. "Regional Atmospheric Modeling: Final Technical Report from AGEDI's Local, National, and Regional Climate Change Programme"

Figure 4-1: Future temperature around the UAE for the historical period (left maps), 2060-2079 under RCP 8.5 (center maps), and percent difference (right maps), averaged over winter (top) and summer (bottom) months.



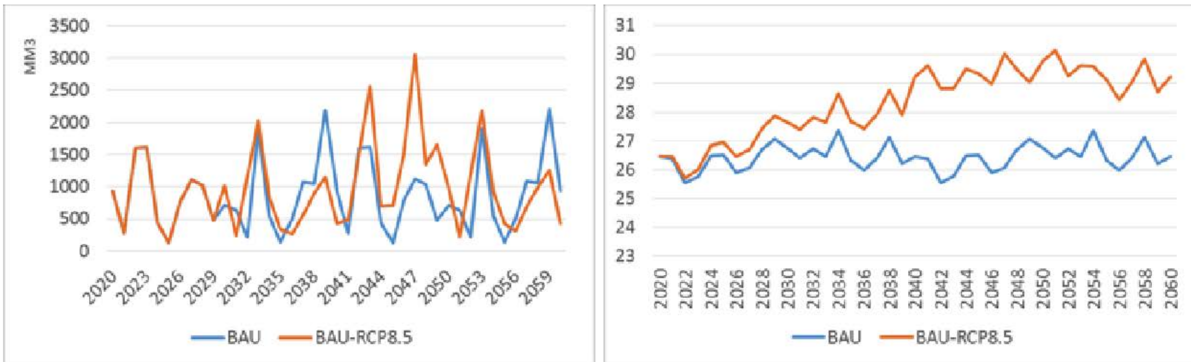
emission scenarios were modeled. One scenario assumed the RCP8.5, analogous to business-as-usual emissions; the other assumed RCP4.5, analogous to global greenhouse gas mitigation activities significantly limit the increase in greenhouse gas concentrations in the atmosphere. Average temperature impacts in the region from climate change are illustrated in Figure 4-1 for RCP8.5.

The results of regional atmospheric modeling were incorporated into the analytical framework of this Al Ain water and agriculture systems study.[4] This was an important consideration as an already hot region will become even hotter, leading to additional water requirements for end uses like irrigation to compensate for higher evaporation rates water, changes in agricultural productivity, and energy use for end uses like air conditioning. An algorithm was developed for, and incorporated into, the modelling framework that addresses the projected seasonal change in average temperatures. The WEAP PGM Al Ain model is run on a daily time step, and includes other meteorological variables such as rainfall, humidity, and wind speed.

The BAU-RCP8.5 scenario shares all the same key assumptions as the BAU scenario except for the role of climate change. From 2015 to 2030, it was assumed that the UAE's historic climate continues. For the period 2031 through 2060, climatic outputs from the regional

[4] For location-specific information about climate change in the Al Ain region, please see the Climate Inspector developed at an output of the regional atmospheric modeling sub-project, available at https://uae.rap.ucar.edu/uae.

Figure 4-2: Future precipitation (left) in millions of cubic meters and annual average temperature in °C (right) for the Al Ain region for the historic climate (BAU) and the future climate projection (RCP8.5).



atmospheric modeling sub-project were used to estimate outdoor irrigation requirements and the amount of rainfall for groundwater recharge in the Oman Mountains. These climate projections are from the regional atmospheric modeling sub-project and include monthly time series of total precipitation and monthly average temperature (see Figure 4-2 for a comparison of future climate trends relative to the historic average). Historic annual average precipitation over the Oman Mountain region is 125 mm, while the future projected annual precipitation is 185 mm per year. While the percent change is significant, the absolute precipitation in the region remains relatively small and with increased warming of more than 2°C by mid-century, the additional rainfall is mostly lost to increased evaporative loss.

4.2. The Business-As-Usual Scenarios

The Business-As-Usual scenarios include population and climatic assumptions that also apply to the policy scenario. The future population forecasts were taken from projections made by the United Nations (2015) and include a single population growth rate projection for the region over time. The UAE's population was estimated at about 9,300,000 in 2015 and is projected to grow to 13,500,000 by 2060 (1.8% per year), with Al Ain growing from 700,000 to about 1.2 million by 2060. Two future climate forecasts (i.e., total precipitation, average annual temperature) were taken from the outputs of LNRCCP sub-project #1 (Yates, et al., 2015): extension of climatic trends for the 1985-2004 period through 2060 and the IPCC's RCP8.5 projection which assumes a global business-as-usual trajectory of greenhouse gas emissions and their resulting concentrations in the atmosphere.

On the other hand, the two (2) BAU scenarios are characterized by resource use trends that are distinct from the policy scenarios. Both the BAU scenario and the BAU under climate change (hereafter: "BAU-RCP8.5) scenario continue past resource use with respect to water and consumption on a per-capita basis, and the technologies associated with their production and delivery. Specifically, this refers to the range of indicators evident in the historical period; e.g., water use per capita, and water use per area based on the activity type (e.g. outdoor, amenity, agriculture, or forestry). These are all assumed to maintain their historical growth levels, with no new policies that would influence water and energy use trends to 2060. Comparison of current and future climate given as the total annual precipitation for the 15 wadis and annual average temperature are shown in Figure 4-2. It is important to note that the total annual precipitation falling on these wadis is less than the total annual water use in the country.

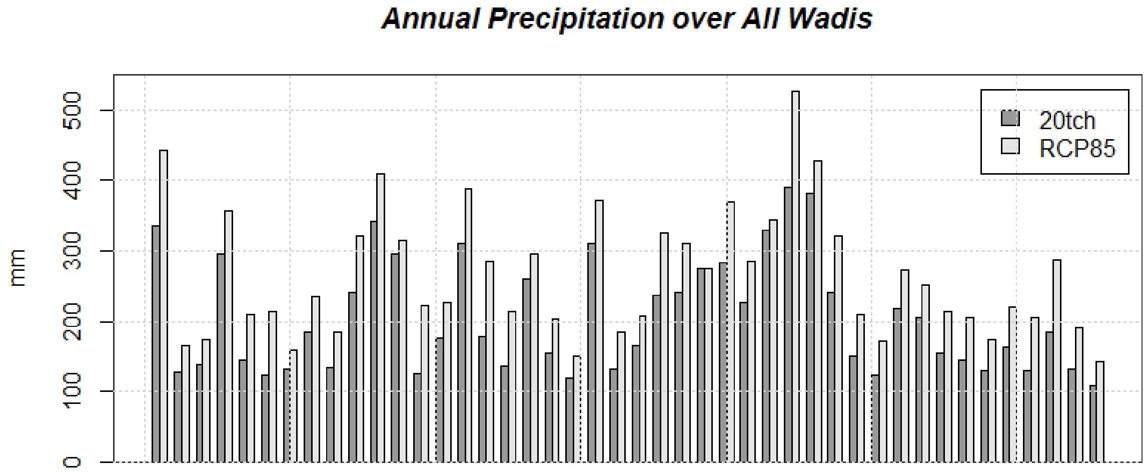
For the BAU scenario, key assumptions are as follows:

- *Climate change.* Not considered.
- *Water use growth In Municipal and Industrial Uses.* For the municipal and industrial water sector, indoor per-capita use remains constant at about 200 liters per capita per day. Population grows from about 700,000 to over 1,000,000 by 2060, while outdoor and amenity area are assumed to grow at a rate of 1% per year for the period 2015 to 2060, with no change in irrigation practice.

For the BAU-RCP8.5 scenario, the key assumptions include:

- *CO_2 concentration:* an increase in atmospheric CO_2 concentrations, increasing from about 410 PPM in 220 to 540 PPM in 2060.

Figure 4-3: Twenty year, annual average precipitation based on the regional climate modeling output for each wadis over the Oman Mountain study region for the 20th century period (20thc) and future period (RCP8.5).



- *Climate change:* Future climate has a 2.7°C increase in average daily temperature by 2060; and an increase in total rainfall. The 20 year, annual average estimate of historic rainfall over the eastern wadis was 200 mm, while the 20 year future projected rainfall for the same region was 265 mm or an increase of about 23%. Figure 4-3 compares the annual average precipitation of the 20th century historic period (20thc) with the future projected precipitation (RCP8.5) for each of the wadis in the model domain. The variability of the rainfall demonstrates the regional climate models ability to capture important topographic gradients across the study domain (see Figure 4.1). Also, wadis with greater precipitation associated with higher altitudes show a proportionality greater amount of rainfall.

Table 4-1: List of policies analyzed in Policy Scenarios

Policy Scenario	Policy Objective
FallowFF	Reduction in these subsidized water sectors which are using fossil groundwater well below the market value. Date Palm, vegetable and fruit production are substituted such that the water saved in the forestry and fodder sector is used by the agricultural sector. Reduction in Forestry and Fodder and an increase in higher valued crops under irrigation.
GWStabilize	Maintaining groundwater levels in a near steady-state condition over a prolonged period of time, by finding the level of imported desalinated water and amenity and outdoor water use that tends to maintain groundwater levels at a constant elevation; while simultaneously strategically using the desalinated water that becomes recharge to this alluvial aquifer system.

4.3. The Policy Scenario: Reduction in Forestry and Amenity Use in favor of Irrigated Agriculture.

We have implemented two policy scenarios to illustrative and demonstrate the kind of analysis that is possible within the WEAP Al Ain modeling framework. As a first policy scenario for this Final technical report, we have assumed that the forestry and fodder productions activities decline linearly from their current levels, which are assumed to exist in 2015 and then are completely removed by 2060 (Table 4-1). Then, using a substitution-of-service assumption, we estimate the total water savings over the 40-year period as forestry and fodder production are phased out. We then assume that the volume of water is available for the higher valued agriculture products (Date Palms, vegetables, and fruits) and we iteratively run the WEAP Al Ain model to find the additional agricultural area that could be put under production and use the equivalent amount of water. We report the additional agricultural production in terms of metric tonnes of output. We have named this scenario Fallow Fodder and Forests or abbreviated as *FallowFF*.

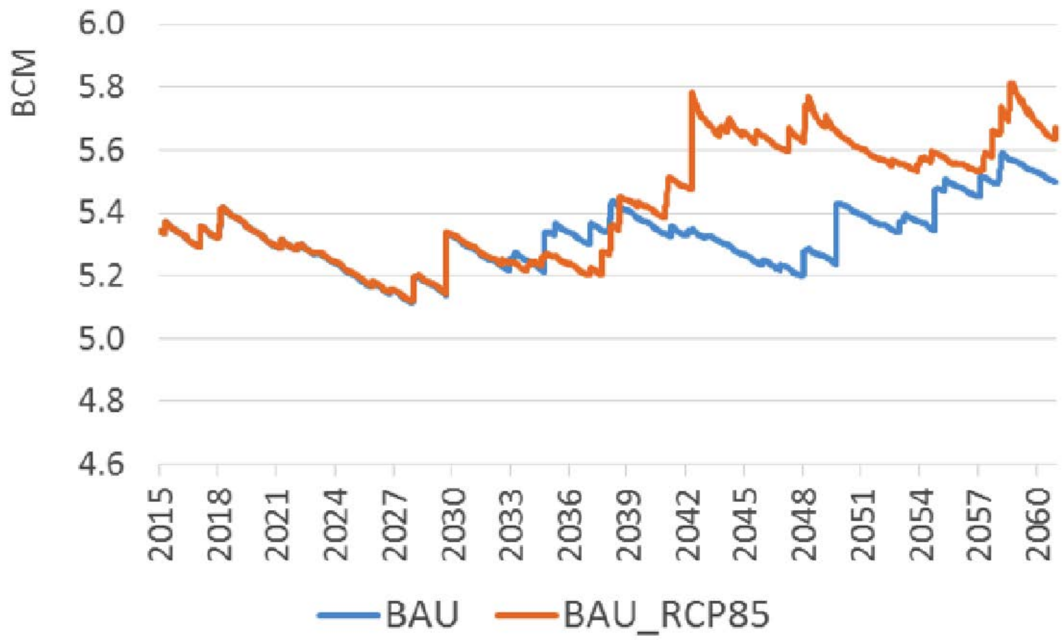
A second policy scenario (*GWStabilize*) aims to stabilize the alluvial groundwater levels in and around the Al Ain region. The importing of desalinized water and its use for outdoor gardens, parks, amenity spaces, and agriculture has led to locally elevated GW; while in some areas, over exploitation of groundwater has led to dramatic groundwater level drawdowns. In the UAE, there are ongoing discussions regarding the use of desalinated water as a strategic reserve through injection in local groundwater systems. In this scenario, we explore what level of groundwater use of and corresponding decrease in imported desalinated water is achievable to maintain GW in a steady state condition. We have labeled this scenario the Groundwater Stabilization scenario and abbreviated as the *GWStablize* scenario. It is important to note the relative scale of the various water sources, as current estimates are that more than 200 MM3 of imported desalinized water are brought into the Al Ain region, nearly 1,000 MM3 are use annually in the region, and about 50 MM3 to 100 MM3 are currently considered as a renewable supply.

This scenario would imply an adaptive management strategy to maintain the alluvial aquifer system in the region, with an enhanced monitoring system that would track the groundwater condition and act accordingly. If local wells were being drawn down to quickly, then a greater fraction of desalinated water could be used, while if it was wet period and groundwater wells were showing signs of an elevated position, then they could be pumped more aggressively, reducing the desalinated imports.

5. Baseline Scenario Results

This section provides an overview of the results for the *BAU_RCP8.5* scenario. The BAU-RCP8.5 scenario incorporates the impact of climate change and is the baseline development scenario against which the policy scenarios are compared. It is important to note that the results of the BAU scenario are not presented to simply focus on the relative benefits associated with various policies and development pathways, rather they are also presented to understand the relative impacts of a changing climate. For this reason, this subsection provides a summary primarily focused on the impacts of climate change.

Figure 5-1: Projections of future groundwater storage of the three alluvial aquifers for the Al Ain region for the BAU and BAU-RCP8.5 scenarios.



5.1.Water supply

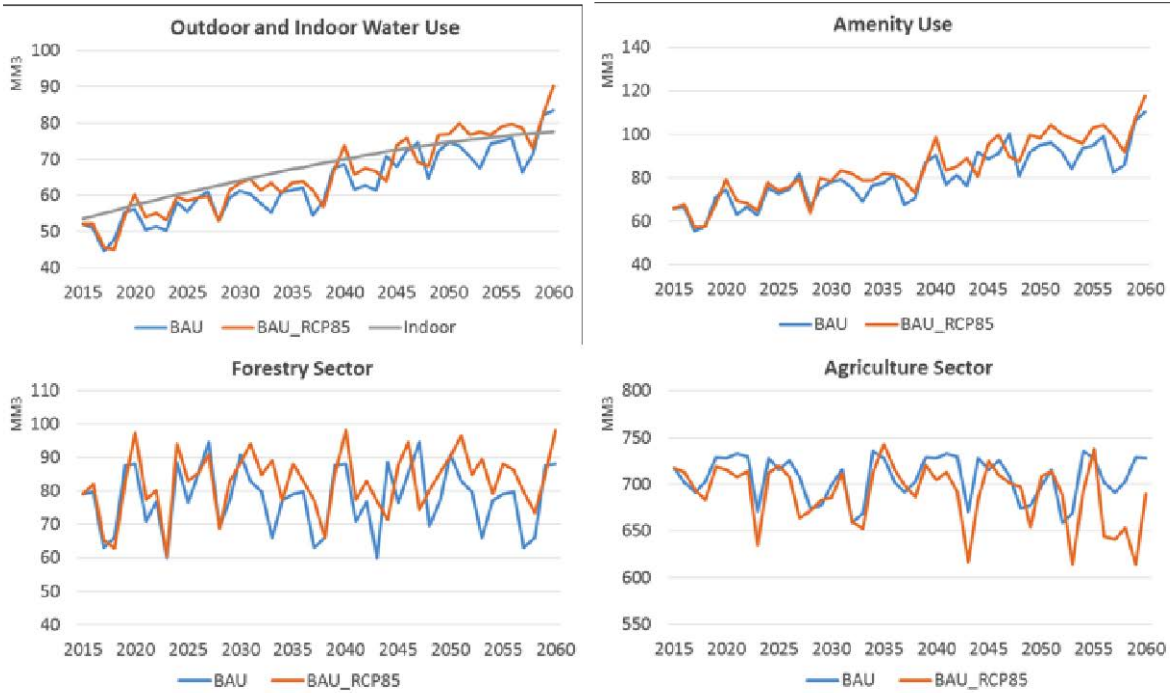
On the water supply side, key trends are evident from a review of Figure 5-1, which shows the projection of future storage in the alluvial groundwater aquifer under the BAU and BAU-RCP8.5 scenario. The BAU scenario shows an overall declining trend, as water use generally leads to reductions in groundwater storage, with fresh groundwater continuing to supply about 6% of the total water used in the region. Under the BAU-RCP8.5 scenario, the increase in rainfall tends to stabilize the surficial aquifer over the study period, suggesting that greater rainfall in the region has resulted in enhanced recharge. In fact, the stabilization of the groundwater suggests that water use at about 6% of total use would results in a sustainable groundwater level, with the knowledge that this groundwater level is significantly supported through the desalinization imports. Under the both the BAU and BAU-RCP8.5 scenario, the use of desalinated water has grown from about 200 MCM in 2015 to 260 MCM by 2060.

5.2.Amenity, Forest, and Municipal Water Use

On the water demand side, several key trends are evident from a review of Figure 5-2. First, agricultural and forestry water demands remain considerably larger than indoor and outdoor water use combined, in absolute terms. By 2060, agricultural water demand is about 800 MCM compared to 150 MCM for indoor and outdoor water use or more than five times more. Second, under BAU assumptions, the share of indoor and outdoor water use increases from about 10% of total demand in 2015 to 13% by 2060; while the share of agricultural water demand decreases from 65% of total demand in 2015 to 61% by 2060. Third, amenity water demand share grows over the 2015-2060 period, driven by the assumption that the growing population seeks greater opportunity for outdoor recreational opportunities in green spaces (parks and turf fields). Over this same 2030-2060 period, indoor, outdoor, and amenity water use grows by just over 0.6% per year as shown in Figure 5-2 While the climate does warm, note that agricultural water demands decrease slightly due to warmer conditions resulting in harvested production coming sooner. This is largely an agricultural management outcome, and is addressed more fully in the policy scenario analysis. In the forest sector, climate change results in an approximate 5% increase in annual water use overall.

The impact of climate change on the water and agricultural systems of the Al Ain Region can be seen by comparing the BAU-RCP8.5 scenario (with climate change; no policies) with the BAU scenario (without climate change; no policies). Several conclusions may be offered as outlined in the bullets below. The next section discusses selected impacts of climate change; complete details of the analysis of the BAU scenarios are available by accessing the WEAP Al Ain water and agriculture systems model that is available on the Al Ain Inspector at http://www.ccr-group.org/al-ain-home.

Figure 5-2: Projections of future water use in the Al Ain region for the BAU and BAU-RCP8.5 scenarios.



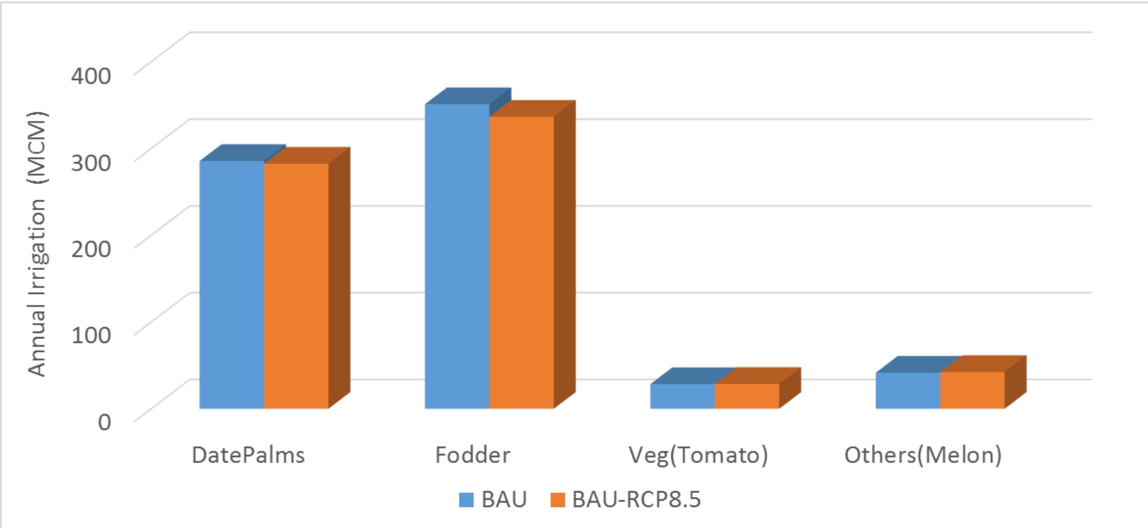
- *Water consumption:* If practices and methods of irrigation remain the same, climate change will cause annual increases in water use for the forestry, amenity, and outdoor water use sectors. Increases are on the order of 5% by 2060, as warming conditions create slightly greater demand for water. However, agriculture uses do not increase due to efficiencies from CO_2 fertilization effects, which lead to more production over a shorter growing season. The new water use in the region is about 1.35 BCM in the BAU and BAU-RCP8.5 scenario.
- *Groundwater levels:* Wetter conditions in the Al Ain region could help support recharge of the alluvial aquifers. The precipitation in the BAU-RCP8.5 scenario assumes an annual increase in precipitation of 13%, leading to a near doubling of annual average recharge, increasing from 58 MCM to about 100 MCM. However, art of this increase is attributed to increased imports of desalinated water.

5.3.Agriculture Water Demand

Additional focus in the analysis is on the water used in agricultural production, given that it is the biggest water use, and is of critical importance in national water policy. The plant growth model first calculates the plant transpiration (potential evapotranspiration and actual evapotranspiration) using the Penman-Monteith equation (see earlier Figure 3-2). Through the implementation of Penman-Monteith, crop irrigation demands are defined. In Figure 5-3, the total annual irrigation by crops is shown for the BAU and BAU-RCP8.5 scenarios where 836 MCM of irrigation is applied during the BAU scenario compare to 815 MCM of irrigation is needed in the BAU-RCP8.5 scenario. A 2.5% decrease in irrigation can be observed mainly due to changes in fodder crop (Figure 5-3). The fodder crop accumulates heat units more rapidly under the RCP-8.5 scenario due to warmer conditions shortening the fodder's growing season and consequently the irrigation demand is less as it is shown in Figure 5-3. Heat units represent an agricultural management action that defines the pace at which crop growth internally in the PGM model. In other words, heat units are the driver of plant's growth. It's important to mention that irrigation demands seems to be less in the BAU-RCP8.5 scenario with respect to BAU however, if farmers have the same growing season's length in the future, irrigation demands will be greater than the BAU scenario irrigation demands.

Dividing the actual evapotranspiration by the potential evapotranspiration defines the water stress factor. A water stress factor of one means no water stress at all and a value of zero indicates full water stress acting on plants. The model was set up to provide all the water needed for irrigation in vegetables and other crops so these two crops are not under any

Figure 5-3: Total annual irrigation in MCM for the agricultural sector represented in the Al Ain WEAP model under the BAU and BAU-RCP8.5 scenarios.



water stress. However, date palms and fodder experience some level of water stress as it is shown in Figure 5-4. Date palms and fodder experience the strongest water stress during mid-summer when temperatures are at their highest. Water stress reduces canopy development and consequently plant biomass production is affected and consequently crop yields are reduced.

Similarly temperature stress was calculated by PGM and it can be observed in Figure 5-5 that under the BAU-RCP8.5 scenario, date palms experiment less temperature stress from November to April. Since the optimal growth temperature for date palms is 32^{o}C, the temperature stress that the crop experiment during these months is due to cooler temperatures. We can observe a similar trend in fodder however, for fodder in the BAU-RCP8.5 scenario during mid-summer, the crop are affected by the mid-summer heat. During the months of July and August, temperature stress increases due to heat. The optimal growth temperature for fodder implemented in the PGM model is 30^{o}C, two degree Celsius less than date palms. Temperature stress also constrains the plants' transpiration, canopy development and crop yields. According to PGM and the temperature data for the BAU-RCP8.5 scenario, fodder crops might be affected in the future due to the heat.

Figure 5-4: Water stress factor for date palms and fodder. A value of one means no water stress and zero means full water stress.

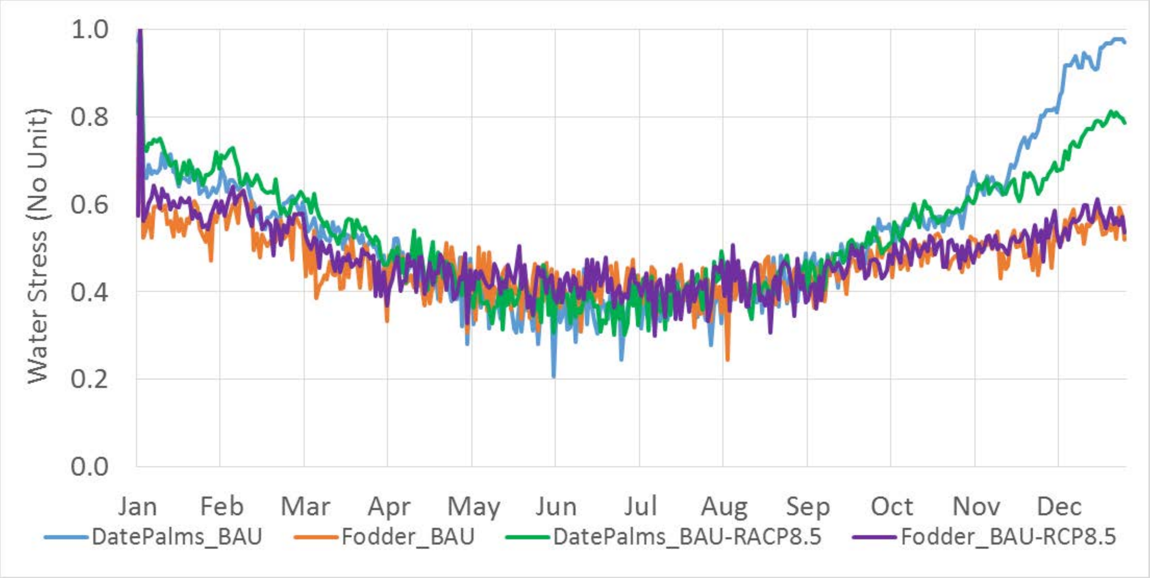
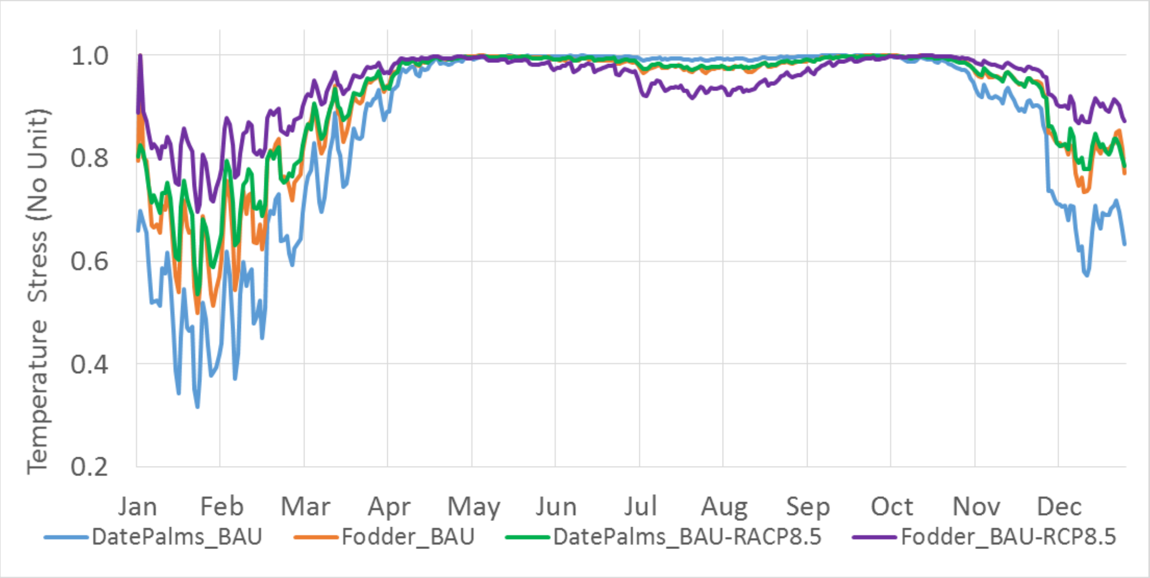
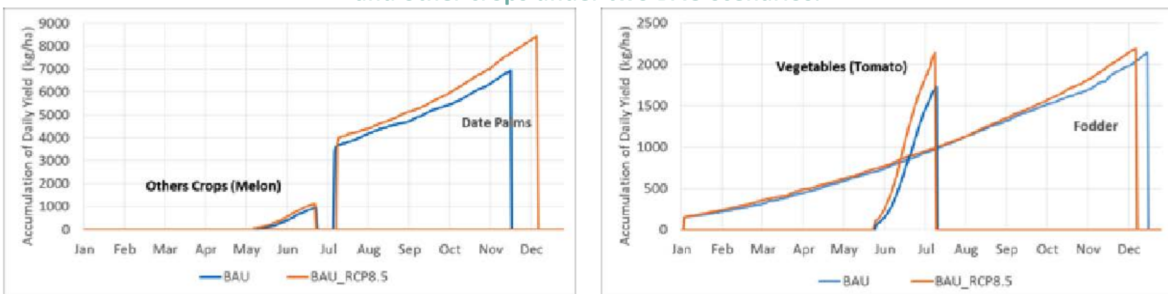


Figure 5-5: Temperature stress factor for date palms and fodder. A value of one means no water stress and zero means full temperature stress.



As water and temperatures stresses have been described and the direct effects on agricultural crops have been mentioned, it is now interesting to observe how these two factors combined are affecting the crop yields. Figure 5-6 shows the accumulation of daily crop yields for the four crops implemented in PGM. In the left plot, date palms crop increase due to the difference in harvest season. Under the BAU scenario, harvest occurs on mid-November and under the BAU-RCP8.5 scenario harvest happens by December 10^{th}. This shows that crops under BAU-RCP8.5 scenario (specifically date palms) can accumulate more heat units due to warming conditions and have a longer growing season. A longer growing

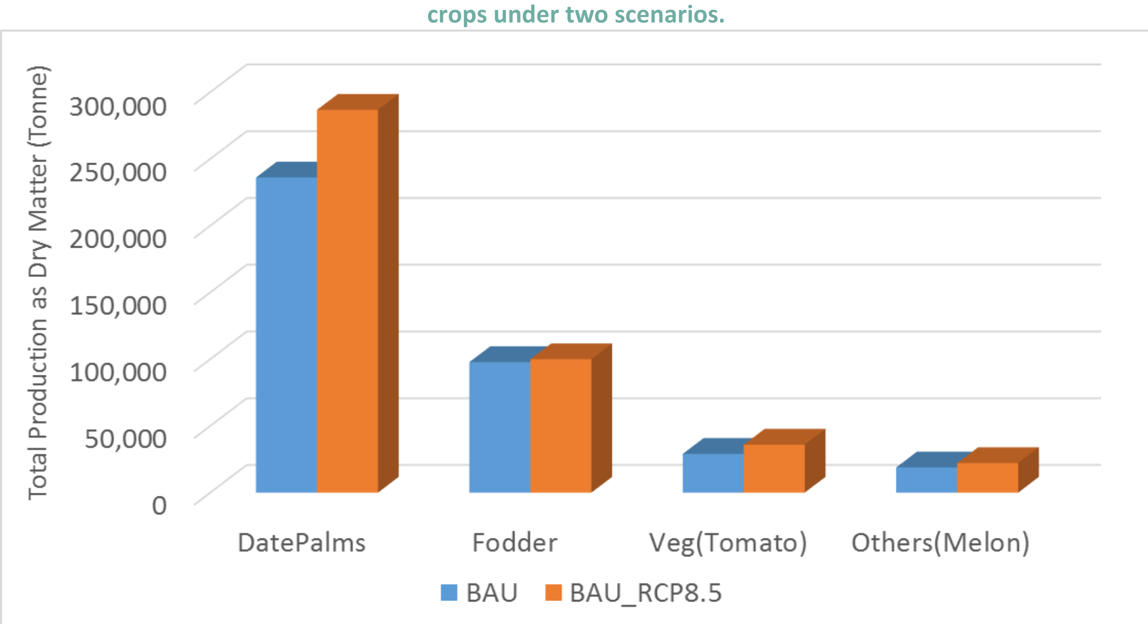
Figure 5-6: Accumulation of daily crop yields in kilograms per hectare for date palms, fodder, vegetables and other crops under two BAU scenarios.



season implies larger agricultural yields if conditions are favorable for crops. In this specific case, date palms have a 7% increase in commercial yield. A similar trend can be observed in fodder. However, for other crops and vegetables, it seems that there are not significant differences under these two scenarios. It is important to highlight that atmospheric CO_2 concentration is playing an important role in these results. Atmospheric CO_2 concentration would increase the production of biomass due to carbon fertilization depending on the type of crop under study. An example is the date palms that have higher crops yields due to a combined effect of a longer growing season and the carbon fertilization.

Now we can examine a larger scale and determine the potential effects of future climate and atmospheric CO_2 concentrations in the Al Ain regional agricultural sector. In Figure 5-7 it can be observed that date palms' production may increase in the future under these conditions. A potential increase of almost 50,000 metric tonnes of date palms fruits can be observed in the Al Ain agricultural sector. This means an increase of about 20% production. In the other hand, fodder may present a minor increase in production of about 2%. Vegetables

Figure 5-7: Total commercial crop production in tonnes for date palms, fodder, vegetables and other crops under two scenarios.



and other crops may experience changes in production in the order of 24 and 17% respectively respect to the BAU scenario.

6. Policy Scenario Results

This section provides an overview of the results for the policy scenarios, which explore 1) A policy that phases out the forestry and fodder production sectors in favor of higher valued agricultural commodities such as date palms (i.e. *FallowFF*) . This scenario largely impacts the regional brackish aquifer and explores what level of additional agricultural production could be realized if the forestry and fodder sectors were slowly fallowed over the 40-year time horizon. 2) A local policy scenario which explores

6.1. The *FallowFF* Policy Scenario

In addition to impacts on the forestry and agriculture sectors, the *FallowFF* scenario incorporates the impact of climate change and can be directly compared to the BAU-RCP8.5 scenario to estimate the impact of the policy scenario net of any climate change impact. Figure 6-1 shows the declining trend in the fodder area and the growth in the Date Palms, Vegetables, and Fruit production. The net planted area increases from about 60,000 ha to 90,000 ha, while the forested area under irrigation decreases from 100,000 hectares in 2015 to being fully fallowed. The fallowing of forests and fodder results in about 12 BCM of water savings over the fully 40-year analysis period. Figure 6-2 shows the increase use of water for the higher valued agricultural goods and the decrease in water use for fodder.

Figure 6-1: Planted area evolution in the Policy Scenario for date palms, fodder, vegetables and other crops.

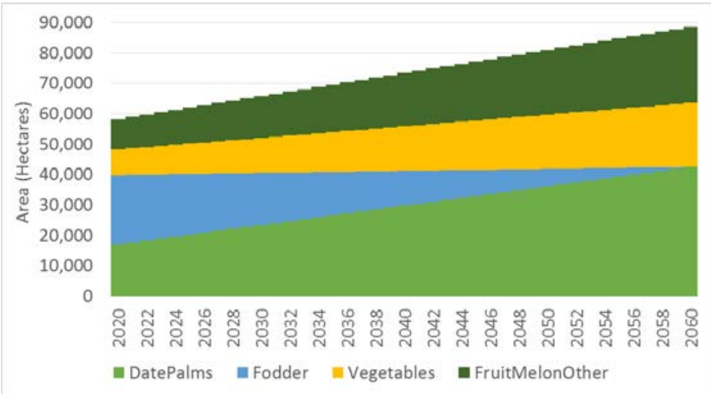
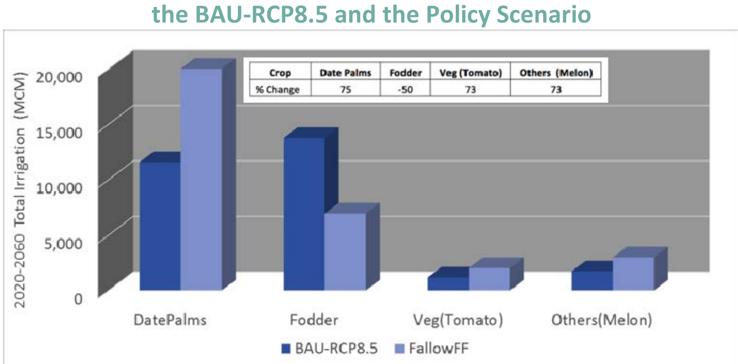


Figure 6-2: Total irrigation for the 2015-2060 period by crops for the BAU-RCP8.5 and the Policy Scenario



The total area in production of higher valued agricultural commodities, including date palm, vegetables, and other crops can grow by 2.5 times over the 40-year period, which would result in an increase of 12 BCM water used over the period. This relative increase in water used for those three agricultural commodities counters the reduction in water use for the forest and fodder sectors.

Figure 6-3 show the level of water use by various sources for the BAU and the Policy Scenario (labeled as the "FallowFF"). Note the nearly identical use of groundwater among these scenarios, where the explicit policy here is the gradual fallowing of trees and fodder in favor of higher valued agricultural commodities using an equivalent amount of water. Figure 6-4 shows the resulting increase in agricultural production under this policy scenario, where Date Palms increase by 75%, vegetable and fruits and other commodities production by 73% in terms of production in units of metric tonnes. These increases in production would require about 2.5 times more area under cultivation needing about 4 BCM of water over the 40 year planning horizon, for these higher valued commodities, with an attending fallowing of forests and fodder over the same period.

Figure 6-3: Total irrigation by source for the 2015-2060 period for the BAU-RCP8.5 and the Policy Scenario

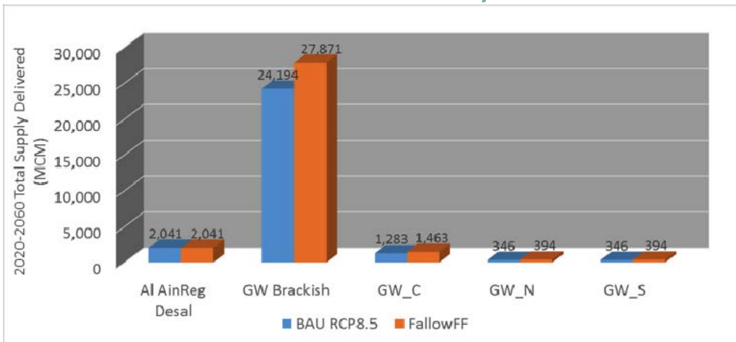
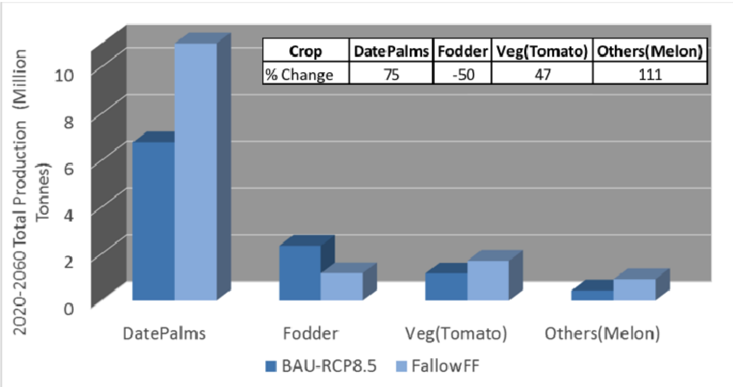


Figure 6-4: Total agricultural production for the 2015-2060 period by crops for the BAU-RCP8.5 and the Policy Scenario.



6.2.The *GWStabilize* Scenario

This policy scenario explores the evolution of the Al Ain alluvial aquifer over the coming decades, within the context of regional population growth, water demand growth, and climate change. As noted previously, the regional alluvial aquifer is the only renewable water supply in the region, and through many years of study over the previous few decades, has shown considerable heterogeneity in terms of groundwater levels, with some regions exhibiting dramatic drawdown of groundwater levels, while others have revealed local phenomena, such as elevated groundwater levels which have caused local problems to infrastructure. While the reason for these elevated groundwater levels are not precisely known, the fact that hundreds of millions of cubic meters of desalinated and brackish water are used in a region with a relatively shallow alluvium, suggests that groundwater levels can fluctuate significantly and could be the cause of local groundwater problems (see earlier Figure 2-3).

Under this *GWStablize* scenario, we first looked at the dynamics of the alluvial aquifers (GW_N, GW_C, and GW_S) relative to their response under the BAU_RCP8.5 scenario, which we show earlier in Figure 5-1 and now in Figure 6-5. Figure 6-5 shows the groundwater storage for all the scenarios (except *FallowFF*), including an estimate of the pre-development, steady-state condition under current and future climate. This demonstrates that in the more wet conditions projected under future climate change, there is an increase in the overall groundwater storage of about 150 MM3, enhanced through an increase in annual average recharge from about 60 MM3 to 90 MM3. Thus, climate change represents an increase in the potential annual sustainable water supply from the alluvial aquifer of about MM3. Note that this still represents only 14% of the imported water and less than 5% of total annual use, and thus desalinated imports would remain a large share of the total water supply.

Figure 6-6 shows the annual desalinated water use for all agriculture, amenity, indoor and outdoor uses for the business as usual scenarios and the *GWStabilize* scenario. The total annual desalinized production grows from about 220 MM3 in 2015 to nearly 360 MM3 due to both population growth and an increase in outdoor and amenity watering.

Figure 6-5: Annual storage of the alluvial aquifer for all scenarios, with the *GWStabilize* scenario shown in yellow.

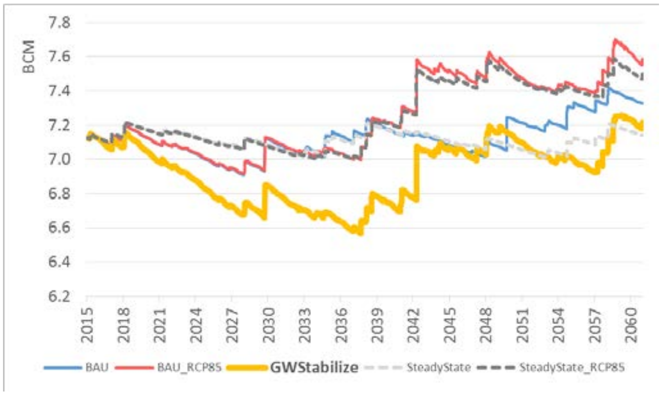


Figure 6-6: The annual production and use of desalinated water for agriculture, amenity, indoor, and outdoor use for the BAU scenarios and the *GWStablize* policy scenario

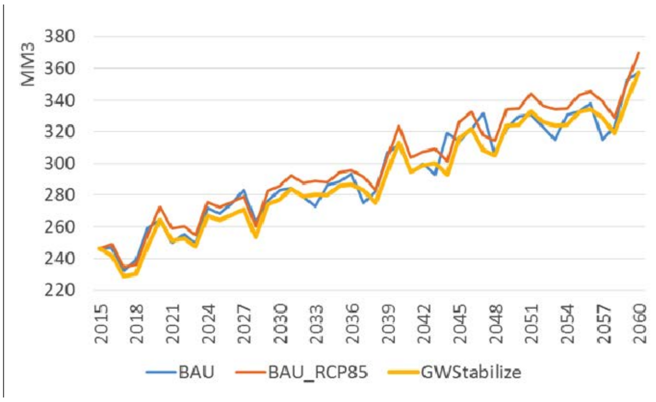
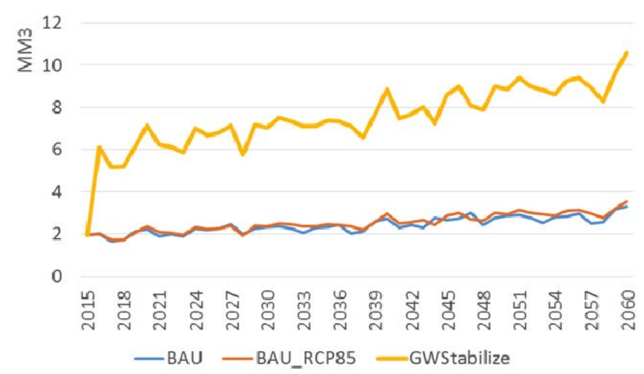


Figure 6-7: Plot of water delivered by the three alluvial aquifers (GW_N, GW_C, and GW_S) to supply a portion of the water supply to the Al Ain region to maintain a relatively constant volume over time



While the separation of the *BAU-RCP8.5* and the *GWStablize* scenarios are modest, the total savings of desalinated water over the 45 year planning horizon amounts to 400 MM3 of saved water. This amount of water would require 5,200 kWh of energy for its production assuming 13 kWh/m^3. Assuming that there are 7.03 × 10-4 metric tons CO2 per kWh, the reduction in desalinized water would result in a carbon savings of about 3.7 million tonnes (MMT) of CO2 equivalent over the 45 year period. The current estimate of UAE greenhouse gas emissions is about 200 MMT with electricity and water generation accounting for the bulk of emissions, at 33 per cent or 65 million tonnes of greenhouse gases. This savings estimate does not include the marginal energy costs for the increased in groundwater pumping from the alluvial aquifer that would occur. Figure 6-7 shows the corresponding increase in pumping from the alluvial groundwater aquifer, noting an annual pumping of about 6 MM3 around 2020, which grows to about 10 MM3 by 2060. We assume this pumping would begin at the beginning of the scenario and grow over time in response to increase demand and availability due to climate change. Note that the relative impact of climate change on groundwater pumping is modest, with a total increase of less than 5% over the study period, driven by increase in water demand caused by the warmer conditions.

7. Conclusions and Recommendations

We have developed a water systems model of the Al Ain region, with a focus on the sustainability of the near surface, unconsolidated aquifers, which are the primary source of the renewable water of the region. The modeling platform is the Water Evaluation and Planning (WEAP) decision support system. The use an integrated modeling framework to explore the tradeoffs among various water sources was demonstrated, and shows that tradeoff analysis between desalinization and groundwater extraction can be evaluated.

Our models of water demand include climate dependent factors, as climate is a major determinate of outdoor water demands for amenity landscapes, gardens, etc. and agricultural. The country is generally characterized as hyper-arid, receiving very little rainfall which can be used to satisfy irrigation demands. The future climate projection applied in this study is characterized by warmer temperatures, with regional mean temperatures more than 2.5^{o}C warmer and mean humidity increasing by nearly 10% by 2060. Projections of future rainfall based on results from Global Climate Model output suggests increases in rainfall, but the change is small relative to the increasing temperature and does little in the way of satisfying overall irrigation requirements or serving as a source of groundwater recharge.

We have demonstrated how the WEAP modeling framework can be used to evaluate various future water use and supply policies in the Al Ain region. The brackish groundwater is likely sufficient to continue to provide for amenity and forestry sectors, but increased use will likely produce increasingly brackish water. Major highlights of the study results are presented in Table 7-1. Key findings are briefly summarized in the bullets below.

- Groundwater in the region is dominated by non-renewable, fossil sources mainly serving the agriculture and forestry sectors, while the bulk of municipal and industrial water is supplied through desalinization. Historically, most seawater desalinization has been made using energy intensive, fossil fuel based technologies, although it is commonly co-

Table 7-1: Policy scenarios: Summary of Results

Policy Scenario	Results
BAU-RCP8.5	Outdoor water consumption increases in 5% by 2060 however, agriculture uses do not increase due to efficiencies from CO2 fertilization effects and shorter growing seasons. Water use in the region by 2060 is about 1.35 BCM. Annual increase in precipitation of more than 10%, doubling the annual average recharge, from 58 MCM to about 100 MCM.
FallowFF	This scenario shows how the fallowing of forestry and fodder production could save 10 BCM of water over the 45-year analysis period. Production of higher valued agricultural commodities, including date palm, vegetables, and other crops could double with this water due to the compensatory increase of 10 BCM of equivalent water reduced by fallowing forest and fodder. Agricultural production grows from 9 MMT in the bAU-RCP8.5 scenario to 13.7 MMT or a 55% increase.
GWStabilize	This scenario demonstrates how the alluvial groundwater system could be sustainably managed by conjunctively using it along with desalinated water. However, these renewable groundwater sources would remain a relatively small portion of overall use (e.g. 8 MCM to 10 MCM annually). Strategic groundwater use could reduce desalinated imports and circumvent problems of locally elevated groundwater, which could be exacerbated under a future climate with wetter conditions and thus greater groundwater recharge.

generated at power plants whose priority is to first generate electricity, but the waste heat is then used to produce water.

- **Renewable groundwater supply is very marginal in the Al Ain region relative to total water demand**. While changes in policy around the forestry and agricultural sectors could have impacts on the brackish groundwater supplies, the only way for the freshwater system to be sustained is through more targeted actions at the local level.
- While the future viability of the forestry and fodder sectors in the harsh desert climate of the UAE is one that is commonly debated, alternative uses of water can be readily assessed within a water and climate change modeling framework. We have demonstrated with an integrated modeling tool, the capability of evaluating alternatives in terms of water savings and the equivalent production of higher valued commodities such as date palms was explored.
- It is highly likely that the importation of desalinated water causing elevated groundwater levels due to use municipal and industrial uses, perhaps even from water leaks from the distribution system. This water can be exploited locally to serve agricultural interest and perhaps lead to reduced groundwater levels in places where elevated water tables are actually a threat to infrastructure.
- The *GWStabilize* scenario demonstrates the possibility of 'win-win' outcomes in terms of stabilizing the local groundwater system by conjunctively using it along with desalinated water. Future climate change shows more wet conditions, which could be used to strategic advantage to periodically reduce desal imports in favor of local alluvial groundwater.

Key knowledge gaps are summarized in the bullets below.

- The data are generalized and could be further developed and explored and the analysis and results analyzed with greater scrutiny. Data regarding indoor use is assumed on a per-capita basis, and the area irrigated for outdoor and amenity uses was approximated from aerial maps and images, and could be further corroborated.
- The groundwater model applies simple first principles of groundwater flow, making use of Darcy's law to characterize the near surface alluvial aquifer that was considered in this study. More detailed groundwater modeling could add credibility to the simplified groundwater modeling assumptions.
- The sensitivity of the crops grown in the region to elevated CO2 in field conditions is not known with certainty. The Plant Growth Model (PGM) in WEAP does exhibit sensitivity to elevated CO2 in in terms of yield, particularly for date palms. This sensitivity could be studied in greater detail.
- That said, the study represents a first-order representation of the overall water supply and demand for the Al Ain region, and demonstrates how detailed modeling of agricultural commodities can be used to better understand the water supply-demand balance.

Key recommendations are summarized in the bullets below.

- To ensure the stability and sustainability of groundwater resources, a restructured monitoring program would be helpful in managing these shared resources under climate change. The results of the study demonstrate that by actively monitoring groundwater levels, building the infrastructure to take advantage of the near surface alluvial aquifers, these aquifers could act as a strategic reserve or serve to reduce the imports of desalinated water.
- Sensitivity analysis should be conducted to explore a greater range of relevant policy scenarios for the region. It would be very useful to continue to develop the water and climate change modeling capabilities with a broader array of stakeholders, where the tools could be used to explore additional targeted questions and regional differences.

8. List of references

AGEDI, 2016a. "UAE Water-Energy Nexus & Climate Change: Preliminary Findings from AGEDI's Local, National, and Regional Climate Change Programme", prepared by Francisco Flores, David Yates, and Stephanie Galaitsi, April.

AGEDI, 2016b. "UAE Water-Energy Nexus & Climate Change: Draft Visualizations from AGEDI's Local, National, and Regional Climate Change Programme", prepared by Francisco Flores, David Yates, and Stephanie Galaitsi, October.

ASR. UAE (2014). Ministry of Energy.

Baker, M. and M. Gabr 2010, Groundwater Level Prediction at a Pilot Area in Southeastern Part of the UAE using Shallow, Seismic Method, *International Journal of Environmental and Earth Sciences,* 1:1 2010

Bright, D. and Eggleston, J. 2016, Groundwater Flow in the Eastern Abu Dhabi Emirate, via Personal Communication.

Bright, D., and E. Silva, 1998: Hydrogeology of the surficial aquifer system in northeastern Abu Dhabi, UAE, US Geological Survey Administrative Report, Prepared for the National Drilling Company, Abu Dhabi, UAE.

Brook, M. C., et al. (2006) Groundwater Resources; Development and Management in Abu Dhabi Emirate, UAE. In: Proceedings of 3rd Joint UAE-Japan Symposium, Sustainable GCC Environment and Water Resources, EWR, 2006.

Dawood, M. (2010) EAD.

Dubai Water and Electricity Authority (2016), Annual Statistics.

Edson, J., Ferraro, B., and Wainer, I., 2015. "Desalination and Climate Change", Final Technical report, Sub-project #10, Abu Dhabi Global Environmental Data Initiative,

Elshibli, Sakina, E. M. Elshibli, and H. Korpelainenl, 2016, Growth and photosynthetic CO2 responses of date palm plants to water availability, Emirates Journal of Food and Agriculture. 2016. 28(1): 58-65.

Environment Agency-Abu Dhabi (EAD). 2009. Climate Change: Impacts, Vulnerability and Adaptation, Abu Dhabi, United Arab Emirates

Environment Agency Abu Dhabi. 2015. Economic Valuation of Groundwater in the Abu Dhabi Emirate. APPENDIX C: METHODOLOGY FOR ESTIMATING GROUNDWATER VALUES FOR THE FOREST SECTOR. RTI Project Number 0214219.001.001. Contract Number: PCD/ZK/IEPP/064/2013

FAO AQUASTAT. 2008. United Arab Emirates. Irrigation in the Middle East region in figures – AQUASTAT Survey 2008. http://www.fao.org/nr/water/aquastat/countries_regions/are/index.stm

Government of Abu Dhabi. 2014. CLIMATE CHANGE STRATEGY FOR THE EMIRATE OF ABU DHABI (2015-2019). A High Level Strategy and Action Plan for the Efficient Management and Conservation of Water Resources.

GTZ/Dornier Consult/ADNOC (2005) Combined artificial recharge and utilization of the groundwater resource in the Greater Liwa Area. Pilot Project Final Technical Report.

Gulf News, 2010, Probe ordered into drastic rise of groundwater table in Al Ain, News Report.

Imes, J.L., Signor, D.C., and Woodward, D.G. (1993), Hydrology and water quality: In: Groundwater resources of the Al Ain Region, Abu Dhabi Emirate, (ed., by D.V. Maddy) USGS Survey Administrative Report, 93-1., Prepared for the National Drilling Company, Abu Dhabi, UAE pp. 168-283.

International Energy Agency. 2015. Projected costs of generation electricity. Organisation for Economic Co-operation and Development/International Energy Agency.

Jamal Salem. DATE PRODUCTION AND MARKETING IN THE UNITED ARAB EMIRATES. http://www.pubhort.org/datepalm/datepalm1/datepalm1_43.pdf

Ministry of Environment and Water (MOEW), United Arab Emirates, 2010, United Arab Emirates Water Conservation Strategy, Old Airport Road, Abu Dhabi UAE.

Murad, A.A., Al Nuaimi, H. & Al Hammadi, M. 2007, Comprehensive Assessment of Water Resources in the United Arab Emirates (UAE), *Water Resour Manage,* 21: 1449. doi:10.1007/s11269-006-9093.

Osterkamp, W., L. Lane and C. Menges, 1995: Techniques of ground-water recharge estimates in arid/semi-arid area, with examples from Abu Dhabi. *J. Arid Environments,* **31,** 349-369

Osterkamp, W., L. Lane, and M. Menges, 1995, Techniques of groundwater recharge estimates in arid/semi-arid areas, with examples from Abu Dhabi, *J. of Arid Environments*, 31, 349-369.

Saif, Omar. 2015. "The Future Outlook of Desalination in the Gulf." Accessed December 14. http://collections.unu.edu/eserv/UNU:2647/FutureOutlookDesalinationGulf.pdf.

SEI 2015, The Plant Growth Model, Technical Documentation, The Stockholm Environment Institute, 11 Curtis Avenue, Somerville, MA 02144-1224

Shahin, S. and M. Salen, 2014, Food security in the United Arab Emirates (UAE): The great competition between the agricultural and forestry sector on irrigation resources, International Research Conference on Science, Health & Medicine (IRCSHM), Dubai UAE.

Sheik Mohammed Centre for Cultural Understanding, 2016, The Importance of Dates in the UAE, (online access https://smccudubai.wordpress.com/ November 2016

Silva, E., and F. Al Nauimi, 1999: Digital simulation of ground-water salvage in northeastern Abu Dhabi Emirate, National Drilling Company, PO Box 15287, Al Ain, United Arab Emirates.

Silva, E., and F. Al Nauimi, 1999: Digital simulation of ground-water salvage in northeastern Abu Dhabi Emirate, National Drilling Company, PO Box 15287, Al Ain, United Arab Emirates.

Symonds, R. B., Robledo A. R. and Al Shateri, H. A. (2005) Use of environmental tracers to identify and date recent recharge to the surficial aquifer of northeastern Abu Dhabi Emirate, United Arab Emirates Pg 471-486 in conference proceedings Vol 1 – WSTA Seventh Gulf Water Conference – Water in the GCC – Towards and Integrated Management – 19–23 November, State of Kuwait.

UN-ESCWA and BGR (United Nations Economic and Social Commission for Western Asia; Bundesanstalt für Geowissenschaften und Rohstoffe). 2013. Inventory of Shared Water Resources in Western Asia. Beirut. http://waterinventory.org/groundwater

United Environmental. 2014. Development of Unified Water Sector Strategy and Implementation Plan for the Gulf Cooperation Council of Arab Member States, Years 2015-2035. Module-II: Report-4: Initial National Water Strategy Targets for GCC States.

United Nations, Department of Economic and Social Affairs, Population Division (2015). World Population Prospects: The 2015 Revision, custom data acquired via website.

United Arab Emirates University, 2014, Date Palm Culture in the UAE, The Date Palm Development Research Unit Department, Al Ain, UAE.

United Arab Emirates Water Conservation Strategy. 2010. Ministry of Environment and Water. UAE.

Woodward, D., and C. Menges, 1992: Neotectonic thrust faulting along the western flank of the Oman Mountains, northeastern Abu Dhabi, Part 2: Hydrogeologic implications. *EOS, Trans. Amer. Geophys. Union, Supplements,* **73**, 188.

Xue, P. and Elfatih A. B. Eltahir. 2015. Estimation of the Heat and Water Budgets of the Persian Gulf Using A Regional Climate Model. *Journal of Climate*. 28

Xue. P, E. Eltahir, P. Malanotte-Rizzoli and J. Wei (2014), Local feedback mechanisms of the shallow water region around the Maritime Continent, J. Geophys. Res. Oceans, 119(10), 6933-6951. doi:10.1002/2013JC009700

Yates D, Sieber J, Purkey D, and Huber-Lee A 2005 WEAP21 - A Demand-, Priority-, and Preference-driven Water Planning Model Part 1: Model Characteristics, Water International, 30: 487–500.

an initiative of

Abu Dhabi Global Environmental Data Initiative (AGEDI)
P.O Box: 45553
Al Mamoura Building A, Murour Road
Abu Dhabi, United Arab Emirates

Phone: +971 (2) 6934 444
Email : info@AGEDI.ae

AGEDI .org

LNRClimateChange@ead.ae