Acknowledgements

The authors are deeply indebted to several individuals who made important contributions to this report. First of all, I would like to thank Mr. Majid Al Mansour Al Mansouri and Dr. Jaber Al Jaberi for their initiative in calling for this study and their continual support throughout the effort. Dr El Waleed Mohamed Hamad El Malik was instrumental in facilitating the many meetings and assisting with the acquisition of needed databases and other information.

There were many individuals who provided invaluable support in obtaining the data and information needed by the models used in the study. Dr. Mohamed Dawoud provided extensive water resource information on water supply and demand that helped in the assessment about the impact of climate change on water resources. Mr. Khaldoun Kiwan, Mr. Maher Kabshawi, and Mr. Mayas Qarqaz, specialists in the Terrestrial Environmental Research Centre were very helpful in helping me to understand the types of data and information available for assessing the impact of climate change on terrestrial ecosystems in Abu Dhabi. Mr. Abdessalaam Thabit provided an essential orientation to information on marine resources and the marine environment in the Abu Dhabi region.

In a study where baseline information on coastal zones, water resources and dryland ecosystems played such a crucial role, Mark Sorensen, Joseph Abdo, Anil Kumar were instrumental in orientation and access to the Environmental Agency's environmental database under the AGEDI framework. Rashed Mohammed Amin Karkain from Dubai and Nabil Alolaqi, Sultan Zaidi, and Rashed Alkaabi from the Abu Dhabi Environmental Agency provided excellent facilitation in arranging meetings.

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ISBN 9789948-408-41-3

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Produced from camera-ready-copy supplied by the publisher

PEFC
PEFC/01-31-83

Paper used is sourced from
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Printed using soya ink.

CLIMATE CHANGE

Impacts, Vulnerability & Adaptation

Coastal Zones in the United Arab Emirates

Water Resources in Abu Dhabi

Dryland Ecosystems in Abu Dhabi

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Foreword

There are many levels at which the United Arab Emirates is concerned about climate change. The UAE is already subject to extreme climatic conditions that will likely become only more extreme due to climate change. Even small long-term variations in temperature and precipitation could have adverse effects on productive activities due to the fragile nature of the nation's precious natural resources and interconnectivity with global economic activity. The key aim of this report is to identify and assess the potential magnitude of the physical impacts due to climate change on three vulnerable sectors in the UAE: coastal zones, water resources, and dryland ecosystems. Additionally, recommendations are suggested regarding sustainable adaptation processes for going forward after this preliminary assessment. This process first requires adjustments in policies, institutions and attitudes that establish enabling conditions, and second is accompanied by eventual technological and infrastructural changes.

There are three major parts of the report offering sector-specific key findings and recommendations as summarized below:

1. "Part 1: Impacts, Vulnerability, & Adaptation for Coastal Zones" in the United Arab Emirates, an analysis of sea level rise on coastal zones throughout the Emirates.

2. "Part 2: Impacts, Vulnerability, & Adaptation for Water Resources" in Abu Dhabi, an analysis of water supply and demand in the face of climate change in the Abu Dhabi Emirate.

3. "Part 3: Impacts, Vulnerability, & Adaptation for Dryland Ecosystems" in Abu Dhabi, a qualitative assessment of the impact of increased variability in rainfall and temperature regimes on dryland systems in the Abu Dhabi Emirate.

It is my hope that this effort paves the way for mainstreaming climate risks into tomorrow's development efforts in the UAE.

Majid Al Mansouri
Secretary-General
Environment Agency-Abu Dhabi

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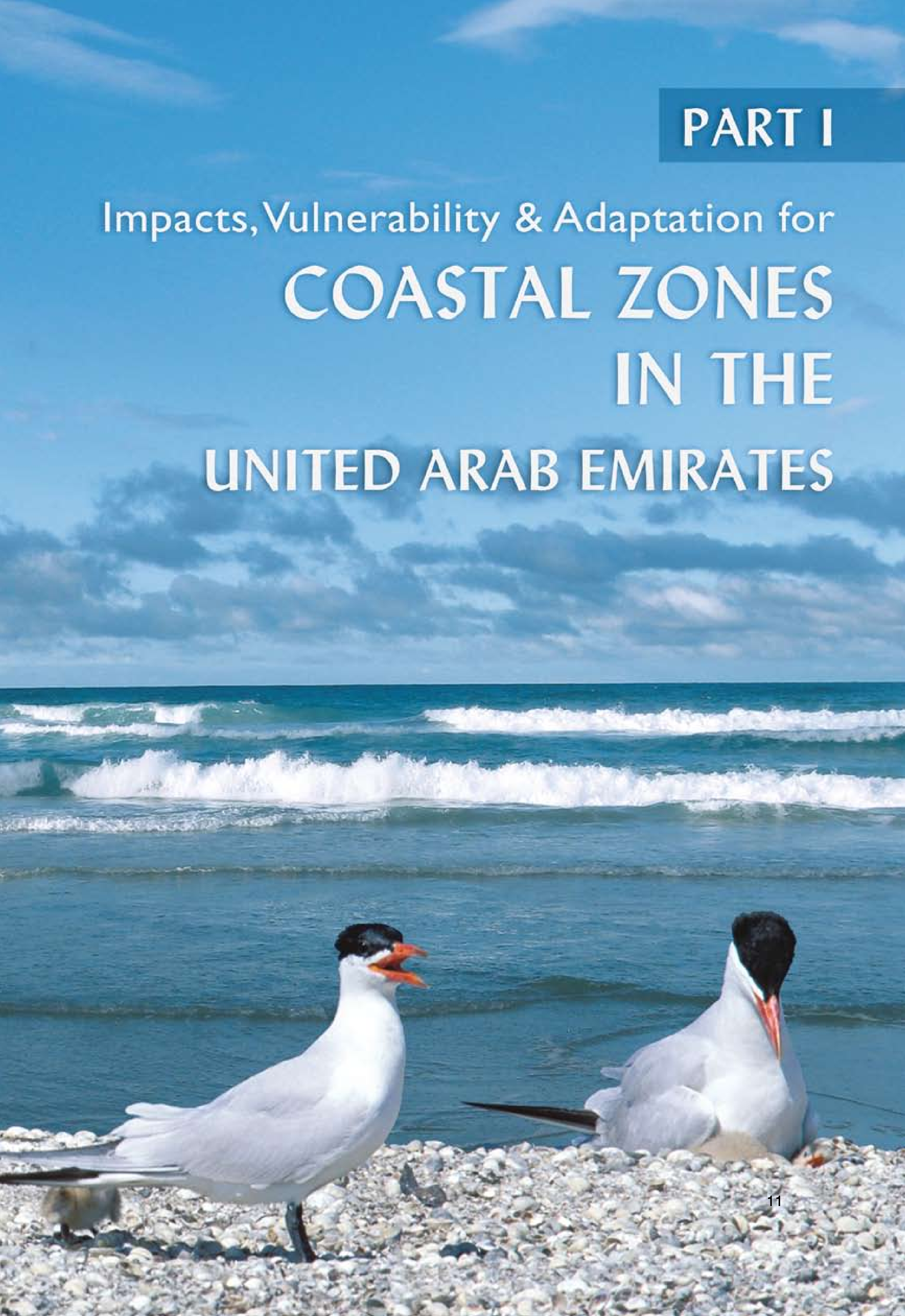

PART I

Impacts, Vulnerability & Adaptation for COASTAL ZONES IN THE UNITED ARAB EMIRATES

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List of Acronyms

APF	Adaptation Policy Framework
AML	Arc Macro Language
CARA	Consortium for Atlantic Regional Assessment
CO_2	Carbon dioxide
CReSIS	Center for Remote Sensing of Ice Sheets
CSI	Consortium for Spatial Information
DEM	Digital elevation model
EGM	Earth Gravitational Model
ENSO	El NiÑo Southern Oscillation
GCC	Gulf Corporation Council
GDP	Gross domestic product
GEF	Global environment facility
GHG	Green house gas (emissions)
GIS	Geographical Information System
GLOBE	Global Land One-km Base Elevation
GPS	Global positioning system
INS	Inertial navigation systems
IPCC	Intergovernmental Panel on Climate Change
IPCC 4AR	IPCC Fourth Assessment Report
IPCC SAR	IPCC Second Assessment Report
IPCC TAR	(IPCC) Third Assessment Report
LiDAR	Light Detection and Ranging
m	meters
MHHW	Mean higher high water
mm	millimeters
MA	Millennium Ecosystem Assessment
mmsl	monthly mean sea level
MSL	mean sea level
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration (USA)
NW	Northwest
PMSL	Permanent Service for Mean Sea Level
RSL	Relative sea level
SLR	sea level rise
SRES	Special Report on Emissions Scenarios
SRTM	Shuttle Radar Topography Mission
SST	Sea-surface temperatures
UAE	United Arab Emirates
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
USGS	US Geological Service
WAIS	West Antarctic ice sheet
WGI	Working Group I of the IPCC
WMO	World Meteorological Organization

1. Introduction

The UAE has nearly 1,300 kilometers of coastline. Approximately 85% of the population and over 90% of the infrastructure of the UAE is located within several meters of sea level in low-lying coastal areas (ERAS, 2005). The UAE is fundamentally different than it was 30-40 years ago. Its rapid GDP growth, economic diversification and coastal tourism, present new challenges for the 21st century. In the UAE, coastal areas are important and highly populated centers of industry, manufacturing, and commerce. Moreover, the coasts of the UAE are home to multiple ecological subsystems (Alsharhan and El Sammak, 2004) and important cultural heritage sites and artifacts (Hellyer and Beech, 2000).

The UAE straddles the Tropic of Cancer and the Abu Dhabi emirate, in particular, is influenced by the direct sun its geographical position allows. The climate is hot and arid, yet on the coast, humidity can reach over 90 percent in summer and autumn. Inland it is far less humid, although the temperature is higher, often exceeding 50ºC before midday in July. The Arabian Gulf coast is extremely shallow and gently sloping continental shelf. The littoral zone of the UAE is characterized by active coastal sabkhas, or salt flats. The UAE sabkhas of the UAE are internationally recognized as the largest and most geomorphologically interesting of sabkha in the world (Aspinall, n.d.).

The coastal zone is threatened by numerous processes. Coastal areas are affected by reclamation, dredging or other usage including oil-related activities; however, much of such development has been for recreational purposes. Population growth, urban sprawl, and expansion of coastal development and tourism have led to extensive reclaimed, dredged, and land-filled areas, reduced wildlife populations, and habitat loss of mangroves, coral reefs and sea grass. Additionally, coastal areas have suffered from past oil spills and remediation techniques. Approximately 31% of the world production of oil passes through the Strait of Hormuz each day impacting marine life from oil pollution and thermal discharges. Numerous studies have been done in these fields, specific to the UAE. Well aware of these issues, the UAE has established a National Environmental Action Plan for the Marine Environment that includes strategies for the conservation of biodiversity, endangered species and habitats, protection of the marine water quality and the marine environment, promotion of sustainable fisheries and environmental awareness in communities and schools, and improved oil spill and waste management responses (Federal Environment Agency, 2002).

Climate change also endangers coastal ecosystems and developments. Climate changes include increases in global sea level, sea water temperature, precipitation intensity, atmospheric CO_2, and changes in wave climate and runoff. Coastal communities may start witnessing changes in storm frequency, intensity, and movement. As the oceans warm, rising sea-surface temperature will lead to thermal expansion and changes in mean sea level. Change in sea-surface temperatures could mean intensified coral bleaching, which affects species' reproduction and migration.

In 1996 and 1998, the UAE faced two catastrophic coral bleaching and mortality events associated with seawater temperature anomalies. Wave conditions could change, risking altered patterns of erosion and accretion (IPCC, 2007). Until now, the effects of climate change induced sealevel rise on coastal populations, infrastructure, and biology has yet to be adequately accounted for in planning activities within the UAE. Broad climate change drivers and potential impacts on coastal zones are summarized in Table 1-1 from Klein and Nicholls (1999).

While it is important to consider all of the potential climate change phenomena affecting coastal zones, sea level rise appears to be particularly important due to the continued and escalating concentration of population, infrastructure, and industry in the coastal zones. A rise in mean sea level is one of the most certain consequences of global warming. As can be seen in Figure 1-1, the IPCC's Fourth Assessment Report (2007), posits an upper boundary for global sea-level rise by 2100 of 0.59 cm. However, the IPCC calculations don't include ice-sheet dynamics. According to the IPCC, sea level rise

Table 1-1. Climate Change and Related Factors Relevant to Coasts.

CLIMATE FACTOR	DIRECTION OF CHANGE	POTENTIAL BIOGEOPHYSICAL EFFECTS
Global sea level	+ve	Inundation and displacement of wetlands and lowlands; coastal erosion; increased storm flooding and damage; salinisation; rising water tables and impeded drainage.
Sea water temperature	+ve	Increased coral bleaching; increased algal blooms; northerly migration of coastal species; decreased incidence of sea ice at higher latitudes
Precipitation intensity	+ve (in many parts of the world)	Increased flood risk in coastal lowlands
Wave climate	Unknown	changed cross-shore and longshore sediment transport, and hence patterns of erosion and accretion
Storm frequency	Regional variation	Changed occurrence of storm flooding and damage
Run-off	Regional variation	Changed sediment supply from rivers to the coast
Atmospheric CO_2	+ve	Increased productivity in coastal ecosystems

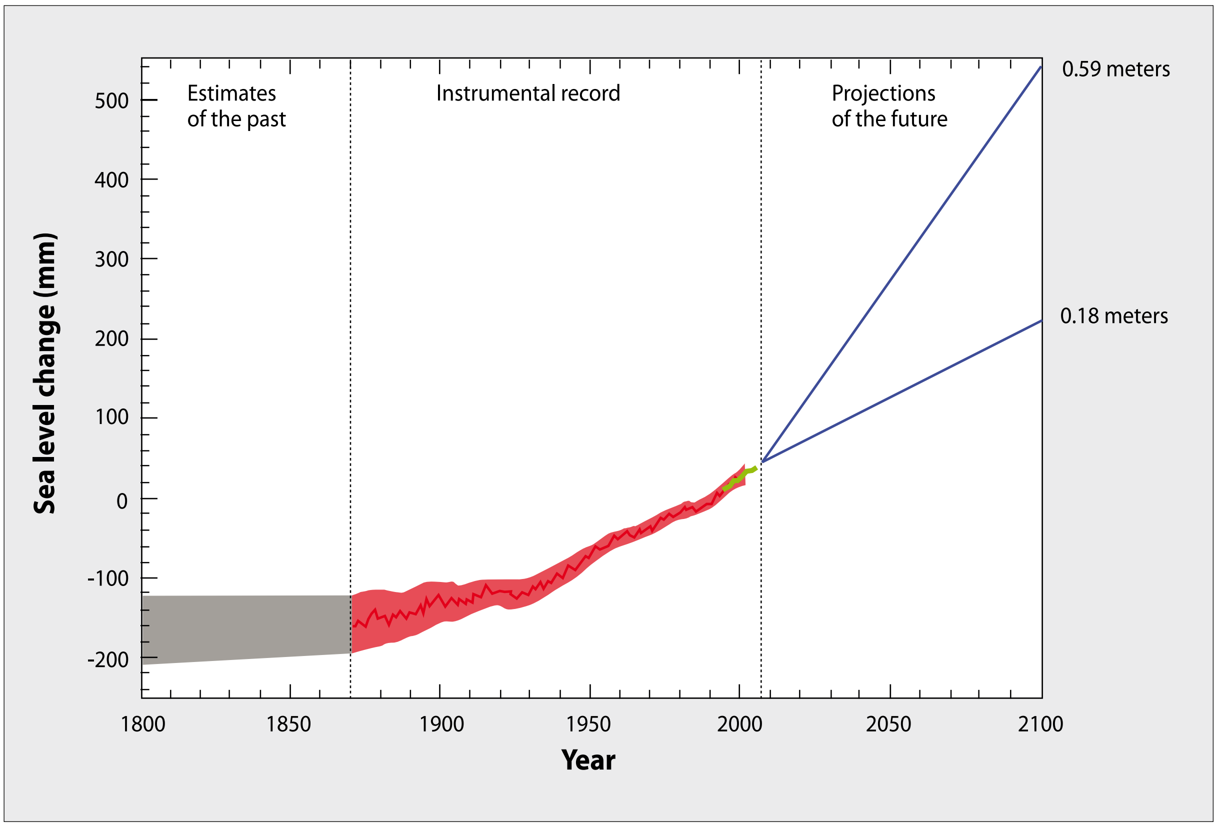


Figure 1-1. IPCC (2007) estimations of sea level rise by 2100.

is expected to continue at a significant rate for centuries, even if climate forcing is stabilized (IPCC, 2001). From a planning perspective, it is important to acknowledge and accept that more than 10 meters of sea-level rise is possible, depending on the emission scenario considered, and albeit over a long time frame (IPCC, 2007).

In addition to the effects of sea level rise on social and economic structures, the vulnerability of coastal ecosystems is also of particular concern. Ecosystems in the UAE are particularly vulnerable, dominated by the intricate ecologies of coastal sabkha (salt-encrusted flats), mangrove wetlands, and areas that provide habitat for a wide variety of flora and fauna. The most extensive system of tidal lagoons and creeks lies in the vicinity of Abu Dhabi city behind the barrier island complex. Regionally, sea level rise is projected to result in increased soil salinization, which will affect inland agriculture and forestry projects, as well as resolved in flooding in most of the Gulf Corporation Council (GCC) coastal cities and towns (Brown, 2003).

The potential exposure of the UAE, Abu Dhabi in particular, to the impacts of sea level rise given its current socioeconomic conditions in coastal areas is quite significant. After accounting for future development and population increases in these areas, sea level rise poses important Emirate-wide policy questions regarding current and future development plans and investment decisions. The Abu Dhabi Environment Agency published a "Marine and Coastal Environment Sector Paper" in April 2006, which devotes some attention to climate change, though the treatment was brief relative to the magnitude of the threat.

This analysis builds on existing work, with substantial space devoted to both a qualitative review of climate change impacts on the coastal zone as well as a quantitative assessment of sea level rise on coastal areas, presented as a series of 2-dimensional maps indicating the extent of coastal inundation. A sea level rise (SLR) inventory of the coastal regions of the UAE is considered central to the assessment of the vulnerability and potential adaptation to climate change in the region and is a key component of the study that follows.

2. Sea-level Rise Impacts on Coastal Systems

Coastal zones are one of the most vulnerable areas to climate change given the increased certainty of a rise in mean sea level. As mentioned earlier, the IPCC's Fourth Assessment Report, posits an upper boundary for global sea-level rise by 2100 of 0.59m. Beyond 2100, sea level rise projections are increasingly dependent on emissions scenarios (IPCC, 2007). Sea level changes are induced by both natural factors such as changing ocean basin volume and depth as the earth's plates separate and collide with each other, as well as deglaciation from anthropogenic global warming.

Taking a step back to clarify the terms used, mean sea level (MSL) is the average level of the sea's surface, as measured relative to a fixed level on the land. MSL is typically calculated over long periods, usually averaged over the 19 year lunar cycle as it smoothes tidal variations. There are seasonal or annual changes in MSL in addition to gradual increases in MSL that scientists have tracked over time.

Deglaciation of continental ice caps, in particular, can change sea level by tens of meters (Emery and Aubrey, 1991). Deglaciation changes the volume of water in the ocean, which is known as a eustatic sea level change. The IPCC estimates, however, do not include ice-sheet dynamics even though over a long time frame, more than 10 meters of sea-level rise is possible, depending on the emission scenario and assumptions regarding ice-sheet dynamics (IPCC, 2007). Figure 2-1 shows a breakdown of contributing factors to mean sea level rise. As the IPCC explains, the data in this figure are for 1961 to 2003 (light blue) and 1993 to 2003 (dark blue). The bars represent a 90% error range. Sea level change is the sum of the upper four entries (thermal expansion through Antarctica) in addition to the observed rate of rise. For the sum, the error has been calculated as the square root of the sum of squared errors of the contributions; to obtain the error for the difference, combine errors of the sum and the observed rate (IPCC WGI, Chapter 5).

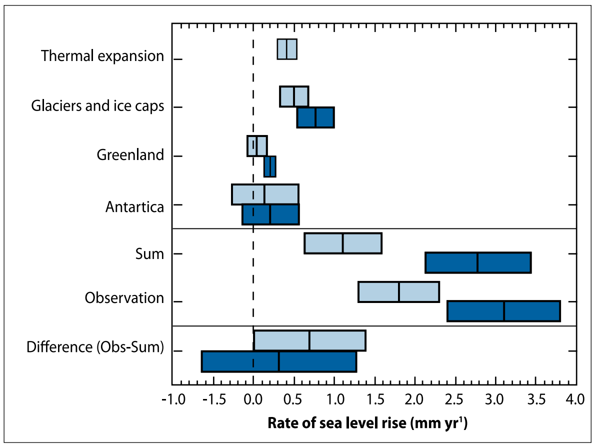


Figure 2-1. Estimates of the various contributions to global mean sea level change. Source: (IPCC, 2007)

Researcher Dr. Vivien Gornitz, jointly posted at the Columbia University Center for Climate Systems Research and NASA's Goddard Institute for Space studies, explains global trends further. She writes that 20th century global sea level, according to tide gauge data, has been increasing by 1.7-1.8 mm/yr and that most of this rise is due to ocean warming and mountain glaciers melting, which have receded dramatically in many places especially during the last few decades. She continues, "since 1993, an even higher sea level trend of about 2.8 mm/yr has been measured from the TOPEX/ POSEIDON satellite altimeter. Analysis of longer tide-gauge records (1870-2004) also suggests possible late 20th century acceleration in global sea level" (Gornitz, 2007). Computed from satellite altimetry from January 1993 to October 2005, Figure 2-2 captures these variations in global mean by plotting the

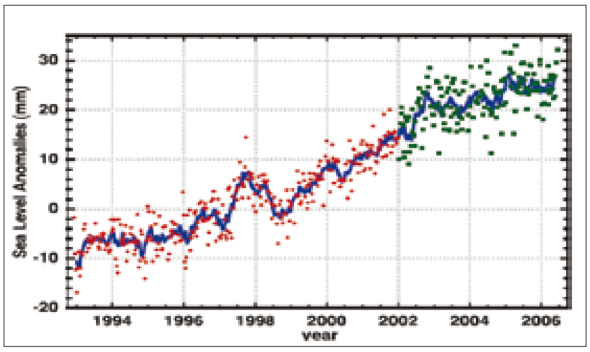


Figure 2-2. Variations in global mean sea level. Source: (IPCC WGI, 2007)

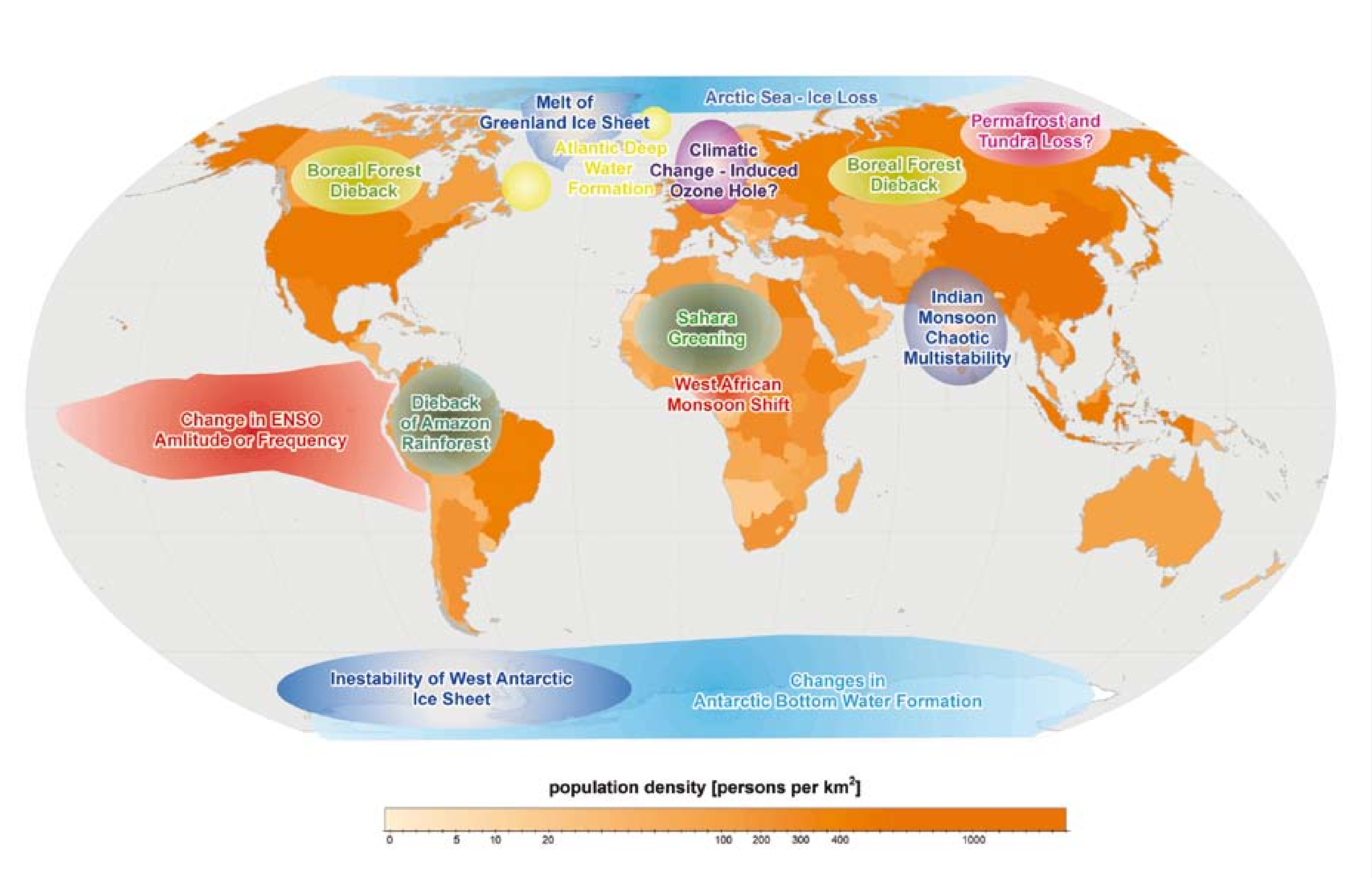


Figure 2-3. Map of policy-relevant tipping elements in the climate system, overlain on global population density. Source: Lenton et al, 2008

differences in observed sea levels to the mean as averaged from 1993 to mid-2001. The dots are 10-day estimates (from Topex/Poseidon Satellite in Fed and Jason Satellite) in green and the blue solid curve corresponds to 60-day smoothing.

Sea levels are not rising uniformly around the world. Meehl *et al.* (2007) found that regional sea-level change will depart significantly from the global mean trends. Local (or relative) changes in sea level differ from global trends due to regional variations in oceanic level change thermal expansion, geological uplift/subsidence, sea-floor spreading, and the level of glaciation, and relative sea level change that drives impacts and is of concern to coastal managers (Nicholls and Klein, 2005; Harvey, 2006a). Both sea level rise and coastal settlement patterns have substantial inertia, and there is high confidence that the unavoidability of sea level rise will continue to conflict with present and future human development patterns (IPCC, 2007).

Coastal areas experience more SLR than the open ocean (IPCC, 2007). According to Short and Neckles (1999), the direct effects of sea level rise on the coastal zones will be increased water depths, changes in tidal variation (both mean tide level and tidal prism), altered water movement, and increased sea water intrusion inland. These effects should be quite noticeable in the shallow Arabian Gulf. In the southern Gulf, studies have already examined sea level rise relative to historic shorelines (Evans *et al.*, 1969, Taylor and Llling, 1969; Purser and Loreau, 1973; Dalongeville *et al.*, 1993; Lambeck, 1996; Kirkham, 1997). Others have examined sea level in relation to geology (Uchupi *et al.*, 1999), or Gulf floor sedimentation (Stoffers and Ross, 1979; Sarnthein, 1972; Reynolds, 1993). About 80% of the monthly mean sea level variance can be related to seasonal changes (Sultan *et al.*, 1995; IPCC, 2007).

2.1. Abrupt or rapid sea level rise

Many researchers identify abrupt or rapid sea level rise as a major problem facing coastal societies (Titus, 1988 and 1990; Mitchell, 1991). Characteristics of rapid sea level rise include both elevation in the mean level of the ocean surface and increase in the tidal variation around the mean (ADEA 2006). Gradual increase in mean sea levels is much easier to adapt to than the rapid sea level rise coastal cities may face. Abrupt sea level rise is worrisome because it happens on a time scale far quicker than most societies are able to adapt.

Large, abrupt climatic changes with major impacts are by no means new phenomena in the course of the planet's history. While historically, much of these abrupt changes have been due to natural causes, most recently, scientists are concerned that human forcing of climate change is affecting the probability of abrupt change (Alley *et al.*, 2003). Abrupt climate change occurs when the climate system crosses a threshold, triggering a transition to a new state. The rate of transition is determined by the climate system, and will likely be faster than the cause of that transition. Rapid sea level rise, for example, could result from crossing a temperature threshold, after which the planet transitions from sea level, at its current status, to a new higher level.

Kasperson *et al.* (2005) conducted a thorough review of the risk of future rapid large sea-level rise (SLR). In their review, the potential collapse of the West Antarctic ice sheet (WAIS) was the primary driver of rapid SLR. Most consider rapid sea level rise of five to ten meters over the next several centuries to be a worst case scenario; the timing of which is also dependent on the rate of warming, ice sheet melts, and reaching one of several tipping points in the other's climate system yielding long-term consequences. A tipping point is a moment in time, at which a small change yields large, long-term consequences for the climate system. The map in Figure 2-3 suggests policy-relevant elements with critical tipping points in the climate system (Lenton *et.al.,* 2008). Any of these could plausibly be triggered in this century, and the main conclusion was that it will be "characterized by potentially catastrophic consequences and high epistemic uncertainty" (Kasperson, 2005). As such, effective risk management demands adaptive management regimes, vulnerability reduction, and urgent mitigation of climate change forces, such as the production of anthropogenic greenhouse gas emissions.

A noteworthy concern is that emissions abatement will not necessarily prevent ice sheets from collapsing; uncertainty remains on whether emissions reductions now may be too little or too late to reverse the trend of ice sheet melts. The policy importance of adequately planning for the worst case scenario will be discussed in greater detail in Section 5.

2.2. Eustatic sea level rise from deglaciation

The IPCC's Fourth Assessment Report (2007) estimates of global sea-level rise by 2100 do not include ice-sheet dynamics, however the continued melt of certain glacial types will yield eustatic sea level rise, or rise corresponding to a change in ocean volume. Floating ice, like what is found in the Northern Polar regions will not affect sea level if it melts because when it melts it will displace and equivalent volume of water. Continental ice sheets, however, are more worrisome. According to marine geophysicist Robin Bell of Columbia University's Earth Institute, sea levels rise by about 1/16 inches for every 150 cubic miles of ice that melts off one of the poles (Bell, 2008). Scientists are concerned that the rate of glacial melt/ is far outstripping the rate of snow accumulation This phenomenon and melt accumulate imbalance can be seen visually in Figure 2-4.

Scientists hypothesize that during the previous interglacial period when the West Antarctic Ice Sheet (WAIS) collapsed; sea level was 6/meters higher than at present (Emery and Aubrey, 1991). In both Kasperson *et al.* (2005) and Tol *et al.* (2006), the primary driver of rapid SLR was the potential collapse of the WAIS. Rising global temperatures could trigger an irreversible breakdown of ice sheets.

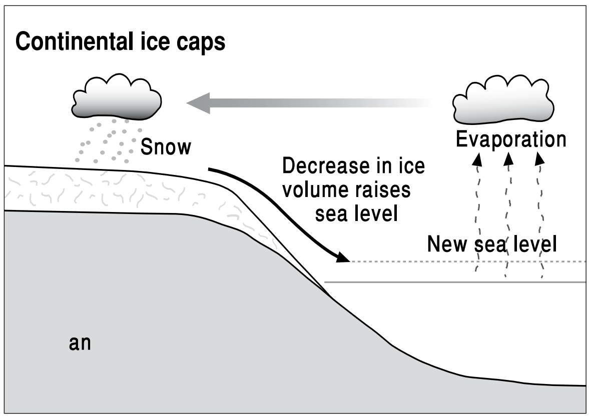


Figure 2-4. How glacial melt raises sea levels in the context of the water cycle.

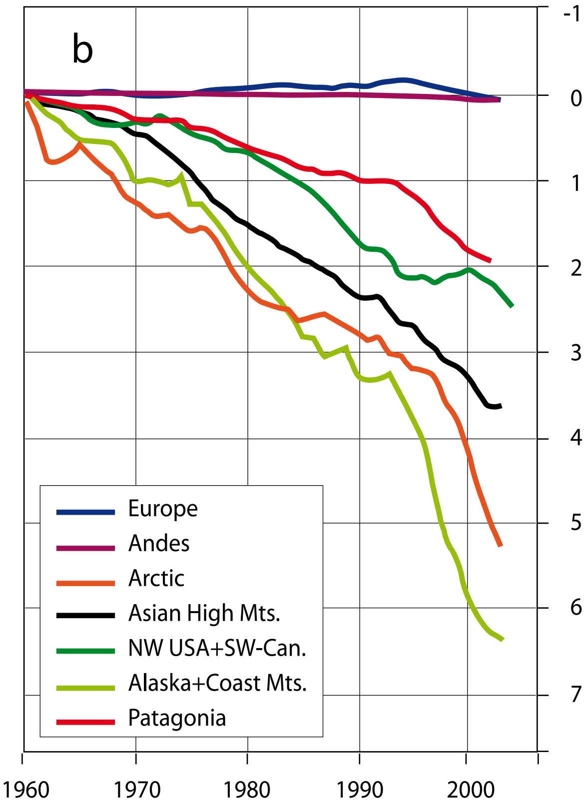


Figure 2-5. Historical, cumulative contribution of deglaciation to sea levels. Source (IPCC, 2007).

If the WAIS were to disappear again, sea level would rise most 19 feet. Additionally, the ice in the Greenland ice sheet could add 24 feet to that, the East Antarctic ice sheet could add yet another 170 feet to the level of the world's oceans, totaling more than 213 feet in all (Bell, 2008). In Figure 2-5 we see the cumulative contribution of continental glaciers and ice-caps to the sea-level rise since 1960, expressed in mm (right axis) and grouped by major zone. For example, melting of Alaska glaciers have contributed to a rise in the world sea level by roughly 6.5 mm since 1960 (IPCC, 2007).

Glacial melt is directly related to ambient air temperature and warming trends; a global temperature rise of 2-5°C could destabilize Greenland irreversibly. Even though such a temperature rise lies within the range of several future climate projections for the 21st century, any significant meltdown would take many centuries.

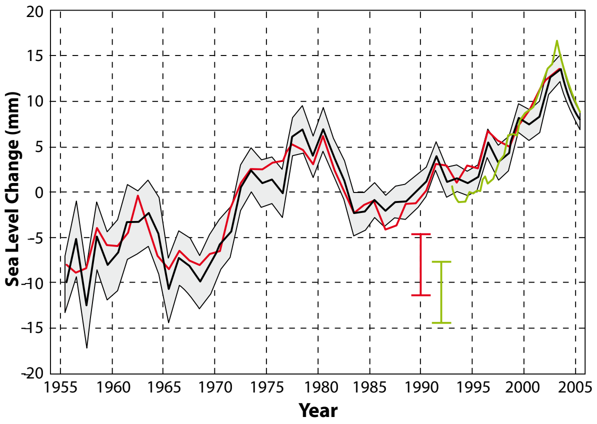


Figure 2-6. Global sea level change due to thermal expansion for 1995 to 2003 Source: IPCC, 2007.

Climate stabilization could mitigate ice sheet breakdown, but sea level rise due to thermal expansion remains likely. Gornitz (2007) cautions against ignoring ice-sheet dynamics and notes the alarming changes that satellites have detected. Parts of the Greenland Ice Sheet at lower elevations are thinning, and glaciers are rapidly disgorging ice into the ocean, adding 0.23 to 0.57 mm/yr to the sea within the last decade. Ice loss by glaciers in Greenland doubled between 1996 and 2005 (NASA, 2006). Small changes in glacial mass balance whether through accumulation from precipitation, ablation from evaporation, or the production and melt of ice bergs are influential in the global sea level budget. There remains, however, a great deal of uncertainty in the specific contribution of the mass balance of Greenland and Antarctic ice sheets (Pugh, 2004).

The global mean sea level rise scenarios are based on thermal expansion and ice melt; the best estimate shows an acceleration of up to 2.4 times compared to the 20th century (see Meehl *et al.*, 2007). For the IPCC A1B scenario, the spatial standard deviation by the 2080's is 0.08 meters (m), with a larger rise than average in the Arctic. While there is currently insufficient understanding to develop detailed scenarios, Hulme *et al.* (2002) suggested that impact analysis should explore additional sea-level rise scenarios of +50% the amount of global mean rise, plus uplift/subsidence, to assess the full range of possible change. Although this approach has been followed in the UK (Pearson *et al.*, 2005; Thorne *et al.*, 2006), its application elsewhere is limited to date.

2.3. Sea-surface temperatures, thermal expansion, and thermosteric sea level rise

Thermosteric sea level rise is the component of the total sea level that results from thermal expansion of ocean waters, (the term steric is used when both thermal expansion and salinity effects are considered) (Berge-Nguyen *et al.*, 2008). Thus sea-surface temperatures (SST) play a vital role in coastal dynamics with respect to the interplay between temperature and sea levels. Dissolved salt content also influences how oceans react to warming such that there are regional differences and delays in thermal expansion depending on a body of water's particular salinity properties.

Sea surface temperature changes the density and thus volume of the oceans. The heat capacity of the ocean is so large there will be a delay before the full effects of any global warming are evident. Warming atmospheric temperatures will continue to cause sea levels to rise far after any global greenhouse gas emissions and subsequent temperature stabilization scheme are reached. Any warming of the ocean, leads to an expansions of ocean volume and thus an increase in mean sea level (Pugh, 2004; IPCC, 2007; Hassanzadeh *et al.*, 2007).

Globally, the IPCC satellite altimetry time series show an overall trend of increasing heat content in the world oceans, allowing for some inter-annual and inter-decadal variations. Near-global ocean temperature data for the last 50 years has recently been made available, allowing for the first observationally-based estimate of the thermal expansion contribution to sea level rise in past decades. For the most recent years, the best estimates of the land-ice contribution to sea level are available from various observations of glaciers, ice caps and ice sheets.

Relying on these data sets, the Fourth Assessment Report (IPCC, 2007) estimates that thermal expansion will contribute more than half of the average sea level rise; increases in sea surface temperatures could reach up to 3°C by 2100. Figure 2-6 captures this observation of sea level change, where each study reviewed is represented by a different line in the graph. The shaded area and the vertical red and green error bars represent the 90% confidence interval. The black and red curves denote the deviation from their 1961-1990 average, the shorter green curve the deviation from the average of the black curve for the period 1993 to 2003 (IPCC, 2007).

Warmer SST will lead to thermal expansion in the Gulf and changes in mean sea level. Sea level data collected from 11 stations in the Arabian Gulf already indicate rising levels. Increased SST could lead to higher peaks of storm surges, increased cyclone intensity, and a greater risk of coastal disasters; warmer waters also undermine temperature-sensitive coastal ecosystem functioning.

Thermosteric sea level is high in the summer (June, July, and August) and autumn (September, October, and November) and low during spring (May, April, and March) and winter (December, January, and February). The distribution of the thermosteric sea level shows larger variations in sea level in spring than in winter. "Worst case scenario" adaptation measures will need to target spring mean sea levels due to both larger thermosteric variations layered on top of large spring tidal means (as will be explored in Section 2.4).

2.4. Increase in the tidal variation around the mean

Tidal dynamics in the Arabian Gulf are admittedly unusual. At most tidal stations, the tidal range maximum occurs in July (summer) and the minimum in February for most stations. In northern and southern mid-latitudes, the lowest sea level in the annual cycle occurs during spring and is highest in the autumn (Hassanzadeh, 1997; Tabata *et al.*, 1998), but over the Arabian Gulf, this feature is different. The vertical extent of the intertidal zone depends mainly on the tidal range, wave action and slope of the shore. On sheltered steeply sloping shores, the height of the intertidal corresponds closely to the tidal range, narrow throughout much of the UAE. Along unprotected coasts, strong wave action causes the intertidal zone to extend upwards above normal high-tide levels.

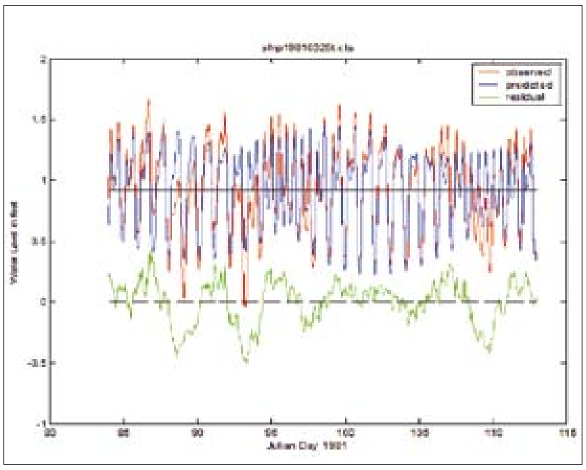


Figure 2-7. Residual change in water level based on observed and predicted water levels.

The tide waves entering the Straits of Hormuz generate two large rotary waves for the semidiurnal tide (two highs and two lows each day), and a single large rotary wave for the diurnal tide inside the Gulf. This leads to two distinct tide patterns in the Iranian coast of Arabian Gulf. One is found at eastern boundary (the Strait of Hormuz) and the other at the northern Gulf or western. Seas of up to 5.4m swells in the Eastern Gulf tend to predominate from NW and SE, and swells of 1.8m and higher occur in the Central Gulf.

Baseline sea level elevation and subsequent tidal variation around a mean is best determined by the monthly mean sea level (mmsl). In Figure 2-7, we can see how mmsl changes: the blue line shown in the figure at left represents the predicted (astronomical) tide. By subtracting the predicted hourly tide from the observed hourly water levels (red line), the researchers obtained the residual change in water level (green line).

Improved estimates of sea level trends rely on improving tidal gauge data collection the in the Arabian Gulf. Mmsl data is publicly available for only three years for the UAE (PSMSL, 2008). As such data is insufficient for a tidal analysis; this report relies on existing analysis of tidal dynamics found in the literature, as synthesized below, to best understand how tidal variation may shift with climate change induced sea level rise.

In Safaniya, a coastal town less than two hundred kilometers to the northwest of Ras Tanura, the tide is mixed, though mainly diurnal. Whereas in Ras Tanura, a major oil terminal on the west side of the Arabian Gulf, has a large

Figure 2-8. Location of Safaniya and Ras Tanura.

spring-neap cycle and a particularly large tide on Julian day 97. This is due to the fact that the tropic-equatorial cycle takes precedence over the spring-neap cycle at places where the tide type is mainly diurnal (Figure 2-8).

In the southern Arabian Gulf the tidal range rarely exceeds 2 meters, and in the Gulf of Oman 2.5 meters. Mean trend of increase in sea level for the Arabian Gulf is about 2.34±0.07 mm/year. The mean spring tidal range is 1.7 and 1.9 meters "An evolutionary model for sabkha development on the north coast of the UAE "; http://www.infomarine.gr/uae/Mubarek/index.html). d; http://www.jstor.org/sici?sici=0016-7398(200003)166%3A1%3C14%3ACCIRAK%3E2.0.CO%3B2-F;. Other resources suggest that the mean range is 1.0m while the spring range is 1.8m. Minimum tidal ranges occur in the Strait of Homuz (Goudie et al., 2000).

2.5. Storms frequency and intensity in relation to rising sea levels

Generally, calm or light seas prevail in the Gulf more than 40% of the year. Thus there is limited concern regarding changes in storm frequency, intensity, movement in the Arabian Gulf. El-Sabh and Murty (1988) explain that the Arabian Gulf is influenced by extra-tropical weather systems because the Strait of Hormuz lies in the boundary region between the west-to-east traveling extra-tropical cyclones and the east-to-west travelling tropical cyclones.

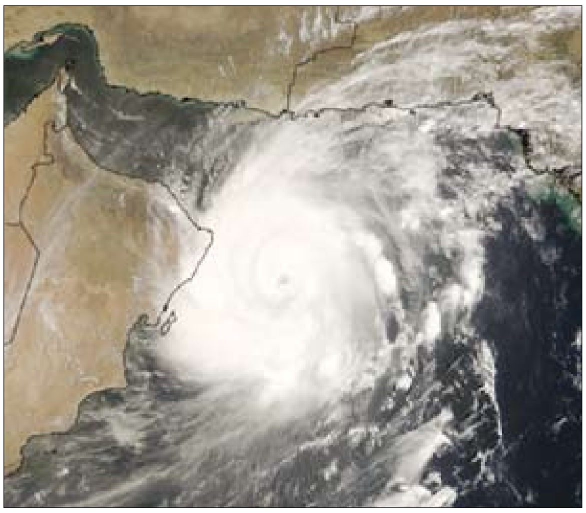


Figure 2-9. Tropical Cyclone Gonu churns off the coast of the Middle East and southern Asia (NASA).

In 2007, Cyclone Gonu became the first documented Category-5 cyclone in the Arabian Sea. Gonu made landfall in Oman with maximum sustained winds near 148 km/hr. In Oman, the cyclone affected more than 20,000 people and was responsible for more than 50 fatalities. In Figure 2-9, Cylone Gonu approaches the Gulf of Oman and Strait of Hormuz *(NASA, n.d.)*.

Gonu moved through the Arabian Gulf making a second landfall in the Islamic Republic of Iran. While historical record does not go back very far, these types of storms are very, very unusual for this part of the world. Gonu, and the possibility of a similar storm in the future, raised concern due to the Gulf region's s sensitive coastal infrastructure of heavy oil drilling activities, tanker traffic, and coastal population density. As a sizeable portion of the world's petroleum exports go through the Gulf of Oman, any slight blip in supply or exporting could be quite noticeable on the world markets.

Some recent global climate model experiments suggest a future decline in tropical cyclone frequency (Royer et al., 1998) while others argue for an increased likelihood of changes in the tropical storms in the event of global warming (Knutson *et al.,* 1999; Henderson-Sellers *et al.,* 1998; Royer *et al.,* 1998 and Krishnamurti *et al.,* 1998; Elsner *et al.,* 2008). Although the studies carried out so far are inconclusive on the likely changes in frequency of cyclones, it is almost certain that an increase in sea surface temperature will be accompanied by a corresponding increase in cyclone intensity. Recent studies suggest a possible increase in cyclone intensity of 10-20% for a rise in sea

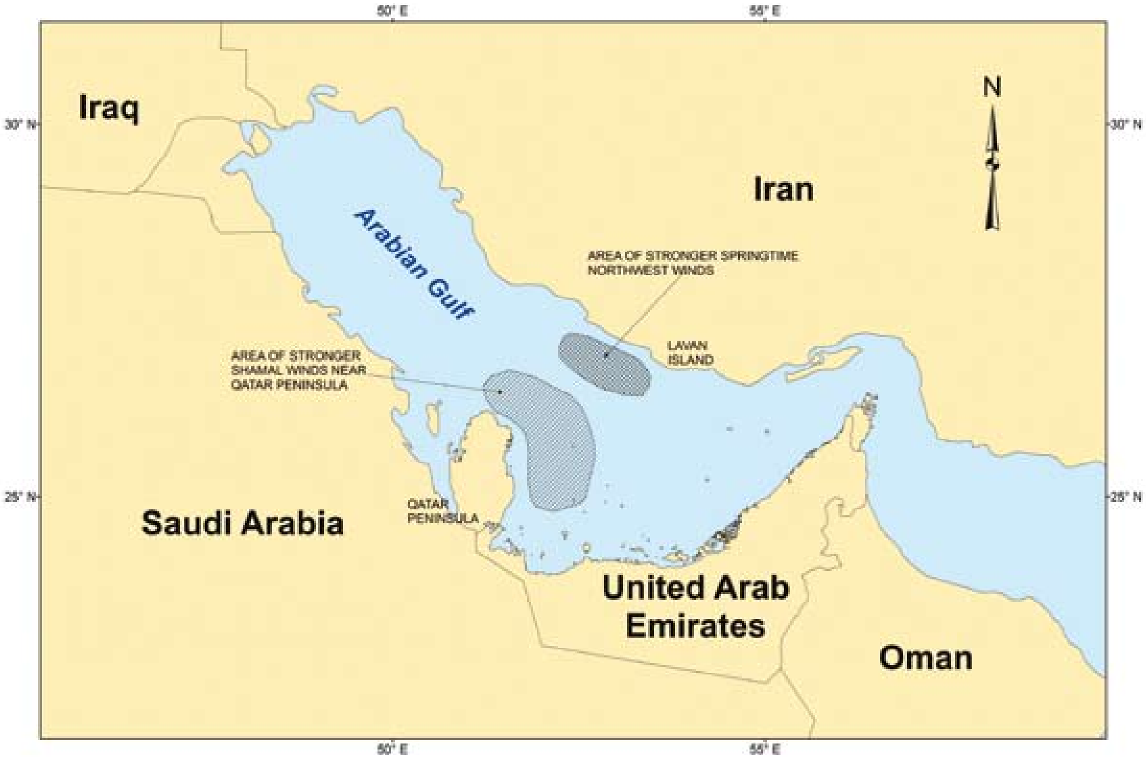


Figure 2-10. Area of stronger than normal northwesterly winds (Shamal) and higher wind waves.

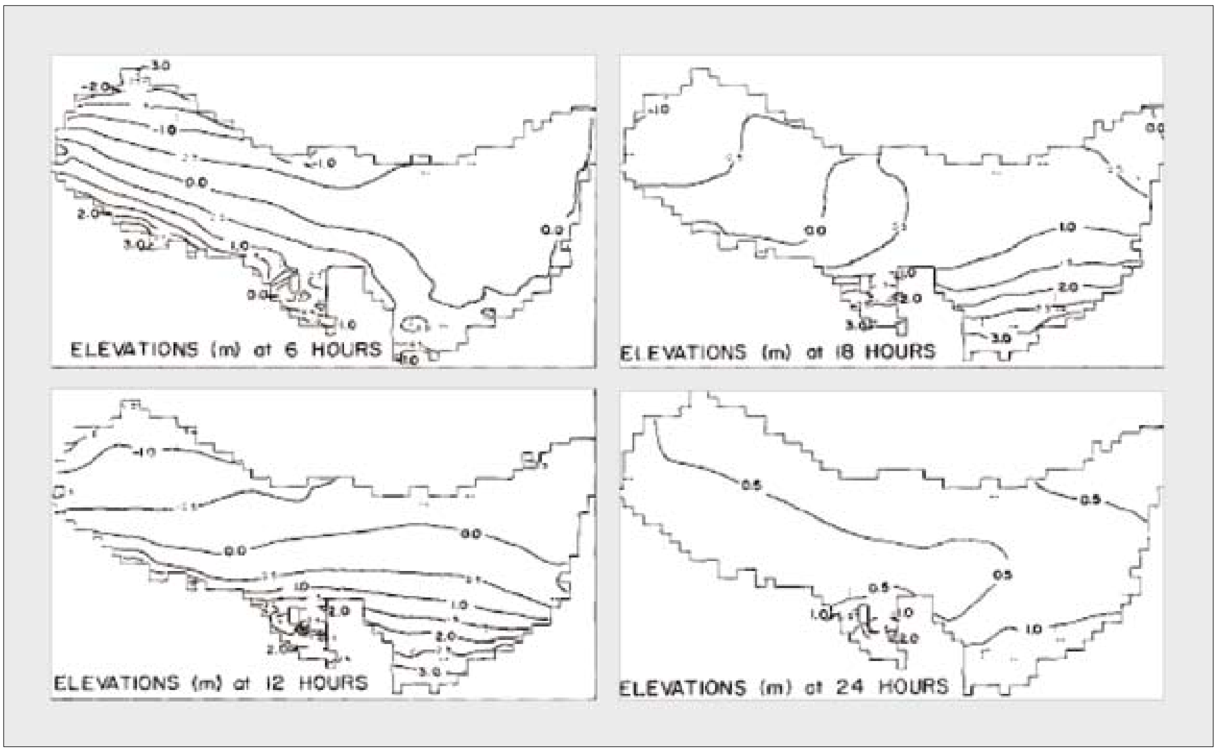


Figure 2-11. Computer simulated distribution of storm surge heights at four different times. (Sabh & Murty, 1989)

Table 2-1. Saffir-Simpson Hurricane Scale, (FEMA)

Scale number	Sustained Winds (km/h)	Damage	Storm Surge (m)	Storm Surge (ft)
1	120-150	Unanchored mobile homes, vegetation and signs	1.2-1.5m	3’11”-4’11”
2	150-170	All mobile homes, roofs, small crafts, flooding.	1.8-2.4m	5’11”-7’11”
3	170-210	Small buildings, low-lying roads cut off.	2.7-3.7m	8’11”-12’1”
4	210-250	Roofs destroyed, trees down, roads cut off, mobile homes destroyed. Beach homes flooded.	4-5.5m	13.’1”-18’
5	More than 250	Most buildings destroyed. Vegetation destroyed. Major roads cut off. Homes flooded.	5.5m+	18”+

surface temperature of 2 to 4˚C.

Any increase in sea surface temperature due to climate change would lead to higher peaks of storm surges and a greater risk of coastal disasters. Climatic changes in both moist static stability of the atmosphere and the underlying SST may be the critical determinants of the potential variations of the maximum potential intensity of tropical cyclones in changed climates (Lal & Aggarwal, 2002). A stronger than normal northwesterly winds is known regionally as a Shamal. Shamal cyclogenesis, the generation of cyclone-speeds winds and even cyclones from strong Shamal winds is another factor in storm surges, however the majority of the UAE is less affected by these winds han other countries in the region. Figure 2-10 shows a map of the strength of Shamal winds. Because the Gulf is so shallow, especially in the southwest part, could be subjected to large amplitude storm surges either from tropical or extra-tropical cyclones. One advantage of the geology of the

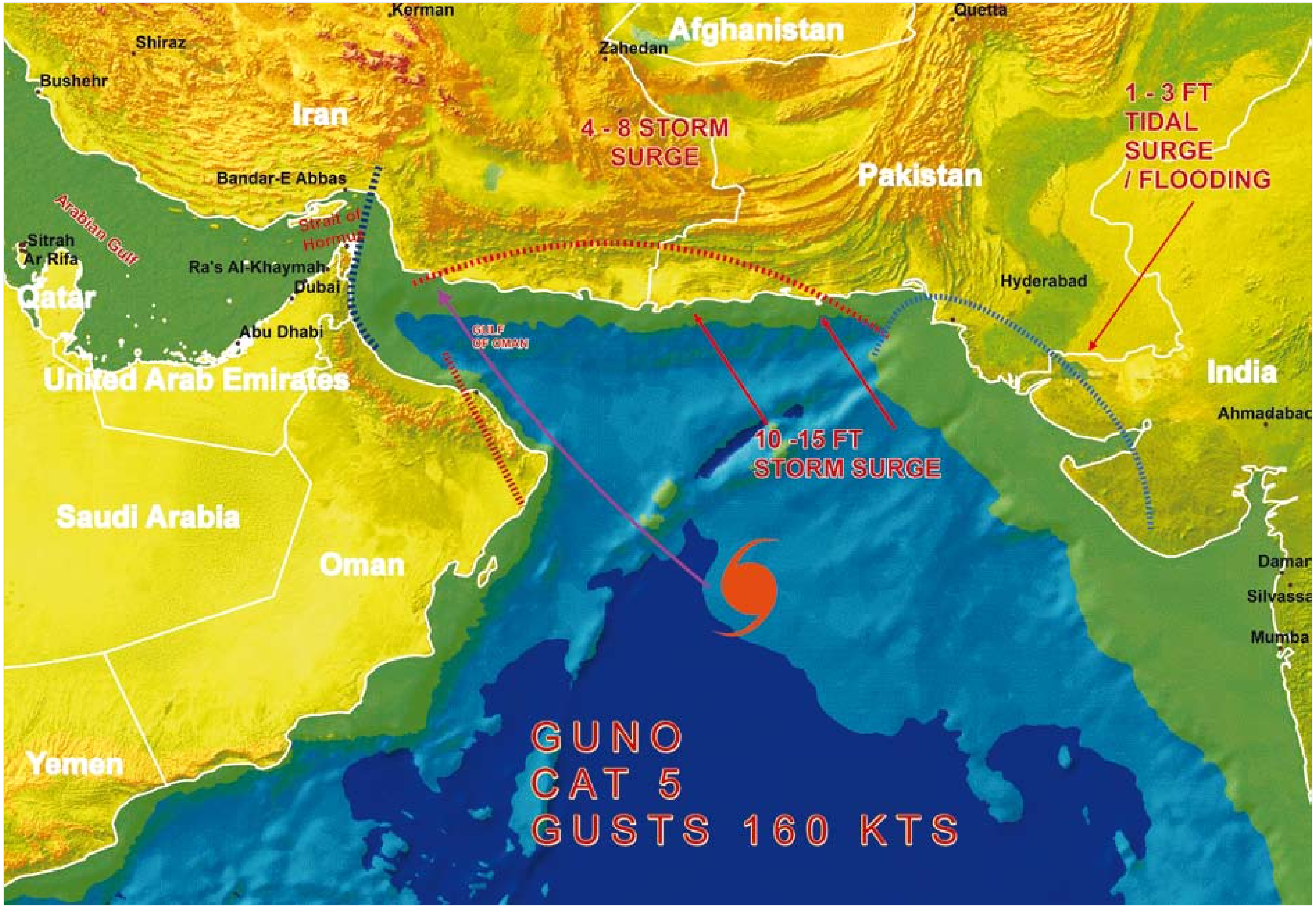


Figure 2-12. Map of Gonu's path

Gulf is that the shallower depth allows for more friction to dissipate storm surges faster, as the Gulf depth increases with sea level rise this effect may diminish.

Overall, the UAE seems to experience relatively lower ranges of storm surge, except for positive surges of up to 3 meter that can appear in the southwest area at 12 and 18 hours as diagrammed in Figure 2-11 from Sabh and Murty (1989). Surges in these water bodies may have amplitudes of up to 5 to 6 m and there is no preponderance of negative surges as in the Arabian Gulf. Surge amplitudes in the Arabian Gulf are comparable to those in the Arabian Sea and the Gulf of Thailand (Murty, 1984; Sabh and Murty, 1989). If hurricanes of Gonu's level of intensity continue, the UAE could see increased storm surges on the order of those summarized in Table 2-1 on (Vaidya, *et al*, 2007).

The implications for the UAE are yet unclear. About 6.5% (of about world's tropical storms are formed annually in the Indian Ocean (Neumann, 1993; McBride, 1995). The frequency of cyclone formation is 5-6 times more common the Bay of Bengal as compared to Arabian Sea. Scientists do remark that the frequency and intensity of summer tropical cyclones forming in the north Indian Ocean could increase in the coming century. Should events like Cyclone Gonu become more common in the Arabian Sea, the UAE's vulnerability will markedly increase. There will be also increased risks to refueling and ship-to-ship supply operations in international waters, especially near Fujairah, UAE. Winds and the atmospheric pressure changes associated with cyclones also generate storm surges that, on top of rising mean sea levels, would severely damage coastal infrastructure.

We highlight the extreme risks from storm surges because even though for the time being it remains an unprecedented event and is even considered by some to be statistically insignificant. A cyclone impairing or destroying production capacity in the world's most important oil region certainly warrants advanced adaptation planning. Gonu may have been an anomaly, or it may be taste of what's to come. It is up to decision makers to decide the extent to which they want to prepare coastal communities for such a low probability, high impact event.

It was such an unprecedented event there are no custom 'storm surge' models available for that area. The Straits of Hormuz may protect Abu Dhabi and Dubai (as shown in Figure 2-12), but critical infrastructure on the Eastern coast near Oman that supports communities in Eastern Emirates (e.g. the Taweelah desalination plant that supplies water to the Al Ain region) would be at risk.

2.6. Coastal erosion and shoreline retreat

An indirect, and less-frequently examined influence of sea level rise on the beach sediment budget is due to the infilling of coastal embayments. As sea level rises, estuaries and lagoons attempt to maintain equilibrium by raising their bed elevation in tandem, and potentially acts as a major sink of sand depositing from the open coast. Recent studies indicate that beach protection strategies and changes in the behavior or frequency of storms can be more important than the projected acceleration of sea level rise in determining future beach erosion rates (Ahrendt, 2001; Leont'yev, 2003). Thus there is not a simple relationship between sea level rise and horizontal movement of the shoreline (Cowell *et al.*, 2006).

In addition to tropical storms, the UAE experiences severe thunderstorms. Squalls result from the subtropical jet-stream re-routing depressions through the Mediterranean basin, and then tracking down the Gulf toward the Arabian Sea. In most years it rains during the winter months, usually in February or March, but occasionally earlier in the form of torrential, frontal, and orographic downpours. Winter rains fall in the Hajar Mountains, and run off rapidly into wadis and thence onto the downwashed gravel plains, perhaps reaching the sea on the East Coast, but invariably braiding widely and soaking rapidly into the desert in the west.

An adaptive response to retreating shorelines means allowing the shoreline to be flexible. In contrast, many societies opt to maintain the status quo and hold the shore in place with seawalls and other infrastructure. We will discuss this more in Section 5 on Adaptation strategies.

3. Climate Change and Coastal Ecosystems

There are multiple ecological subsystems that have evolved along the coasts of the UAE including: embayment, barrier island-lagoon, spit-lagoon, and beach-sabkha subsystems (Alsharhan and El-Sammak, 2004). The effects of climate-induced sea level rise, increases in sea surface temperatures, and other factors must be studied in the context of each of these ecosystems. Major ecosystems at risk discussed in this chapter include sabkhas, mangroves, sea grass, and coral reefs as well as the influence of climate change on coastal wildlife populations.

3.1. Sabkhas coastal ecosystems

Abu Dhabi's sabkhas coastal ecosystems are a hallmark of the Emirate's ecological and geological heritages and cover roughly 60% of the Emirate's coastline (ADEA). Sabkha is the local Gulf Arabic word for a flat, salt-crusted desert. The sabkhas are low-lying, sand and salt flats that stand only a few centimeters above high-tide mark (See Figure 3-1 for geographic visualization of sabkha location along the UAE coastline Evans and Kirkham, 2000). There are three main kinds of sabkhas ecosystems: 1) coastal sabkha, is inundated with marine tides, 2) supra-littoral sabkha, is rarely inundated by tides, and 3) inland sabkha, is never inundated by tides. Sabkhas form from the interplay between seasonal inundation of Gulf water, rain water and sandstorm deposits during the hot-dry season. Sabkha ecosystem dynamics are highly influenced by geo-ecological factors of the surrounding areas: sand, hydrology, vegetation, and climate.

Abu Dhabi's sabkha plain is partly depositional and partly erosional. Beach ridges suggest that sea level around 4000BC was higher than it is today. As such, the coastal sabkha is made up of sediments deposited 4,000 to 7,000 years

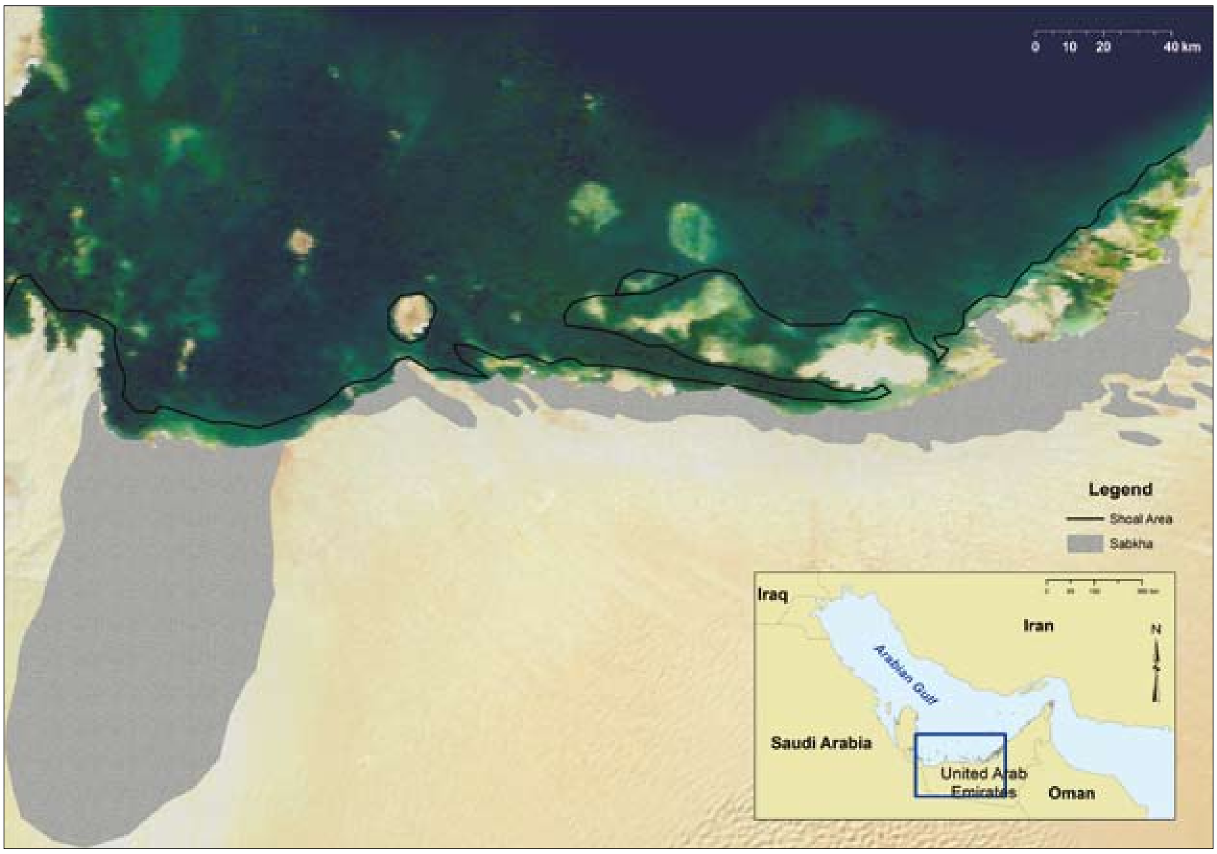


Figure 3-1. Coastal Sabkhas in Abu Dhabi. (Evans and Kirkham, 2000)

ago when sea level was a few meters higher. When sea levels began to retreat, progradation of mainland shore began and continues with sedimentation and progressive infilling of sheltered lagoons, as well as colonization of newly emerging land as the coastline is shifting seaward.

Sabkhas are the most obviously endangered geological feature in the UAE. Coastal sabkhas are regularly flooded from winter rains and higher spring tides. Natural rainfall-pooling patterns in the Sabkhat are already interfered with by civil engineering projects along the coastline. Roadway plantations and subsequent fresh-brackish irrigation applications are changing salinities of sabkha water and may have negative consequences on sabkha flora and fauna. Once easy to find near Abu Dhabi Island, coastal sabkhas are also quickly disappearing to make place for roads, power lines, industrial estates and housing developments.

Even though these ecosystems have undergone a lot changes throughout time, particularly from infilling and fragmentation that occurs during development, the evidence of former coastlines can still be seen. The highway from Abu Dhabi to the western industrial zone of Ruwais, for example, passes across the sabkha, and to the south, inland, the old shoreline can be identified, a low range of hills that mark the beginnings of the desert (Richardson and Hellyer, n.d.). The old shoreline then reached the low cliffs that can be seen south of the highway to Tarif, the shore may return to that place as seas rise, which is fine for sabkhas development but less fine for existing road networks and built environment that depends on coastline in its current position.

Most sabkhas, at least coastal sabkhas, are only a few meters above sea level. The lack of topographic relief and altitude allows sea water to move several kilometers inland during high tide, rare storm surges, and even further inland with future sea level increases. Without adequate adaptation, sabkhas human and faunal populations may have to relocate inland. Additionally, any change precipitation and sea levels due to climate change will alter the evaporites that are at the core of ecosystem functioning (Lieth and Menzel, 2002).

Anticipated sea level rise will lead to coastline retreat inland, once again, and low-lying sabkha will be flooded by the advancing waters relatively quickly. For those coastal settlements and existing infrastructure that are situated in the sabkha zone, they may have a relatively limited lifespan if and when the pace of sea level rise increases. Even now, sabkhat are vulnerable to exceptional meteorological events like strong onshore winds (shamals) that can drive seawater from lagoons inland, over the outer parts of the sabkhas.

3.2. Mangroves

The Emirates' mangroves have a high ecological value to the Arabian Gulf (Saenger and Blasco, 2000; Saenger *et al.*, 2004). Coastal vegetated wetlands like mangroves are sensitive to climate change and long-term sea-level change because their location is intimately linked to sea level. Mangroves play a vital role in the life-cycle of many valuable seafood species and provide a safe nesting, feeding and roosting site for many birds (Aspinall). Mangroves also offer coastal production by reducing wave energy The Abu Dhabi Environment Agency's 2006 report on the Marine and Coastal Sectors, discusses past efforts to inventory existing mangrove habitat. In 2004, the Abu Dhabi's marine atlas project, recorded the distribution, density and structure of mangrove vegetation throughout Abu Dhabi Emirate; Figure 3-2 is a map derived from this survey data. Mangroves naturally occur between Ras Ghanada in the northeast to Marawah Island further to the west at suitable sheltered sites that have reduced wave energy and are protected from strong winds. Data from remote sensing suggests that there are about 40 km^2 of mangroves in Abu Dhabi.

Sasekumar, *et al.*, (1994) explain that mangroves are found above sea level because the mud where they take root needs to be totally exposed, or free from inundation, for some period each day. Under situations of constant inundation, mangrove root systems are unable to take in oxygen and new trees will be unable to take root as seeds float in higher water. Additionally, any increase in extreme storms may induce erosion of the mudflats, around which mangroves thrive. Mudflats do undergo a natural cycle of accretion

Figure 3-2. Mangroves around Abu Dhabi, (E.A. data layer.)

and erosion, but storms could mean damage to the system and subsequent irreversible coastal erosion.

3.3. Seagrass

Seagrass ecosystems have huge ecological importance for coastal areas of the Emirates. Seagrasses predominate coastal shallow water habitats of water depths less than 10 meters. The majority of the UAE coastline, along the shallow Arabian Sea, meets this criterion. Seagrasses provide a stable coastal habitat, improve coastal water quality, and support fisheries production making them one of the most valuable marine resources and ecosystems (Bell and Pollard, 1989; Bostrom and Mattila, 1999; Heck and Orth, 1980; Heck et al., 1989, 1995; Orth et al., 1984; Thayer *et al.,* 1979). The importance of the seagrass systems in Abu Dhabi lies not only in the direct food value to wildlife such as the dugong and green turtle, but also in its value as a habitat for the growth of both commercial and non-commercial fish and invertebrates, and especially as a refuge from predators for juvenile fish (ADEA, 2006).

The very high growth rate and primary production of seagrasses also leads to extremely high biodiversity (both plants and animals) as well as facilitates major nutrient recycling pathways for both inshore and offshore habitats. The perennial habitat maintains local biodiversity and serves as a foundation for complex food chains because of its high rate of primary productivity and high leaf densities. Seagrass detritus also contributes nutrients and energy to sabkha substrate, contributing to the development of storm-berms at seaward edges and supporting halophytic fauna and flora. Halophytic root systems then help stabilize the Sabkha substrate which minimizes the effect of wind erosions and retains water in coastal soils (Phillips, 2002).

Scientists have every reason to believe that, as with the predicted terrestrial effects of global climate change, impacts to seagrasses will be great. Short and Neckles (1999) highlight a need for more research directed toward the impact of global climate change on seagrasses. Seagrass habitats are influenced by sea temperature regimes, tidal variations, salinity content, changing water depths, as well as ocean carbon dioxide content. Tidal height and tidal range effects on available light, current velocities, depth, and salinity distribution, are all factors that regulate the distribution and abundance of seagrasses.

These climate factors are all implicated in expected regional climate changes. Organisms in tropical waters are known to live much closer to their upper thermal limits. An assumption that follows is that as the waters of the Gulf reach extreme limits of temperature and salinity, the same would be true for the three seagrass species that live in it. Change sea surface temperatures could lead to altered growth rates and even impair other physiological functions of the plants like sexual reproduction or geographic distribution. Temperature changes that lead to increased eutrophication and changes in the frequency and intensity of extreme weather events indirectly affect seagrass ecosystems.

Numerous studies have shown an association between seagrass distribution and water depth (Short *et al.*, 1999 cites the following: Zimmerman and Livingston, 1976; Bay, 1984; Averza and Almodovar, 1986; Dennison and Alberte, 1986; Dawes and Tomasko, 1988; Orth and Moore, 1988; Duarte, 1991). Sea level rise, as it contributes to increased water depth, leads to a subsequent reduction in light available for seagrass growth. One study suggests that the projected 50 cm increase in water depth due to sea level rise over the next century could reduce available light by 50%, which in turn may cause a 30-40% reduction in seagrass growth and productivity (Short and Neckles, 2002).

Changing tidal range is likely to exacerbate the effects of increased water depth on seagrass habitats; however, whether tidal range remains the same but just shifts with sea level, or if sea level rise actually influences high and low tide levels is yet to be determined. Any decrease in tidal range will decrease the amount of intertidal exposure at low tide such that plant distribution expands shoreward. In shallow waters, these subtidal species may be able to expand inland towards intertidal areas and continue to thrive (Kentula and McIntire, 1986). Where geomorphology or human infrastructure does not permit successful ecosystem migration, the UAE can expect a loss in seagrass areas.

3.4. Coral Reefs

Coral reefs are Abu Dhabi's most diverse marine ecosystem. The variety of life and the complex interactions of reef organisms are of major fisheries, scientific and tourism value to the Emirate. Sea levels in the Arabian Gulf have been near present levels for about 2000 years (Lambeck, 1996), and have therefore provided corals with a stable bathymetric environment in which to develop into reefs (ADEA, 2006). Corals are vulnerable to thermal stress and have low adaptive capacity. Increases in sea surface temperature of 1 to 3°C are projected to result in more frequent coral bleaching events and widespread mortality, unless there is thermal adaptation or acclimatization by corals (IPCC, 2007). Coral bleaching and mortality appear related to the frequency and intensity of ENSO events in the Indo-Pacific region, which may alter as a component of climate change (IPCC, 2007).

Since 1995, there has been a heat-induced die-off of around 90 per cent of all coral in the southern Gulf. In 1996 and 1998, the UAE experienced two catastrophic coral bleaching events associated with seawater temperature anomalies. These prolonged higher-than normal summer seawater temperatures (positive SST temperature anomaly of over 2°C) led to the catastrophic bleaching and death of a large percentage of the previously living corals along the length of Abu Dhabi Emirate. High seawater temperatures have often been close to or may have exceeded the physiological tolerance limits.

The long-term prognosis for the survival of coral reefs in the Emirates, if summer seawater temperatures continue to rise, is not good. In the past, poor development of reefs in the southern Gulf has been attributed to high sedimentation and low winter temperatures (Shinn, 1976). Now, water temperatures in the Gulf exceed 33°C in summer, falling in winter to 16°C in the north and 22–24°C in the south (Chiffings 1994). Some level of resilience could be expected because reefs exist in this area of historic environment stressors such as extreme fluctuations in seawater temperature and high salinity (Kinsman, 1964; Sheppard, 1988; Sheppard & Sheppard, 1991) as well as frequent high turbidity. On the other hand, scientists warn that corals have probably reached their upper physiological temperature limit of the already well-adapted hermatypic corals forming the reefs of Abu Dhabi (EA). Already, there is evidence of the temperature sensitivity of coral because at the western extremity of the Abu Dhabi coastline the annual range of seawater temperatures is somewhat greater and consequently coral diversity is less (George & John, 1999, 2004, 2005b; John & George, 2001: Riegl, 2003).

Riegel (2003) also explains that sea-level rise would have severe impacts on nearshore Arabian Gulf corals because so much of the southern shoreline is barely above sea level. While the effects of flooding remain unclear, researchers anticipate that coastal flooding could mobilize sediments and induce reef "switch offs" similar to flooded lagoons and drowned barrier reefs as seen in US Virgin Islands. Reefs would also be damaged from the extensive area of shallow sea created by flooding, these "seas" would be lethally heated and cooled by the Gulf's temperature extremes (Loughland, 2005; Loughland and Sheppard, 2001, 2002; Riegl 2001, 2002, 2003).

3.5. Influence of sea level rise and sea surface temperature warming on coastal fauna.

Many of the Emirate's islands hold internationally important numbers of breeding seabirds and numbers of visiting shorebirds, nesting and feeding grounds of turtles, cetaceans (including both whales and dolphins) and dugong herds,

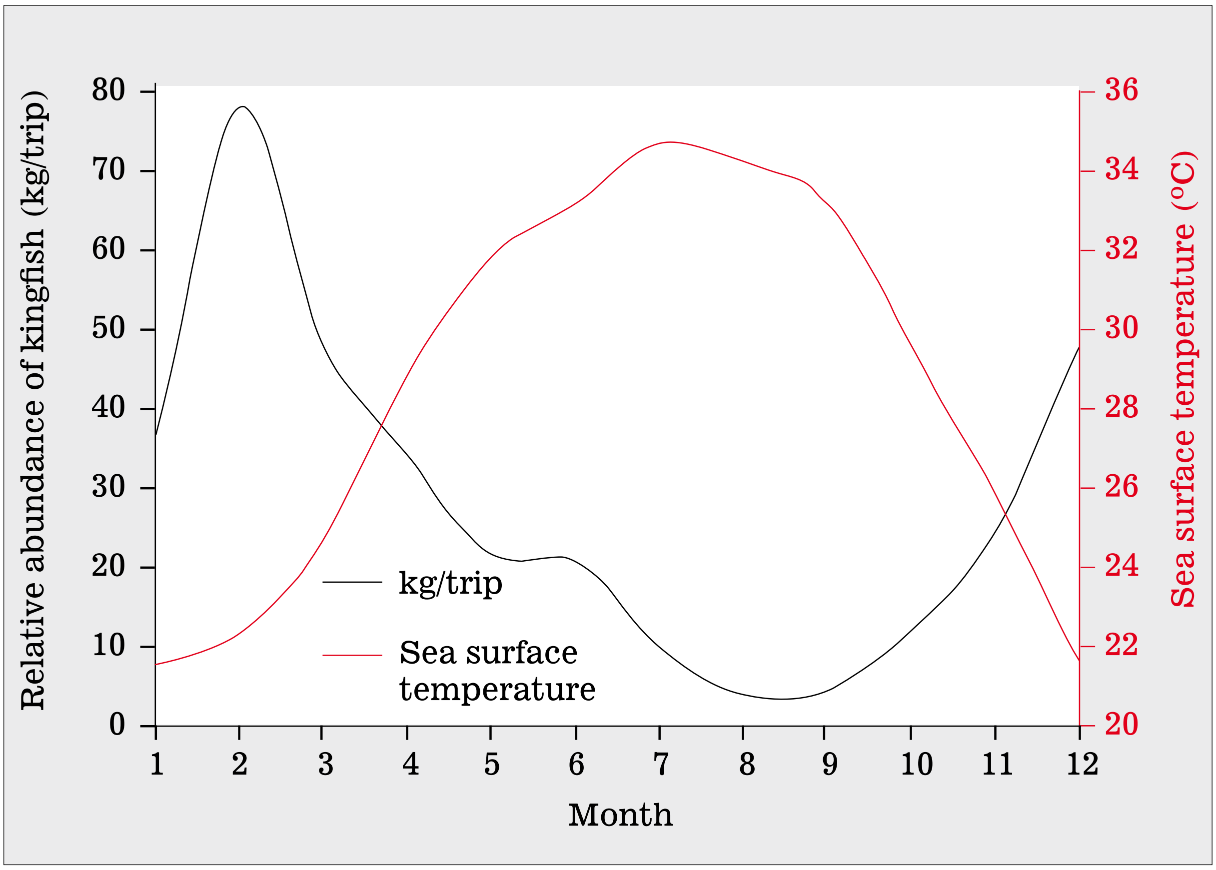


Figure 3-3.Kingfish abundance vs. SST.

amongst others. Sea level rise may induce changes in turbidity, temperature and salinity that affect all of these flora and fauna. Any changes in ecosystem conditions could lead to improved conditions for diseases of plants and animals, as well as open areas to invasive species.

The bathymetry of the Gulf is already quite shallow; sea level rise would extend these shallow coastal areas inland. The problem with shallower water is that it is more susceptible to strong heating and cooling, and density changes from evaporation, both of which negatively affect temperature sensitive species that had lived along the coast before changes forced migration.

Much of the Abu Dhabi Emirate's unique biodiversity is found in coastal ecosystems. The hawksbill turtles breed on more remote beaches, and dugongs are found in great numbers feeding on the seagrasses in more sheltered waters. Dugongs are already threatened internationally, mostly from drift nets and other man-made pressures. While UAE Federal Law protects them to an extent, sea level rise and changing in coastal water temperatures may negatively affect the habitats in which they thrive—notably the sea grass communities which are sensitive to both water depth and salinity.

The abundance of some of the Emirate's most important fisheries like kingfish are associated with these seasonal climate patterns, e.g. the extreme temperature fluctuation between the summer and winter months (see Figure 3-3). Depending on how ambient and sea surface temperatures change over time, kingfish and other similarly vulnerable populations will either need to migrate, adapt to new temperatures in their current habitat, or potentially become extinct. These options hold true across the board for both animal populations as well as populations of sea grasses and mangroves who may be able to adapt to slow paced change but ill equipped to handle abrupt sea level rise, particularly when coupled with existing anthropogenic pressures.

4. Inundation analysis of coastal areas

After much debate, the general agreement is that "vulnerability is neither an outcome nor a static internal condition but rather a dynamic property emerging from the structure of human relations, the internal attributes of specific populations and places, and the nature of social-environmental interaction" (Encyclopedia of the Earth). The goal of any model in which vulnerability is operationalized is to then capture both the internal and external dimensions of vulnerability. The benefit of obtaining a better understanding of vulnerability is that it can better inform policymakers to the appropriate response actions. With respect to climate change, the magnitude of vulnerability can then be met with adequate adaptation measures. What follows is a quantitative assessment of the UAE coastline's vulnerability to sea level rise. The initial focus was on the urban built environment in each of the major cities of the UAE (i.e., Abu Dhabi, Dubai, Sharjah, Umm al-Quwain, Ajman, Ras Al Khaimah, and Fujairah). Where data permits, this was included in the study. For the non-built environment, the focus was on the coastline of the Abu Dhabi Emirate only.

4.1. Introduction

Coastal systems are inherently dynamic and continually changing in response to natural processes like tides, and other global ocean-atmospheric interactions like the North Atlantic Oscillation (NAO), El-Nino Southern Oscillation (ENSO) and seasonal rainfall and sea-surface temperatures. Human decisions and development patterns often undermine coastal ecosystems' abilities to respond to these natural phenomena and, when juxtaposed against the added extreme changes expected from climate change, vulnerability is an even more pressing concern. Vulnerability to sea level rise causes particular anxiety for coastal societies like those along the UAE's Arabian Gulf shoreline, since the ability of coastal systems to adapt to rising seas is inherently constrained by the extensive human infrastructure found on the coast. At the same time, the human built environment buffering those ecosystems face its own challenges from sea level rise. In the inundation analysis, both ecosystems and human systems, and the extent to which they are vulnerable to four different scenarios of sea level rise are considered. After a discussion of the methodology is a description of scenarios used and their results.

4.2. Methodology

Geographic Information Systems (GIS) was the main tool used in the analysis. GIS is a software tool that allows for the representation of data in spatial form, both in two dimensions and three dimensions. The use of this software will facilitate the management and integration of data, the performance of advanced spatial analysis, modeling and automating certain processes, and displaying results in high-quality maps for presentation purposes.

The sections below reflect on previous attempts to use GIS in conducting a spatial assessment

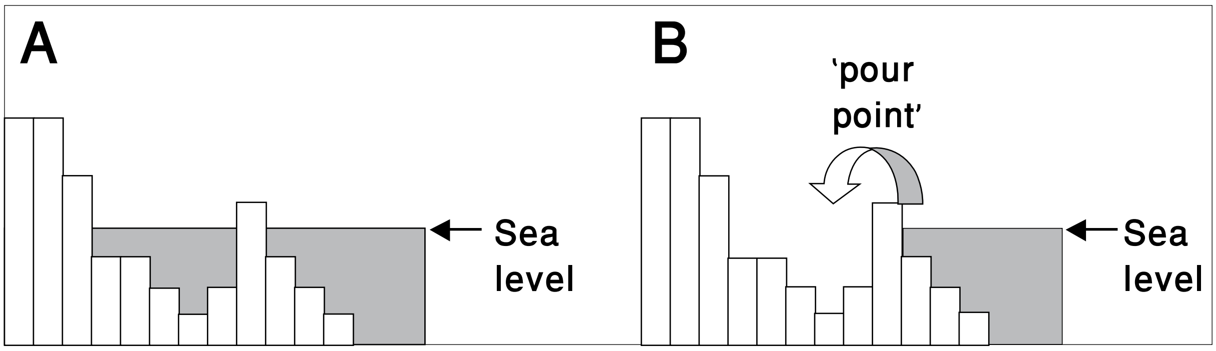


Figure 4-1. Depictions of two main sea level rise modeling strategies.

Figure 4-2. Data displaying areas susceptible to sea level rise. (University of Arizona)

of zones of inundation from sea level rise, or the identification of vulnerable zones under different scenarios. We reflect on how we have defined Mean Sea Level, in this study, and the implications of our assumption on changes in sea level based on that mean. We review further the data limitations and methodological considerations which posed a challenge to mapping sea level rise in Abu Dhabi and explain in detail how we used GIS and a flood-fill algorithm to map contiguous zones of vulnerability at 1 meter, 3 meter, and 9 meters of inundation and the data that underlies our analysis.

There are two main ways that researchers spatially model sea level rise and subsequent coastal inundation (see Figure 4-1). The two GIS methods are A, a contour-based method that relies solely on elevation data, while some low-lying areas appear inundated despite being surrounded by areas of higher elevation, as was done by Mulligan (2008) (see Figure 4-3) and B, using a more accurate flood-fill model that identifies low elevation 'sinks' that only flood when the 'pour point' is reached. (Note: the 'pour point' for coastal flooding is the value of elevation that water needs to reach before flowing into the 'sink') as was done in Figure 4-1 (Brown, 2005). An error with either method, recognized by two reports is that elevations do not directly state how far the land is above sea level.

Titus and Richman (2001), Mulligan (2008), and Stanton and Ackerman (2007) all rely on the first method. The drawback is the lack of differentiation between coastal and inland areas of the same elevation. As you can see a +1 meter 'rise' scenario results in the labeling of inland cells as vulnerable to sea level rise when they are are also at 1 meter of elevation regardless of whether flood waters will actually travel that path.

A group of researchers at the University of Arizona, worked to determine areas susceptible to sea level rise of one to six meters using a 1km DEM (GTOPO) for a global model, and a 30-meter cartographically derived DEM for their model of the US. According to their researchers, the SRTMs were not available at the time of their inundation map creation and they seemed to indicate they would have chosen it over the 30-meter DEM (J. Weiss, personal communication, February 26, 2008). Their method differs from Titus and Richman (2001) and Mulligan (2008) in that they created an algorithm to conduct cell-by-cell analysis of their chosen DEMs. They determined for each cell whether its elevation value was less than or equal to a particular integer and, if so, whether or not this cell is adjacent or connected to the sea by cells of equal or lesser value (UofA, 2003). The University of Arizona results are shown in Figure 4-2.

Similarly, researchers at the Center for Remote Sensing of Ice Sheets (CReSIS) at the University of Kansas simulated global sea level rise for 1- 6 meters, using Global Land One-km^2 Base Elevation (GLOBE) digital elevation model (DEM). The GLOBE DEM covers the entire world with a spatial resolution of 30 arc seconds

Figure 4-3. 1 meter scenario for Abu Dhabi, visualized in Google Earth. (Mulligan, 2008)

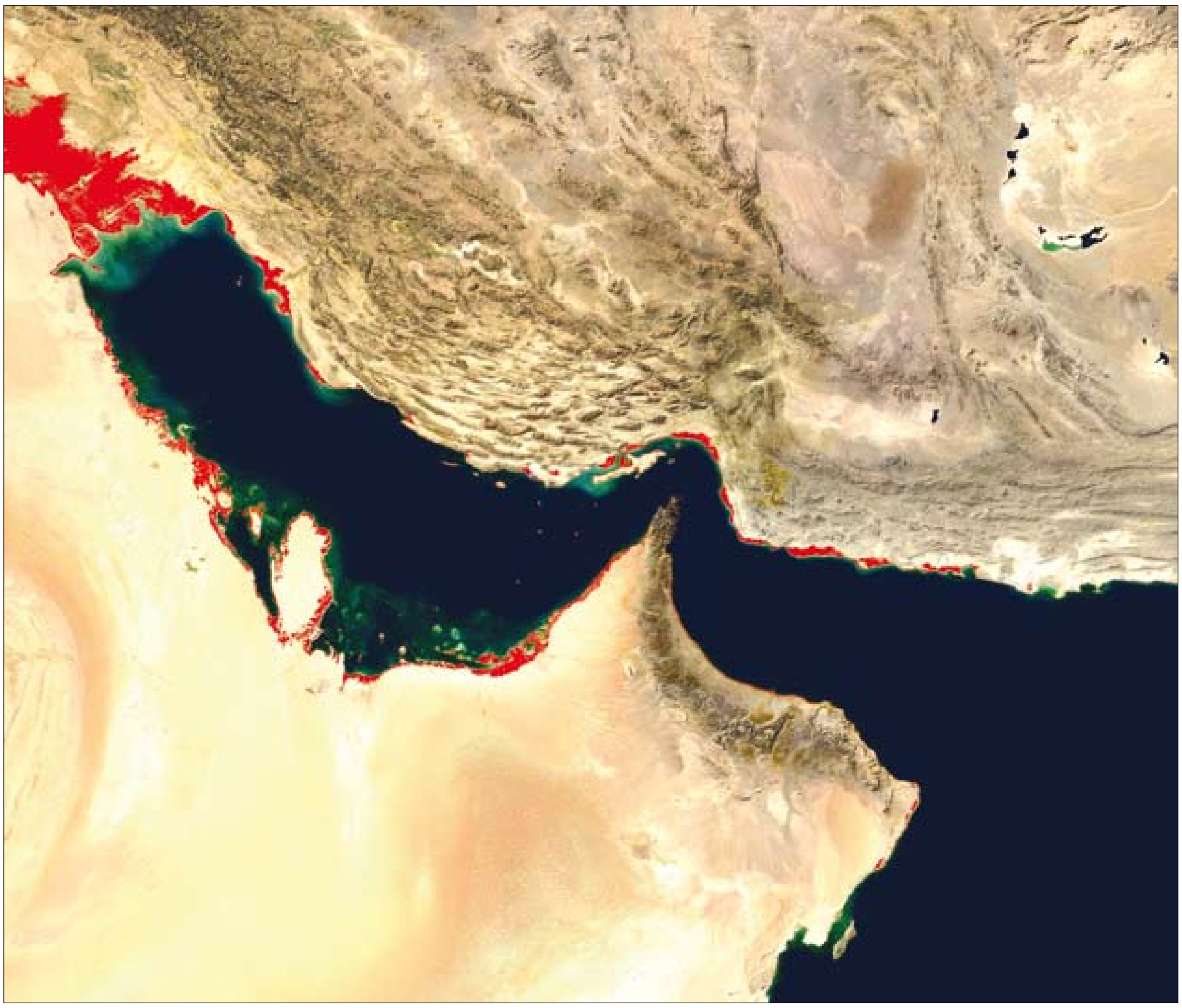


Figure 4-4. CReSIS, 6m inundation. (CReSIS, University of Kansas)

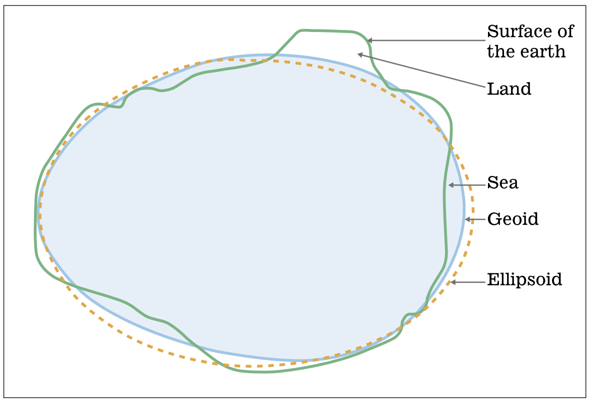
of latitude and longitude (approximately one kilometer at the Equator), with each land cell in the grid assigned an elevation value (meters) in whole number increments (see output in Figure 4-4).

Using raster analysis, the University of Kansas team identified potentially inundated areas based on elevation and proximity to the current shoreline. Using an algorithm, similar to the UofA team, they flagged all raster cells adjacent to the contiguous ocean and then did a second order of analysis to flag cells whose elevation value is less than or equal to the desired sea level rise increment. Since the initial pass floods only those cells that are directly adjacent to the current ocean, the two-step procedure is repeated until all cells connected with cells adjacent to the ocean are inundated (CReSIS, 2008).

4.3. Data limitations, methodological considerations: challenges to mapping sea level rise

Accurately mapping areas potentially inundated by rising seas depends on accurate measurements of current mean sea level as well as high-resolution terrain data to position in relation to mean sea level. The uneven distribution of masses across the planet makes it tricky to measure relative sea level. A quick technical tangent explains this fact further. The geoid is the level of surface that the sea surface would assume in the absence of

Model of the Earth



The geoid approximates mean sea level. The shape of the ellipsoid was calculated based on the hypothetical equipotential gravitational surface. A significant difference exists between this mathematical model and the real object. However, even the most mathematically sophisticated geoid can only approximate the real shape of the earth.

Figure 4-5. Model of the Earth, approximating sea level and geoid. (Fraczek, 2003)

external gravitational forcing.

Sea level approximates the geoid in most areas, and as the geoid migrates depending on various geo-physiological changes in the earth's core, the level of the sea must migrate similarly (Figure 4-5 from Fraczek, 2003). Most maps and mapping systems, however, use a reference ellipsoid- which is an idealized, smoother rendition of the earth's surface that may suggest misleading mean sea levels on which sea level rise scenarios are layered (Fraczek, 2003).

Coastal risk assessment to sea level rise has become a major area of research over the past couple decades, however, assessments are still limited by the availability of accurate data. NOAA (2006), USGS Woods Hole Field Center (Thieler *et al.*, 2007), the Clean Ocean and Shore Trust (2001), in addition to many university departments (UofA, 2003; Yohe *et al.*, 2006; CReSIS, 2008) have taken on the task of mapping those areas at greatest risk to inundation. Titus and Richman (2001), for example, mapped lands vulnerable to sea level rise along US coastlines. Challenges experienced in accurately representing coastline elevation are different from inland elevations due to land subsidence, tides, and other factors that complicate models.

Modeling anticipated sea-level rise of 1-meter or less is often poorly matched to available contour line intervals found in topographic maps (Titus and Richman, 2001). Their project used coarse DEMs (1:250,000 series) to illustrate land that is below the 1.5- and 3.5-meter contour lines. The reasons for choosing these contour lines lie in the fact that were high tide to have an elevation of 1 meter, then in areas with minimal wave erosion, the 1.5- meter lines would be areas potentially inundated were sea level to rise 0.5 meters.

In more complex and rapidly changing coastal environments, like wetlands, the 1.5-meter contour line may be ineffective at conveying actual inundation levels that are less than 1 meter (Titus and Richman, 2001). Even if flat, coastal areas are more likely to have reliable DEMs (Wu and Najjar, 2006); Titus and Richman (2001) reviewed available topographic maps for various countries and found the vertical resolution ranged from 1 meter to 40-50 meters. If 5-10 feet is the smallest increment we have for modeling sea level, researchers interested in 18-60 centimeter sea level rise by 2100 (IPCC, 2007) are going to be limited in their ability to model near-term impacts of climate change.

In contrast to ill-suited contour lines, the National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission (SRTM) developed global and US national elevation data. The SRTM data were collected with a technique known as interferometry that allows image data from dual radar antennas to be processed to extract ground heights (USGS, 2006). NASA released data at 90-meter resolution globally and 30-meter resolution for the USA. To date, the SRTM dataset at 90m resolution is the best publicly available topographic datasets for near-global use. For higher resolution and more localized data, on international projects researchers must rely on national or municipal DEMS that are likely cartographically or photogrammetrically derived (Mulligan, 2007).

Mark Mulligan, a researcher at the University College of London developed sea level rise scenarios in collaboration with NASA using their SRTM dataset. With the SRTM data, Mulligan (2008) and his team were able to map the following scenarios according to the CSI processed SRTM topographic dataset available: 1) -120m, the sea levels during the last glacial maximum (approx, 18,000 years ago); 2) +0m, calculated for error assessment; 3) +1 meters ; and 4) +4 meters of sea level rise. He explains, *"given that the typical error in SRTM altitudes is of the order of 3 meters in most coastal areas [...] this is a very preliminary analysis intended as a global first assessment and can be much improved by taking on board (a) tides and tidal ranges, (b) better error assessment, (c) improved DEMs in critical areas such as coastal cities"* (Mulligan, 2008).

While the SRTM dataset is helpful in understanding 1 meter sea level rise from the mean (0 in our dataset), it poses challenges when interested in modeling 0.3 or 0.6 meters sea level rise—which is what the IPCC posits for 2050 and 2100 respectively (excluding ice-sheet dynamics).

The challenge, to date, has been estimating vulnerable zones based on these <1 meter SLR scenarios while using topographic maps and digital elevation models whose vertical resolutions range from 1.5 to 10 to 100 meter intervals. To come with broad estimations of places that may be at risk, studies have strived to use the best available data and interpolation methods, with the likely exception of the highly accurate (and highly expensive) -- LiDAR data have errors in the range of +/- 0.3 meters-- the accuracy of these estimations will remain a problem. LIDAR is three technologies integrated into a single system- lasers, global positioning system (GPS), and inertial navigation systems (INS) (Mosaic, 2001). Figure 4-6 explains how the LIDAR's integrated technologies work together to create high resolution datasets.

Broad estimations using lower resolution datasets, however, point roughly to areas for more precise studies and can be used in recommendations for investing in select area of LiDAR data. Some countries and cities have made the investment in LIDAR (Light Detection and Ranging) data.

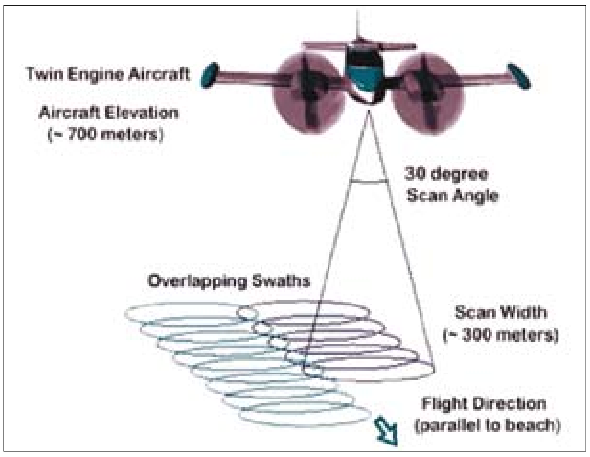


Figure 4-6. Illustration of how the LIDAR sensing instrument captures elevation points.

Mosaic Mapping Systems Inc., (2001) described the accuracy of LIDAR data as a function of terrain type and vegetative cover; in areas of extremely dense vegetation, like tropical rain forests, the percentage of laser points that penetrate the canopy and reach the ground decreases influencing the accuracy of resultant DEMs. The relative accuracy of data is summarized in the table below:

LIDAR data has been used widely develop DEMS and field data for the delineation of floodplain boundaries and identify areas at risk to flood hazards. Using LIDAR to collect shoreline topography has proven to be faster and less costly than traditional beach surveying methods in some areas. LIDAR enables the collection of shoreline measurements used to determine erosion rates, or sand volume needs for beach nourishment projects, for example, as well as measuring the effectiveness of existing management strategies like jetties and seawalls (NOAA, 2007). Coastlines

Table 4-1. Relative accuracy of LiDAR data. (Mosaic Mapping Systems, 2001)

+/- .15 meters (vertical accuracy)	Hard surfaces and open regular terrain
+/- .25 meters (vertical accuracy)	Soft/vegetated surfaces (flat-rolling terrain)
+/- .30-.50 meters (vertical accuracy)	Soft/vegetated surfaces (hilly terrain)
+/- .50-.75 meters (horizontal accuracy)	All but extremely hilly terrain (depending on flying height and beam divergence)

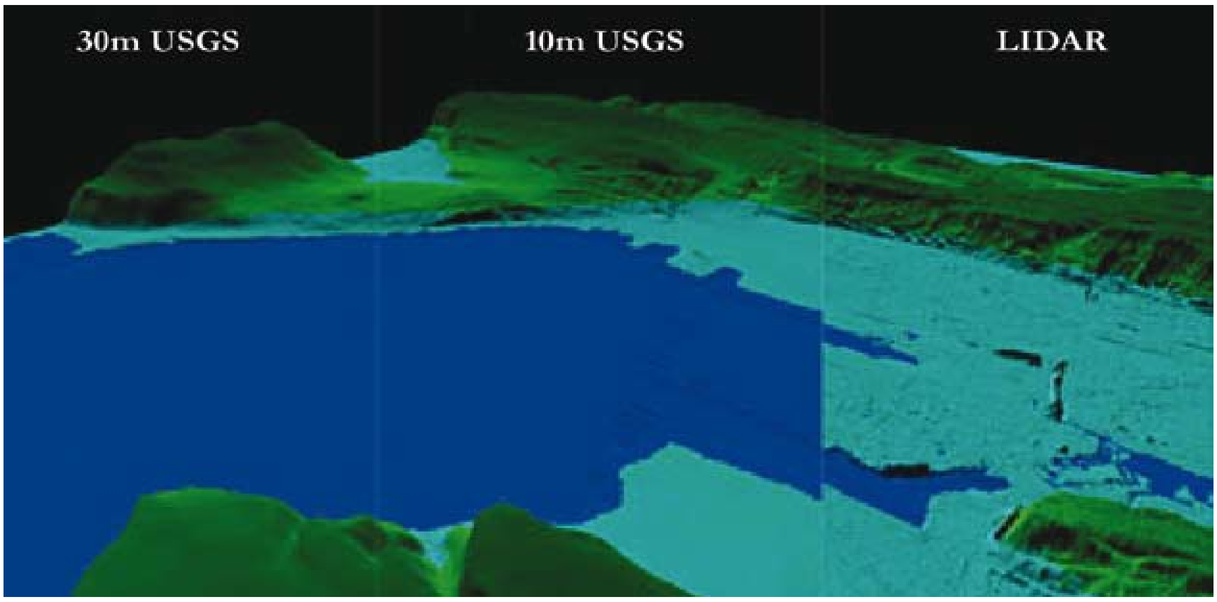


Figure 4-7.Comparison of 30-meter USGS, 10-meter USGS, and 3-meter LiDAR data for US coast. (Wu and Najjar, 2006)

are highly dynamic environments- need frequent update of baseline data such as periodic LIDAR missions and SRTM data as it is available, rather than relying on DEMs derived from outdated cartographic maps.

Wu and Najjar (2006), as part of the Consortium for Atlantic Regional Assessment (CARA) project, compared DEM data from quad maps (both 10-meter and 30-meter for the US) with available LIDAR data (interpolated to a 5-meter grid) (See Figure 4-7). Their goal was to determine the level of accuracy of the DEMs in five coastal areas and the associated error in the inundation estimates. They compared .38-, .66-, and 1-meter sea level rise scenarios using DEM and LIDAR layers and then pooled the results to estimate the area inundated, summarized in Table 4-2.

From their analysis, and based on the relatively small average discrepancies between DEMs and LIDAR in calculating inundated areas, they concluded that using the DEM30 was an "appropriate" choice for making future sea-level rise inundation estimates (acknowledging that the maps produced are a first-order assessment, and more detailed-assessments are needed).

4.4. Defining mean sea level for the UAE: reliance on tidal and elevation data

As previously mentioned, baseline sea level elevation and subsequent tidal variation around a mean is best determined by the monthly mean sea level (mmsl). Most researchers rely on tidal data to estimate the elevation of spring high water, which is the highest level the sea reaches during the year and is thus a salient benchmark when determining worst-case scenario sea level rise. The spring high tide is generally the Mean higher high water (MHHW). In spatial analysis, we used the MHHW as a tidal datum, or the average of the higher high

Table 4-2. Comparison of inundated areas using different elevation datasets. (Wu and Najjar, 2006)

	Inundated area (km^2)			Difference with LIDAR(%)	
Sea-level Rise	DEM30	DEM10	LIDAR mean	DEM30	DEM10
Below 0.38 m	8.72	8.70	8.09	7.80	7.47
Below 0.66 m	8.87	8.88	8.54	3.95	4.04
Below 1 m	10.29	10.32	9.47	8.66	9.03

water height of each tidal day observed over the National Tidal Datum Epoch. Unfortunately, Mmsl data is publicly available for only three years for the UAE, (PSMSL, 2008) and MHHW was not available from sources consulted. Since available tide data is considered insufficient for a tidal analysis, this report relies on existing analysis of tidal dynamics found in the literature, as referenced below, to best understand how tidal variation may shift with climate change induced sea level rise.

Mean sea level is not just influenced by tidal dynamics but by Arabian Gulf thermal expansion as well. For a detailed explanation of those dynamics it is suggested to revisit sections "2.3 Sea-surface temperatures, thermal expansion, and thermosteric sea level rise" and "2.4 Increase in the tidal variation around the mean". Separate from these processes, which have altered sea levels for millennia, based on the available literature, net sea level rise is defined as the historical sea level rise rate plus the accelerated rate due to global warming minus the estimated accretion rate for each type of tidal wetland calculated annually over the 200 year time period (Jones and Strange, 2008).

For lack of better elevation data, the analysis on SRTM data is from the CGIAR-CSI (Consortium for Spatial Information) GeoPortal which provides processed SRTM 90m DEM for the entire world. Produced by NASA originally, the data made available by CGIAR-CSI was processed to fill data voids and to facilitate its ease of use by a wide group of potential users. This was found to be the most comprehensive and consistent elevation data for the United Arab Emirates available publicly at the time of the analysis. Also, it is worth noting that the SRTM data is also only available in integers the implications of which, with respect to the floodfill model, limits the scenarios we can run to the values in the existing data set.

The flood fill program considers the elevation values in the cells of a grid, and then assesses the elevation differential from the elevation in neighboring cells. Take the example grid cell shown in Figure 4-8. Those cells with a value of "0" signify mean sea level. When one adds a 1 meter scenario to the grid in Figure 4-8b, the flood fill program calculates which neighboring cells in 8 directions (N, S, E, W, NW, NE, SW, SE) the water could possibly travel, based on elevation. With 1 meter rise, inundation will extend to the blue-shadec cell. In the case where sea level rises by 2 meters in Figure 4-8c, inundation extends throughout the shaded 1 meter and 2 meter cells, and are only blocked by the 3- and 4-meter cells inland. Our reliance on the SRTM dataset, also determines where mean sea level is in our model. The SRTM vertical datum is mean sea level and is based on the WGS84 Earth Gravitational Model (EGM 96) geoid. The EGM 96 is the closest approximation of the geoid in most areas, and therefore mean sea level (since sea level mirrors the geoid as explained by Figure 4-5).

4.5. GIS and a flood-fill algorithm

As explained in Section 4.2, there are two main sea level rise (SLR) modeling approaches typically drawn upon. Either one is suitable for GIS analysis. Inaccuracies arise, however, when deriving a vulnerable zone based on the contour-method because it does not consider contiguous cells the way that a pour-point or flood-fill model would. SEI developed a flood-fill program to calculate flooded areas adjacent

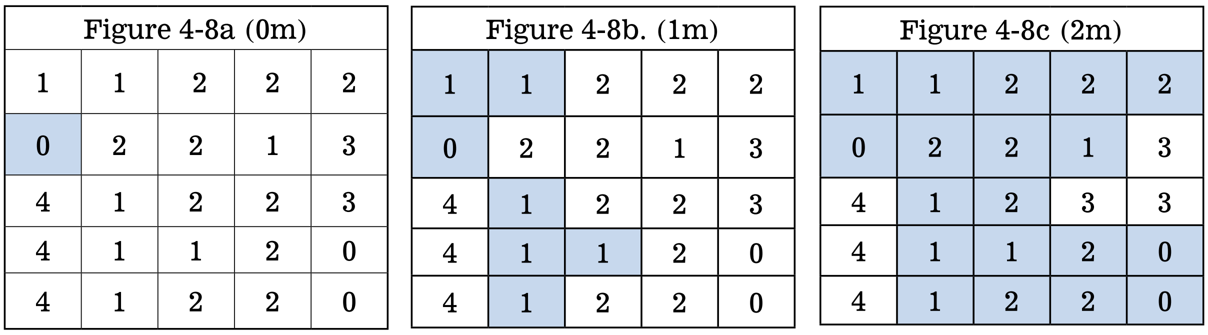


Figure 4-8a (0m)				
1	1	2	2	2
0	2	2	1	3
4	1	2	2	3
4	1	1	2	0
4	1	2	2	0

Figure 4-8b. (1m)				
1	1	2	2	2
0	2	2	1	3
4	1	2	2	3
4	1	1	2	0
4	1	2	2	0

Figure 4-8c (2m)				
1	1	2	2	2
0	2	2	1	3
4	1	2	3	3
4	1	1	2	0
4	1	2	2	0

Figure 4-8 a,b,c. Example flood-fill process.

to water using SRTM data.

In this way, the floodfill algorithm was used to establish 'vulnerable zones' of inundation at specified scenarios of sea level rise. For detailed GIS methodological steps of how these vulnerable zones were overlain with urban infrastructure and coastal ecosystem data to quantify areas and locations vulnerable to sea level rise, see Annex 1.

4.6. Scenario development

In developing our scenarios, we modeled those areas outside the intertidal zone to identify areas newly inundated given certain degrees of sea level rise. As discussed previously in the southern Arabian Gulf the tidal range rarely exceeds 2 meters, and the mean spring tidal range is 1.7 and 1.9 meters. Other resources suggest that the mean range is 1.0m while the spring range is 1.8m. The tidal range is the vertical difference between the highest high tide and the lowest low tide; most extreme tidal range (otherwise known as the spring tide) occurs when the gravity of both the Sun and Moon are pulling the same way or exact opposite way (full). For simplicity and because the SRTM data is only available in integers, we use 2 meters as the tidal range.

SLRn = Mean Sea Level (0) + (tidal range)/2 + n meters SLR

In practice this means that we ultimately shift our elevation-based scenarios +1 meter to establish sea level rise outside of the existing tidal range:

SLRn = Mean Sea Level (0) + 1 + n meters SLR

We have chosen to model four scenarios of sea level rise, representing different plausible rises over the next century or so. The likelihood of these scenarios is largely dependent on degrees of warming (2˚C to 4˚C) and the extent to which global warming continues to influence ice cap melt. We do know, however, from research by Jim Hansen of NASA's Goddard Institute, that there is plausible scientific basis to show that linear projections of sea-level rise are no longer acceptable—making room for abrupt changes, in the case of arctic melt, for example.

Scenario #1: No accelerated ice cap melting

i) 2050: 1 meters above mean sea level

ii) 2100: 2 meters above mean sea level

Scenario #2: Accelerated ice cap melting

iii) 2050: 3 meters above mean sea level

iv) 2100: 9 meters above mean sea level

For each scenario (where data allows), we have quantified the area inundated for Abu Dhabi based on the Environment Agency's land use and ecosystem classifications: mangrove, sabhka, salt marsh, sea grass, built up area, empty areas, road buffer, agriculture, forests, urban greening or amenity, archaeology sites/areas of significant historical/cultural value, and populations based on a rough estimate of city location and population. The focus of the analysis is on the Abu Dhabi Emirate, however, the elevation data inherently covers all UAE coastal cities, including those summarized in Table 4-3.

4.7. Results and Discussion

Cartwright et al. (2008) note that extreme high tides tend to be experienced at certain times of the year, most notably during the spring and autumn full-moon spring tides. As such the probability of sea-level rise events causing the type of damage described in this report is unevenly distributed throughout the year and tends to be clustered around certain, reasonably predictable, times of the year (spring tides). The analysis assumes that the government is interested in planning for at least the shorter estimate of 2050. This is a somewhat extended period over which fixed infrastructure depreciates, however, given that the probability of these extreme high tide events may increase as the frequency and intensity of storms increases, and that mean sea-level rise impairs the ability of coastal systems like the sabkhas to act as natural buffers to such events it may be worth it to prepare coastal infrastructure for 1-3m higher sea levels in the short term.

The impacts of sea-level rise cannot be fully understood without some discussion of human activities in the coastal zone. There is a growing awareness of the potential for (often well-meaning) efforts aimed at responding to natural disasters to inflict unforeseen consequences and damage of their own that outweigh the benefits of the action (Parry and Carter, 1998).

Table 4-3. UAE Coastal Cities.

Arabian Gulf Cities	Sharjah	Al Batinah Coast Cities
Al Mafra	Ajman	Hisn Diba
Tarif	Umm Al Qaywayn	Khawr Fakkan
Abu Dhabi	Jazirat Al Hamra	Al Fujayrah
Dubai		Kalba

It is, for example, now accepted that in the wake of the tsunami that devastated the Indonesian coastline, ill-conceived and mis-directed relief efforts contributed to the undermining of local livelihoods.

One of the findings of this study is that the risks of sea-level rise are caused not only by the biophysical impact of high seas, but also by the social and institutional changes that these high-sea events trigger. Abu Dhabi has ambitious coastal development plans as outlined in its 2008 Year in Review. One infrastructural improvement is the underground rail, slated for 2010, which will need to account for coastal intrusion of seawater. Also, Saadiyat Island to the east of the Corniche is being transformed into a luxury leisure and cultural destination.

Yas Island is already the emirate's sports and leisure centre, and will be home to a new Ferrari Theme Park, a Formula One circuit, a water park and several golf courses, polo fields, equestrian centre and high-end hotels. With respect to Dubai, the number of traffic lanes crossing Dubai Creek is being increased from 19 in 2006 to 47 by 2008, and to 100 by 2020—while these roads may be okay through 2020 and beyond, infrastructural improvements beyond that may need to take into account higher mean sea levels (UAE National Media Council, 2008). If sea level rises to street or foundational levels of urban structures then there are several potential impacts. First, the structure itself could compact on top of the soil. There may also be general subsidence of the soil (El Raey *et al.*, 1999).

Cost implications of a changing coastline with respect to the tourist industry and other sectors dependent on coastal infrastructure could be the subject of additional study. To evaluate effective anticipatory adaptation, this financial component is critical, however, outside the scope of the current study.

To provide readers with a sense of the extent of inundation, the following pages include several summary maps that depict the vulnerable zones in each scenario; however, more detailed maps are included in Annex 2: Inundation maps.

Using the Abu Dhabi Coastal Ecosystems as our base map, we have overlain the three sea level rise scenarios listed below on top of the various coastal ecosystems for inclusion in the main body of this report. Additional inundation maps are provided in Annex 4.

Scenario #1: No accelerated ice cap melting
  i) 2050: 1 meter above mean sea level

Scenario #2: Accelerated ice cap melting
  ii) 2050: 3 meters above mean sea level
  iii) 2100: 9 meters above mean sea level

4.7.1. 2050: 1 meter above mean sea level

At a bird's eye view, it is difficult to tell what exactly is inundated as the sea rises one meter. Much of Abu Dhabi remains above water, but is that because it actually is higher than 1m above the sea or due to the fact that the way the data was collected- elevation values were taken off of infrastructure heights, rather than using ground truths.

Zooming into Abu Dhabi city center, it is easier to see where the lower-lying areas of the coast are and where once certain areas flooded, water continues to flood inland areas.

4.7.2. 2050: 3 meters above mean sea level (Accelerated ice cap melting)

Several more offshore islands are visibly underwater now; and inland flooding is extensive. Comparing this with key features highlighted in Google Maps (below), the 3m map suggests that Mangrove Village is flooded,

Figure 4-9: Abu Dhabi Coastal Ecosystems, no Sea level rise.

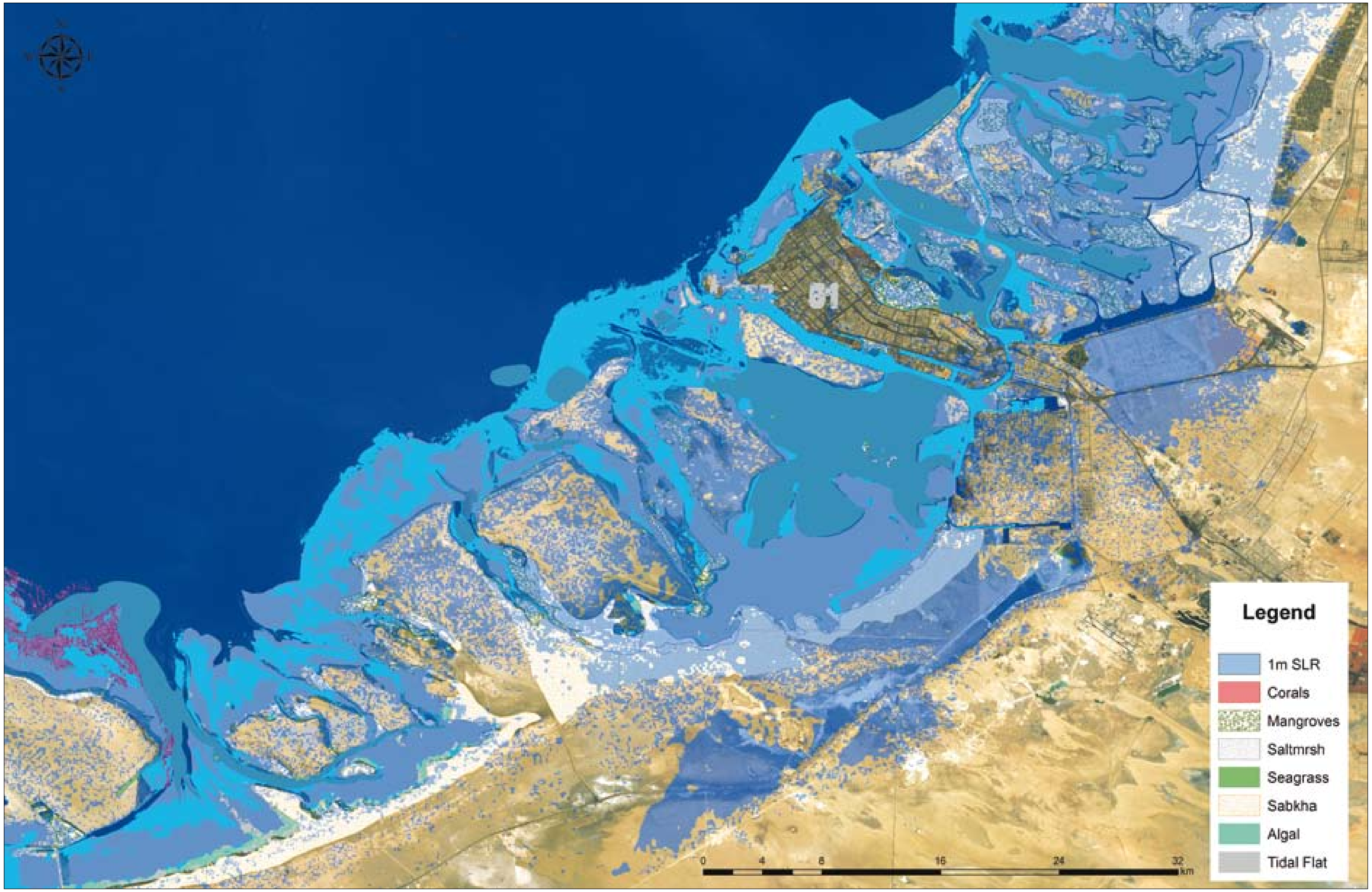


Figure 4-10: 1 meters above mean sea level by 2050

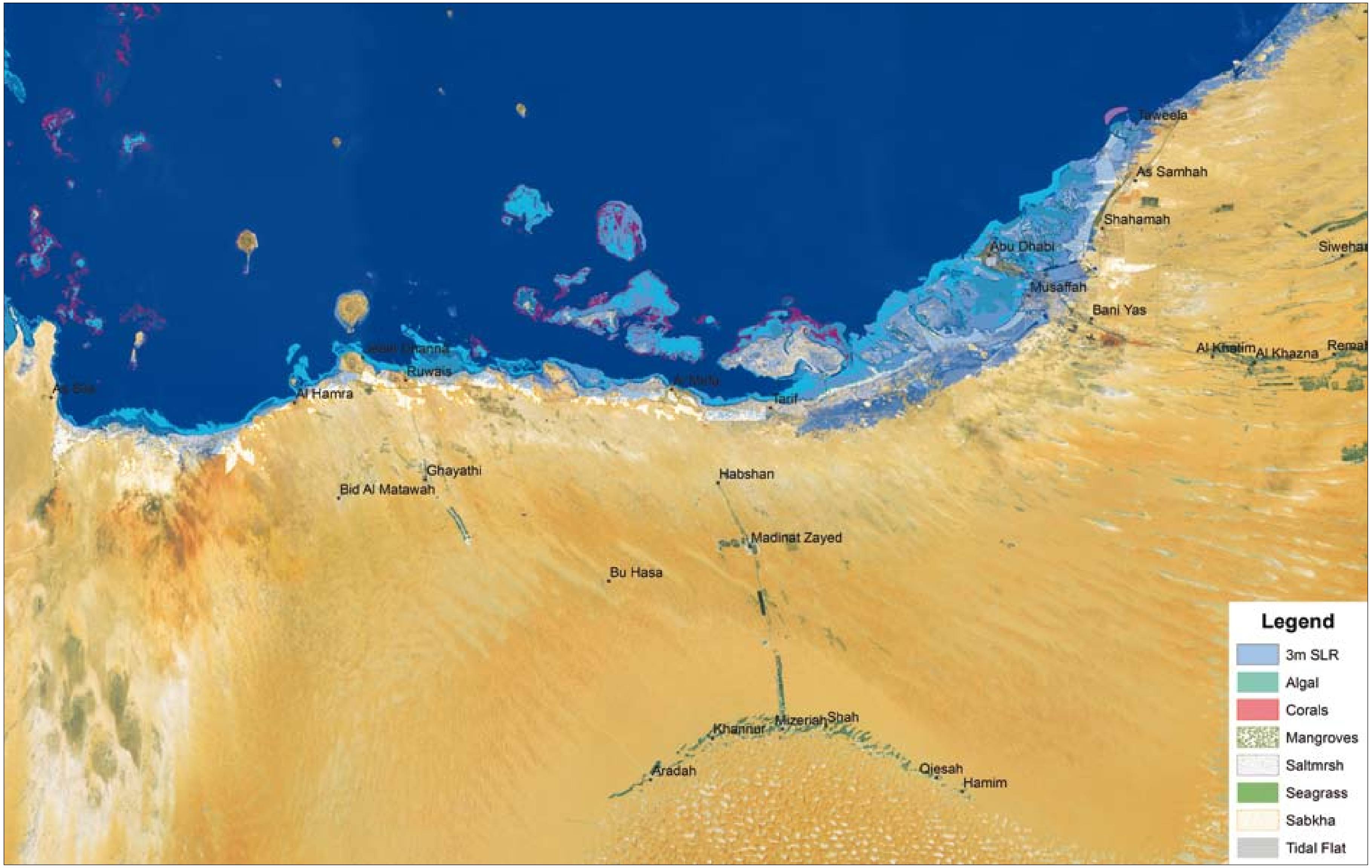


Figure 4-11: 3 meters above mean sea level (Accelerated ice cap melting / by 2050) (Regional View)

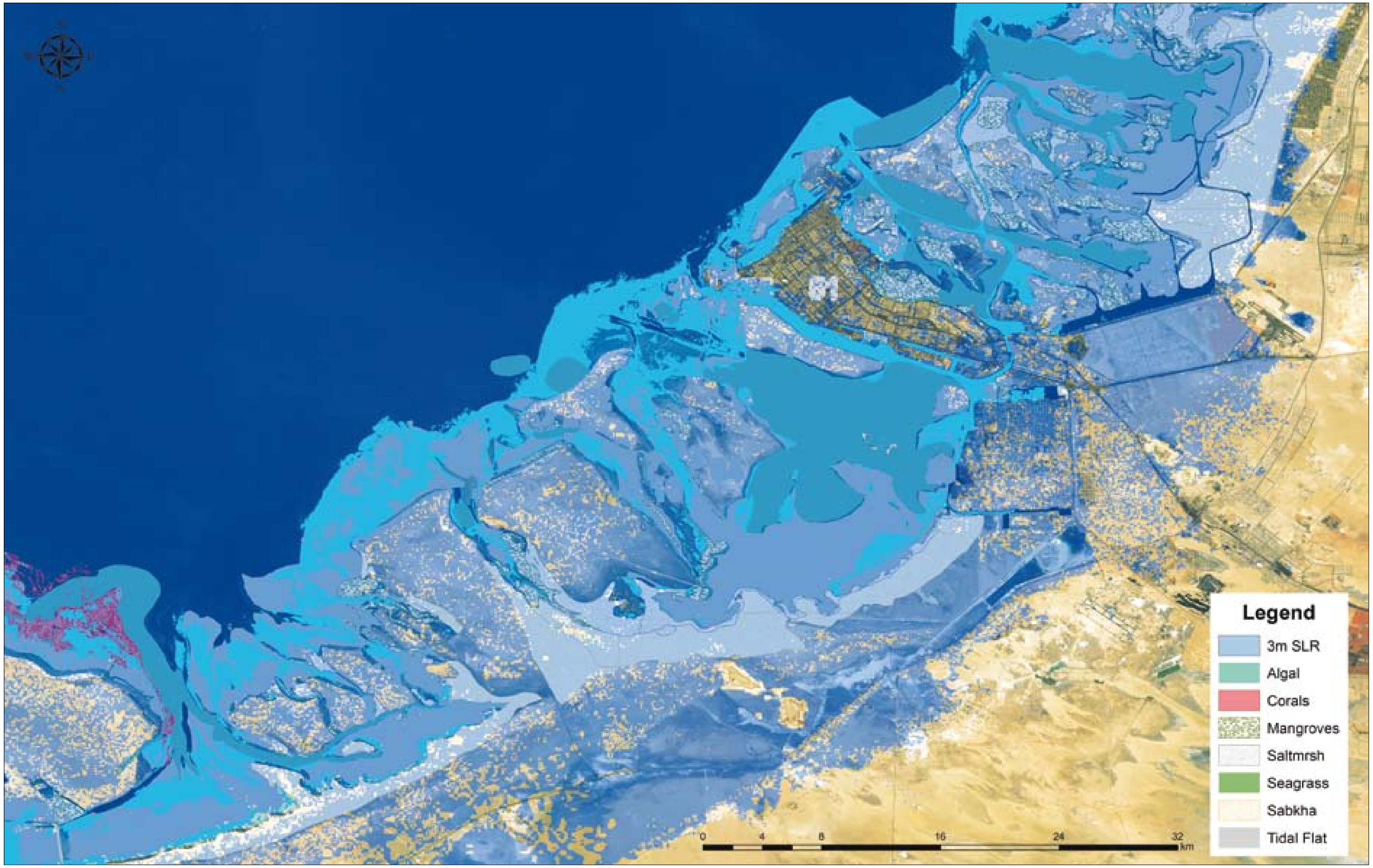


Figure 4-12: 3 meters above mean sea level (Accelerated ice cap melting / by 2050) (Zoom view on Abu Dhabi)

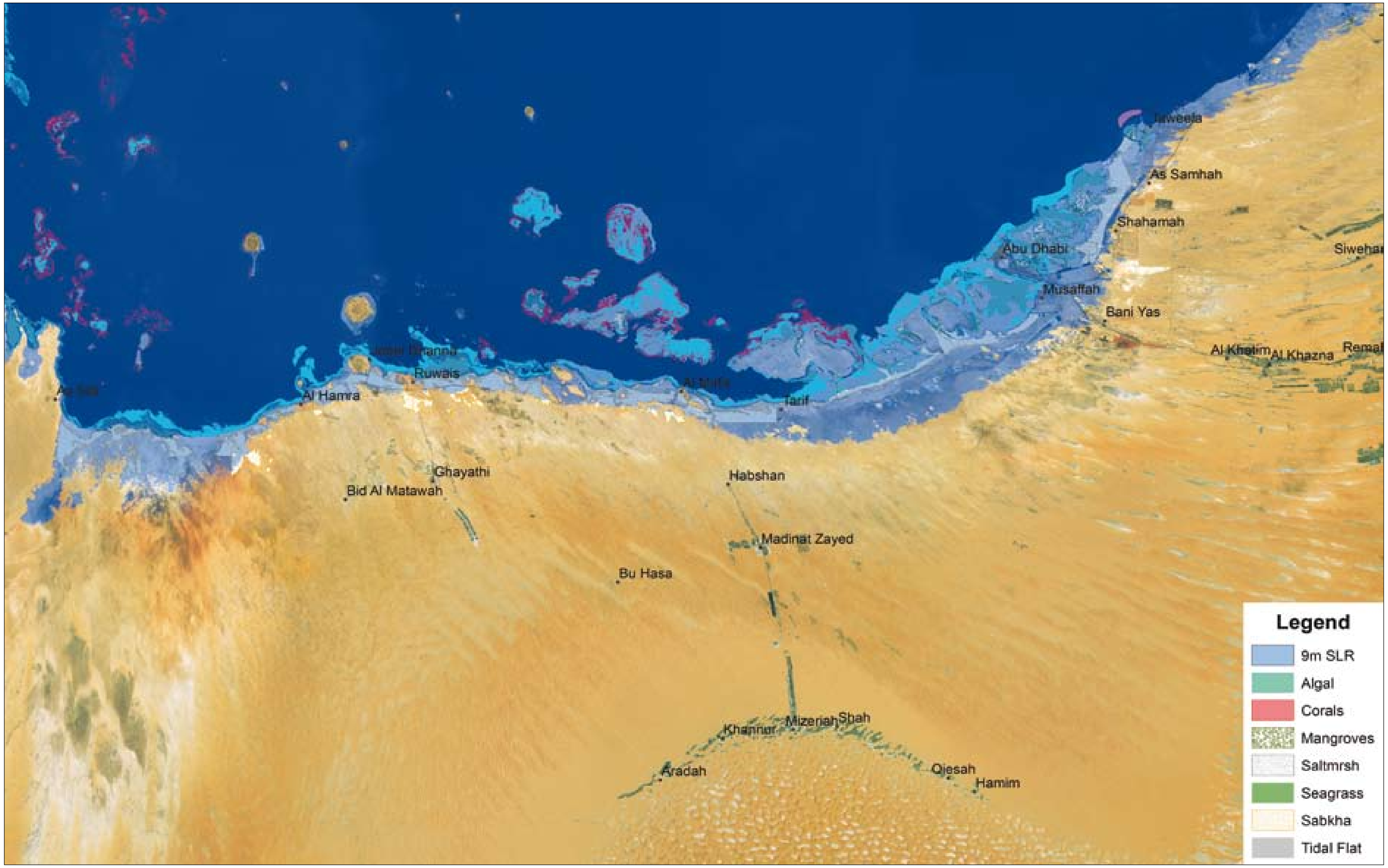


Figure 4-13: 9 meters above mean sea level (Accelerated ice cap melting) by 2100 (Regional View)

as well as parts of the Industrial City south of the main island. We know that much of the mangroves northeast of the main island are of ecological importance to the region, experts will need to identify appropriate habitat migration corridors so that mangroves are able to move inland as the shoreline retreats. The inundation of seagrass, was we've discussed is problematic because of its temperature and light sensitivities. More research should be done on its ability to migrate inland to shallower waters.

4.7.3. 2100: 9 meters above mean sea level (Accelerated ice cap melting)

At 9 meters of sea level rise, Abu Dhabi will look fundamentally different as a city and society from what we know it as today. A great deal of what will define that future community depends on how it chooses to adapt over time, but also on numerous other factors like continuing to emit greenhouse gas with no global limits, which would force us into a warmer world where deglaciation was a) possible and b) yielded 9 meters sea level rise. Additionally, should storm surges become a reality and no longer a black swan- then these sea level rise/flood fill analyses could hint at what the coast would face from a pending storm surge of that magnitude. Please note, that modeling storm surges and their probability were outside the scope of the report and we merely hint at the possibility to suggest more research is needed.

4.8. Summary Tables

The tables below provide a summary of the spatial extent of inundation for the Abu Dhabi and Dubai emirates.

Table 4-4. ABU DHABI Zones of Inundation (km^2).

LAND USE	1m rise	3m rise	9m rise
Mangrove	723	110	116
Sabhka	127	369	908
Built up area	6	24	62
Empty area	3	7	14
Road buffer	4	11	29
farm(s), small	2	7	33
forest	19	55	127
urban greening	109	220	377
urban park	0.4	2	6
TOTAL	344	804	1,672

Table 4-5. DUBAI Zones of Inundation (km^2).

LAND USE	1m rise	3m rise	9m rise
Barren lands	2	3	4
Built up Urban	7	133	200
Others (education, hospital, cemetery, etc.)	1	3	5
Transportation (Roads, Ports, Airport)	1	3	4
Grass	.4	1	1
Plantation/ Orchard	1	1	2
Woody Vegetation (Prosopis)	0.3	1	2
Shrub (Leptadenia)	0.3	1	1
Coastal/ Saline	0.04	0.1	0.2
Mangrove	0.02	0.03	0.03
WaterBodies	0.2	0.3	0.3
Wetlands (Tidal Flat, Mud Flat, Creek)	1	1	1
TOTAL	14	147	221

5. Framework for climate change adaptation in coastal areas

Urban vulnerability to sea level rise includes both risks to infrastructure as well as on island settlements and coastal cities. In particular, numerous culturally valuable buildings and ecological zones are at risk when seas rise and shorelines retreat. For example, Sir Bani Yas Island is home to a seventh century Nestorian monastery and church, the only known Christian remnant in the country prior to the arrival of Islam and the largest one ever found in Eastern Arabia. And Dalma Island is known for yielding some of the region's earliest evidence of date palm cultivation along with shards of Ubaid or Mesopotamian pottery and finely flaked stone tools. Much of the discussion below focuses on the role of technologies in adapting to the risks of inundation and is based on a recent paper by Klein, *et al* (2006).

5.1. Historical context for adaptation in coastal zones

Around the world, the historical emphasis for dealing with coastal hazards has traditionally been on protecting developed areas using hard structures like sea walls. The actual skills and technologies required to plan, design and build these structures have depended on their required scale and level of sophistication. On a small scale, local communities have used readily available materials to build protective structures. For larger-scale, more sophisticated structures, technical advice and engineering has been required for design purposes, as well as a contracting firm to build the structure.

Until recently, it was rarely questioned whether a country's coastline could be protected effectively if optimal management conditions prevail. It has become increasingly clear, however, that even with massive amounts of external funding, coastlines may not be effectively protected by hard structures. In addition, increasing awareness of unwanted effects of hard structures on erosion and sedimentation patterns has led to growing recognition of the benefits of "soft" protection (e.g. beach nourishment, wetland restoration and creation) and of the adaptation strategies retreat and accommodate, which are discussed later in this section. An increasing number of private companies in the industrialized world are now discovering market opportunities for implementing soft-protection options. Interest in the retreat and accommodate strategies is also growing among coastal managers, but these strategies require a more integrated approach to coastal management than is currently present in many countries, so their application is still less developed.

In spite of this pattern to consider technologies for adaptation other than hard protection, many structures are still being built without a full evaluation of the alternatives. One reason could be that hard structures are more tangible and hence appeal more strongly to the imagination of decision makers and stakeholders and, by their visibility, may be perceived to provide more safety and hold the sea at bay forever. In addition, it is generally felt that hard structures are less maintenance-intensive than soft structures. However, past experiences suggest that the design of soft structures is particularly important in determining the level of maintenance required, but that appropriate design and implementation often require good knowledge of coastal dynamics as well as effective coastal management institutions.

A second trend for coping with coastal hazards is an increasing reliance on technologies to develop and manage information. This trend stems from the recognition that designing an appropriate technology to protect, retreat or accommodate requires a considerable amount of data on a range of coastal parameters, as well as a good understanding of the uncertainties involved in the impacts to be addressed. National, regional and global monitoring networks are being set up to help to assess technology needs and opportunities.

Third, many efforts have been initiated to enhance awareness of the need for appropriate coastal technologies, often as maladaptive practices have become apparent. For example, before a new hospital was built in Kiribati in 1992, a substantial site-selection document had been prepared, examining numerous aspects of three alternative sites, but without consideration of coastal processes. A serious shoreline erosion problem, advancing rapidly to within eight metres of the hospital, was discovered by 1995 (Forbes and Hosoi 1995). Options to enhance awareness include national and international workshops and conferences, training programmes, online courses and technical assistance and capacity-building as part of bilateral or multilateral projects. A suggestion moving forward is to designate sabkha research reserves to better understand how higher seas will impact an ecosystem increasingly bordered by man-made infrastructure. As seas rise and more salt is deposited inland, recent research suggests that seawater irrigation could remove the salt crust and reduce the substrate salinity to ocean levels thus allowing for reforestation with local mangrove species and other halophytes (Lieth and Menzel 2002).

The remainder of this section presents a framework to consider adaptation in the coastal areas in the UAE. Specifically, the focus is on a 4-fold framework described in Klein *et al* (2006) that involves a) the development of information systems, b) development of planning and design strategies, c) implementation of such strategies, and d) monitoring and evaluation of their performance. Note that no attempt has been made to provide all-inclusive lists of options and measures for various types of coastal environments in the UAE (e.g. coral atolls, coasts of inland waters, small islands). The measures discussed in the subsections below are meant to be illustrative and to encourage coastal planners to consider as wide a spectrum of options for adaptation as possible in the Emirates.

5.2. Information Systems

Regarding information, data collection and information development are prerequisites for coastal adaptation in Abu Dhabi, in particular to identify adaptation needs and priorities relative to the findings described earlier. The more relevant, accurate and up to date the data and information available to the coastal manager, the more targeted and effective adaptation strategies can be. Coastal adaptation requires data and information on coastal characteristics and dynamics, patterns of human behavior, as well as an understanding of the potential consequences of climate change. It is also essential that there is a general awareness among the public, coastal managers and decision makers of these consequences and of the possible need to take appropriate action.

A large-scale global and regional data repositories could be established for a number of climatic and socio-economic variables relevant to coastal zones in the Abu Dhabi Emirate. These sources of data could be integrated into a type of Abu Dhabi Sea Level Center. This Center could also provide a network for the assessment of climate and socio-economic scenarios as understanding evolves at the international level (i.e., IPCC assessments) as well as in the Emirate itself. The Center should also be a good repository for detailed information on a range of technologies that can serve to increase the understanding of the coastal system (which involves data collection and analysis), to conduct planning as well as further climate impact assessments in coastal zones (so that potential impacts can be quantified for given scenarios) and to raise public awareness that some form of adaptation is necessary.

Many technologies could be “soft” options that are vital to building capacity to cope with climatic hazards. For example, some technologies make use of GIS which combines computer mapping and visualization techniques with spatial databases and statistical, modelling and analytical tools. Collected data can be stored in a geographical information system that can be useful in developing new insights and information, and visualized for interpretation and educational purposes.

5.3. Planning and Design

When the available data and information point towards a potential problem that would justify taking action, the next stage is to decide which action could best be taken and where and when this could best be done. The answers to these questions depend on the prevailing criteria that guide local, national or regional policy preparation, as well as on existing development and management plans that form the broader context for any adaptation initiative. Important policy criteria that could influence adaptation decisions include cost-effectiveness, environmental sustainability, cultural compatibility and social acceptability in Abu Dhabi. In addition, individual emirates should choose to take a precautionary approach as postponing action involves substantial risks, even though uncertainty may still be considerable.

Coastal planners in Abu Dhabi will always face a certain degree of uncertainty, not only because the future is by definition uncertain, but also because knowledge of natural and socio-economic processes is and always will remain incomplete. This uncertainty requires planners to assess the environmental and societal risks of climate change with and without adaptation. The information thus obtained can help to determine the optimal adaptation strategy and timing of implementation. There are a number of decision tools available to assist in this process. Examples of these tools include cost-benefit analysis, cost-effectiveness analysis, risk-effectiveness analysis and multicriteria analysis. The last technique is particularly relevant when great significance is attached to values that cannot be easily expressed in monetary terms.

GIS can assist planners in identifying appropriate technologies for adaptation, as well as the optimal locations for their application, depending on the criteria of the decision maker. One simple, first-order application of GIS in coastal adaptation would be overlaying scenarios of sea-level rise with elevation and coastal development data to define impact zones, as has been demonstrated in this study through the analysis of sea level rise scenarios. More sophisticated applications may include the modelling of morphodynamic and ecological responses to climate change. In addition, GIS allows for the non-invasive, reversible and refinable testing of specific technologies for adaptation before these are implemented in the real world. After implementation, newly acquired data can be analysed to evaluate technology performance. Once created, a GIS database will have further utility in other aspects of management and policy.

The modelling of potential futures based on plausible scenarios is pertinent for the planning and design of Abu Dhabi development that accounts for adaptation, when relevant impacts are quantified, alternative adaptation options are evaluated and one course of action is selected. Climate impact assessment requires models of relevant changes in morphological, ecological and human factors, as well as their interaction over appropriate time scales (i.e. a decade or longer). The necessary modelling capabilities are increasing rapidly and current developments in information technology are facilitating the transfer and application of these tools as they are developed. However, the limitations inherent in all models (i.e. they are representations of a part of reality for a specific purpose) must not be overlooked. Human expertise and interpretation remain essential for the intelligent use of any model.

The quality and effectiveness of future planning and design process in Abu Dhabi to account for sea level rise will be influenced by the context in which decisions are made. The successful implementation of many coastal policies, including adaptation to climate change, will likely be increasingly dependent on public acceptance at the community level, especially if large scale retreat from ocean proximity is involved. In addition to informing the public so as to raise their awareness of the issues at stake, it may also be important to involve them throughout the planning process. Gaining public acceptance is an important prerequisite for identifying and transferring appropriate technologies for adaptation. Further, local expertise will be required for successful technology implementation, application, maintenance and enforcement.

In response to difficulties encountered in planning and designing adaptation strategies, a number of frameworks have been developed to assist in these activities. One recent decision framework that has relevance to the planning and design of adaptation is the Adaptation Policy Framework of the United Nations Development Programme (APF) (Lim and Spanger-Siegfried 2005). The APF is intended to complement existing policymaking relating to climate change in developing countries, including processes of assessment, project development and monitoring.

5.4. Planning for Adaptation: the UNDP Adaptation Policy Framework (APF) in coastal zones

Klein and Nicholls (1998) concluded that most coastal adaptation options require strategic planning, whereas few would occur autonomously. In addition, options to protect against sea-level rise can be implemented both reactively and proactively, whereas most retreat and accommodation options are best implemented in an anticipatory manner. To date, the assessment of possible adaptation strategies in coastal zones has focused mainly on protection. The range of appropriate options will vary among and within countries, and different socio-economic sectors may prefer competing adaptation options for the same area. The existence of such a broad range of options is one of the reasons why adaptation to climate change is recommended to take place within the framework of integrated coastal zone management. The UNDP Adaptation Policy Framework (APF) is one way countries have been able to identify and prioritize integrated and cross-sector adaptation policies.

The UNDP Adaptation Policy Framework (APF) provides useful guidance on designing and implementing projects that reduce vulnerability to climate change, by both reducing potential negative impacts and enhancing any beneficial consequences of a changing climate. Think of the APF as a structured approach to developing adaptation strategies, policies, and measures to ensure human development in the face of climate variability and change. The APF links climate change adaptation to national development and environmental issues. The APF has been shown to be particularly applicable for and effective in countries where the adaptation measures need to be integrated into broader sector specific policies, economic development, or other policy domains. The APF strives to enable the integration of national policy-making with a "bottom-up" movement that builds on participatory processes and local knowledge.

It is structured around the following four major principles: a) adaptation to short-term climate variability and extreme events is explicitly included as a step towards reducing vulnerability to longer-term climate change, b) adaptation policy and measures should be assessed within a developmental context, c) adaptation occurs at different levels in society, including the local level, and d) both the strategy and process by which adaptation activities are implemented are equally important.

The APF helps people answer the questions:

- What kind of policy instruments will reduce vulnerability to climate change?
- What kind of policy decisions might be influenced by a project?
- How might project results be introduced onto the local, or national policy agenda?

The APF not prescriptive; it is a flexible approach in which the following five steps may be used in different combinations according to the amount of available information and the point of entry to the project: (1) defining project scope and design, (2) assessing vulnerability under current climate, (3) characterizing future climate related risks, (4) developing an adaptation strategy, and (5) continuing the adaptation process. The framework focuses on the involvement of stakeholders at all stages. For example, the UAE is already well informed regarding its vulnerability under current climate, and have invest time and resources in characterizing future risks to climate change. What remains is to define the scope and design of future adaptation efforts, begin the planning process for adaptation, and to start mainstreaming known risks to climate into all aspects of the country's 2030 visions, master sector plans, and any other long term planning process that, to date, has yet to adequately account for a changing climate.

Developing an adaptation strategy for future climate change requires a clear idea of key objectives. At the broadest level, the overall objectives of an adaptation strategy must fit within the development priorities of a country (for example, water security, food security enhancement, action plans under multilateral environmental agreements, etc). At a more operational level, there are at least five important objectives:

- Increasing the robustness of infrastructure designs and long-term investments;
- Increasing the flexibility and resilience of managed natural systems and social systems;
- Enhancing the adaptability of vulnerable natural systems;
- Reversing trends that increase vulnerability (also termed “maladaptation”); and
- Improving societal awareness and preparedness for future climate change.

Developing an adaptation strategy also requires a vision that balances the need to reduce climate change impacts with the constraints inherent in national policymaking processes. Ultimately, whatever the decisions reached regarding the most appropriate options and measures to reduce vulnerability, the packaging of those decisions into an adaptation strategy streamlined for implementation will be facilitated by policy coherence across sectors, spatial scales, and time frames.

5.5. Implementation

Once all options for coastal adaptation have been considered and the most appropriate strategy has been selected and designed, implementation of the strategy is the next stage. An adaptation strategy can include the application of technology, but this does not have to be the case. In coastal zones, an adaptation strategy to sea-level rise can comprise one or more options that fall under the three broad categories protect, retreat and accommodate (IPCC CZMS 1992). It should be noted that, in addition to the subdivision between protect, retreat and accommodate, there are various other ways to classify or distinguish between different adaptation strategies, both in generic terms (e.g. Smit *et al.*, 2000) and for coastal zones (e.g. Kay *et al.*, 1996; Pope, 1997).

In Abu Dhabi, where there are sophisticated insurance markets that could cover climate risks, insurance can have a positive or a negative role in promoting adaptation to climate change and any associated technology transfer. This may happen directly via contacts with customers or indirectly via the lobby institutions of the insurance industry. Technology underpins this interaction, as improving data management and modeling capability give the insurance industry more detailed information of both the risks and opportunities that climate variability and change present. However, more knowledge may benefit the insurance industry, but it does not necessarily lead to overall social benefits. Clark (1998) argued that partnerships between governments and the insurance industry can benefit both the industry and wider society in terms of reduced exposure and maintain the long-term viability of the insurance industry.

5.6. Monitoring and evaluation

Effective evaluation of the effectiveness of adaptation measures implemented for Abu Dhabi coastal areas will require a reliable set of data or indicators, to be collected at some regular interval by means of an appropriate monitoring system. Indicators are a tool for reporting and communicating with decision makers and the general public. They should have a range of properties, including (i) a relationship to functional concepts, (ii) be representative and responsive to relevant changes in conditions and (iii) be easily integrated within a broader evaluation framework. Evaluation is an ongoing process and the monitoring should be planned accordingly. There is limited experience of such long-term monitoring, so in many situations it is unclear which are the most appropriate data or indicators (Basher, 1999).

For coastal physical systems, experience can be drawn from countries where the coast has been monitored for long periods. In The Netherlands, for instance, data on the position of high water have been collected annually for nearly a century and cross-shore profiles have been measured annually since 1963 (Verhagen, 1989; Wijnberg and Terwindt, 1995). Observations of the natural evolution of the coast allow trends to be estimated reliably and hence the impact of human interventions on the coast (breakwaters, nourishment, etc.) to be evaluated. Additionally, given the long-term nature of climate change, the adaptation policy process and implemented strategies will need to make adjustments over time as climate impacts manifest themselves.

5.7. Adaptation Strategies

There are various ways to classify or distinguish between adaptation options. First, depending on the timing, goal and motive of its implementation, adaptation can be either reactive or anticipatory. Reactive adaptation occurs after the initial impacts of climate change have become manifest, whilst anticipatory (or proactive) adaptation takes place before impacts are apparent. A second distinction can be based on the system in which the adaptation takes place: the natural system (in which adaptation is by definition reactive) or the human system (in which both reactive and anticipatory adaptation are observed). Within the human system a third distinction can be based on whether the adaptation decision is motivated by private or public interests. Private decision-makers include both individual households and commercial companies, whilst public interests are served by governments at all levels. Figure 5-1 below shows examples of adaptation activities for each of the five types of adaptation that have thus been defined (from Klein *et al*, 2005).

A key point is that adaptation to climate change is an ongoing and reiterative process that includes information development, awareness raising, planning, design, implementation and monitoring. Reducing vulnerability requires having mechanisms in place and technologies, expertise and other resources available to complete each part of this process. The mere existence of technologies for adaptation does not mean that every vulnerable community, sector or country has access to these options or is in a position to implement them.

In response to sea level rise, the literature and other countries have identified several major coastal adaptation strategies: retreat, resettlement, and improve coastal infrastructure like breakwaters and embankments to physically protect existing infrastructure. The study of Climate's Long-range Impacts on Metro Boston (CLIMB) identified three overarching ways for a city to adapt to anticipated climate changes, including sea level rise (Kirshen *et al.*, 2003). The scenarios here have been adapted to the UAE context in Table 5-1.

		Anticipatory	**Reactive**
Natural Systems			• Changes in length of growingseason; • Changes in ecosystem composition; • Wetland migration.
Human Systems	**Private**	• Purchase of insurance; • Construction of house on stilts; • Redesign of oil-rigs.	• Changes in farm practices; • Changes in insurance premiums; • Purchase of air-conditioning.
	Public	• Early-warning systems • New building codes; design standards; • Incentives for relocation.	• Compensatory payments, subsides; • Enforcement of building codes; • Beach nourishment.

Figure 5-1. Types of Adaptation. (Klein et al, 2005)

Table 5-1. Potential adaptation scenarios (Kirshen et al., 2003)

Scenario Title	Policy	Demographic	Technology
"Ride It Out"	Present trends in region continue. There are no adaptation actions such that ecosystems unable to migrate inland	Same as current scenario of continued sprawl of major metropolitan zones, mid-high population growth rate; current migration rates	Business as usual rate of penetration of green and innovative technology by sector (e.g. Masdar Initiative); however less concern on rising sea levels
"Build Your Way Out"	Same as "Ride It Out" but replace and protect systems as they fail (reactive adaptation); ecosystems unable to migrate inland	Same as "Ride It Out"; populations may be forced to move inland if protection systems fail "retreat"	Same as "Ride It Out"
"Green"	Restrictions on construction locations. Stronger bldg codes and natural hazard zoning. Emphasis on centralized and 'climate proofed' development; (proactive adaptation) natural systems are allowed to move inland	Limited population growth rate;	Higher rate of green technology penetration than "Ride It Out"; "smart growth" development such that infrastructure is no longer built in vulnerable zones (as identified by increasingly accurate inundation mapping)

6. Conclusions and recommendations

Cross-sectoral and ministerial collaboration and partnerships are essential in addressing the challenges posed by climate change. To more accurately assess vulnerability, the planning agencies in the UAE could work with city planners who have current building footprint, property value and other important data sources, agencies with high resolution elevation datasets, as well as with those responsible for the census and population studies that can help spatially reference those populations the most vulnerable. A complimentary analysis focusing on the costs or financial losses to infrastructure may be a logical next step in identifying where, when, and how much areas will need investment for adaptation.

To better identify appropriate adaptation strategies much more detailed data is required for sufficient mapping, for making financial or infrastructural decisions, or for model potential population movements given a 'worst case scenario'. It is likewise important to improve scientific understanding around extreme events and the probability of cyclones like Gonu becoming a recurring event. Cyclone and storm surge modelling were outside the scope of this study, except to say that if the coastal cities anticipate a 3m wave surge, the vulnerable areas are the same regardless of whether it's gradually or abruptly inundated. This analysis is a broad assessment, given available data, that suggests area for future studies—particularly those areas who find themselves vulnerable to only 1m of sea level rise which we may see by the end of the century. A second consideration is the complexity of shoreline systems. As a first cut inundation study we have stayed away from modelling how the shoreline and ecosystems will physically respond to rising sea levels, however, an accurate shore-dynamics model that include topographic data of even up to 10cm vertical resolution as well as eco-system specific habitat migration research would help in this regard.

While we may not be able to pinpoint exactly when to expect one meter gradual rise in sea level, we do know that it may be sooner than most scientists ever thought possible. Much of the urban landscape may be fundamentally different by then. In coastal cities, infrastructure and investment are obviously ongoing. Urban plans of grand high rises, rapid underground public transit infrastructure, modernized utility pipelines, and anything else on the table, that likely (or hopefully) have a longer lifespan than the twenty-five to thirty years we may have before our first critical time marker.

Work on adaptation so far has addressed the impacts of climate change, rather than sufficiently addressing the underlying factors that cause vulnerability to it. While there is a significant push all around for adaptation to be better placed in development planning, there is a missing step if vulnerability reduction is not considered central to this. A successful adaptation process will require adequately addressing the underlying causes of vulnerability. A sustainable adaptation process appears to first require adjustments in policies, institutions and attitudes that establish enabling conditions, and second be accompanied by eventual technological and infrastructural changes.

In thinking towards future sea level rise, we usually identify 2050 as the first critical benchmark, after which most quasi-protected, or at least non-island state, societies should start to worry. Past conception of invincibility to coastal events are no longer supported by science. Southeast Asia, and low lying states like Bangladesh are already planning for migrating millions of people to higher ground. The UAE, at least those Emirates that border the Arabian Gulf, have seemed somewhat protected from the ravages of Indian Ocean cyclones. However it too is a low-lying nation. The majority of the coastline and coastal ecosystems find themselves within 0-5 meters elevation above mean sea level.

Given the intersection of Abu Dhabi's new and planned infrastructure with increasing climate risks, the current trajectory could unwittingly be headed towards disaster if it does not adequately take into account known climate risks into plans. If the planet were to reach any kind of global tipping point, whether from quickened ice-sheet melt, or high concentrations of carbon in the atmosphere and ocean warming both we could start to witness the abrupt disruption of local (and previously somewhat predictable) weather patterns and coastal dynamics. The uncertainty of 'when' and 'to what extent' are we really vulnerable placates many into a 'wait and see' mentality—trending towards a "Ride it out" or "Build Your Way Out" Adaptation Strategy (use Table 5-1). As has been experienced time and time again in many places across the world, Ride it Out may no longer be an option. Build Your Way Out may an option for those with sufficient resources it is not a viable long-term response. The UAE can continue to lead by example on climate change by choosing the "Green" adaptation strategy, a strategic response that calls for proactive and innovative thinking, and a coordinated effort across ministries and sectors.

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8. Glossary

Adaptation: Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory, autonomous and planned adaptation.

Adaptive Capacity: The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. (IPCC)

Adaptive Management: Adaptive management seeks to aggressively use management intervention as a tool to strategically probe the functioning of an ecosystem. Interventions are designed to test key hypotheses about the functioning of the ecosystem. This approach is very different from a typical management approach of 'informed trial-and-error' which uses the best available knowledge to generate a risk-averse, 'best guess' management strategy, which is then changed as new information modifies the 'best guess'. Adaptive management identifies uncertainties, and then establishes methodologies to test hypotheses concerning those uncertainties. It uses management as a tool not only to change the system, but as a tool to learn about the system. It is concerned with the need to learn and the cost of ignorance, while traditional management is focused on the need to preserve and the cost of knowledge. (www.resalliance.org/565.php)

Climate change: Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC, 2001). Note, however, that the United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". The UNFCCC thus makes a distinction between "climate change" attributable to human activities altering the atmospheric composition, and "climate variability" attributable to natural causes.

Climate hazards: Climatic hazards are threats to a system, comprised of perturbations and stress (and stressors), and the consequences they produce. A perturbation could be a major spike in pressure (e.g., a tidal wave or hurricane) beyond the normal range of variability in which the system operates. Perturbations commonly originate beyond the system or location in question. Hazards can include latent conditions that may represent future threats and can be single, sequential or combined in their origin and effects. Each hazard is characterized by its location, intensity, frequency and probability.

Climate Model: commonly thought of as a numerical or mathematical representation of the physical, chemical and biological properties (atmosphere, ocean, ice and land surface) of a climatic system, which incorporates scenarios (coherent internally consistent and plausible descriptions of a possible forthcoming states of the world; Carter et al, 1994) allowing for the generation of future predictions (Santer et al., 1990).

Climate variability: Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability) (IPCC, 2001).

Climate threshold: The point at which external forcing of the climate system, such as the increasing atmospheric concentration of greenhouse gases, triggers a significant climatic or environmental event which is considered unalterable, or recoverable only on very long time-scales, such as widespread bleaching of corals or a collapse of oceanic circulation systems (IPCC, 2007).

Climate change scenarios: coherent and internally-consistent descriptions of future climate given certain assumptions about the growth of the emissions of greenhouse gases and about other factors that may influence climate in the future. The uncertainties associated with the modeling of future climate scenarios have been divided by the Hadley Centre into three broad categories: (1) emissions uncertainty; (2) natural climatic variability; and (3) modeling uncertainty (UKCIP).

Climate Impact Assessment: the practice of identifying and evaluating the detrimental and beneficial consequences of climate change on natural and human systems (IPCC).

Impacts of climate change: The effects of climate change on natural and human systems. Depending on the consideration of adaptation, one can distinguish between potential impacts and residual impacts:

- **Potential impacts:** all impacts that may occur given a projected change in climate, without considering adaptation.
- **Residual impacts:** the impacts of climate change that would occur after adaptation. See also aggregate impacts, market impacts, and non-market impacts.

Mitigation: An anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases (IPCC, 2007)

No-regrets adaptation measures: fail-safe adaptation options whose benefits, such as reduced energy costs and reduced emissions of local/regional pollutants equal or exceed their cost to society, excluding the benefits of climate change mitigation. They are sometimes knows as “measures worth doing anyway”. For example an infrastructure no-regret option would increase the durability and longevity of a building to climate variability over time. (IPCC, http://www.ipcc.ch/pdf/climate-changes-1995/2nd-assessment-synthesis.pdf)

Sea-level rise: An increase in the mean level of the ocean.

- Eustatic sea-level rise is a change in global average sea level brought about by an increase in the volume of the world ocean.
- Relative sea-level rise occurs where there is a local increase in the level of the ocean relative to the land, which might be due to ocean rise and/or land level subsidence. In areas subject to rapid land-level uplift, relative sea level can fall. (IPCC, 2007)

Sensitivity: Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise) (IPCC, 2007).

SRES: The storylines and associated population, GDP and emissions scenarios associated with the Special Report on Emissions Scenarios (SRES) (Naki enovi *et al.*, 2000), and the resulting climate change and sea-level rise scenarios. Four families of socio-economic scenario (A1, A2, B1 and B2) represent different world futures in two distinct dimensions: a focus on economic versus environmental concerns, and global versus regional development patterns (IPCC, 2007).

Thermal expansion: In connection with sea-level rise, this refers to the increase in volume (and decrease in density) that results from warming water. A warming of the ocean leads to an expansion of the ocean volume and hence an increase in sea level. (IPCC, 2007).

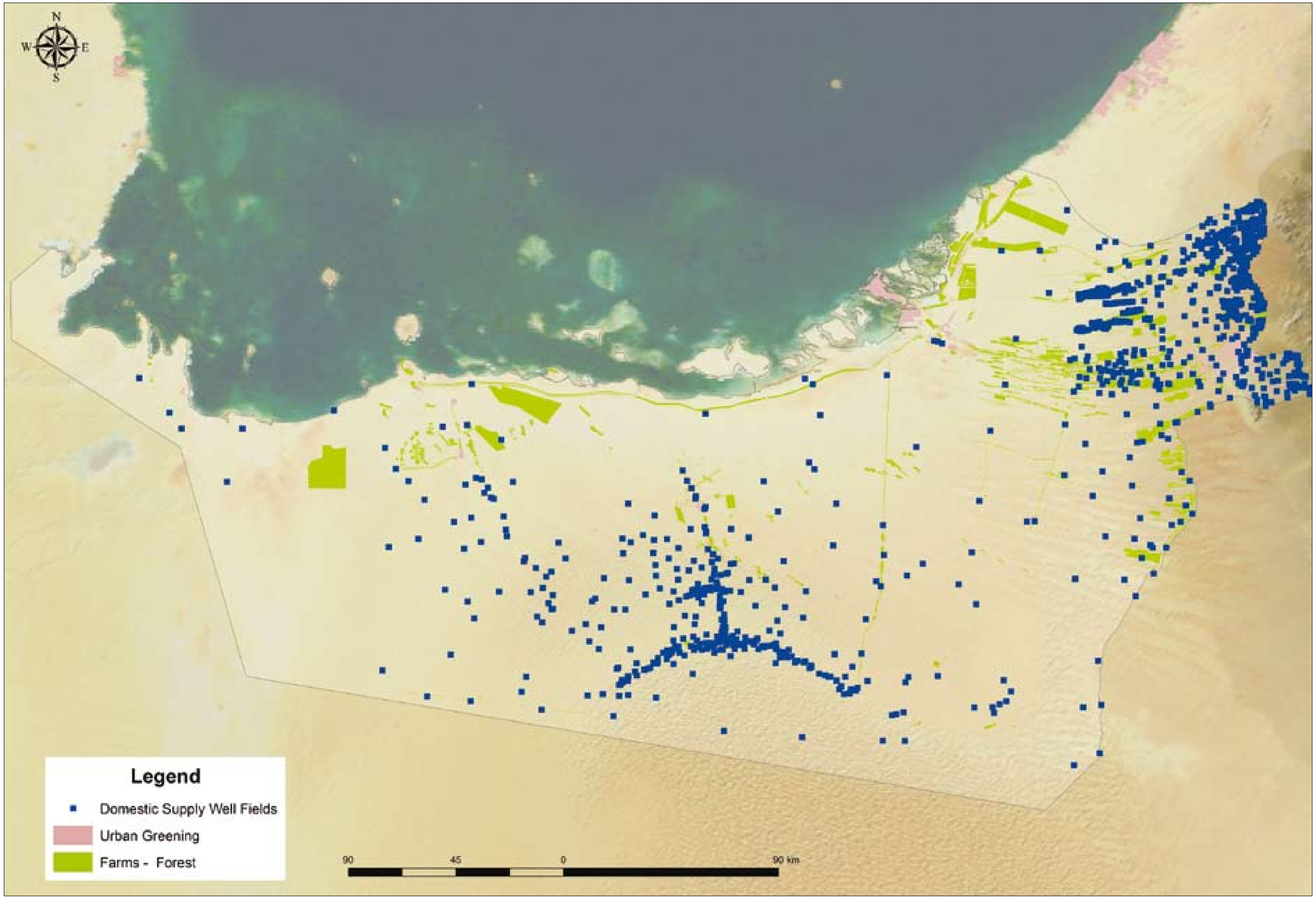
Thermohaline circulation (THC): Large-scale, density-driven circulation in the ocean, caused by differences in temperature and salinity. In the North Atlantic, the thermohaline circulation consists of warm surface water flowing northward and cold deepwater flowing southward, resulting in a net poleward transport of heat. The surface water sinks in highly restricted regions located in high latitudes. Also called meridional overturning circulation (MOC). (IPCC, 2007).

United Nations Framework Convention on Climate Change (UNFCCC): The Convention was adopted on 9 May 1992, in New York, and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the ‘stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system’. It contains commitments for all Parties. Under the Convention, Parties included in Annex I aim to return greenhouse gas emissions not controlled by the Montreal Protocol to 1990 levels by the year 2000. The Convention entered in force in March 1994 (IPCC, 2007).

Vulnerability: Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity (IPCC, 2007).

To calculate areas inundated by land use category: Spatial Analyst Tool "Intersect" Floodfil Output File with Environment Agency's landuse GIS layers

Example Map includes: Domestic Supply Well Fields, Farms, Forest and Urban Greening



Annex 1: Elevation Data Sensitivity Analysis

Introduction: *the influence of digital elevation models (DEMs) on models of sea level rise.*

Topographic information is integral to analyses in many fields of research including ecology, hydrology, agriculture, geology and others. With technological advances, many researchers have transitioned to using digital elevation models (DEMs) for computer-based processing. A DEM is merely numerical representation of surface elevations over a region of terrain (Cho and Lee, 2001). There are multiple ways to derive DEMS- from time-consuming digitization processes of paper quadrangle maps to shuttle radar missions. A body of literature has emerged around both assessments based on DEM source (Hodgson *et al.*, 2003) as well as the impact of DEM resolution on the results of research projects.

DEMs are used in an array of projects. Elevation data contributes to site suitability analysis for property development, transportation networks and other infrastructural developments, as well as identifying ecosystem and biodiversity conservation or migration. Researchers also use coastal DEMs to identify the extent of areas vulnerable to sea level rise and storm surges. As scientists have begun realizing that the pace of climate change is much faster than initially expected, there is an urgent need for more accurate modeling of regional and abrupt sea level rise, coastal inundation of flood plains from storm surges, and a range of other climate change impacts.

DEM Comparisons

Jarvis *et al.* (n.d.) explored different DEM through a serious of case studies in Ecuador, Honduras, and Columbia. In Ecuador, the researchers analyzed the SRTM DEM against the global, GTOPO30 data set and in Honduras the compared the SRTM against cartographically derived TOPOGRID at 1:50,000[1]. SRTM is vast improvement on global DEM (GTOPO), and care should be taken when interpolating SRTM holes with GTOPO data. The researchers found that based on their analysis of specific locations that SRTM data are was accurate to +/- 16-meters. After comparing SRTM values against an existing GPS database of elevation points, the team found that SRTM values were close to GPS values 80% of the time. On average, the SRTM differed from the TOPOGRID by 8 meters and from the GPS points by 20meters.

The researchers found that terrain heavily influenced the elevation difference between the DEMs. In addition, as hydrologic properties are inherently tied to terrain, the quality of terrain data affects the accuracy of hydrologic models. Researchers agreed that the 1:10,000 cartographic derived DEM is the best scale especially when dealing with hydrological models; however, high-resolution cartographic data exists for few areas in tropical countries. Even in countries with a strong tradition of cartographic mapping, like the US, age of cartographic maps on which national DEMs are based adds another dimension to the accuracy of models; for example, 1950s contour lines in one region may not accurately reflect more recent land changes.

Typically, in tropical countries, the SRTM overestimates for northeast facing slopes and underestimates for southwest facing slopes; an occurrence that correlates with shuttle flight path directions. In general, the SRTM data tended to have more surface detail and roughness than the TOPOGRID. For hydrological modeling, the SRTM performs well

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[1] The cartographically derived maps were digitized by the Centro International de Agricultura Tropical (CIAT). The entire country, 280 topographic sheets and an additional 250 maps from the national forestry commission that needed rectifying were digitized at a 1:50,000 scale (with 100m contour lines, and 10m contour lines <100m above sea level) . The result was a 90-meter resolution TOPOGRID DEM to match the SRTM DEM (Jarvis et al, n.d.).

but it is definitely better to use high-resolution maps like cartographic maps at 1:25,000 or smaller to improve accuracy (Jarvis *et al*., n.d.). Other authors point out that coarser resolution DEMs ignore details of surface characteristics like steep slopes (Dong *et al*., n.d.) and because the values are often represented as integers (at least in USGS DEMs), modeled slope for areas of limited reliefs would even show "artificial jumps" in slopes over shorter distances (Hodgson *et al*., 2003; Carter, 1992).

Cho and Lee (2001) and Dong *et al.* (n.d.) confirm the emphasis in Jarvis *et al.* (n.d.) with respect to the influence of DEM accuracy on hydrological models. Cho and Lee's paper exploring sensitivity considerations found that with a 1:24,000 DEM (7.5 minute), their hydrologic model revealed higher runoff volumes which the 1:250,000 (1 degree) DEM flattens the watershed's slope yielding delayed stream flow and underestimating runoff and erosion. The two credited the finer resolution of 7.5-minute dataset, with yielding increased average slope and thus higher runoff when the simulation was run. Dong *et al*., (n.d.), in their comparison of Synthetic Aperture Radar (InSAR), LiDAR, and photogrammetrically derived DEMs (Noble *et al*., n.d.), similarly found that the main differences in topographic attributes revealed during their research were in river channels, having implications for hydrological processes. Their paper highlights importance of accurate terrain modeling on hydrologic simulations on the Broadhead watershed in New Jersey; their conclusions can extend to coastal flood plains and would affect storm surge and sea level rise modeling.

Conclusion

Elevation of coastal land is a critical factor in determining its vulnerability to sea level rise, a key impact of climate change on coastal areas. Most sea level rise (SLR) scenarios estimate 50-100cm inundation over the next century depending on the region. In modeling sea level rise based on elevation, following components of a DEM are in question.

- Data source and method of collection
- Vertical and horizontal resolution
- Aspect
- Slope

Terrain is another important determinant of DEM accuracy, particularly for DEMs derived from SRTM and LiDAR data. Jarvis *et al*. (n.d.) found that SRTM overestimates for northeast facing slopes and underestimates for southwest facing slopes (correlating with flight path directions). Others highlighted the challenge of modeling areas of limited relief using elevation intervals of 1 meter, or even 10-50 meter jumps as many do, and the inappropriateness of such data for limited relief coastal areas vulnerable to sea level rise.

The challenge, to date, as we noted in the body of the report has been estimating vulnerable zones based on these <1 meter SLR scenarios while using topographic maps and digital elevation models whose vertical resolutions range from 1.5 to 10 to 100 meters. Studies have used the best available data and interpolation methods to come with broad estimations of places that may be at risk; with the exception of highly accurate (and highly expensive) -- LiDAR data have errors in the range of +/- 0.3 meters-- the accuracy of these estimations will remain a problem. Broad estimations can, however, point to areas for more precise studies and can be used in recommendations for investing in select area of LiDAR data.

Annex 2: Inundation maps

3. Urban Vulnerability: Abu Dhabi (All Scenarios)

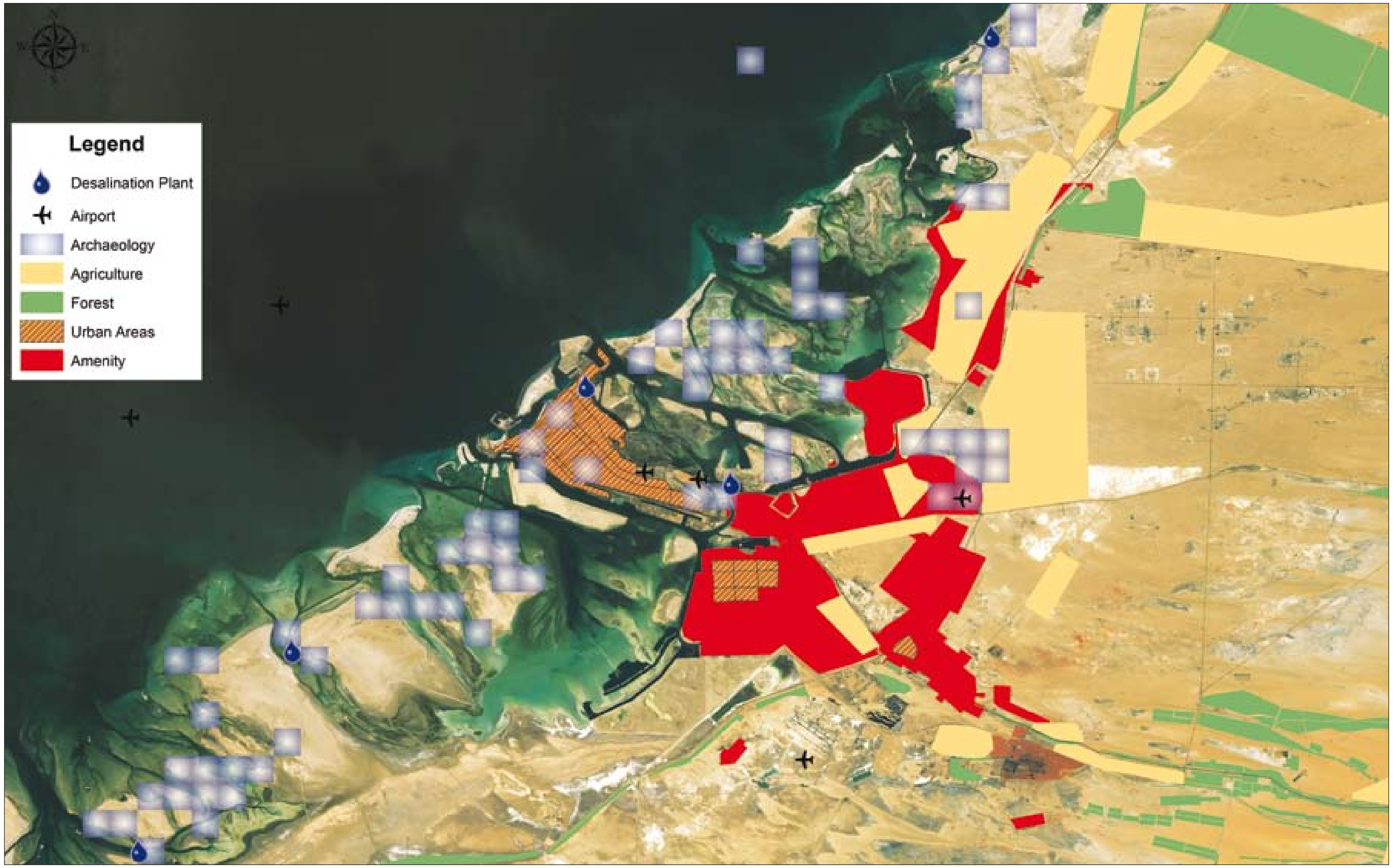


Figure A2-1 Baseline map, Abu Dhabi

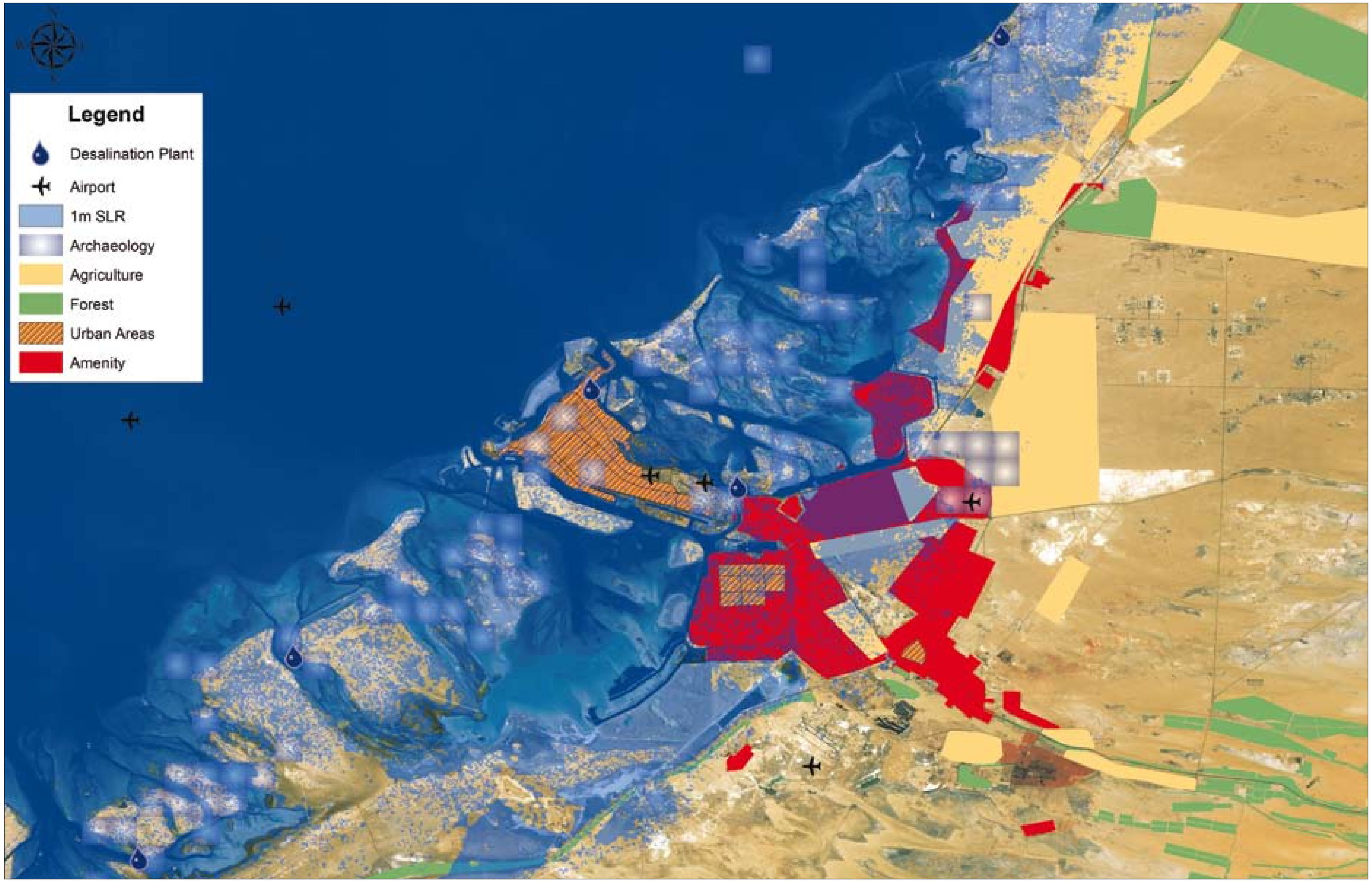


Figure A2-2   1 meter sea level rise, Abu Dhabi

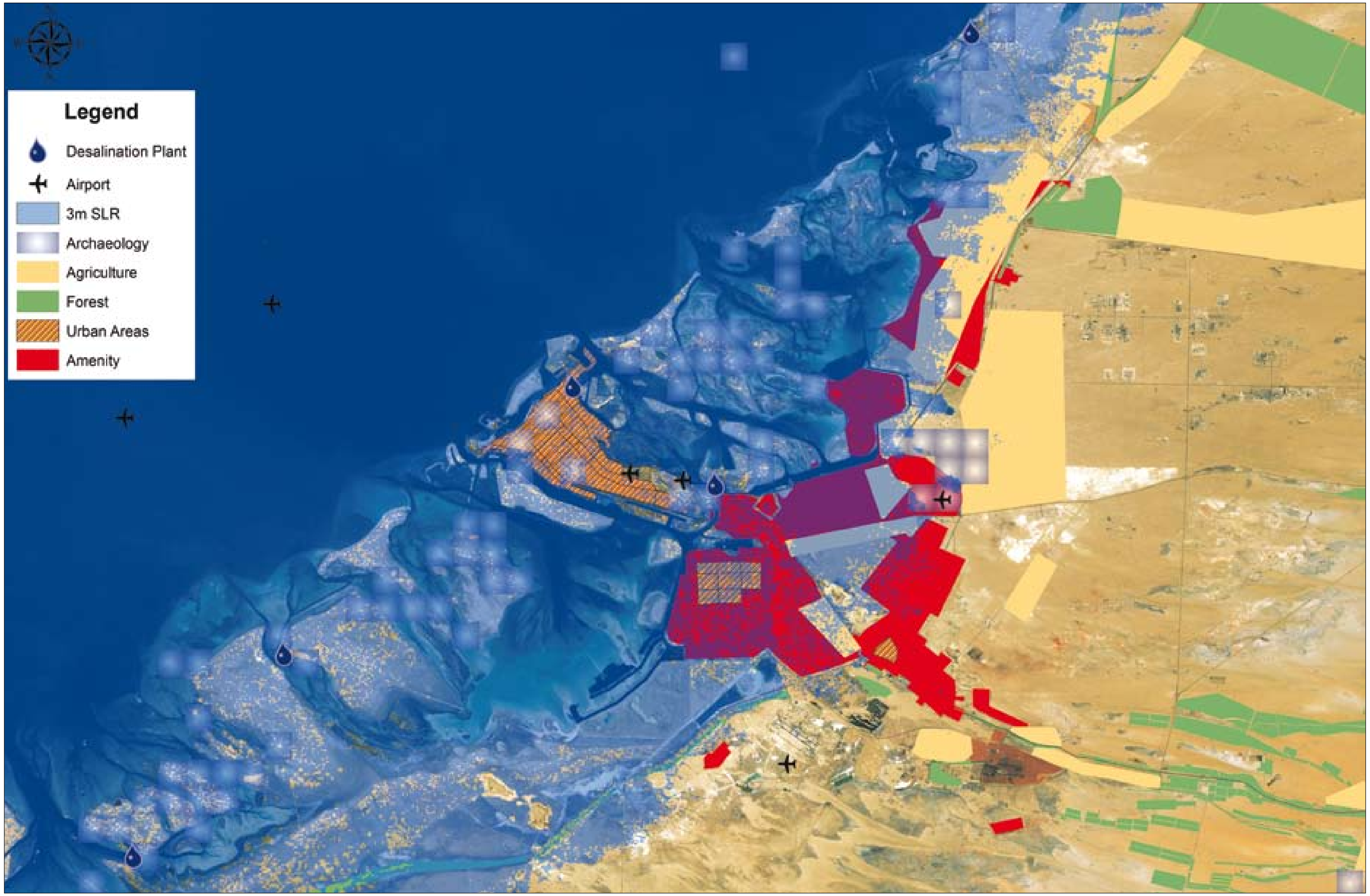


Figure A2-3 3 meters sea level rise, Abu Dhabi

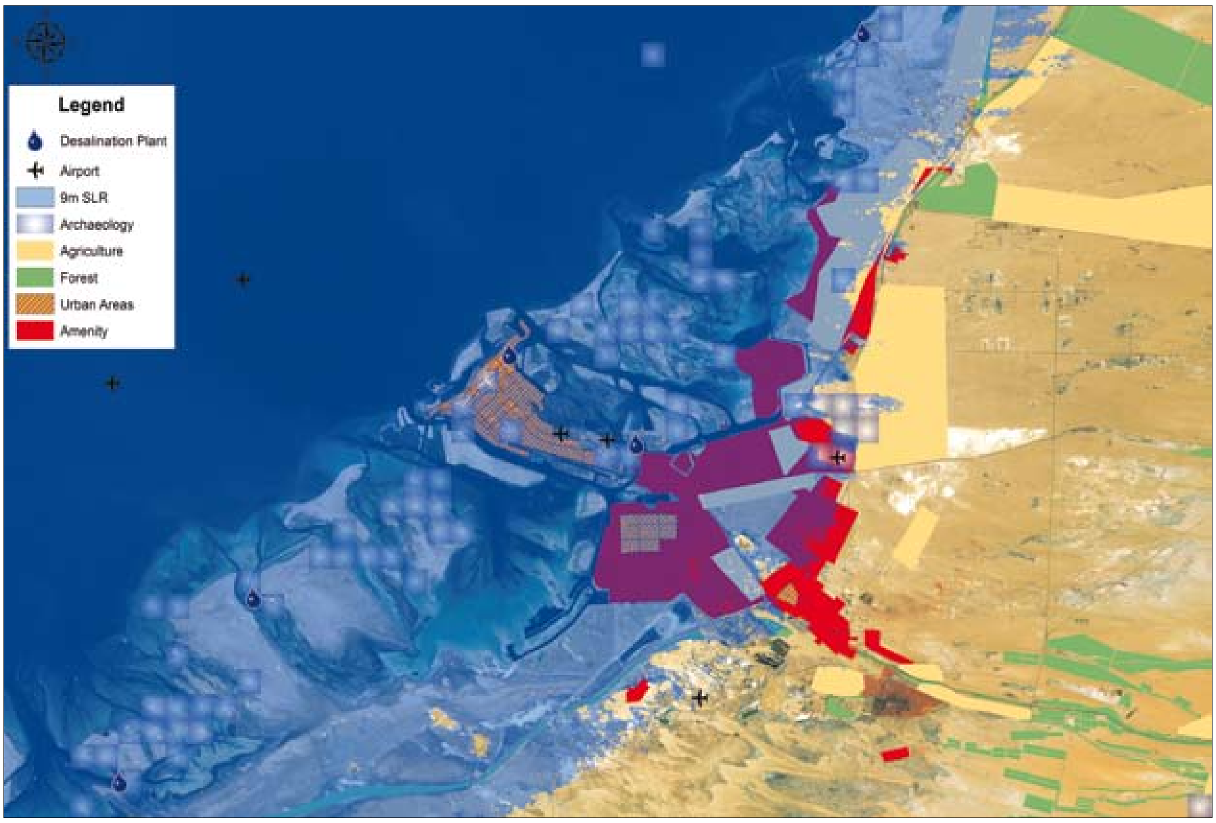
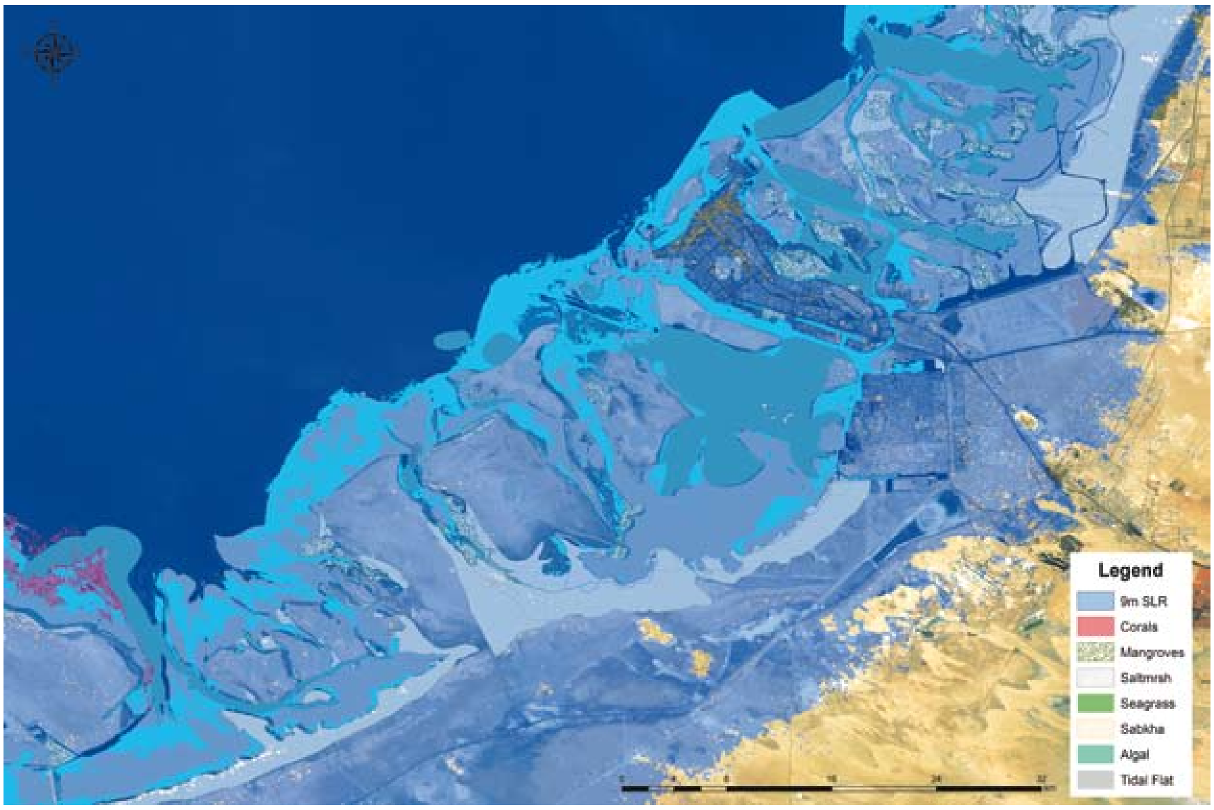


Figure A2-4 9 meters sea level rise, Abu Dhabi (Infrastructure impacts)



A2- 5 9 meters sea level rise, Abu Dhabi (ecosystem impacts).

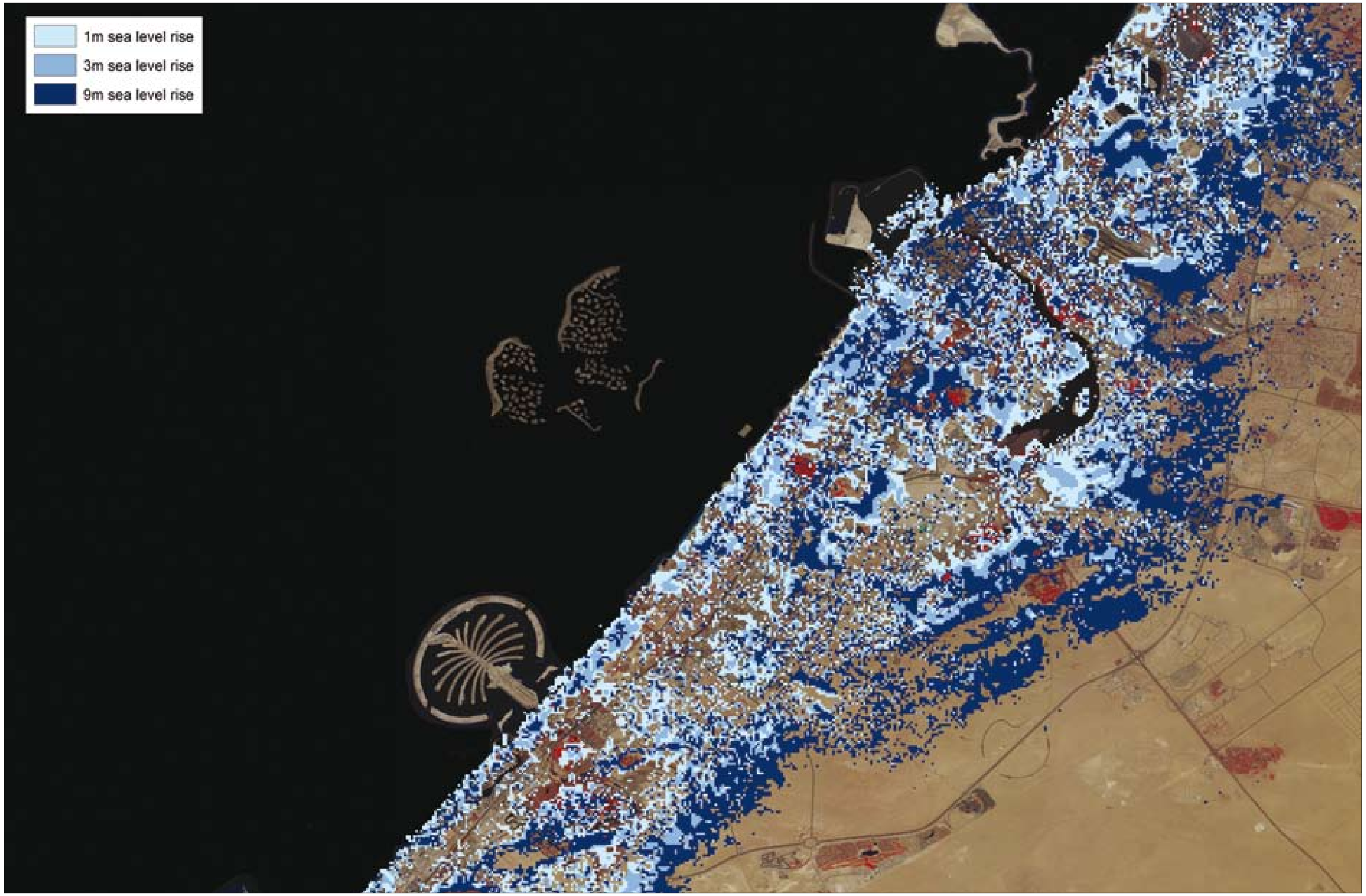
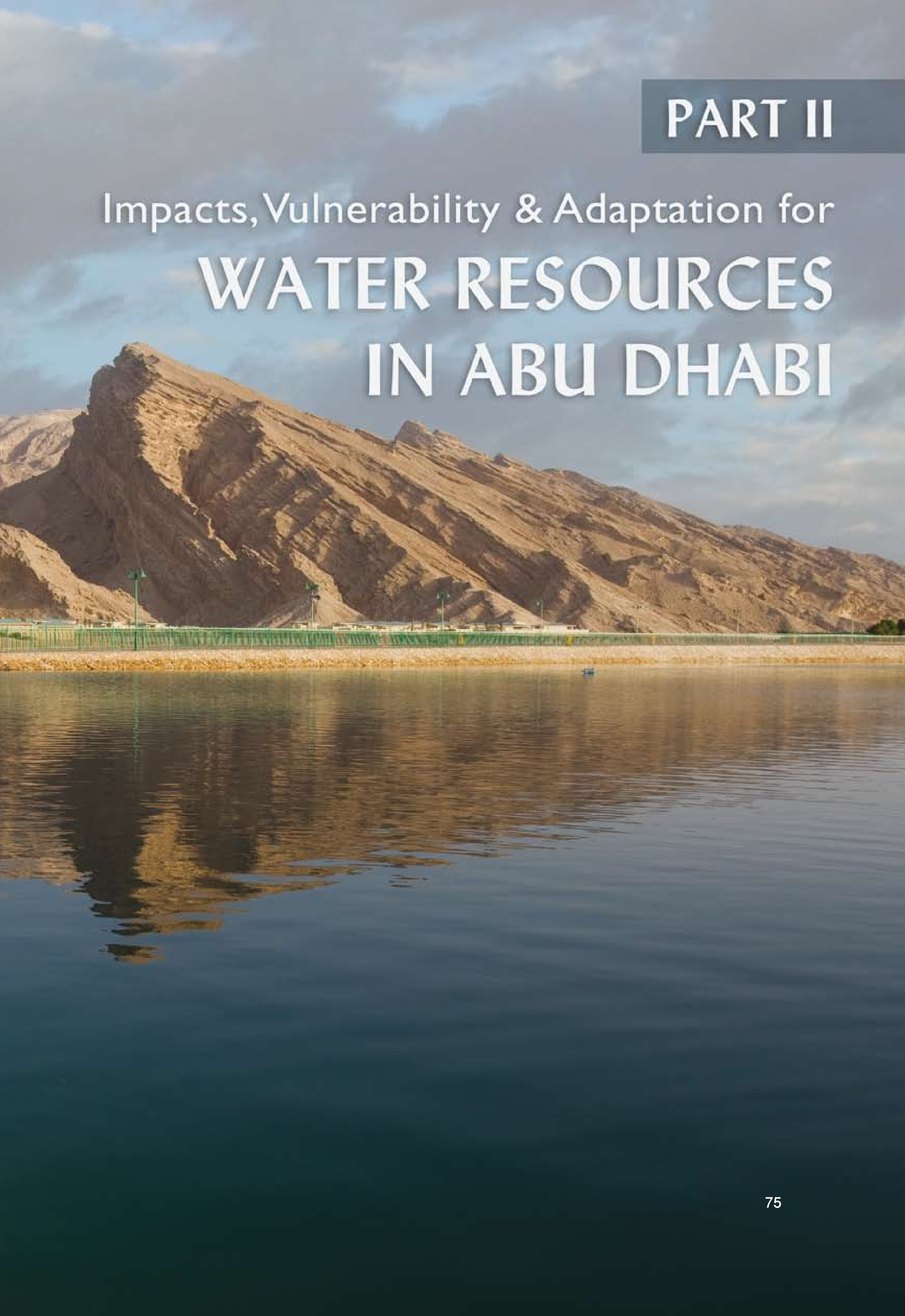


Figure A2-6 1,3,9 meters sea level rise, Dubai

PART II

Impacts, Vulnerability & Adaptation for WATER RESOURCES IN ABU DHABI



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List of Acronyms

ADWEA	Abu Dhabi Water and Electricity Authority
ADE	Abu Dhabi Emirate
APF	Adaptation Policy Framework
AR4	Fourth Assessment Report of the IPCC
Bm^3	billion cubic meters
CO_2	carbon dioxide
DSS	Decision Support System
ENSO	El NiÑo Southern Oscillation
FAO	United Nations Food and Agricultural Organization
GCM	global climate models
GDP	gross domestic product
GEF	Global environment facility
GHG	green house gas (emissions)
GIS	Geographical Information System
gpd	gallons per day
IPCC	Intergovernmental Panel on Climate Change
Kc	crop coefficient
Km^3	cubic kilometers
l/c/day	liters per capita per day
m^3/d	cubic meters per day
LOSU	Level of Scientific Understanding
MA	Millennium Ecosystem Assessment
MED	Multi Effect Distillation
MGD	million gallons per day
M&I	municipal and industrial
Mm^3/yr	million cubic meters per year
MOR	Middle-of-the-Road
MSF	Multi Stage Flash
PET	Potential evapotranspiration
Ppmv	parts per million by volume
RF	Radiative Forcing
RH	relative humidity
SRES	Special Report on Emissions Scenarios
TDS	total dissolved solids
TSE	treated sewage effluent
UKCIP	United Kingdom's Climate Impacts Programme
UNFCCC	United Nations Framework Convention on Climate Change
USGS	US Geological Service
WEAP	Water Evaluation and Planning model
WGII	Working Group II of the IPCC
W/m2	watts per square meter
WMO	World Meteorological Organization
UAE	United Arab Emirates

1. Introduction

The Abu Dhabi Emirate (ADE), is one of the seven Emirates that comprise the United Arab Emirates (UAE), which occupies an area of 67,340 km^2, almost 80% of the total area of UAE. The Emirate has a hyper-arid climate with less than 100 mm/yr of precipitation, a very high potential evaporation rate (2-3m / yr), a very low groundwater recharge rate (<4% of total annual water used) and no reliable, perennial surface water resources. Surface waters that are present, resulting from flash flooding in wadis, more often damage planted areas rather than benefit them.

Despite this paucity of renewable freshwater, the ADE has experienced explosive population and economic growth, with GDP and population growth rates exceeding 8% per annum (CIA, 2008). Prior to statehood, most of the population of the region was supported by groundwater from shallow wells and the traditional Falaj system of groundwater collection systems and hand dug tunnels. Most of these systems have since dried, and in their place is an extensive system of boreholes that mine the region's underlying groundwater supplies.

Most socio-economic growth has been supported by these groundwater resources, albeit most are brackish and saline in nature. Despite rapid population and economic growth and limited freshwater supplies, the bulk of freshwater continues to be used by the agricultural, forestry, and plantation sectors, with some estimates that these demands are more than 80% of the total annual water use of 3.4 billion m^3 (Bm^3). Amenity planting, forestry and agriculture farms are expanding irrigated areas with few constraints on water use until recently. Over the past few decades there have been government programs that have 'greened the desert' and subsidized a growing agricultural sector that has meant much greater water use and increased reliance on non-traditional water sources like desalinization.

Municipal water demand also contributes to scarcity concerns, as Emirate-wide population growth is roughly 6% per year, and slightly higher in Abu Dhabi City and Al Ain while per capita consumption is increasing even more at roughly 8%.

At present, water for domestic and industrial uses is largely derived from desalinization, provided by the Abu Dhabi Water and Electricity Authority (ADWEA). Left unchecked, rising domestic consumption will increasingly be met by desalinated supplies.

Over the past few decades there have been efforts to further develop groundwater recharge zones in the western portion, near the Oman Mountains and Al Ain. Recharge zones and storage dams have been developed along wadi drainages, and a rainfall augmentation program is being developed (Abdulla Mandoos- Director, Center for Meteorology and Seismology, personal communication). Exploration efforts have included the Groundwater Research (USGS/NDC, 1994) and Groundwater Assessment Programs (GTZ *et al.* 2005), conducted near the Liwa Crescent. Found to its north was groundwater storage estimated at about 100 Bm3, of which 16 Bm3 is fresh (as reported by Brook et al. by the USGS/NDC, 1993). Practically, there is no modern day groundwater recharge in the western aquifers of Abu Dhabi. Although substantial groundwater reserves have been discovered, the majority of these were recharged some 6,000 to 9,000 years before present and so the fresh groundwater water lenses are fossil in nature (Wood and Imes, 1995).

Two major studies, GWRP (USGS/NDC, 1993) and GWAP (GTZ et al, 2005), independently estimated the groundwater stored through the Abu Dhabi Emirate, with estimates of total groundwater reserves of 253 Km^3 (7% fresh, 93% brackish) and the GWAP total estimate of 640 Km^3 (79.4% saline). The GWAP analysis used a substantially higher salinity threshold of to 100,000 mg/l TDS, whereas the GWRP included groundwater salinity threshold of less than 15,000 mg/l TDS. The most striking feature of both estimates is that the amount of fresh groundwater remaining in storage is very small, ranging from 2.6% to 7% of the total.

According to the GWAP assessment more than three-quarters (12.5 km^3) of the fresh water in storage occurs in the Liwa lens and only about 4 km^3 in the Eastern region. Moreover, according to the GWRP assessment, at current groundwater abstraction rates, it is projected that the fresh and brackish groundwater resources will be depleted in 50 years. Long-term strategies for water planning, management and conservation are not yet in place. Water projects are usually massive and require high investments while the economic returns of are generally low as compared to other investment sectors. Efforts launched to date have been hindered by the shortage of available funds for water development and conservation projects.

Water resource management typically implicates numerous and diverse socio-economic sectors including agriculture, human and ecosystem health, coastal zones, and infrastructure. The case is no different for the UAE, where any changes in climate conditions, such as temperature and precipitation, can place further stress on already severely limited groundwater and surface water resources. Potential changes in climate are then a cause for serious concern and careful consideration and planning.

Because groundwater resources in Abu Dhabi are derived from fairly deep geologic structures, and those near the coast are already highly saline, the impact of rising sea levels along the Arabian Gulf likely will not appreciably impact the groundwater quality over the next century. Rather, the bigger concern with regard to climate change appears to be the potential for even larger growth in water demand that could be superimposed on the already explosive demand presently stressing these scarce groundwater resources. For example, while summer temperatures are already extreme through the ADE, changes in winter climate, including increasing temperatures and changes in precipitation could mean incrementally larger water use during the winter.

Winter is historically a time when the region has a respite from the intense summer heat, water use drops, and crop irrigation and production is most substantial. Because the bulk of these demands are consumptive and driven by climate, opportunities for reuse are small and climate variability and change could increase the consumptive demands of these uses. This brings into question the long-term sustainability of these water supplies and how future water demands will be met.

Utilizing water resources decision support tools, this study focuses on quantification of potential future water stress in the region by combining climate model outputs, projected water budgets, and socioeconomic information. The country's existing climatic context has already demanded innovation in how water resources are managed. A baseline water demand modeling framework is developed for the Abu Dhabi Environment Agency that could be used to assess future demand and supply requirements, and look at the overall sustainability of the sector under future stressors, including population, economic growth, and climate change. Program like the GTZ and Groundwater Assessment Project developed comprehensive inventory and database of the groundwater resources throughout Abu Dhabi.

This project relies on these databases, by making an ADE-wide water supply and demand model that harvests these data held at the Environment Agency of Abu Dhabi (EAD). A Water supply/demand model was built using the Water Evaluation and Planning (WEAP) decision support system, and this used to assess potential climate change impact and adaptation options for the ADE.

We have found that climate change would have a marginal impact on water resources relative to the bigger socio-economic drivers of per-capita demand, assumptions about future populations, and future agriculture and forestry policies that would either limit or encourage irrigation of these sectors. While this is a report about the impacts and vulnerability for the water sector with respect to climate change, supply is uninfluenced by climate (given limited recharge and even more restricted rainfall) so primary adaptation strategies fall to demand-side management.

2. Current water stress and planned responses

Natural sources of freshwater are insufficient to meet demand. The main reasons for the water shortage problem in the Abu Dhabi Emirate are related to rapid increases in water demands across various sectors, depletion of groundwater resources, low annual rates of precipitation and groundwater recharge, and so far, an absence of integrated water resource management strategy. Abu Dhabi supplements its remaining freshwater reserves with its large desalination capacity, most of these plants run in tandem with the power stations.

The little rainfall that does occur falls in winter, and provides up to 80% of the Emirate's annual precipitation. These short, heavy rainfalls produce the best opportunities for aquifer recharge. Runoff occurs in the non-vegetated Oman Mountains and collects in wadis which drain into the U.A.E, eventually recharging the shallow alluvial gravel aquifers. Rainfall available for runoff and aquifer recharge varies widely in both time, space, and geographically though overall amounts are small in this arid environment (Brook *et al.*, 2005). Summer rains can occur from Indian monsoons over the Arabian Sea, rare cases of the Inter Tropical Convergence Zone shifting northward over UAE and causing overcast weather and thunderstorm activity.

The booming economy and industrial development in Abu Dhabi Emirate have increased water demands in the various water consumption sectors. Notably, the per capita share of freshwater consumption has tripled during the last three decades. The average annual precipitation over UAE and the Abu Dhabi Emirate has reached its lowest levels during the last decade with severe implications for natural recharge of groundwater systems. Groundwater quality and quantity have deteriorated due to the excessive pumping mainly for agriculture purposes along with the extensive use of chemicals and fertilizers in agriculture. A detailed discussion of groundwater quality is outside the scope of this report.

Technology transfer between applied research and practice is a major impediment to sustainable resource management. The gap between the scientific advancements related to water conservation techniques and application of the technology is still huge; the slow transfer of technologies due to both poor coordination and poor networking among stakeholders. Leakage from distribution networks has never been properly assessed -low water use efficiency and high water losses in the water distribution system continue to thwart any efforts to mitigate increasing consumption. The lack of maintenance and rehabilitation programs to improve and maintain system performance at the highest possible level has contributed to the severity of this problem.

The UAE faces difficulties in changing the unfavorable social habits and attitudes towards water uses and conservation. This is mainly due to poor public awareness programs in the Emirate. The education curriculum at primary and elementary schools does not address water conservation in an effective manner.

2.1. Regional Supplies: West (including Liwa) and East (Abu Dhabi City and Al Ain Oasis)

The Western and Eastern/Central regions of the Emirate face vastly different supply constraints. Groundwater occurs in the Emirate as either consolidated or unconsolidated surficial deposit aquifers or as bedrock / structural aquifers and contributes 79% to the total water demand. The other water source contributions are from desalination and treated wastewater (see Figure 2-2 for a breakdown).

There are six main desalination plants that meet Abu Dhabi's needs. The Emirate uses several different methods are available to desalinate seawater; the three commercially proven processes being distillation, reverse osmosis

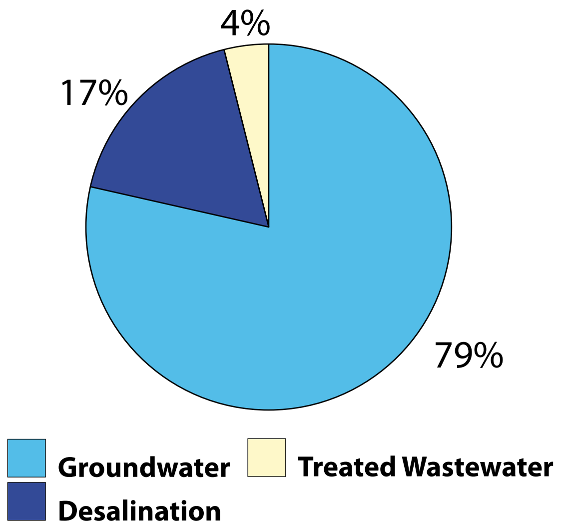


Figure 2-1. Percentage of total supply.

and electro dialysis. Today, the evaporation technique is dominant in the desalination field, where 96% of desalinated water is produced by Multi Stage Flash (MSF) and Multi Effect Distillation (MED). The remaining 4% is produced by reverse osmosis. To improve the desalination process economics, the MSF process is usually coupled with electric power generation in the so called cogeneration plants.

Of the six main plants, five are situated along the Arabian Gulf coastline at Shuweihat, Mirfa, Abu Dhabi, Um al Naar and Taweelah and the can be found on the Gulf of Oman at Qidfa, Fujairah. The Qidfa, Fujairah plant began production in 2003 and is the first inter-emirate transfer of water from Fujairah to Abu Dhabi.

Table 2-1. Abu Dhabi Emirate groundwater reserves estimate from GWAP (GTZ, 2005a).

	Volume of Drainable Groundwater (km3)			
	Total	**Fresh**	**Brackish**	**Saline**
Upper Aquifer (West)	221	12.5	70	138.5
Shallow Aquifer (East)	58	4	10.25	43.8
Western Aquitard (WA)	326.7	0	9.9	316.8
Eastern Aquitard (UF)	35.2	0	25.7	9.5
Sum (km3)	640.9	16.5	115.8	508.6
Percentage of Total GW:	100.0%	2.6%	18.1%	79.4%
Sum West (km3)	547.7	12.5	79.9	455.3
Percent West	85.5%	75.8%	69.0%	89.5%
Sum East (km3)	93.2	4.0	35.9	53.3
Percent East	14.5%	24.2%	31.0%	10.5%

Table 2-2. Western Region Potable Water Consumption from Mirfa and Sila Desalination Plants.(2003)

Center	Weekly Consumption gallons	Weekly Consumption Cubic meters	Annual Consumption Cubic meters	% of total
Ghayathi	7727620	35130	1826748	6%
Delma	9917000	45083	2344299	8%
Mirfa	4786470	21759	1131483	4%
Liwa	46147640	209787	10908933	37%
Madinat Zayed	32675000	148541	7724109	26%
Habshan	9629000	43773	2276219	8%
Asab	2500000	11365	590980	2%
Sila	10536300	47898	2490697	9%
TOTALS	123919030	563336	29293467	

*Based on weekly consumption for last week April, 2003

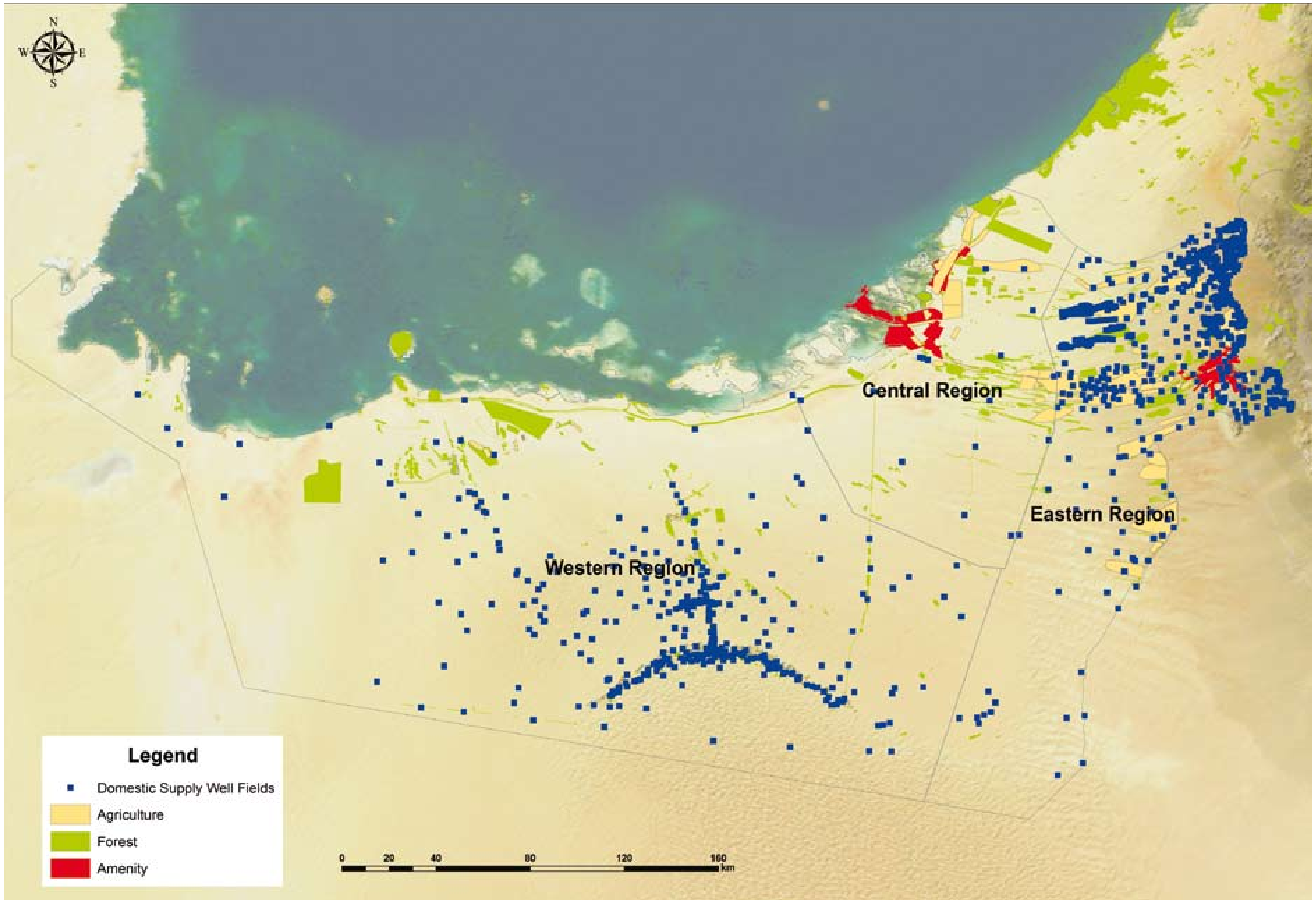


Figure 2-2. Regional divisions used with indications of irrigated areas, and Eastern domestic well fields.

Total installed capacity equals 648 million gallons per day (MGD) and 16.45 MGD in remote plants, for a combined capacity of 746 Mm^3/yr, 35% of which is currently unutilized (ADEA, 2002). Al Ain City relies on this inter-emirate transfer because much of its desalinated water is imported from the Qidfa plant for domestic, agriculture and forestry usage (Brooks *et al.*, 2005). Western domestic demands are entirely met with desalination.

By 2003, 1.2 million people produced 140.8 Mm^3 of treated wastewater from 23 operating plants, equaling 4% of the total water consumed that year. Utilization of the treated effluent is largely used for irrigation of parks, gardens and recreation facilities, and to a much smaller degree, irrigation of fodder crops. Notably, the main Al Ain city plant and the Mafraq plant, with an installed capacity of 260,000 m^3/d (or equivalent of ~725,000 persons), treat 65 % of the total population's wastewater.

Previously, all of Al Ain city's domestic water requirements were met from these domestic wellfields, however, massive increases in domestic demands have placed increasing stress and resulted in declining water levels, increasing in groundwater salinity, and decreasing in total production (Brooks *et al.*, 2005). In 2003, the total domestic eastern well-field production is only 26 Mm^3/yr, meeting only 17% of the total domestic requirements in the eastern region.

The balance of domestic demand in the eastern region and the full requirements for the western region as well, are now met by desalinated water. Groundwater levels in Al Ain are actually increasing due to the artificial recharge of groundwater from treated sewage effluent (TSE) and desalinated irrigation water widely used to keep the garden city of Al Ain green (Brooks *et al.*, 2005).

Treated wastewater (effluent) [TSE] is a non-conventional or non-traditional water source growing in importance in the Emirate. As urban populations and industrial consumption expands, so do the waste volumes and the amount available for re-use. Abu Dhabi has one of the best records for collecting, treating and re-using wastewater and all wastewater which is produced in Abu Dhabi City and its environs is collected, treated and re-used (Brooks *et al.*, 2005). The use of TSE in irrigation could have positive effect on groundwater recharge, particularly in areas suffering from overdraft.

The Western Region population is sparse with 116,177 in 2001, just 10% of the entire Abu Dhabi Emirate population. The major mainland settlements are Ruwais, Madinat Zayed, Al Mirfa, Ghayathi and Liwa and the main Island settlements are Dalma, Das and Zakum. Island populations include permanent settlements associated with offshore oil & gas installations e.g. oil rigs etc. Municipal consumption is met from groundwater abstraction, from treated sewage effluent (TSE) and from desalination. This discussion is continued in relation to the water balance model.

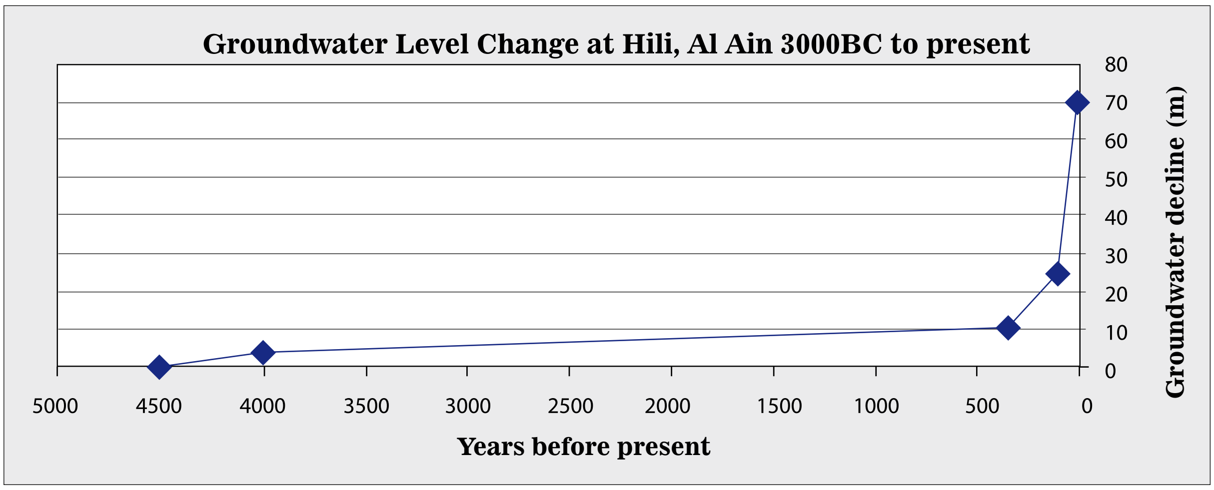


Figure 2-3. Changes in groundwater levels at Al Ain over the last 4,500 years.

The only fresh groundwater in the Western area is fossilized water immediately north of the Liwa Oasis (USGS/NDC, 1994). This basin occupies an area of 2,400 Km^2 with an average thickness of about 30m, although the unconfined "Liwa Aquifer" has a maximum thickness of 120m. Brackish to saline groundwater is used in the Madinat Zayed, Ghayahthi and Al Wathbah regions and very saline water is also used in the Al Wathbah region. In the Western region, farmers must use groundwater with salinities of mostly over 10,000 mg/l and up to 40,000 mg/l mixed with fresh groundwater imported from Kashona well field in the eastern region and more recently, with desalinated water from Taweelah Citation: (Brook and Hovgani, 2003). Brackish groundwater must be pumped at a considerable distance from the wellfields in the central part of the Western Region to irrigate the trees along the Abu Dhabi – Al Sila highway. All public water supply is provided from desalinated water produced by plants at Mirfa (22.3 Mm^3/yr) and Sila (2.4 Mm^3/yr). In 2004, a new 166 Mm^3/yr desalination plant was commissioned in Shuweihat. An approximate estimate of the relative contribution from these sources is summarized in Figure 2-6.

2-2 Demand Projections

Even though domestic consumption is only roughly 15% of total water consumed in the Emirate, there are numerous issues that threaten to increase municipal consumption. Domestic consumption in the UAE includes mainly residential, commercial establishments, hospitals, hotels, offices, and shops. In government sponsored housing development schemes and agricultural activities there has been a significant increase in customer demand for water and even more so in the farming and forestry sectors. Municipal water demand in Abu Dhabi Emirate is expected to increase from 208 million gallons per day (gpd) in 2000, to 700 million gpd in 2010, and then to 800 million gpd in 2015. In 1997, per capita consumption was around 130 (gcd). Only five years later, consumption had grown to 199 (gcd).

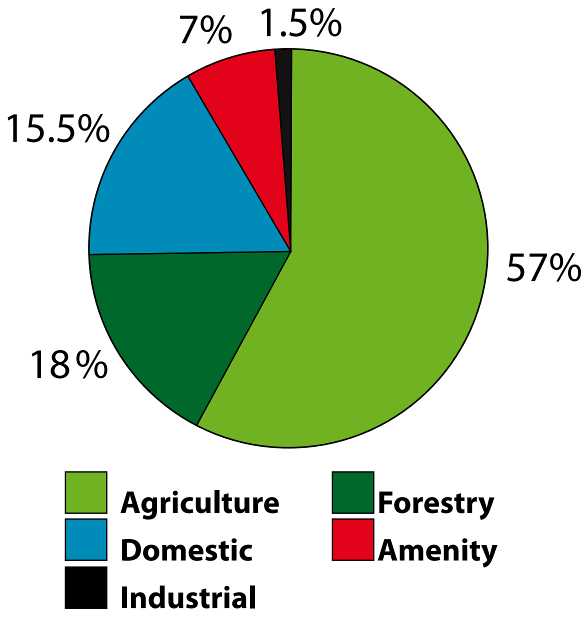


Figure 2-4.Summary of total sector consumption by region (2002).

Table 2-3. Total water consumption in Abu Dhabi for the year 2003

(ERWDA, 2002	EAST		WEST		% TOTAL		Efficiency of Irrigation
	(Mm^3)	%	(Mm^3)	%	(Mm^3)	%	
Domestic	107.81	7.07	332.8	19.6	440.6	13.7	
Industry	11.9	0.78	36.9	2.2	48.8	1.5	
Agriculture	1191	78.06	772.9	45.6	1963.9	61.0	90%
Forestry	105	6.88	407	24.0	512.0	15.9	90%
Amenity	110	7.21	145.98	8.6	256.0	7.9	80-90%
TOTAL	1525.7	100.0	1695.58	100	3221.3	100.0	

Without demand management strategies implemented, per capita consumption is likely to continue to increase at 6% annually. Additionally, total population is growing. In 2007, the population of the Abu Dhabi metropolitan area was 930,000 people. Researchers estimate that by 2013, metro area population will grow to 1.3 million, and then 2.0 million by 2020 and 3.1 million by 2030. As water is scarce for a present total Emirate population of 1.5 million (ADEA, 2002), it is unlikely that the region will have enough water to support per capita consumption of 220+ gallons per day for 3.1 million people.

As economic development and improved standards of living continue to be a national trend, Emiratis have become larger water consumers. In fact this trend may prove independent of economic growth as Figure 2-9 shows where despite lower GDP between 1983-1990 due to lower oil prices (main revenue driver) per capita consumption contined to grow.

The Industrial sector currently only accounts for 1.5% of total Emirate water consumption (in 2003). This proportion will increase as expansion in the sector grows with the development of a number of new industrial estates in Abu Dhabi, Al Ain and elsewhere. For the time being, most off-shore facilities meet their own water demand with independent desalination plants. In the western region, industrial demand is restricted mostly to 18 group companies. Ruwais, for example is an on-shore facility with the largest demand, although it is both an industrial and residential zone. There are 1300 units and houses which are home to about 20% of the total population in the western region. The housing complex consumes 1.4 Million m^3/yr of water: 57 % from treated Effluent and 43 % potable.

2.3. Irrigation Strategies

Overall, agriculture, forestry and amenity watering make up roughly 82% of Abu Dhabi's total water consumption, and most if not all of this demand is met through various irrigation strategies. (Mac Donald, 2004). Between 1979 and 1985, agricultural production increased nationally six-fold; between 1995 and 2006, agriculture in the Abu Dhabi Emirate practically doubled but has since level off, likely due to water scarcity. At the same time, agriculture contributes less than 2 percent of the UAE's GDP (Federal Research Division). Agriculture is generally dominated by two perennial crops, dates and Rhodes grass, with some seasonal plantings of short season annual vegetable crops; a limited area of cereals and fruits are

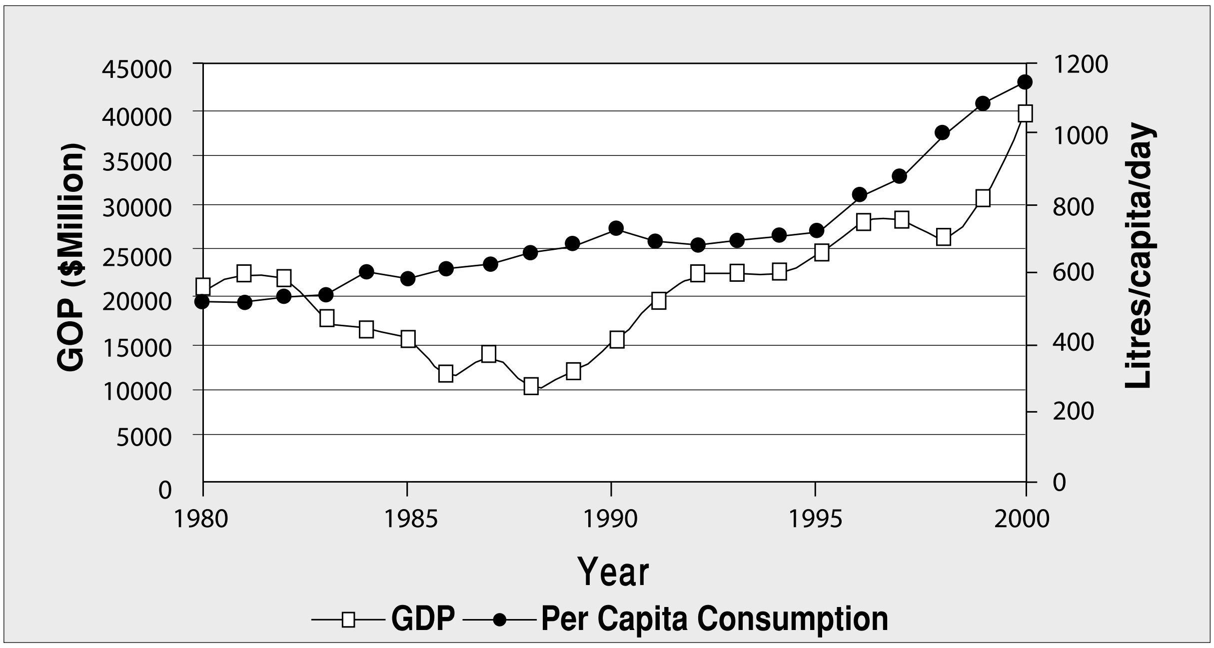


Figure 2-5. GDP and bulk per capita water use in Abu Dhabi.

also grown. Most agriculture is on small private farms that have been established in relatively recent times, but there are also small areas of traditional date palm gardens and larger government forage production units. Since the 1970s, there has been a drive to increase agricultural production that has led to a rapid depletion of underground aquifers, lowered water tables, and caused extreme increases in soil and water salinity.

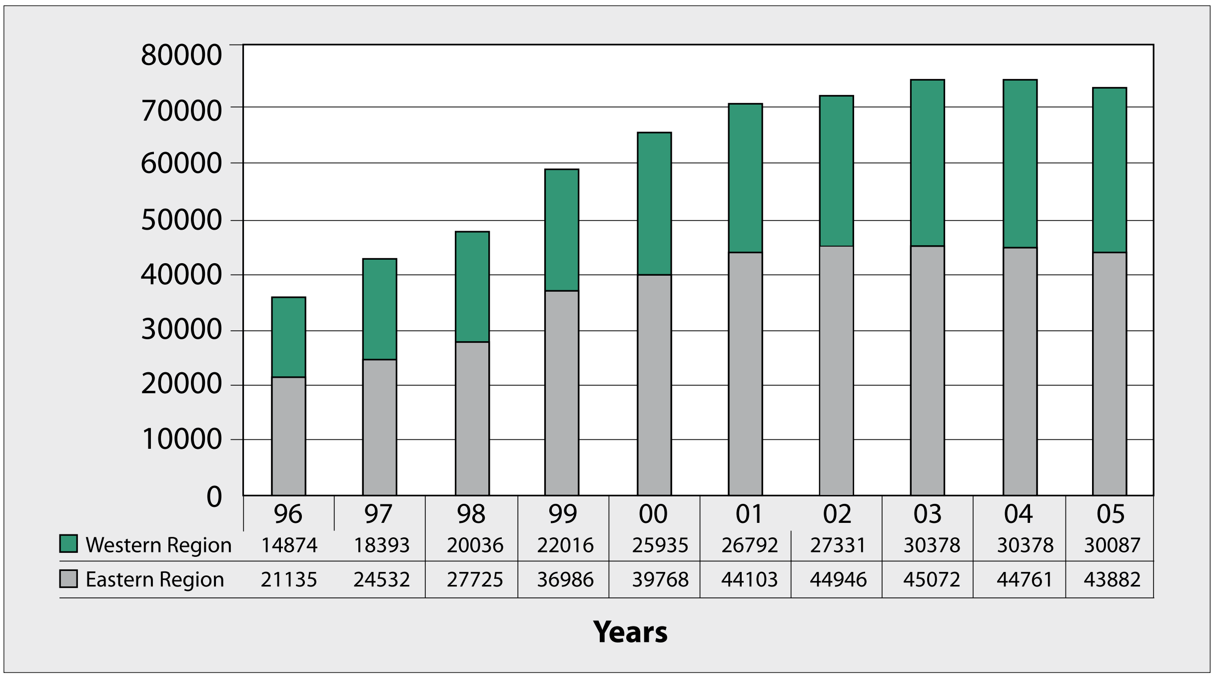
A considerable amount of investment has been made to 'green' the desert. In 1974, there was only one public park in Abu Dhabi with very little greenery, but today the number has increased to about 40, covering an area of more than 300 hectares. The expansion of the green areas in the Emirates is in line with the department's goal of extending the greenery to cover 8 per cent of Dubai's total urban area. During 2003, another 30 ha were added to Dubai's greenbelt. At present, the planted area amounts to about 3.2 % or 2200 ha (Ma, 2005). Amenity plantations use an estimated 245 Mm^3/yr of water from a combination of treated effluent, desalinated water and also local groundwater. In Al Ain, traditional oasis plantations that relied previously on aflaj irrigation have since become supported by wells when the aflaj flows ceased in the early 1990's.

The lack of arable land, intense heat, periodic locust invasions, and limited water are major obstacles for the agriculture sector. Lack of precipitation means that agriculture is dependent on irrigation, which is sourced from groundwater (both fresh and desalinated brackish and saline), treated sewage effluent (TSE), and desalinated water. The main problem is that groundwater systems can no longer adequately support existing, large agricultural developments. Alternative water sources are now being investigated and utilized. Much of the farm and forest sector use brackish groundwater while amenity plantings rely on both TSE and wells, especially in Al Ain city where over 400 have recently been inventoried. Treated effluent is also used for irrigation of small scale fodder farms. Amenity watering relies predominantly on TSE. For example, at the Nakheel and Al Ajban farms, desalinated water is now being utilized for irrigation, allowing for a much wider and marketable range of crops. At the former site, desalinated water, imported from the Qidfa, Fujairah plant, is blended with indigenous, brackish water to produce an irrigation water quality of about 1000 mg/l TDS, once again allowing for growing of fruits and vegetables.

Users employ traditional water utilization and conservation along with new management methods. Water conservation and new technologies to sustain supply in the semi-arid climate include desalination plants, construction of dams, restoration of traditional underground water channels (falaj system), well drilling and aquifer testing and exploration. For the last 3,000 years or so aflaj have provided for sutstainable agriculture and civilisation in the Al Ain Region. While historically reliant on the aflaj, water users in the Al Ain region have seen their usability decrease to declining groundwater levels in the source or mother well areas over the last 20-25 years. Despite the difficulties in maintaining the aflaj flows, it is the strategy of Al Ain Municipality who supports the falaj systems, as per decree by the late Sheihk Zayed bin Sultan Al Nayhan, will continue to finance the Falaj and the area of oases that they sustain at all cost. At the same time, the water table in the vicinity of the aflaj shari'a itself has steadily risen in recent years due to artificial recharge of groundwater from treated sewage effluent and desalinated irrigation water which is now widely used to keep the garden city of Al Ain green (Brook et al., 2005).

Localized irrigation strategies are dominated by drip, trickle, and bubbler methods but some overhead irrigation is used on lawns and some forage. Most forage is grown with drip irrigation. A small amount of flood irrigation (basin) is still undertaken in traditional date garden areas. For several reasons (rising average salinity of groundwater, difficulties in maintaining yields of irrigation water from boreholes, a dramatically increasing irrigated farm area), drip irrigation has become almost the sole irrigation method, a situation which is probably unique in the world.

For a while, subsidies promoted agricultural expansion to the tune of 3,000 new farms (of 2-3 ha) each year, although expansion is currently restricted due to exhaustion of groundwater supplies and has leveled off somewhat. We



	96	97	98	99	00	01	02	03	04	05
🟩 Western Region	14874	18393	20036	22016	25935	26792	27331	30378	30378	30087
▨ Eastern Region	21135	24532	27725	36986	39768	44103	44946	45072	44761	43882

Figure 2-6. Expansion and plateau of Abu Dhabi Citizens Farms, 1996-2005

expect this trend to continue, if not lead towards a decline of farmed hectares as water becomes scarcer and more expensive (if agriculture increases reliance on desalinated sources).

All forestry is irrigated by groundwater; however recently, there is a development to supply limited desalinated water to some projects in the western region. The forestry sector is faced with operational challenges related to poor water quality, lack of sufficient quantity of irrigated water and also poor quality soils. Fortunately, this has led to an emphasis on planting indigenous species allowing the use of brackish and saline waters through drip irrigation in an extreme arid zone environment. The Al Ain Forestry Department estimates water use, which vary according to site, at between 6.1 and 11.1 gallons/tree/day. The Forestry Department also estimate that 58,319,700 gal/day are pumped from 2,663 wells to supply 52,775 ha of forest. It is notable that some natural forests of Ghaff, Samar and Arta survive without irrigation. Where water supply is not constrained, daily irrigation schedule is based upon 8 hr/day groundwater well pumping; this is said to give between 1220 and 2220 gal/ha/day (equivalent to 0.55 and 0.99 mm/ha/day.

On forest sites where water is scarcer, irrigation is restricted to alternate days. In general, trees are under- irrigated because of water shortage (i.e. irrigation is related largely to water supply) and acknowledge that the irrigation is not really monitored in any way. In the Abu Dhabi Municipality, irrigation for amenity watering is not monitored but there has been a rough target of 5-8 gallons/tree/day, while 4 gallons/day is more likely due to acute shortages of water. For a description of hectares under irrigation in different regions used in our model see Annex 1.

3. Qualitative climate impact assessment of water resources

The hyper-arid climate of the UAE suggests that the primary driver of water supply changes will be demand and the subsequent rate of groundwater abstraction. As the situation stands today, precipitation and recharge are not major contributors to the Emirate's freshwater resources. The water supply is dominated by the abstraction of fossil groundwater or ground water that has been in underground aquifers for millennia. The intense rate of development expansion, combined with additional pressures from population growth and per capita consumption in the Emirates has called upon this non-renewable water resource.

An increase in municipal and industrial water demand, due to climate change, is likely to be rather small, e.g., less than 5% by the 2050s in selected locations (Mote et al., 1999; Downing et al., 2003). An indirect, but small, secondary effect would be increased electricity demand for the cooling of buildings, which would tend to increase water withdrawals for the cooling of thermal power plants. For example, all of Al Ain city's domestic water requirements were once met from wellfields. More recently, massive increases in domestic demands, from an annual population growth rate of 8 %, has meant that wellfields have been placed under increasing stress, resulting in declining water levels, increase in groundwater salinity with a resultant decrease in total production. Population growth and per capita increase changes in water demand are likely to be the primary drivers of water scarcity in the UAE; however, the following sections will pull from the international literature in order to raise awareness to what can be understood as potential climate change impacts on water resources. These sections include:

- 3.1 Global Climate Change
- 3.2 Regional Climate Change
- 3.3 GCM Scenarios for the UAE
- 3.4 Temperature Increase and diminished surface water reserves
- 3.5 Increased monthly precipitation variability
- 3.6 - Rainfall variability and flash flooding
- 3.7 - "Greening the desert": a vision at risk
- 3.8 - Vulnerability of Irrigated Agriculture
  - 3.8.1 - Groundwater over pumping
  - 3.8.2 - Salt buildup

We conclude with a discussion of the uncertainty of climate change-related impacts, and a challenge to water planners.

3.1. Global Climate Change

The scientific evidence for human-caused global climate change has become quite compelling in recent years. The Intergovernmental Panel on Climatic Change (IPCC) recently released the first of four parts of its Fourth Assessment Report (AR4 IPCC 2007), describing the science and physical evidence surrounding climate change. The consensus among involved scientists and policy makers is that "[… global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 …] and the understanding of anthropogenic warming and cooling influences on climate leads to very high confidence that the globally averaged net effect of human activities since 1750 has been one of warming" (IPCC, 2007). Certainly, other forcings act on the climate system beyond human influences, most notably solar, volcanic, oceanic, and cryogenic (ice), but when these processes are included alongside human forcing, an anthropogenic "fingerprint" emerges.

CO_2 is a major green house gas, contributing somewhere between 10 and 25 percent of the natural warming effect, second only to water vapor. As the earth emits long wave radiation toward space, atmospheric constituents like water vapor, CO_2, ozone, and methane absorb this energy flow and radiate energy back to earth. Climate models suggest that without these greenhouse gases the average earth temperature would be about $-19^{o}C$, and in the absence of other changes and feedbacks in the

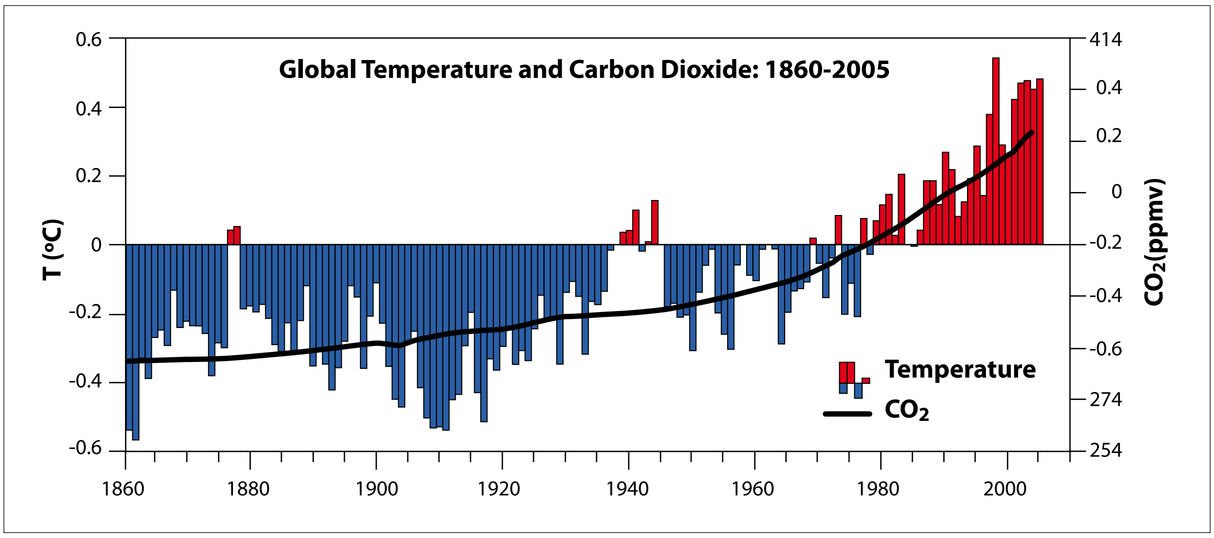


Figure 3-1 Global average temperature and CO_2 trends (Karl and Trenberth 2003).

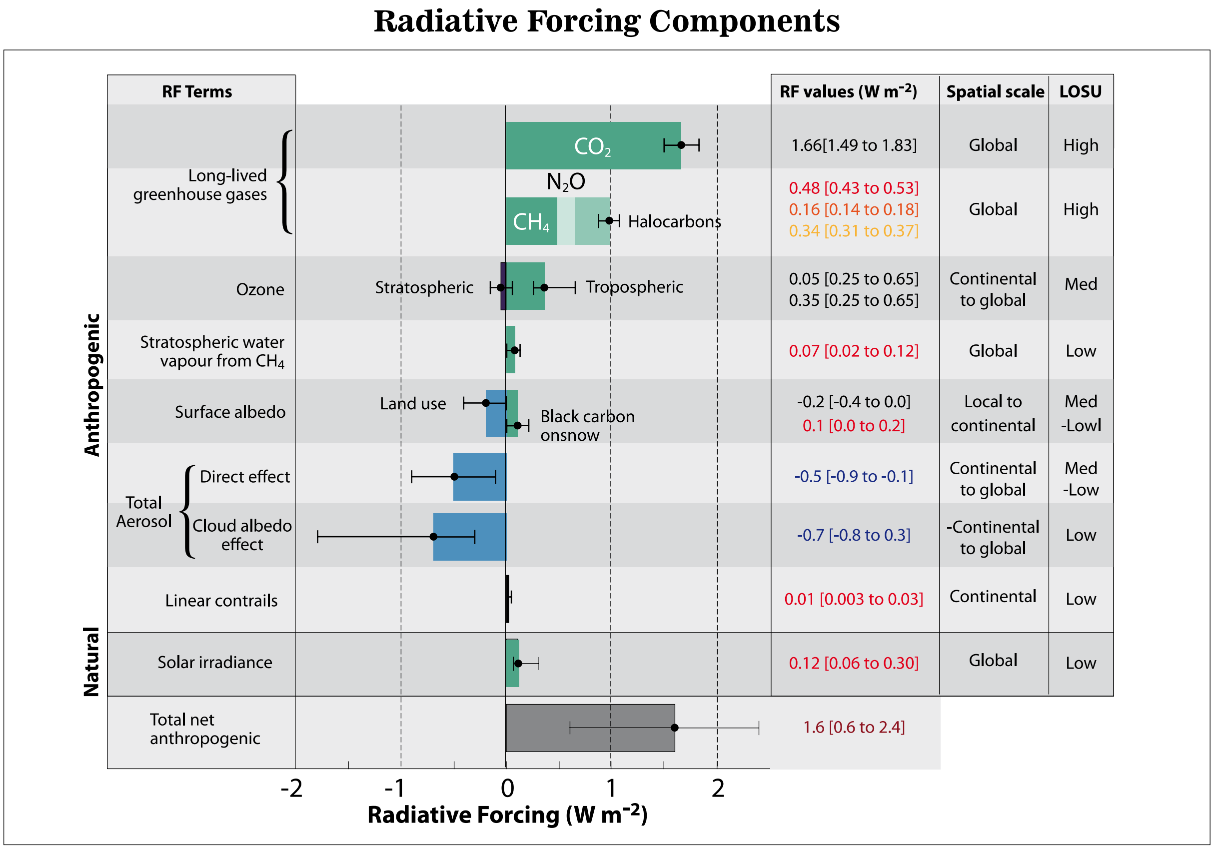
climate system, a doubling of CO_2 would warm the lower atmosphere by about 1.2°C (Kiehl and Trenberth, 1997).

Figure 3-1 is a plot of annual mean departures from the 1961-90 average for global temperatures, with an underlying mean of 14.0°C, and carbon dioxide concentrations from ice cores and Mauna Loa (1958 on), with a mean of 333.7 ppmv (updated from Karl and Trenberth 2003). The plots show that the rise in CO_2 coincides with a rise in global average surface temperatures.

Increasing CO_2 is not the only human activity affecting our climate system and in fact, CO_2 is only responsible for about two-thirds of the greenhouse effect, the reset being methane, nitrous oxide, chlorofluorocarbons, and ozone. Changes in land use, aerosol emissions from fossil fuel burning, the storage and use of water for agriculture, etc. are all environmental changes that affect climate (Pielke et al., 2007).

Climatologists have tried to quantify the relative role of various human factors on the climate system in terms of each component's "radiative forcing", which are summarized from the IPCC Fourth Assessment Report (IPCC, 2007). Most notably, the radiative forcing of CO_2 is the largest single component, with natural solar irradiance (solar variability) substantially smaller. Also, there are human activities that counteract the positive forcing of CO_2. For examples, aerosols from the burning of fossil fuels tend to reflect heat back into space, reducing the net heat at the surface. When all the components are considered, there is a net positive radiative forcing on the order of 1.5 watts per square meter (W/m^2). In Figure 3-2, "positive" means that the earth is gaining energy faster than it is losing it (RF-Radiative Forcing; LOSU- Level of Scientific Understanding)

Problematically, CO_2 has a relatively long residence time in the atmosphere and while its sources are local, it is generally globally distributed. Recognizing that it is a strong forcing component, the IPCC has convened panels of experts that have developed "storylines of the future", which are used to project concentrations of greenhouse gases. These transient concentrations are then used in Global Climate Models (GCMs) to project the relative contribution of CO_2 (and other factors) to future warming. Most GCMs consist of an atmospheric module that is coupled to the other key components of the climate system, including representation of oceans, sea ice, and the land surface. The major GCMs include tens of vertical layers in the atmosphere and the oceans, dynamic sea-ice sub-models and effects of changes in vegetation and other land surface characteristics (Washington, 1996; Gates et al., 1999). The atmospheric part of a climate model is a mathematical representation of the behavior of the atmosphere based upon the fundamental, non-linear equations of classical physics. A three-dimensional horizontal and vertical grid structure is used to track the movement of air parcels and the exchange of energy and moisture between parcels.



RF Terms	RF values (W m^{-2})	Spatial scale	LOSU
Long-lived greenhouse gases: CO$_2$	1.66[1.49 to 1.83]	Global	High
Long-lived greenhouse gases: N$_2$O, CH$_4$, Halocarbons	0.48 [0.43 to 0.53] 0.16 [0.14 to 0.18] 0.34 [0.31 to 0.37]	Global	High
Ozone	0.05 [0.25 to 0.65] 0.35 [0.25 to 0.65]	Continental to global	Med
Stratospheric water vapour from CH$_4$	0.07 [0.02 to 0.12]	Global	Low
Surface albedo	-0.2 [-0.4 to 0.0] 0.1 [0.0 to 0.2]	Local to continental	Med -Lowl
Total Aerosol: Direct effect	-0.5 [-0.9 to -0.1]	Continental to global	Med -Low
Total Aerosol: Cloud albedo effect	-0.7 [-0.8 to 0.3]	-Continental to global	Low
Linear contrails	0.01 [0.003 to 0.03]	Continental	Low
Solar irradiance	0.12 [0.06 to 0.30]	Global	Low
Total net anthropogenic	1.6 [0.6 to 2.4]		

Figure 3-2 Relative radiative forcing attributable to human activities. (IPCC, 2007)

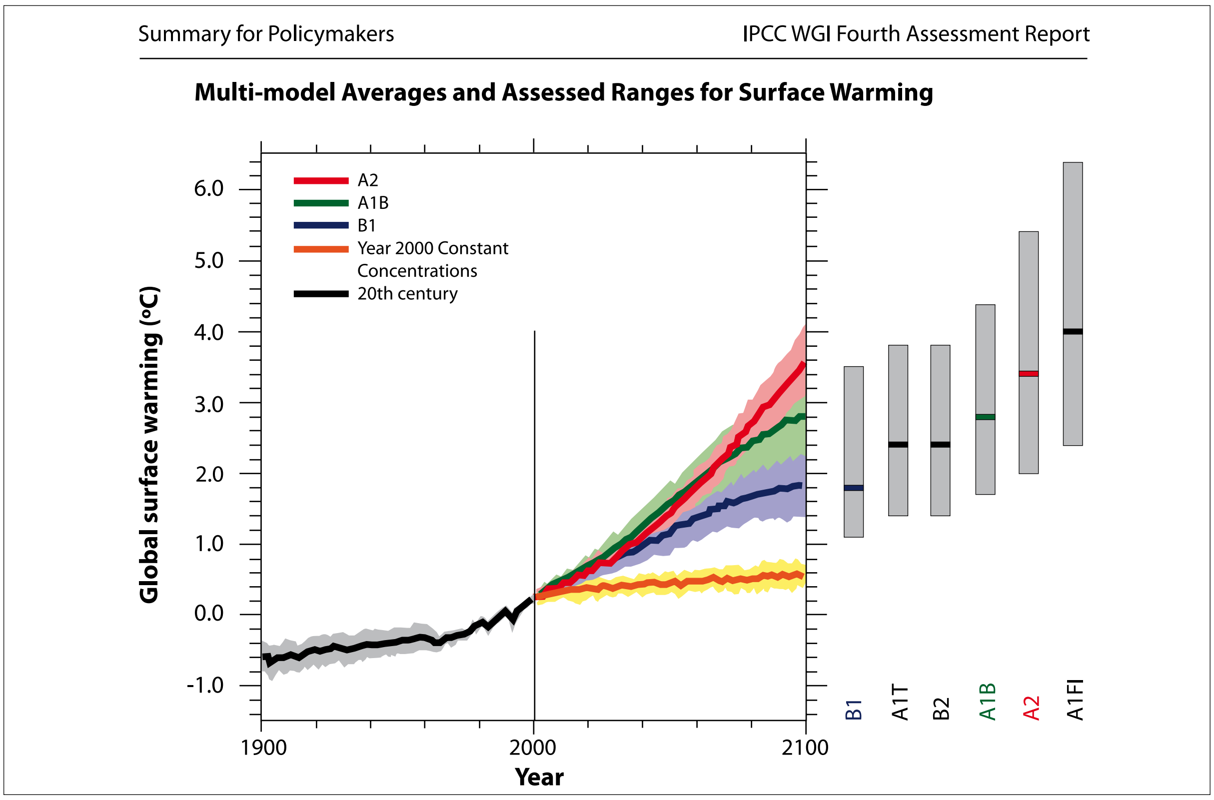


Figure 3-3. Historic observed global average temperatures, and projected global average temperatures based on various projections of global CO$_2$ concentrations. (IPCC, 2007)

The CO_2 storylines include both “green” centered trajectories that moderate fossil fuel use and fossil fuel intensive trajectories, leading to either low or high green house gas concentrations, respectively. These different emission pathways then imply different mean global and regional climate warming rates. The details of these Scenarios are beyond the scope of this report, but Figure 3-3 summarizes the projected global average surface warming based on a consensus derived from several GCMs across a range of future projections (e.g. referred to ‘A2’, ‘A1B’, and ‘B1’ Scenarios, for details about the different Scenarios, see http://www.ipcc.ch/pub/sres-e.pdf). Note this figure includes a projected global average temperature if we were to keep CO_2 at 2000 concentration levels, suggesting that we are already committed to some additional warming beyond anything that has taken place already (IPCC 2007).

The consequences of the projected future warming are likely to be changes in atmospheric and oceanic circulation, and in the hydrologic cycle, leading to altered patterns of precipitation, groundwater recharge, and surface runoff. Warmer temperatures and even changes in other climate variables like wind and humidity, could lead to change in water demands for outdoor irrigation needs. Warmer temperatures, accompanied by increases in wind and lower humidity in the interior could lead to higher demands in the agricultural sector. Scientists agree on some of the important broad-scale features of the expected hydrologic changes, the most likely of which will be an increase in global average precipitation and evaporation as a direct consequence of warmer temperatures. That, however, does not mean that there will be more precipitation everywhere or that groundwater recharge would increase in proportion to precipitation, as other factors like changes in evaporation could overwhelm any increased precipitation.

3.2. Regional Climate Change

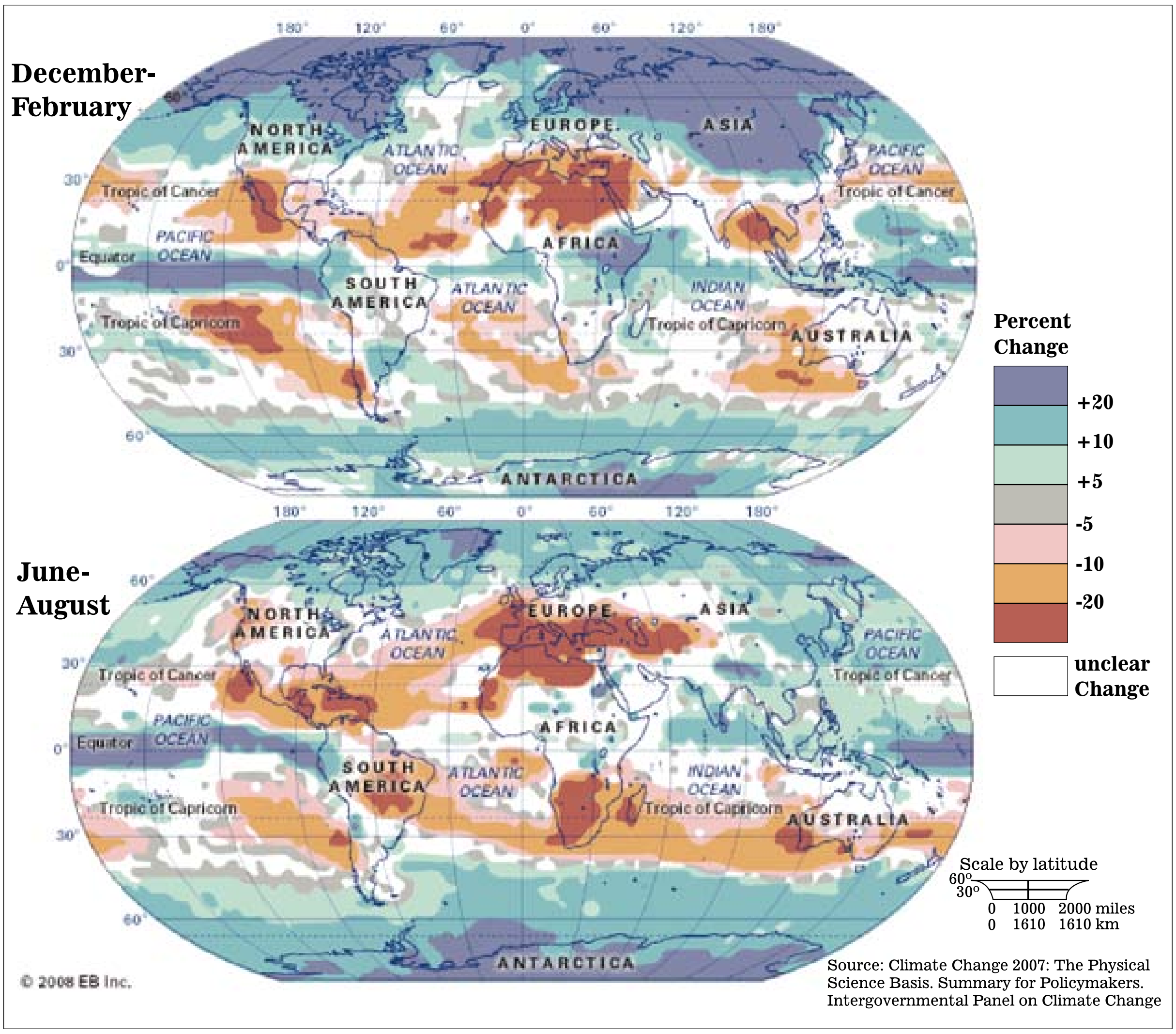
At the regional scale, such as the ADE, there is high confidence in projections of future temperature change, with less confidence in projections of future precipitation change (Dai, 2006). Changes in circulation patterns will be critically important in determining changes in precipitation, and climate models can provide only a crude picture of how those patterns may change. The currently available evidence suggests that arctic and equatorial regions may become wetter, and that subtropical regions may experience drying. Projections of precipitation changes for mid-latitude regions such as the ADE are less consistent.

In some places, there is stronger consensus among different climate models that gives rise to stronger ‘confidence’ in regional precipitation changes. For example, a recent report by Seager (2007) argues for an imminent transition to a drier climate in southwestern North America. He points out the consistency of climate models in producing a human-induced aridification caused by large scale changes in the atmospheric branch of the hydrological cycle, stating that “the subtropics are already dry because the mean flow of the atmosphere moves moisture out of these regions whereas the deep tropics and the higher latitudes are wet because the atmosphere converges moisture into those regions. As air warms it can hold more moisture and this existing pattern of the divergence and convergence of water vapor by the atmospheric flow intensifies. This makes dry areas drier and wet areas wetter.”

Figure 3-4 shows projected patterns of precipitation change. Note the general pattern of drier conditions in the mid-latitudes and desert regions, and wetting in the tropics and high latitudes (IPCC 2007). The dark stipples in this figure are places where there is consensus among models with regards to the direction of future climate change. So in the poles and some tropical regions, there is more stippling, suggesting more model agreement, suggesting the greater likelihood that the poles will get wetter and the mid-latitudes drier. Problematically for the ADE, Figure 3-4 shows in white no stippling, suggesting no strong trend in precipitation (either wetter or driver) and thus little agreement among models. Thus, for the water resources sector of the ADE, a conservative assumption regarding future precipitation is that the near future will be like the recent past- very arid.

Despite tremendous technological advances

Proejected Changes in precipitation from 1980-99 to 2090-99



Source: Climate Change 2007: The Physical Science Basis. Summary for Policymakers. Intergovernmental Panel on Climate Change

Figure 3-4. Statistical summary of projected patterns of precipitation change from multiple General Circulation Models for December, January and February (left) and June, July, and August (right).

in computing capability, it is still very time consuming and costly to use these models to simulate future climates. One of the most important compromises for achieving model results in a reasonable amount of time is to decrease the model's horizontal resolution. This limitation means that it is prohibitively costly to run a GCM at a spatial resolution that would accurately depict the effects of mountains and other complex surface features on regional climates.

The problem with such a coarse horizontal resolution is that important processes occurring at finer scales are not well defined. Topography, for example, is very important in determining the location of precipitation. As moist air rises over mountains or hills, the moisture condenses, producing clouds and, if conditions are right, precipitation. Although there has been marked improvement over the last three decades in the simulation of precipitation, it is still not well represented in GCMs, especially in areas of complex topographies, since the coarse horizontal resolution of GCMs tends to smooth out important landscape features that affect atmospheric processes. At the resolution of most GCMs the models do not adequately represent the Oman Mountains and if they do, they are simply gentle ridges and do not resolve finer scale features that influence regional climate. Clearly, that level of spatial resolution is too coarse to reproduce the effects of topography on the region's precipitation and groundwater recharge patterns (Grotch and MacCracken, 1991; Giorgi and Mearns, 1991; Pan *et al*., 2004).

The current inadequacies of GCMs and the recognition that each has its own strengths and weaknesses has led researchers to conclude that no single model can be considered 'best' and it is important to utilize results from a range of coupled models for regional impact and adaptation studies (Allen et al., 2000). Tebaldi et al., (2005) presented a probabilistic approach that combines the regional output of 21 unique GCMs to produce probabilistic projections of regional, future climate change. Their statistical model combines information from each GCM, including each model's ability to re-create the regional climate over the period 1960 through 1990 (a measure of a model's bias), and the agreement among models in future projections. Models that diverge greatly from other models are given less weight in deriving the final statistical distributions of change.

Figure 3-5 shows probabilistic projections of future seasonal temperature and precipitation change for the region of the United Arab Emirates for the decade around 2050 for the low CO_2 emission, B1 scenario; and the high A1 emissions scenario. The projected mean differences among the two Scenarios at 2050 for temperature are about 0.5°C. The B1 projection of the change in annual average temperature is about 1.5°C, while the A1B projected change in at 2050 is about 2.0°C It isn't until later in the 21st century, that the projections diverge under the various CO_2 Scenarios.

The Tebaldi *et a*l., (2006) results suggest a GCM model consensus of temperature increases a bit below 1°C over the next 20 years (not shown), with some seasonal variation. For precipitation, the B1 Scenarios seems to suggest a slight "probability" of a decrease in precipitation given as an annual average in units of mm/day. There is substantial spread across the distribution in terms of both increases and decreases in annual precipitation, with the A1B scenario showing the same kind of spread, although its mean value seems to be right at the 0 mm/day relative change, suggesting equal likelihood of either increase or decreases in precipitation by the middle of the 21st century. Section 3.3 goes into greater detail on the seasonal distribution of change and the generation of specific climate Scenarios for this analysis.

In Figure 3-5, the SRES Scenarios B1 (Figure 3-5a and 3-5c) and A1B (Figure 3-5b and 3-5d), and annual average change in temperature and change in precipitation in mm/day. The colored makers and labels are the individual models that contribute the creation of the distribution.

3.3. Generating Climate Scenarios for the ADE

Given the ambiguity of future change in precipitation and the strong consensus of changes in temperature on the order of 1°C to the middle of the 21st century, we developed relative "simple" climate change Scenarios that reflect these general observation of projected climate change from a host of GCMs. Results from downscaled General Circulation Models (GCM) provide the maximum and minimum projected change in temperature and precipitation for Abu Dhabi city in 2050 and 2100. For each of four climate change Scenarios (A1, A2, B1, and B2), the projected maximum/minimum changes are calculated based on 5 GCM outputs (CCC196, CSI296, ECH496, GFDL90, and HAD2TR95). Table 3-1 presents absolute values (e.g., annual average temperature in Abu Dhabi in 2050) and projected changes in absolute values (e.g., incremental rainfall relative to the 1961-90 annual average).

Two summary Scenarios can be derived from these projections: 1) a best case scenario in which precipitation actually increases 10.33% compared to the 1961-90 baseline and average air temperatures warm +1.74°C by 2050; and 2) a worst case scenario in which temperatures warm 2.67°C and precipitation decreases 21.20%

Table 3-1. Summary of GCM Outputs for Abu Dhabi

Temperature	Precipitation
+1.74 to 2.67°C (2050)	-21.20% to +10.33% (2050)
+3.11 to 4.76 ° C (2100)	-37.82% to +18.42% (2100).

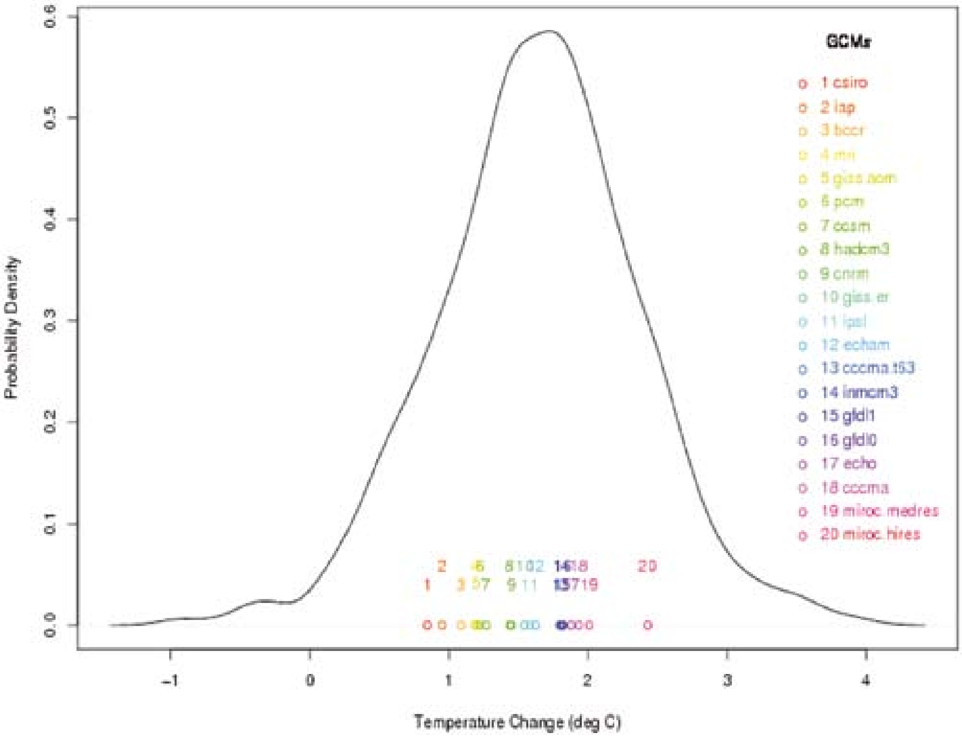


Figure 3-5a. Probability Density Function -b1_temp_2050_annual

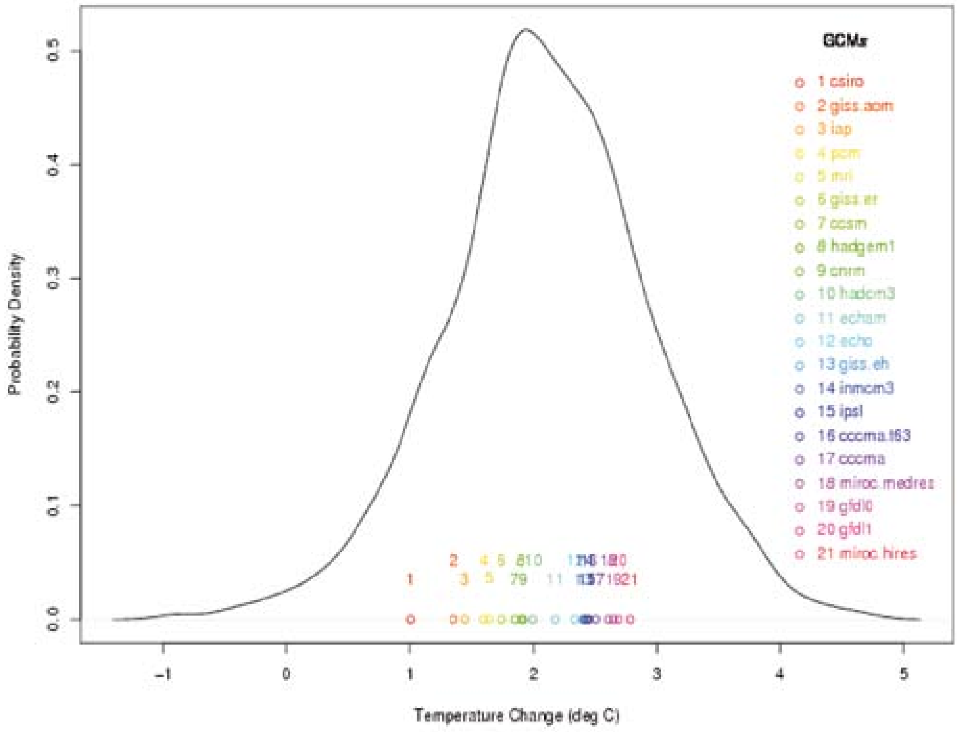


Figure 3-5b. Probability Density Function -a1b_temp_2050_annual

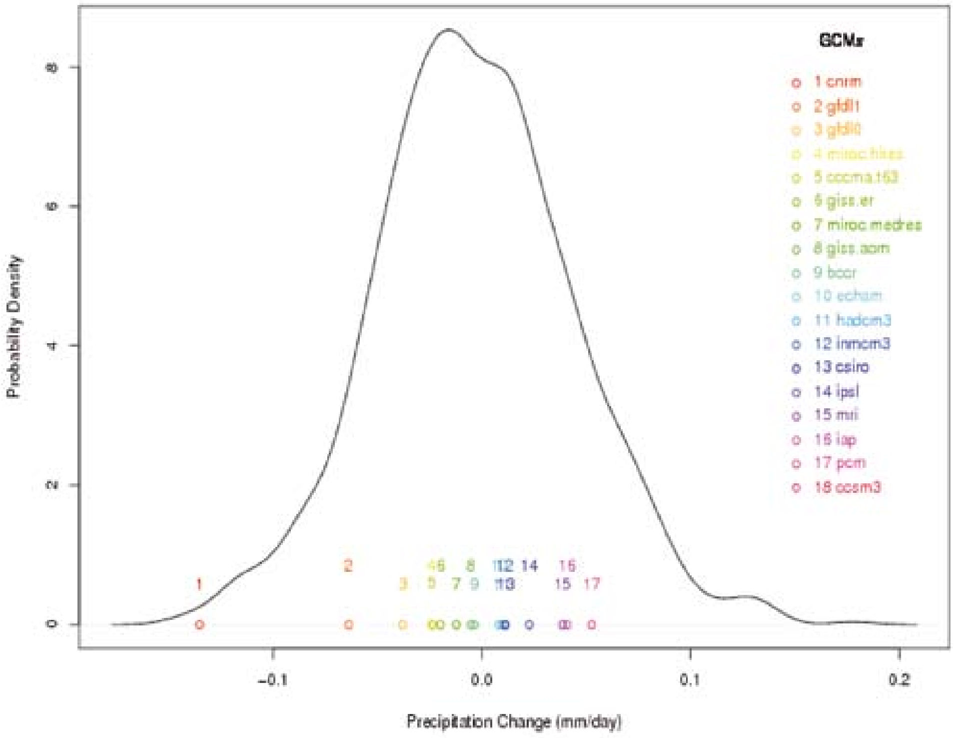


Figure 3-5c. Probability Density Function - b1_precip_2050_annual

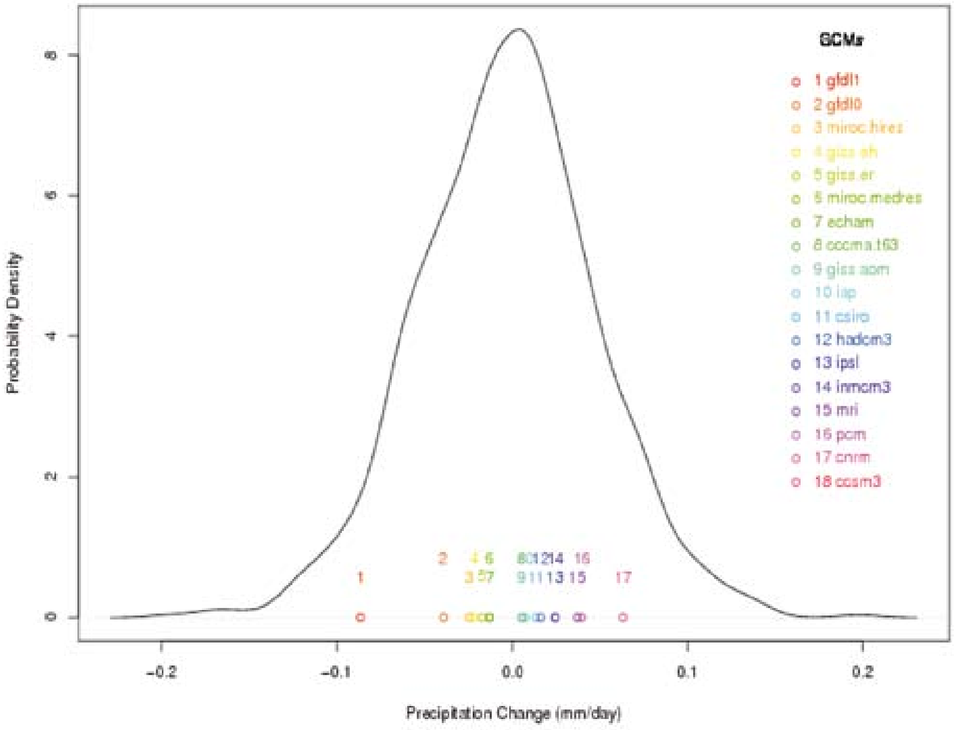


Figure 3-5d. Probability Density Function - a1b_precip_2050_annual

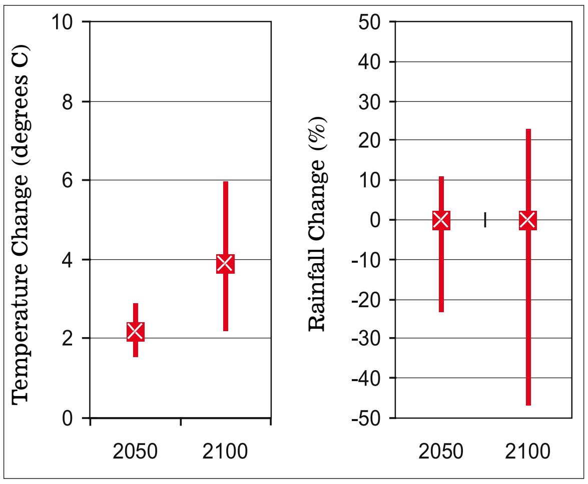


Figure 3-6. Maximum and minimum projected temperature and rainfall change. (UAE, 2006)

by 2050.

GCM outputs illustrated in Figure 3-6 show that temperatures are projected to be between about 1.6°C and 2.9°C warmer in 2050 than they were over the period 1961-90, and between 2.3°C and 5.9°C warmer than this baseline period by 2100.

The precipitation projections, however, are more varied. Some models project a dryer region with decreasing precipitation, while others project a wetter region with a significant increase in precipitation. Figure 3-8 in Section 3.5 conveys the projection of rainfall in 2050 to be between 20% less to 10% more than has occurred over the period 1961-90, and between 45% less to 22% more by 2100. Additionally, the IPCC notes an increasing trend in the extreme events observed during the last 50 years, particularly heavy precipitation events, hot days, hot nights and heat waves. Projections indicate this trend will continue, if not worsen.

3.4. Temperature Increase and diminished surface water Reserves

Projected changes in monthly temperature vary widely across the various GCMs, Scenarios considered, and cities within the UAE. Average monthly temperatures in 2050 will be warmer than they were for the corresponding months over the period 1961-90:- from 1.6°C in January to about 2.5°C in September (Figure 3-8). Similarly, for 2100, increases in average monthly temperature could range from about 3.3°C in February to about 4.5°C in October (again, relative to the corresponding monthly average over the 1961-90 baseline periods).

Temperature strongly influences the amount of evaporation in an area. In hot, dry climate evaporation of irrigation water is a serious problem whether from the soil, plant leaves or other wet surfaces. Improving irrigation efficiency allows farmers to avoid severe water loss. The key is custom-designed strategies to get more output and benefit from water by creating a best-fit technology linked to local climate, hydrology, water use patterns, environmental conditions, and other relevant characteristics.

3.5. Increased monthly precipitation variability

Rainfall within Abu Dhabi Emirate is erratic both in time and space. Rainfall provides water for runoff, which eventually results in aquifer recharge, especially in the eastern regions where numerous wadi systems cross over the border from Oman to provide preferential pathways for percolation and recharge. This recharge water is important, however, it only contributes, on average, 4% annually to the Emirate's total water consumption. Even so, changes in precipitation patterns threaten to eliminate even that small contribution to Emirate water supply.

Precipitation projections show even greater variation than temperature. Some models project a dryer region with decreasing precipitation, while others project a wetter region with a significant increase in precipitation. As illustrated in Figure 3-8, average monthly rainfall in 2050 is projected to range between 8% less in April to about 45% more than these corresponding months over the period 1961-90. For 2100, average monthly rainfall changes are projected to range between 15% less in June to about 88% more in September, relative to the 1961-90 baseline period.

Mean annual rainfall for the western region of the Emirate is less than 50 mm/yr and for the eastern region, varies between 80-100 mm/yr. An estimate of 100 mm/yr has been shown to be required in order to activate sufficient runoff to

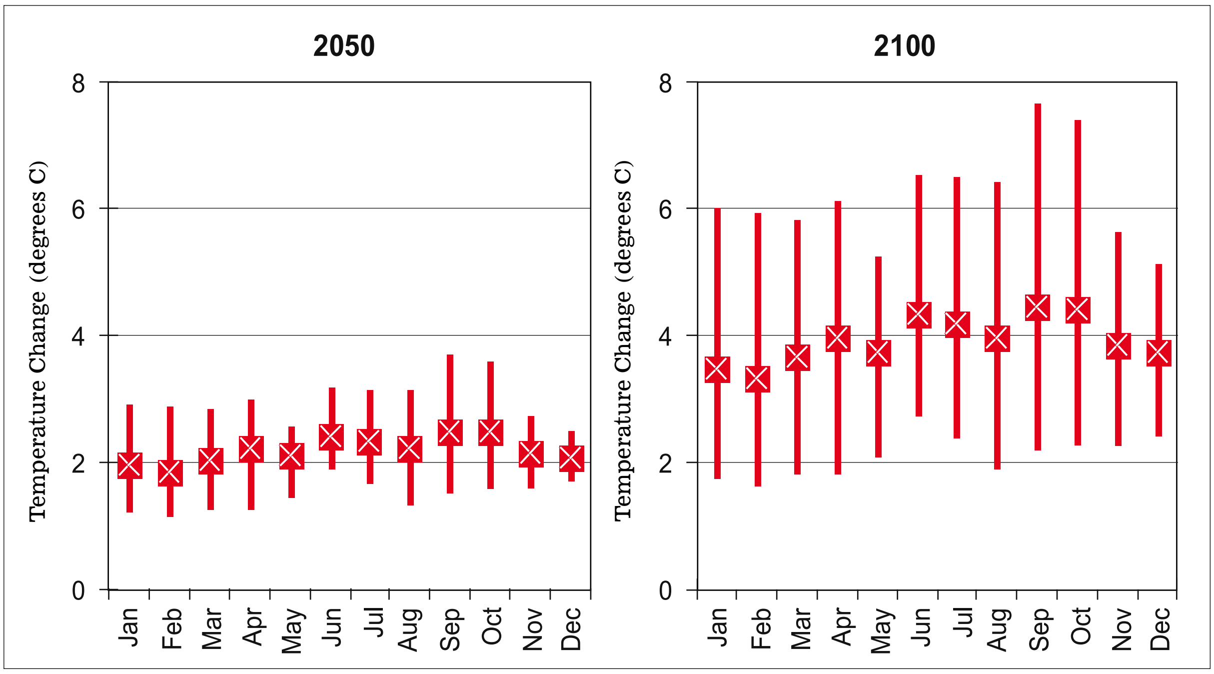


Figure 3-7. Projected monthly temperature change, 2050 and 2100. (UAE, 2006)

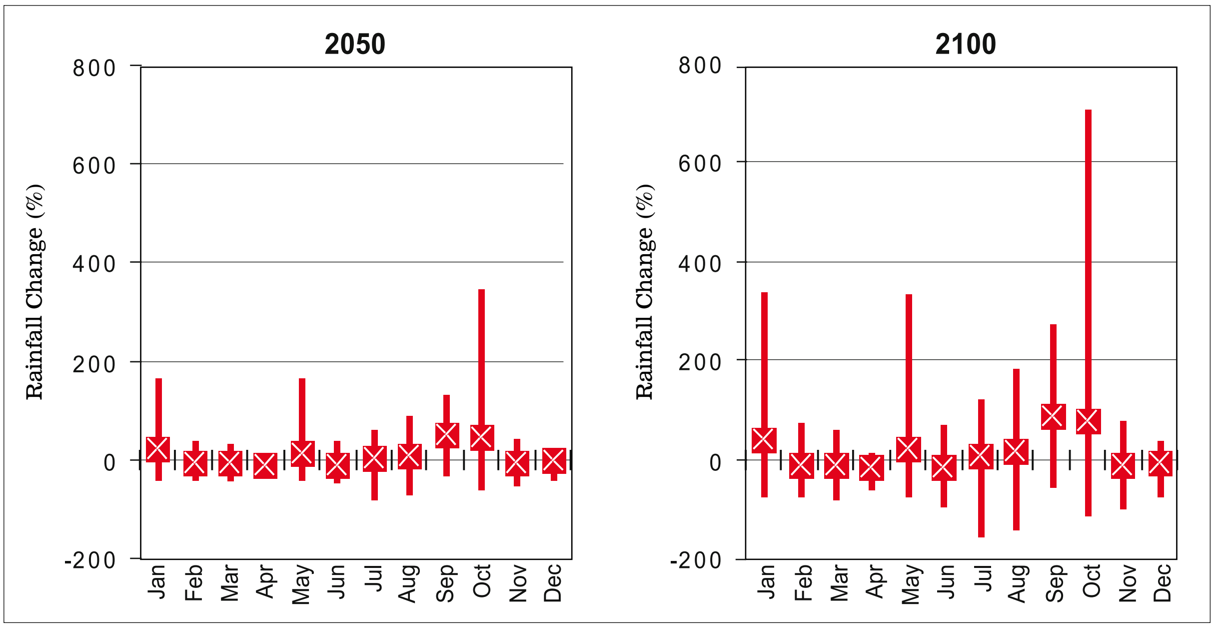


Figure 3-8. Projected monthly rainfall change, 2050 and 2100. (UAE, 2006)

cause aquifer recharge (Dincer, 1974; Faloci & Notarnicola, 1993).

3.6. Rainfall variability and flash flooding

Some years, there is no rain at all, and in others, rain occurring on only a few days in the year can total more than three times the long term annual average and have a very significant impact on restoring groundwater levels (ADEA, 2002). Groundwater systems are controlled by recharge processes, the geology of the host rocks, and residence time of groundwater and discharge processes. The resultant groundwater quality is largely influenced by groundwater residence time and type of recharge process, and in more recent times, by anthropogenic

Table 3-2. Shwaib diversion structure.

Project Item	Dimensions Capacity	Mm3
Shwaib Dam	Length 3000 m, height 11m	5
Approach Channel	Length 3600 m, width 150 m	5.5
Shwaib Reservoirs	Seven reservoirs	21
Total Shwaib Dam and Reservoirs project		31.5

activity and its availability by aquifer type and surrounding development (ADEA, 2002). Currently, the highest risks of flash flooding occur in wadis Shik, Sidr and Ain Al Faydah and the lowest risk in wadis Khuqayrah and Muraykhat. The predicted long term annual average runoff for the former basins is 1.96 Mm^3/yr and for the latter, 13.78 Mm^3/yr.

Droughts, floods, and other events that alter rainfall may overwhelm even an advanced society's ability to cope. Archeological evidence suggests that the abandonment of several cities in the course of history can be linked to water scarcity and changes in water availability. Flash flooding and any subsequent inability to capture rainfall adequately will lead to extreme runoff, nutrient loading, and, depending on proximity to coastlines, sedimentation of coastal ecosystems like sensitive corals.

Abu Dhabi has invested in new dams across the Emirate. Designed to divert wadi flow into surface reservoirs, as temperatures rise surface water reserves are increasingly at risk. Warmer air, while increasing evaporation of surface water, also means that the atmosphere holds more moisture and rainfall patterns will shift. Increasing frequency of extreme and/or erratic rainfall events have led to dam overflow and flash flooding in other countries, and while it is unlikely that these kinds of events will occur in the UAE, the possibility still exists, putting downstream agriculture at risk of flash floods (Postel, 1999). Water quantities that pass through the Shabit structure are summarized in Table 3-3; the main beneficiary of the structure's enhancement of groundwater recharge is agriculture as numerous farms exist immediately south of the diversion structure.

3.7. "Greening the desert": a vision at risk

UAE President Sheikh Zayed bin Sultan Al Nahyan dreamed of turning the country green. Over the last few decades, a massive programme of afforestation has led to the planting of over 120 million trees, as well as 25 million date palms. Some of these trees were planted in urban centres, where carefully-maintained parks and luxuriant roadside gardens offer a pleasing quality of life for the people. Most of the planting, though, has been conducted in the desert, where huge new forests have been established. This "greening the desert" initiative has an important cultural value for Abu Dhabi, and serious consideration will are needed in determining the costs and benefits of continuing to green the desert, given the challenges of climate change.

Climate change has a profound impact on the forestry sector. This includes changing the habitat location of forest species, especially the less tolerant ones and the extinction of low tolerant species. The Municipality Agriculture Department explains that irrigation of forestry is undertaken mostly, with a small number of farms, parks, gardens and road verge projects. Based on an 8-hour/day pumping regime, the combined water requirement is about 64Mm^3/d. The Ministry also notes that trees tend to be under-irrigated and species are chosen that are tolerant of the salinity levels of groundwater.

3.8. Vulnerability of irrigated agriculture

Ancient civilizations depended on irrigation to sustain agriculture just as much of the world does now. At least half a dozen major irrigation-based civilizations have been undermined by salt, silt, neglected infrastructure, regional conflict, and unexpected climatic change (Postel, 1999). It is no secret that major empires throughout human history have collapsed from abrupt climate change, increased salination of the soil, and water scarcity. Unless contemporary irrigation strategies are transformed, societies whose agricultural productivity is entirely dependent on irrigation will be undermined by similar threats. In particular, as the risks from climate change to agriculture are unequivocal and imminent, Abu Dhabi's reliance on irrigation is a serious consideration when devising an adaptation plan for the water resources sector.

Postel (1999), in her book *Pillar of Sand: Can the Irrigation Miracle Last?*, warns that as urbanization leads to higher urban and industrial water demands, it's likely that these demands will be met through a transfer of water resources from agriculture. In a country whose economy is heavily dependent on agriculture, the farm-to-city reallocation of water could undermine the ability to feed itself and more broadly, the world's ability to feed itself. One way to mitigate the farm to city transfer, in addition to improving irrigation efficiency, is the increased use of treated urban waste water for irrigation.

Impacts of climate change on irrigation water requirements may be large. A few new studies have further quantified the impacts of climate change on regional and global irrigation requirements, irrespective of the positive effects of elevated CO_2 on crop water-use efficiency. Döll (2002), in considering the direct impacts of climate change on crop evaporative demand, but without any CO_2 effects, estimated an increase in net crop irrigation requirements (i.e., net of transpiration losses) of between 5% and 8% globally by 2070, with larger regional signals (e.g., +15%) in south-east Asia. (IPCC 2007; IPCC SR 2008).

3.8.1. Groundwater over-pumping

Groundwater over-pumping may be the single biggest threat to irrigated agriculture, exceeding even the buildup of salts in soil (Postel, 1999). Countries with large and growing populations and large irrigated areas are drawing down aquifers to meet today's needs, leaving less for future needs. Groundwater over-pumping is a prime example of the tragedy of the commons; the explosion of private and unmonitored wells, tapping into Abu Dhabi's underground resources undermines any existing sustainable water resource management strategies. It is far more serious when drawing on non-renewable or fossil aquifers, such as those found in arid regions like North Africa and the Middle East, because they have little to no replenishment from scarce rainfall. The issue is that agriculture in these regions is supported by the equivalent of deficit financing, and countries are racking up large water deficits that will likely have to be balanced at some point—whether by artificial groundwater recharge, or shifted reliance to 100% desalination.

Without changes in water withdrawal and irrigation behaviors, further degradation of soil and reduction of available water resources is inevitable (Postel, 1999). Fortunately, groundwater consumption has decreased somewhat. The total water used in 2005 is 8% less than that used in 2003. Aquifer depletion under a general regime of unsustainable development brought about a corresponding 18% reduction in groundwater used (ADEA, 2005). The biggest opportunity for narrowing the supply-demand gap lies in slowing population growth, improving efficiency of water use, and shifting it out of agriculture—particularly given climate change.

3.8.2. Salt buildup

Salt can undermine soil productivity when too much remains on soil. In hotter and drier climates, farmers must fight high rates of evapotranspiration by applying more water to the soil. As water evaporates, salt remains on the surface, poisoning crops. Soil salinity is likely undermining a good percentage of increased productivity achieved by advances in irrigation. Seepage from heavy irrigation areas then raises the salinity of groundwater.

To mitigate this effect, drainage systems need to be installed at the time of irrigation infrastructure, rather than after the fact. Additionally, the hyper-saline drainage water needs to be dealt with. Releasing this water to the Arabian Sea has potentially grave impacts on near-coastal ecosystems. Reducing drainage is key; implemented by reducing irrigation volume using advanced technologies and eliminating system inefficiencies. Drainage water can also be captured and reused for plants with higher saline tolerance.

3.9. Uncertainty of climate impacts: a challenge to water planners

There are several potential sources of uncertainty associated with the GCMs used to provide the results summarized above. These uncertainties include the way that atmospheric boundary conditions are represented in the models, the manner in which aerosols and drift are addressed, as well as the inherent uncertainty associated with the greenhouse gas emissions Scenarios themselves. While droughts and changes in precipitation patterns are typically regarded as inevitable, uncertainty surround the degree of severity and the extent to which remaining resources are impacts.

Water use, in particular that for irrigation, generally increases with temperature and decreases with precipitation; however, there is no evidence for a climate-related long-term trend of water use in the past. This is due, in part, to the fact that water use is mainly driven by non-climatic factors, and is also due to the poor quality of water-use data in general, and of time-series data in particular (IPCC 2007). Stresses on water resources are also evolving simultaneously so population pressures on aquifers are now layered with increased temperatures and decreasing precipitation.

Among the most important drivers of water use is population, economic development, and changing societal views on the value of water. The latter refers to the prioritization of domestic and industrial water supply over irrigation water supply and the efficient use of water, including the extended application of water-saving technologies and water pricing (IPCC SR on water, June 2008). This is particularly salient when discussing irrigation, because the rules of irrigation game and working towards sustainable management strategies revolves around how irrigation is managed and how water is allocated (Postel, 1999).

Tropical storms and other hazards are of particular concern if and when the majority of the UAE's water supply for human consumption and otherwise relies on the country's capacity to desalinate Persian Gulf seawater. Desalination plants are easily sabotaged; they can be attacked from the air or by shelling from off-shore; and their intake ports have to be kept clear, giving another simple way of preventing their operation (Bullock and Darwish, 1993). According to the Central Intelligence Agency's "Middle East Area Oil and Gas Map" there is a stunning concentration of oil facilities in the region. (Middle East Area Oil and Gas Map, Central Intelligence Agency map #801357, June 1990). The Persian Gulf has 29 major tanker ports and 16 major shore-based refineries and the United Arab Emirates exemplifies this pattern with 10 tanker ports and 3 coastal refineries that share approximately 300 miles of coastline with 40 major desalination plants (Wangnick, 1990).

One team of researchers has already modeled the effect of an oil spill near Umm Al Nar desalination plant. Malek and Mohame (2005) used a hydrodynamic model to predict the direction and concentration of oil around the station with emphasis on the places where seawater was used as feed water to the station. They discussed the influence of oil contaminated seawater, when it is used as the feed water to the desalination plant, on the performance of system equipments and production water. The found that contamination of the facilities by oil negatively affects the efficiency of the seawater desalination, the product water itself will be polluted which would cause the complete stop of the potable water supply and a lower efficiency rate generation of the thermal power station.

In addition to the uncertainty described above, research of global historical data suggests that heavy rainfall events and prolonged droughts should be included in modeling efforts. Studies of coral assemblages in the Arabian Gulf suggest that the area has at least a partial link to the monsoon and El NiÑo Southern Oscillation (ENSO) events (Purkis and Riegl, 2005). These events have increased in magnitude since the 1970s and it has been suggested that climate change may continue to change the frequency and magnitude of the ENSO (Haines et al., 2000), although the extent of the effect is uncertain. Addressing the uncertainty around the changes of tropical storms occurrence, on the scale of 2007's Cyclone Gonu, is outside the scope of this report, though is an area worth further research by water planners. While it is difficult to model potential changes related to ENSO, heavy rainfall, and drought events, they all have the potential to significantly affect the social and natural systems of the UAE. Circulation in the Arabian Gulf is linked to ENSO events therefore changes in the cycle of these events may directly affect the UAE. Risks to the Emirate's off-shore, desalination infrastructure whether from oil spills, or cyclones could suggest a worthwhile investment in a strategic water reserve safe from these hazards.

4. Quantitative climate impact assessment of water resources

Observed water supply and demand data summarized in Sections 2 and 3 were used as the physical basis to develop a water resource planning model to broadly characterize future projections of water use and supply, calibrated with historic data. This model, constructed using the Water Evaluation and Planning (WEAP) platform, broadly represents the regional supply characteristics described in Section 2.1 (e.g. Regional fossil supplies in the West, including Liwa), Central (Abu Dhabi City), and East (Al Ain Oasis), limited renewable freshwater supplies in the east near Al Ain, and both existing and future desalinzation that supply both coastal and inland demands, as well as municipal waste water reclaimed and used again primarily for amenity (gardens and parks) uses. The water resource model explicitly captures total water demands of the municipal/ industrial (M&I) sectors based on estimates of population and per capita use, which together comprise domestic indoor uses such as bathing, toilet flushing, washing, and water for industrial production.

This model simulates the observed growth in water demand by the domestic sector, with an increase in consumption of around 15% from 2002 to 2003 (e.g. 440 to 522 Million Cubic Meters, and the forestry sector from 510 to 607 Million Cubic Meters), and the small recorded reductions of 1% and 5% in the agriculture and amenity sectors, respectively. A smaller consumption in the agriculture sector is a result of a policy to reduce the area under irrigation in large state fodder farms; the 2002 irrigated area of 24,000 ha reduced to 17,000 ha in 2003. This WEAP model has the capability of including changes in cropped area and assumptions about irrigation and water use strategies, and thus the model should be capable of simulating the broad, observed water use patterns. Estimates of supplied water use for the years 2002, 2003, and 2005 were estimated at 3,200 MCM, 3,360 MCM, and 3,111 MCM respectively, and we apply the water resources model to simulate these uses, driven by both per capita use and climate driven irrigation demands.

Outdoor water use was treated explicitly to account for the climate factors that drive irrigation demand, as higher temperatures, lower humidity and high wind speeds increase irrigation requirements of crops. These dynamics are included in order to estimate future irrigation demand under various climate change Scenarios. A crop water simulator based on United Nation Food and Agriculture (FAO) methods, was used to estimate monthly irrigation demand for the agricultural, forestry, and amenity sectors. The FAO method uses estimates of potential evapotranspiration and crop coefficients (Kc) to determine required irrigation requirements. In addition, we used estimates of acreage planted, irrigation efficiencies, and leaching requirements to derive estimates of monthly and annual irrigation demands that would closely match reported estimates.

4.1. The Water Evaluation and Planning (WEAP) model of Abu Dhabi Emirate

The Water Evaluation and Planning (WEAP) model was used as the Decision Support System (DSS) for this study. WEAP is an integrated DSS platform designed to support water planning with consideration of both water supplies and multiple water demands characterized by spatially and temporally varying allocation priorities and supply preferences. Allocation priorities identify under conditions of scarce resources, which demands are supplied first before other competing demands. Supply Preferences identify the water source(s) that supply specific water demands. The WEAP representation of the Abu Dhabi Emirate water supplies and demands are presented in the figure below, with the inset Figure 4-1 showing the details of the model objects in and around Abu Dhabi, and will be used in the discussion below to describe some of WEAP's functionality.

WEAP employs a transparent set of model objects and procedures that can be used to analyze a full range of issues and uncertainties

Table 4-1. Irrigated Hectares (Ha) from GIS layers.

Region	Crop	Ha
E	Forests (total)	88,749.92
E	Amenity/Urban greening/ residential properties of palaces Al Ain (5814.39ha); Abu Dhabi (20,260ha)	26,074.29 (total)
E	Farms (total)	89,571.00
W	Forests (total)	105,647.5421
W	Amenity/Urban greening (total)	8580.59
W	Hey/Fodder	2185.66
W	Farms (total)	36,114.74

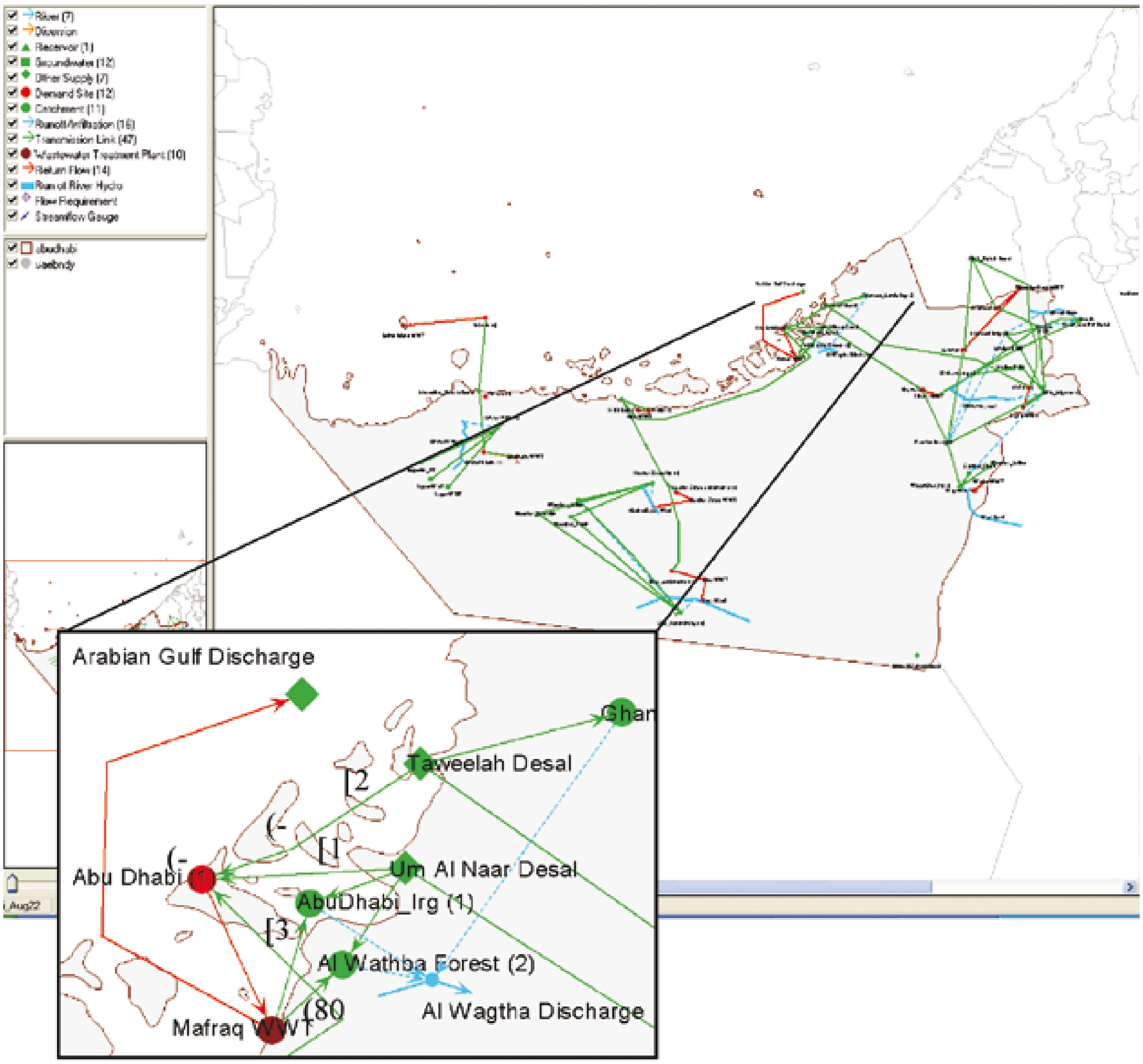


Figure 4-1. A WEAP schematic of the Abu Dhabi Emirate.

faced by water planners, including those related to climate, watershed condition, anticipated demand, ecosystem needs, regulatory climate, operational objectives and available infrastructure. The model possesses a graphical user interface that supports the construction of site-specific network representations of watersheds and the water systems contained within them, and that facilitates multi-participant water management dialogues organized around scenario development and evaluation. WEAP uses a priority-based optimization algorithm as an alternative to hierarchical rule-based logic that uses the concept of Equity Groups to allocate water in times of insufficient supply (Yates et al. 2005 a,b). More information on WEAP can be found at http://weap21.org.

4.2. Data requirements and acquisition

Several supporting datasets have been utilized in this study, most notably those provided by the Abu Dhabi Environment Agency's Water Resources Department in the form of annual water resource statistical reports that summarize regional water demands and supplies by sector and source. Data from these reports have been used to represent the physical infrastructure such as desalination plants, waste water treatment plants, and well fields, their capacities; and how they are connected to various demand sites. These include estimates available groundwater storage stratified by fresh, brackish and saline, population and per-capita use estimates in both the western and eastern regions of the ADE. Climate data included daily observations of minimum and maximum air temperature, wind speed, relative humidity, and precipitation for Abu Dhabi and Al Ain airport for the period 1994 through 2008.

Geographical Information System (GIS) datasets were also use to spatially locate the supplies and demands throughout Abu Dhabi, and determine the amount of irrigated acreage in each region and by type (agriculture, amenity, forests). The GIS layers include those listed Annex 1: Data sources and key assumptions, and the aggregate irrigated area is summarized in Table 4-1

4.3. Representing Water Demands and Supplies in WEAP

Figure 4-1 shows the representation of Abu Dhabi water supply and demand as depicted in WEAP. The inset box shows some of the detailed objects near and around Abu Dhabi. The aggregate municipal and industrial demands for the city of Abu Dhabi are represented by a single demand node (inset; red circle). Within this demand object are fields that represent the number of people, their per capita demand, their monthly use pattern, and their consumption. Transmission losses and consumption are depicted as % values along transmission links and at the Abu Dhabi demand site.

The demand priority for Abu Dhabi municipal and industrial demand is given a priority of one - it has first priority for water supplies that serve its needs, which are linked to the demand node by three transmission links (green arrows) for sources Um Al Naar, Mirfa, and Taweelah (desalination plants designated with green diamond model objects). Data input for the desalination sources include their installed capacity in millions of gallons per day (e.g. Taweelah at 228 mgd and Un Al Naar at 160 mgd). In 2003, the total desalinization production was estimated at about 400 mgd, so these two desalinization objects represent the bulk of the potable supply. Wastewater is conveyed from the demand node to the Mafraq waste water treatment plant with a return flow link (red arrow). The 'Red-Line' exiting the Abu Dhabi demand node in Figure 4-1 is the conveyance to the, with the two conveyance lines (green lines).

Transmission links from Mafraq represent the reuse of treated waste water for non-potable, outdoor irrigation. Irrecoverable transmission losses in the distribution system from the desalinization water treatment plant are assumed to be 15%, Consumption within the municipal and industrial demand node is assumed as 10% of what is delivered to the node. The model also assumes that 80% of water that is returned to a waste water treatment plant can be used for outdoor irrigation (e.g. amenity watering). These fractions are shown along the transmission links summarizes the drivers of municipal demands for the region including estimates of population and per-capita demand.

The average per capita domestic demand is estimated at 525 to 600 l/cap/day, with network losses of about 25%. In some areas, where the population uses water for irrigating the green areas around Villas, this average consumption can grown to more than 1000 l/cap/day. This is a very high rate of use, with USA use rates of about 300 l/cap/day and Europe 125, l/cap/day. By simply multiplying per capita use by population, the total residential water use in 2003 was about 280 Mm^3, which represents about 45% of the desalinized water use. Government and commercial use another 45% and outdoor watering of gardens the remaining 10% of desalinized water. To reflect government, commercial, and other outdoor uses, we have simply doubled per capita use to 1100 and 900 l/cap/day in the western and eastern regions, respectively.

In this table, per capita consumption reflects just residential uses and is estimated simply as the product of population and per-capita water use estimates. Government, schools, and commercial uses are assumed to double this rate (Abu Dhabi Water and Electricity, Regulation and Supervision Bureau). The per-capita consumption rate is doubled in the WEAP model to reflect all M&I uses.

When different outdoor demands are served by different supply sources or have different priorities, another 'Green Circle' is introduced into the model. These catchment nodes (Figure 4-1 inset; green dots) represent land cover water demands, including outdoor irrigation. For example, the Abu Dhabi Irg node represents the outdoor amenity water and agricultural irrigation for the commodities represented in the model. The 'Green Dot' labeled 'Al Whathba' Forest represents the planted trees outside the main municipal area, which receive the same sources of water as the 'Abu Dhabi Irg' but have a lower priority (Priority 2) for receiving water. In times of shortage, Abu Dhabi Irg will receive water before Al Whathba Forest.

Data attributes for the catchment model objects include representative area; irrigation timing and efficiency, and climatically driven potential evapotranspiration. Irrigation demands are calculated using the standard United Nations Food and Agricultural Organization (FAO) method summarized in Crop evapotranspiration - Guidelines for computing crop water requirements (Allen et al. 1998).

The WEAP representation of the eastern region of Abu Dhai Emirate is shown in the figure above Figure 4-2, and includes several municipal/industrial demand nodes (e.g., Swehan, Al Shoosh and Al-Ain); and catchment nodes representing irrigation demands (e.g., Al Shoot Irrig, Al Ain_Irrigated, Al Khazna Ag, etc.). The eastern-most portion of the study domain includes a representation of the Oman Mountain Wadis, and natural recharge to the shallow, freshwater aquifer (green square labeled Shallow E FR) occurs via a runoff link (blue dashed arrow) from Shwaib_Hayer_Swehan Irg object, leakage from the Swaib Dam object, which represents all surface water storage in Abu Dhabi, with a total capacity of 26 mcm. This leakage rate was assumed as 20% of the previous month's storage in the reservoir. It was assumed that only the East-Fresh aquifer is a renewable resource and undergoes modern-day recharge via the Oman Mountains to the west of Al Ain.

Other aquifers represented include those characterized by shallow brackish water (Shallow E BR), shallow saline (Shallow SA); and deeper sources such as East Aquitard Saline and Brackish. It was assumed that only the Shallow East-Fresh aquifer is a renewable resource and undergoes modern-day recharge via the Oman Mountains to the west of Al Ain. This recharge is represented by the Shwaib_Hayer_Sweihan Irg node, that in WEAP includes a natural, un-irrigated land class which applies the same FAO

Table 4-2. Municipal and industrial water demand, 2003.

	Population	Per capita demand (l/cap/day)
Western	655,000	550
Eastern	533,000	450

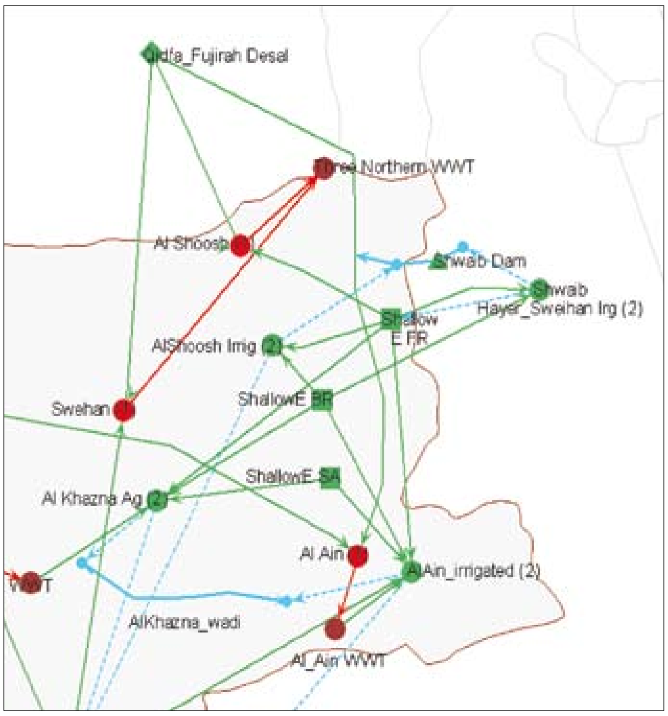


Figure 4-2. Eastern region supply and demand representation in WEAP.

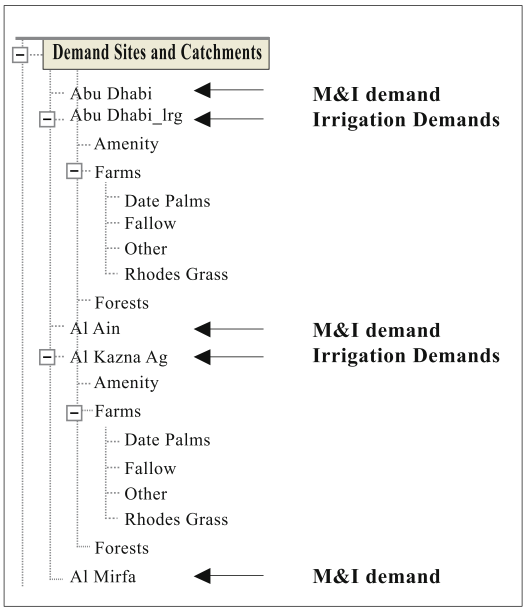


Figure 4 3. The directory tree in WEAP, suggesting the data structure used to represent M&I demands ('Red Dots') and Irrigation Demands ("Green Dots")

hydrologic model that simulates monthly runoff to Swaib Dam as simply Runoff (mm/month) = min(0,Precipitation – Evaporation). Swaib Dam is used to represent all surface water storage in Abu Dhabi, with a total capacity of 26 Million Cubic Meters (MCM). Water stored behind the Swaib Dam is recharged back to the '(Shallow) (E)ast (FR)esh' aquifer, with an assumed recharge rate equal to 20% of that held in storage from the previous month, taking into account evaporation from the water surface of the reservoir.

A 2003 estimate of groundwater resources suggests that fresh groundwater sources constituted only 7% of the total available supply (see Section 2.1) as belts along the Eastern region on the border with Oman and also as a large basin in the Liwa – Beda Zayed area. Only 22% of the fresh water is in the eastern region, where modern-day, alluvium recharge occurs, accounting for roughly 4,000 Mm3 of renewable volume in 2003. Table 4-3 summarizes the 2003 estimate of total available groundwater supplies. Saline groundwater sources are assumed not used to meet M&I or irrigation demands and we have assumed somewhat higher amounts of Eastern Brackish and Western Fresh groundwater than is reported in Table 4-3 but is consistent with higher availability volumes that have been reported by the Groundwater Assessment (GTZ et al. 2005) Programs.

Table 4-3. Total supplies represented by the WEAP model. (GWAP/ G72,2005)

	Fresh (Mm^3)	**Brackish (Mm^3)**	**Desal (mgd)**
Eastern*	4	128	528
Western	12.5	80	101

*Only the freshwater in the eastern region, near Al Ain can be considered "renewable". All other groundwater is mined.

4.4. Representing Irrigation Demands

Irrigation demand for the three main irrigated land use types (e.g. agriculture, forests, and amenity) in the WEAP model is driven by climate. Irrigation requirements for a demand site are computed using the FAO crop requirements method, which assumes a simplified hydrological and agro-hydrological process. Parameters and variables used in computing crop water demand include precipitation, evapotranspiration, crop coefficients, irrigation efficiencies, leaching factors, total planted area, fraction of planted area per crop type, a crop coefficient (Kc), irrigation efficiency, leaching factor, and fraction planted.

Agricultural irrigation demands represent the largest single use of water in Abu Dhabi Emirate. In WEAP, these demands are represented for the eastern and western region by disaggregating farms into three representative crop types, including 'Date Palms', 'Rhodes Grass', and an 'Other Crop' category that would include things like vegetables and grains. Evaporative demand or Precipitation Shortfall for each crop is estimated in WEAP based on the estimate of PET, the crop coefficient, irrigation efficiency, and a leaching factor. The crop coefficient, Kc, is used to characterize the degree to which irrigators apply water to their crops to satisfy crop water demand. For a given crop, a Kc of 1.0 implies that 1) the crop is fully watered, so evapotranspiration is limited by energy availability; and 2) the evapotranspiration rate equals that of a "reference" crop, which is typically alfalfa.

In the Abu Dhabi Emirate, Kc values are typically much less than 1.0, as deficit irrigation is the norm given the scarcity of water. Irrigation efficiency is simply the percentage of water that is delivered to demand site but does not serve a beneficial use to the crops. A 90% irrigation efficiency implies that 10% of the delivered water is lost in transmission and/or lost to evaporation in a way that does not benefit the plant. Seasonal variation in Kc values is implemented to represent the reality that winter irrigation is more substantial than in summer, as more farmers fallow land in the summer due to the intense heat and resulting inefficiencies. Irrigation efficiencies were assumed to range from a low of 70% for 'Rhodes Grass', which assumed irrigation inefficiencies through transmission and application losses, 85% for 'Forests' and a high of 90% for 'Amenity', as trees and gardens are typically water with hand placed, drip irrigation.

The leaching fraction represents an increase in crop water demand to help leach salts from the soil column. A leaching fraction of 0.2 indicates that an additional 20% of crop water demands is needed to help in soil-salt management. These coefficients used in the WEAP application for the five plants are summarized in Table 4-4.

The 'Amenity' type is a generic category of land cover that represents green spaces, parks, gardens, etc. that have been planted around the Abu Dhabi Emirate. We have assumed that the Kc value of the Amenity land cover is relatively high, consistent with the overall policy of keeping those spaces green. The 'Forests' plant type represents planted trees that have been established throughout the country. For

Table 4-4. Irrigation coefficients for the five represented crops/plants.

Crop/Plant	Kc	Irrigation Efficiency %	Leaching Fraction %
Forests (trees)	0.2	85	5
Amenity	0.6	90	2
Ag-Date Palms	0.4	80	20
Ag-Rhodes Grass	0.7 (winter) 0.5 (summer)	70	20
Ag-Other	0.6 (winter); 0.4 (summer)	80	20

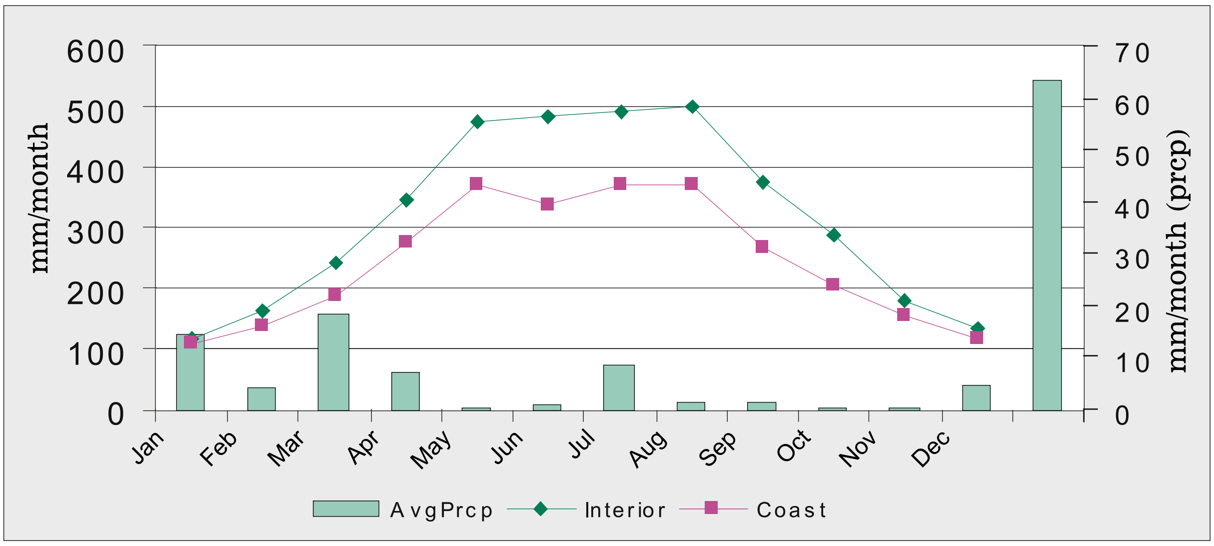


Figure 4-4. Al Ain "average" monthly PET and rainfall over the period 1994-2005.

this cover it was assumed that the Kc value is relatively low, implying a general strategy of under-watering. The Forests land use type makes use of the same crop demand model used for the Agriculture and Forestry objects in the WEAP model.

Potential evapotranspiration (PET) is estimated using the well known Penman Montieth method (FAO-56) and are given in units of mm/month. The PET was computed from monthly observations of average air temperature (OC), relative humidity (RH), wind speed (m/s), and solar radiation. In addition, time series of monthly total precipitation were used to modify crop water requirements, although in this hyper-arid region, annual evaporation demand far exceeds annual precipitation, and so the benefits from rainfall in terms of satisfying crop water demands are very marginal. Figure 4-4 shows a plot of the average monthly PET estimate for the coast (Abu Dhabi) and Interior (Al Ain). The coastal PET value is substantially lower than the interior, as the high RH suppresses PET, while lower RH and substantially higher air temperatures raises PET in the interior of Abu Dhabi Emirate. Figure 4-4 also includes a plot of "average" monthly rainfall over the period 1994 through 2005 for Al Ain, and should be referenced with the right y-axis of the figure. Annual rainfall is only about 1% of annual PET on average.

4.5. Calibration using observed data

Having described the general approach to estimating M&I, agricultural, amenity and forestry water demands, we now summarize WEAP's ability to replicate the broad annual water supply and demand for two select years, 2003 and 2005. We have chosen these two years since they correspond to water reporting years available from the Department of Water Resources at ERWDA. Table 4-4 summarizes the reported water use by sector for 2003 and 2005 (gray columns); and the corresponding modeled water use (columns labeled "Model").

Our estimates of Municipal and Industrial water use are less than the reported water use, but are consistent with the per-capita and population estimates given for 2003 and 2005. The discrepancy is likely due to other uses of desalinized water that are part of the reported estimate, including irrigation. Our 2003 estimates of agricultural, water, and amenity uses closely match observations, while our 2005 estimate of these same sectoral uses is about 15% higher than those reported. This discrepancy is a result of higher evaporative demands in 2005 relative to 2003, which increased modeled irrigation requirements in all sectors. In addition, there is a reported 40% reduction in the western forestry sector "due

Table 4-5. Comparison of Historical Estimated and WEAP Modeled Demands.

2003	East (Mm³)		West (Mm³)		TOTAL (Mm³)	
	Obs Est.	Model	Obs Est.	Model	Obs Est.	Model
M&I	152	152	428	320	580	472
Agriculture	1109	1200	840	770	1949	1970
Forestry	123	115	484	445	607	560
Amenity	111	114	134	134	245	248
TOTAL	1495	1581	1887	1669	3381	3250

2005	East (Mm³)		West (Mm³)		TOTAL (Mm³)	
	Obs Est.	Model	Obs Est.	Model	Obs Est.	Model
M&I	111	170	641	351	752	521
Agriculture	980	1230	760	750	1740	1980
*Forestry	125	115	237	488	363	603
Amenity	118	124	137	154	255	278
TOTAL	1334	1639	1775	1743	3109	3382

*The Environment Agency of Abu Dhabi reports a substantial reduction in forestry in the 'Uo El Dabsa Plantation' in 2005.

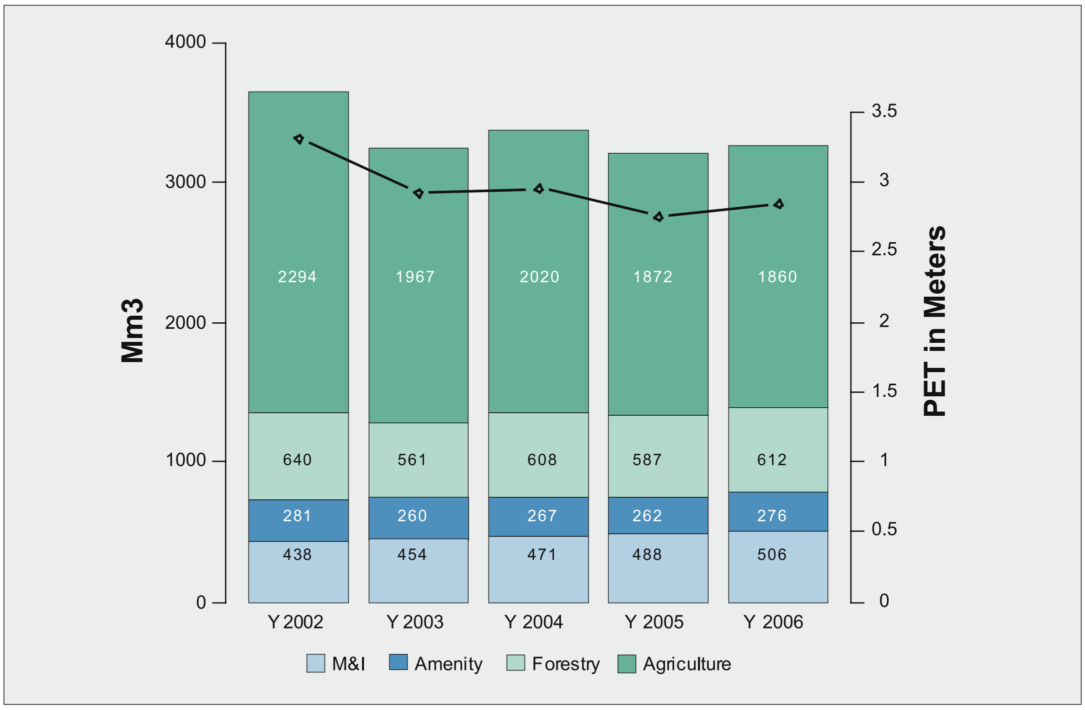
mostly to the down-scaling of the Uo El Dabsa plantation", which we did not assume.

The allocation algorithm in WEAP automatically allocates water supplies to the various demands, with results of that allocation from the 5 year simulation (2002 through 2006) summarized in Figure 4-5 and Figure 4-6.

Figure 4-5 shows the WEAP estimate of total annual demand for the agriculture, amenity, forestry, and M&I demands for the years 2002 through 2006. This simulation assumes that the M&I demands increase only due to the growing population, as per-capita demands were fixed over the simulation period. For the agriculture, forestry and amenity demands, it was assumed that the cropping pattern and cropped area did not change, thus the year-to-year variability are only due to climatic variability. The figure includes the total annual potential evaporative demand for these two years to illustrate the magnitude of the climatically forced fluctuation of PET. There is a strong correlation between PET and the sectoral demand.

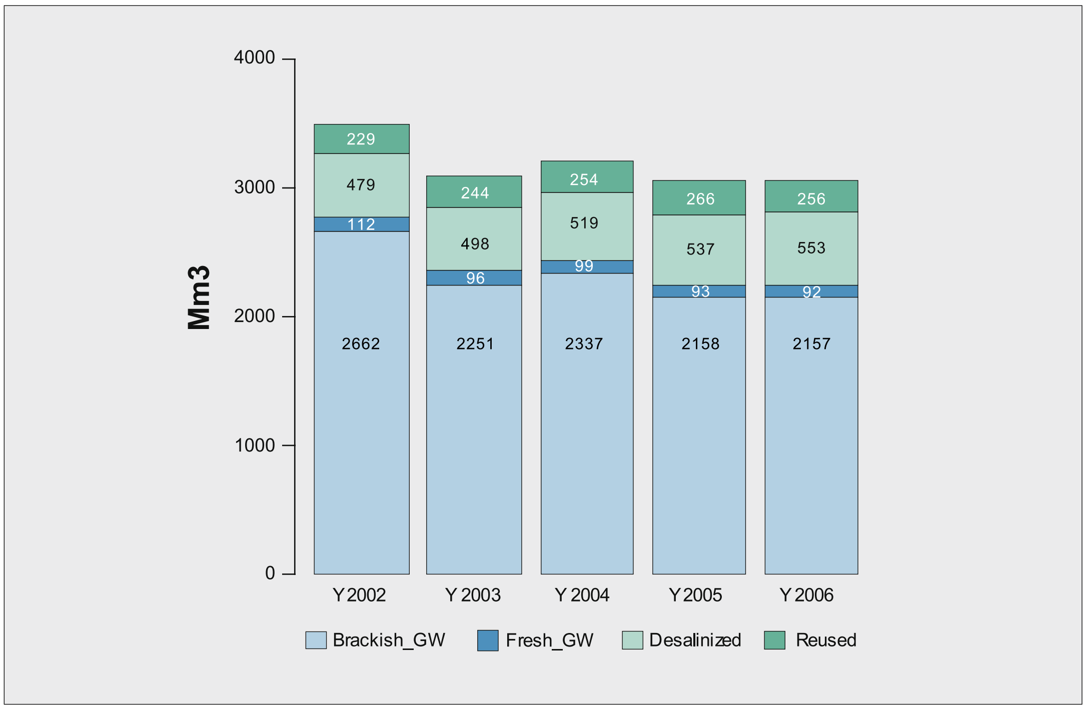
Figure 4-6 shows that WEAP allocated about 78% of the total delivered water supply from brackish groundwater sources, 3% from fresh groundwater, and 13% from desalinized water, while reused water made up about 6% of the total supply. These results are fairly consistent with the supply make-up shown in Table 2.1. It is important to realize that the WEAP allocation algorithm is making the allocation "decision" from the various supply sources to the demand sites based on demand priorities and supply preferences made a-priori.

The WEAP-based, climatically driven water resources model of the ADE adequately reflects the spatially and temporally specific water supplies and demands. This model was used to simulate future water demands and supplies based on Scenarios and assumptions about future climate, population growth, per-capita water use, and sectoral demands. The Scenarios, assumptions, and results are described below.



Annual Demand

Figure 4-5. WEAP estimates of total annual water supply used to meet the demands.



Annual Supply Delivered by Source

Figure 4-6. WEAP model estimates of total annual demand (left axis) and potential evapotranspiration (solid line, right axis).

4.6. Scenarios and Key Assumptions

It is impossible to know definitely the path of economic growth, demographic changes, water use patterns and priorities, etc. throughout the ADE over the next 30 to 40 years. For this reason, the analyst must make assumptions regarding the future and then investigate what those assumptions might mean for the water supply and demand balance. In this study, these assumptions are bundled into a set of Scenarios that fall into three broad categories, labeled "Optimistic", "Pessimistic", and "Middle-of-The-Road". For each of these three broad Scenarios, we will make assumptions about the drivers of future water demand, including population growth rates, per-capita water use, and climate change. Accompanying these drivers are assumptions regarding future water use priorities such as possible reductions in agriculture and amenity watering, and future water supply sources such as new desalinization capacity or the development of strategic reserves through aquifer storage and recovery projects. These later assumptions will be referred to as "adaptation options", and will be included as part of our Scenarios, which are summarized in the scenario matrix of Table 4-8 (Page 113). The study horizon for our analysis is 2008 to 2050.

4.7. Developing Climate Change Scenarios

As explained previously, there is strong scientific consensus that the earth has been warming, that this warming is driven substantially by human emissions of greenhouse gases, and that warming will continue. Climate models project that temperatures will increase globally by 1 to 2°C in the next 20-60 years. The projections are fairly consistent for the next 20 years, with a 1°C increase, but exhibit larger uncertainty in the 40-year projections. Scientists agree on some of the important broad-scale features of the expected hydrologic changes, the most likely of which will be an increase in global average precipitation and evaporation as a direct consequence of warmer temperatures. Regional changes, however, are more uncertain and in fact could be quite different from region-to-region, with some place experiencing more and others less precipitation. Generally, Global Climate Models agree that the mid-latitudes and sub-tropics will be warmer.

Table 4-6. 5 GCM outputs projected maximum/ minimum changes.

Temperature	Precipitation
+1.7 to 2.7°C (2050)	-21% to +10% (2050)
+3.1 to 4.8 ° C (2100)	-38% to +18% (2100).

Climate Scenarios are rooted in downscaled General Circulation Models (GCM), which provided a maximum and minimum projected change in temperature & precipitation for Abu Dhabi in 2050 and 2100. Below, we report the projected maximum/minimum changes for 4 Scenarios (A1, A2, B1, and B2). For each of the 4 Scenarios (A1, A2, B1, and B2), the projected maximum/minimum changes are based on 5 GCM outputs (CCC196, CSI296, ECH496, GFDL90, and HAD2TR95) area as follows:

These projected climate changes are used as guidelines in the development climate change Scenarios that are used by the WEAP model to simulate ADE water supplies and demands. We developed three climate change sequences, given as time series of monthly mean air temperature and total monthly precipitation for the period 2005 through 2050. While GCMs are able to simulate large-scale climate features realistically, they typically exhibit biases at regional-scales. The regional biases are problematic for analysis of climate implications for hydrology and water resources (Maurer, 2007).

Recognizing the regional limitations of GCMs has led to the application of "downscaling" as a means of trying to understand how local scale processes, of greater interest to water resource planners, might respond to larger-scale weather and climate changes (Wilby et al., 2004). Regardless of the technical approach, the primary goal is to process or interpret the GCM output so that it reflects the large-scale features and temporal trends from the GCM simulation, but also the historical patterns of climate variables at the regional and local scale (Wood et al., 2004). Downscaling can produce more sub-regional detail and eliminate system biases between observed local climate and climate generated by GCMs. Downscaling does not necessarily provide more reliable information nor increase our confidence in a particular GCM scenario for climate change.

Downscaling techniques generally fall into several classes, including simulated (dynamical), statistical and bias-correction/disaggregation, and sensitivity methods. Dynamical downscaling involves the use of regional climate models run at a relatively high resolution over a limited area with boundary conditions (and sometimes interior domain information as well) prescribed from the lower resolution GCM. Statistical downscaling methods involve deriving statistical relationships between observed small-scale (often station level) variables and larger (GCM) scale variables, using analogue methods (circulation typing), regression analysis, or neural network methods (Mearns, 1999; Yates et al., 2003, Clark and Hay, 2004).

Our climate Scenarios are based on repeating the observed climate from 1994 through 2008, but then adding an absolute, random change in temperature (T' = dt + T) and a percent change in precipitation P' = dp*P to the historical record. This results in new time series of temperature and precipitation for the period 2008 through 2050, with changes in temperature and precipitation bound by the magnitude of the changes suggested by GCMs. These Scenarios are akin to a sensitivity analysis of climate change, as we are assuming that the climate of the past repeats itself into the future, with a predefined, albeit random, change in temperature and precipitation dictated by GCM results.

For the worst-case or pessimistic scenario, the climate models suggest a 2.7°C annual average warming and a 20% decrease in total annual precipitation, with the best-case or optimistic scenario includes a more modest 1.0°C warming and 10% increase in precipitation over the next 50 years. Note that because of the extreme aridity in the UAE, the optimistic scenario of a 10% increase in precipitation is practically insignificant, while a 20% decline in precipitation suggests that the ADE would continue to need to manage its water resources from the perspective of even greater aridity. No scenario suggests that the future climate change will mean increased renewable water supplies for the ADE.

Table 4-7. Summary of climate changes included in WEAP modeled scenarios.

	Climate Changes over 1961-90 baseline	
Climate Outcome	Temperature Change	Precipitation change
1) Optimistic	+ 1.7°C	+10%
2) Pessimistic	+ 2.7°C	-20%
3) Middle of the Road MOR)	+ 2.2°C	+5%

Climate change will likely have its most important impacts if there were substantial warming in the winter months, as the summers are already extremely warm and dry. Climate change could mean more winter season evaporative demands and thus more water demands for the domestic, amenity, and agricultural sectors. This sensitivity analysis was used to understand the response of the hydrologic system to a warmer climate, with particular emphasis on water demand.

In an effort to make the scenario analysis efficient and informative given the broad range of GCM results and the uncertainty in future socio-economic conditions, we developed three categorical Scenarios which attempt to bracket the range of possible future climate and socio-economic outcomes referred to as: Optimistic, Pessimistic, and Middle-of-the-Road. The Scenarios are explained in more detail in the following section but are summarized here by Table 4-7, and Figures 4-7 and 4-8.

In Figure 4-7, we graph the average monthly temperature for the Middle-of-the-Road (MOR) scenario for both the coastal (light blue) and interior (dark blue) areas. A 5-year moving average is included in the plot to demonstrate the embedded warming trend of about 2°C for this scenario. Figure 4-8 graphs precipitation trends for all Scenarios, including the "Optimistic", "Pessimistic" and "Middle-of-the-Road".

4.8. Summary of Modeled Scenarios

Using Optimistic, Pessimistic, and Middle-of-the-Road assumptions about future climate as

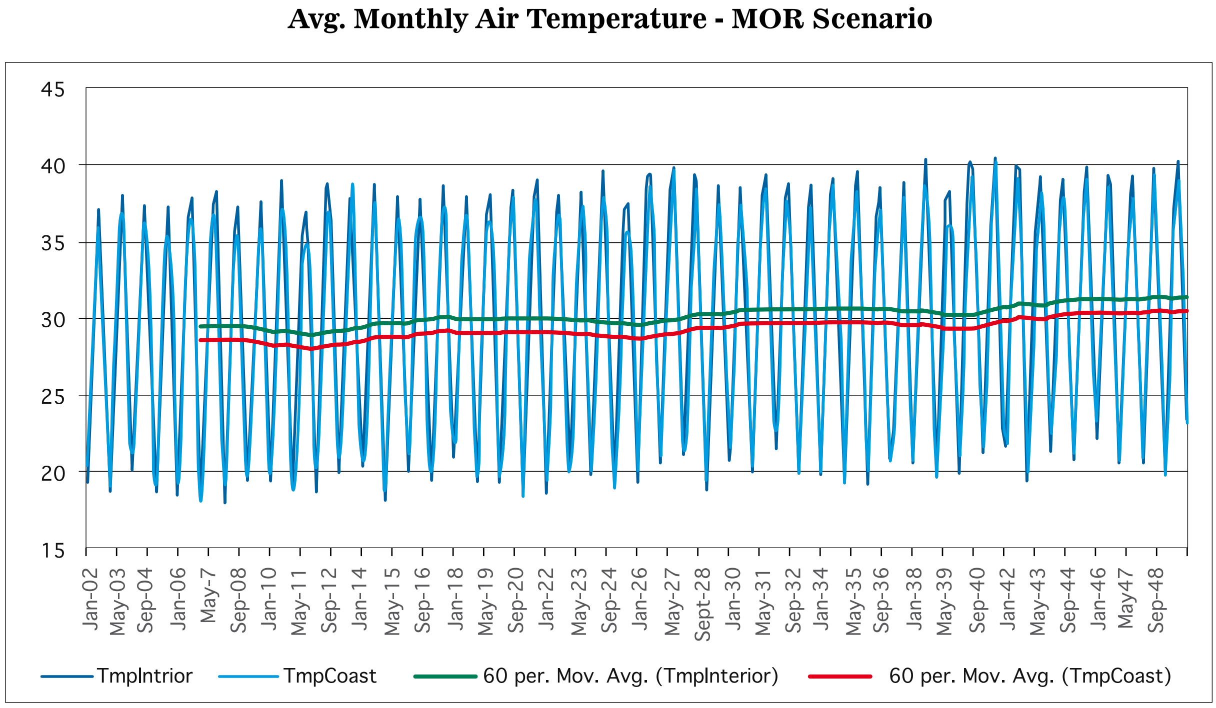


Figure 4-7. The average monthly temperature for the Middle-of-the-Road (MOR) Scenario.

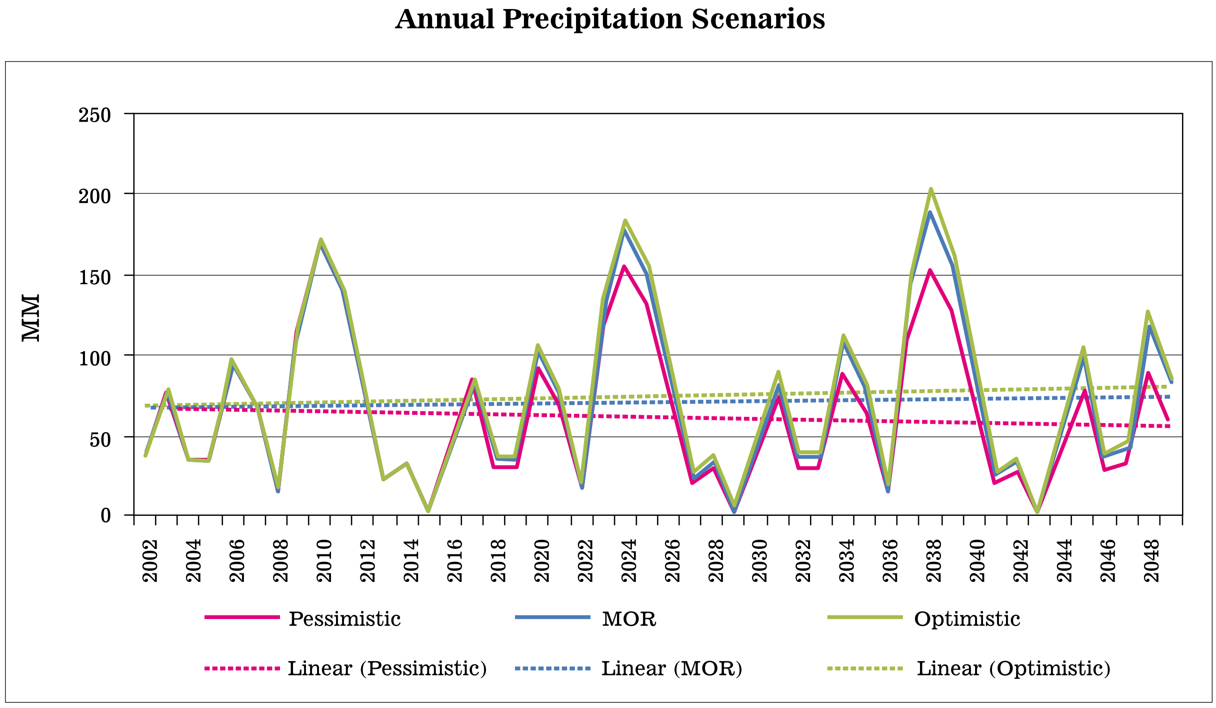


Figure 4-8. Total annual precipitation for the three climate change Scenarios.

well as water demand and population growth, we developed three unique Scenarios that were analyzed as part of this study to establish a range of plausible, future water balance conditions throughout the ADE including:

- **Optimistic** - lower population growth rates, improved per capita demand, moderate climate change
- **Pessimistic** - more warming and extreme climate change, high population, not as successful per capita-use reductions
- **Middle of the road** - 'business as usual' growth rates with 'expected' or average climate projection

In addition, we have developed and run five other Scenarios which tier off of the three baseline Scenarios, making assumptions about future adaptations to reduce water demand. The paragraphs below include descriptions of all the Scenarios that were created and analyzed as part of this study, as well as summaries in Table 4-8, Page. 113.

The Scenario drivers included assumptions about population growth (column 2), per capita demand (column 3), and climate change (column 4), and a set of adaptation options (column 5). For the Optimistic Scenario (1), we have assumed that a high population growth rate of 8% per annum continues until 2015, with the rate decreasing to 4% through 2025 and then to 2% for the remainder of the study period. This Scenario assumes that conservation programs are successful and per capita water demand for domestic, industrial, and garden watering is reduced to 800 l/cap/day by 2010 and then to 700 l/c/day by 2012 according to stated policy objects, with this demand rate continuing through the end of the study period. Note that this still is an extraordinary per-capita rate. The climate change assumptions are shown in column 3, with a 1.7°C warming through 2050 and a 10 increase in precipitation for the Optimistic Scenario.

Many if not all of the Emirate's water shortage issues are demand driven, so we have modeled adaptation strategies accordingly while operating in the context of possible climate changes by 2050. For example, given that the amenity, forestry, and agriculture sectors are very water use intensive, the question of long-term sustainability of groundwater resources is critical. Current irrigation practices in these sectors suggest that non-renewable groundwater supplies could be pumped dry through the next few decades. Much of the adaptation strategies modeled include decreasing amenity area and summer watering (when evaporation and temperature are highest), decrease forestry and agricultural area, layered on top of different suggested population growth rates and per capita consumption rates.

4.8.1. The Optimistic Scenarios (1, 1.1, and 1.2)

The Optimistic Scenarios embed lower population growth rates, more success in reducing per capita demand, and moderate future climate warming. The idea behind this Optimistic Scenario was to model stated policy objectives, optimistically assuming they will be successfully implemented, and then layering climate change on top of those assumptions.

Given the current rate of population growth and aggressive development policies, one could imagine a Scenario where population growth rates stay very high into the middle of the 21st century, but water conservation programs achieve some success in reducing per-capita demand, amenity water use is curtailed through fallowing of planted area and summer time irrigation is reduced as a strategy to just maintain green-space viability through the extreme summer heat. Reductions in agriculture and forestry water demand are achieved through reductions in planted area of 30% after 2015. Scenario 1.2 makes the same assumptions as Scenario 1.1, but without climate change to better illustrate the relative impact of climate on overall demand.

4.8.2. The Pessimistic Scenarios (2, 2.1, and 2.2)

The Pessimistic Scenarios assume greater climate warming, high population growth rates, and marginally successful per capita-use reductions. For the Pessimistic Scenario (2), it was assumed that population growth continues at a rate of 8% per annum until 2015, tapering off to 6% thereafter. This Scenario

Table 4-8. Summary of scenarios used in Abu Dhabi Emirate climate change analysis.

Scenarios	Scenario Drivers			
	Annual Pop'n Growth Rate[1]	**Domestic Water Use (liters/cap/day)**	**Climate Change (2050)**	**Adaptation Options**
1) Optimistic	8,4,2% hi to 2015 med to 2025 and low to 2050	800 (by 2010) 700 (by 2012) [in line with stated policy objective]	+ 1.7°C over 1961-90 baseline, +10% precipitation over 1961-90 baseline	None
2) Pessimistic	8% to 2015, then 6% thereafter	1100 all years (behavior doesn>t change)	+ 2.7°C over 1961-90 baseline decline -20% precipitation over 1961-90 baseline	None
3) Middle of the Road (MOR)	8,6,4% hi to 2015 med to 2025 and low to 2050	1100 to 2015; 900 from 2015 through 2020 then 800 through 2050	+2.2°C over 1961-90 baseline +5% precipitation over 1961-90 baseline	None
1.1) Optimistic + reductions in amenity, forestry and ag water use	8,4,2% hi to 2015 med to 2025 and low to 2050	800 (by 2010) 700 (by 2012) [in line with stated policy objective]	+ 1.7°C over 1961-90 baseline, +10% precipitation over 1961-90 baseline	Decrease amenity area and summer watering by 20%; decrease forestry and agricultural area by 30% after 2015
1.2) Optimistic with adaptation, no climate change	8,4,2% hi to 2015 med to 2025 and low to 2050	800 (by 2010) 700 (by 2012) [in line with stated policy objective]	No warming No trend in precipitation	Decrease amenity area and summer watering by 20%; decrease forestry and agricultural area by 30% after 2015
2.1) Pessimistic + Municipal Demand Management, reductions in amenity, forestry and ag water use[2]	8% to 2015, then 6% thereafter	1100 to 2015; 900 from 2015 through 2020 then 800 through 2050	+ 2.7°C over 1961-90 baseline - 20% precipitation over 1961-90 baseline	Decrease amenity area and summer watering by 20%; decrease forestry and agricultural area by 30% after 2015
2.2) Pessimistic with adaptation, no climate change	8% to 2015, then 6% thereafter	800 (by 2010) 700 (by 2012)	No warming No trend in precipitation	Decrease amenity area and summer watering by 20%; decrease forestry and agricultural area by 30% after 2015
3.1) MOR with no climate change Reference Scenarios	8,6,4% hi to 2015 med to 2025 and low to 2050	1100 to 2015; 900 from 2015 through 2020 then 800 through 2050	No warming No trend in precipitation	None

Notes

* per-capita use is domestic, industrial, and outdoor uses by citizens.

** Per capita demands uses a factor of 2 to reflect industrial and outdoor uses. (e.g. 550 l/c/d * 2).

*** "Domestic water us when modelled in line with stated policy objective is not considered an adaptation strategy except for Scenario 2.1 where pessimistic population growth is counter balanced by suggested per capita reductions" also assumes that conservation programs are mostly unsuccessful in reducing per-capita demand. The climate change assumptions include a nearly 2.7°C warming by 2050 relative to the historic baseline, with the ADE becoming even more arid due to a 20% decline in annual average precipitation.

Scenario 2.1 assumes the same adaptations as Scenario 1.1 (reductions in amenity and agricultural water use), but differs from the optimistic baseline Scenario implying greater reductions in domestic water use. Scenario 2.2 tiers off Scenario 2.1 but without climate change to illustrate the relative impact of climate on demand.

4.8.3. The Middle of the Road Scenarios (3)

The Middle-of-the-Road (MOR) Scenario (3) assumes that population growth is high, but considerable measures are taken to reduce the recent high population growth, as rates quickly fall from 8% then 6% per annum, with a final rate of 4% through 2050. The climate change assumptions for the MOR Scenario include a 2.2°C warming through 2050 and a 5% increase in annual precipitation relative to the 1961-90 baseline. Scenario 3.1 tiers off of Scenario 3, but assumes no warming in order to assess the relative impact of climate change on water demand (see further explanation in the Reference Scenario).

4.8.4. The Reference Scenario (3.1)

To demonstrate the marginal impact that climate change has on water supply and demand relative to the other drivers of population growth, per-capita demand, and water use by the amenity, forestry, and agriculture sectors, Scenario 3.1 tiers off the MOR Scenario but assumes no future climate change. This final Scenario was also run, assuming no change in per-capita demand, no reductions in sectoral use, a continued population growth rate of 8%, and no climate change. With no assumptions about future conditions considered and current patterns of use and population growth assumed, this was referred to as the ‘reference’ Scenario and suggests an extreme future total water demand condition.

5. Results and Discussion

The climate change assumptions for the three main Scenarios are reflected in the previous section in Table 4-8, column 3. To remind you, over the 1961-1990 baseline, the optimistic climate change Scenario models a 1.7°C warming through 2050 and a 10 % increase in precipitation for the optimistic Scenario; the pessimistic Scenario models 2.7°C warming through 2050 and a 20 % decrease in precipitation; while the middle of the road (MOR) scenario models 2.2°C warming through 2050 and a 5% increase in precipitation. Many if not all of the Emirate's water shortage issues are demand driven, so we have modeled adaptation strategies accordingly while operating in the context of possible climate changes by 2050.

5.1. Water Demand

Figure 5-1 shows the total annual water demand projections for all Scenarios through the end of the simulation period (2050). The total water demand is computed as a requirement, but does not necessarily reflect the amount of water supplied to meet those demands. Total demand ranged from a low about 4,000 Mm^3 for the Optimistic Scenario with adaptation (2.1) to more than 18,000 Mm^3 for the Reference Scenario, where population growth, per-capita water use and amenity, forestry, and agriculture water use patterns remain at current levels through the full simulation period. While the Reference Scenario is highly unlikely, it does suggest an upper bound on future water needs if there were no policy interventions.

The Optimistic Scenario (1) suggests a future ADE population of nearly 7,000,000 by 2050, requiring more than 5,000 Mm3 of water annually. Despite reductions in per-capita water use assumed in the Optimistic Scenarios, overall water demand increases, driven by population growth in the M&I sector. The Optimistic Scenario with adaptation (1.1) suggests that future total water demand could be kept near current levels even with substantial population growth. Reductions in water demand from the three big outdoor users (agriculture, amenity and forests) saves more than 1,000 Mm^3 per year when compared to the Optimistic Scenarios without these adaptations. Future climate change in the Optimistic Scenarios results in a relatively small increase in water demand of about 3% by 2050 (1.2), and thus a comparison of all three Optimistic Scenarios suggests that societal adaptations to reducing water demand will likely be more important than future warming.

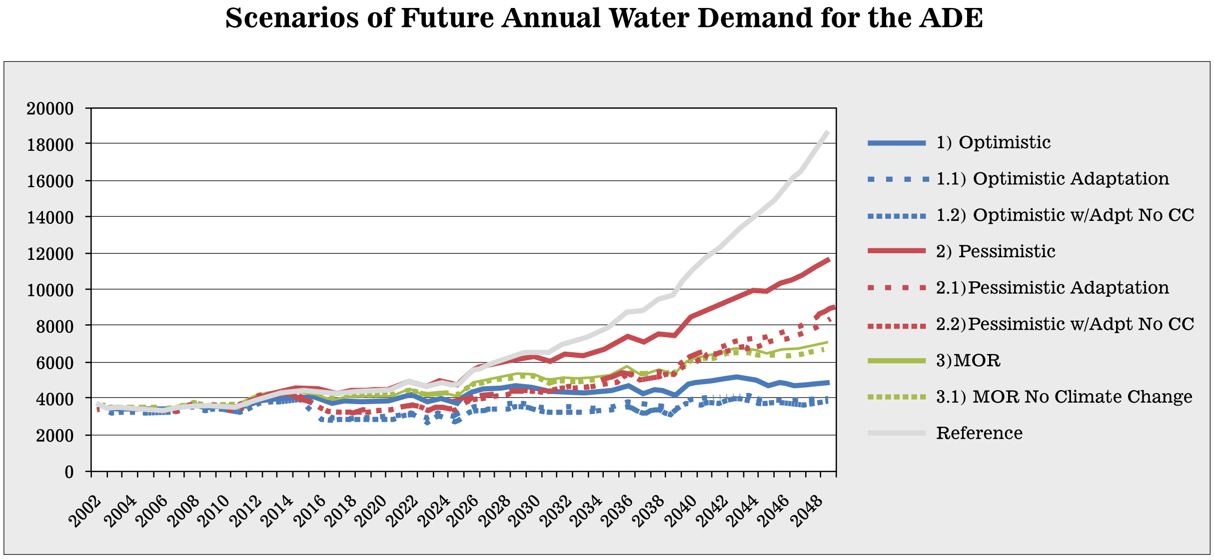


Figure 5-1. Total annual water demand estimates for the nine Scenarios.

Future climate change in the Optimistic Scenarios results in a relatively small increase in water demand of about 3% by 2050 (1.2), and thus a comparison of all three Optimistic Scenarios suggests that societal adaptations to reducing water demand will likely be more important than future climate warming. Figure 5-2 summarizes the demands for the four sectors for this Scenario. Note that the adaptation does lead to reductions in agriculture water demands. The plot includes the projection of future agriculture demands without climate change influences and suggests that warming increases agriculture demands by about 7% by the middle of the 21st century. Climate included changes in the forestry and agriculture demands are about 5% (not shown).

Population under the Pessimistic Scenario (2) grows to more than 20,000,000 by 2050, and combined with high per-capita use, M&I demands outpace the demands of the other three sectors (amenity, forestry, and agriculture), with total annual demand nearing 12,000 Mm3 by 2050! With the same assumptions about future population, Pessimistic Scenarios 2.1 and 2.2 include adaptations in the form of reduced per-capita demand and reductions in outdoor irrigation from the amenity, forestry and agriculture sectors. These adaptations reduce annual water demand to about 8,000 Mm^3, suggesting the importance that reductions in per-capita and other sectors water use would have on overall water demand throughout the ADE. Note the marginal impact of climate change on total water demand, with the increase in demand attributable to climate warming of about 3.7%.

For the MOR Scenario, population grows to more than 13,000,000 million, and while there are per-capita demand reductions, they are not substantial enough to reduce overall demand, which grows to about 7,000 Mm3 by 2050. With no adaptations in the other demand sectors (amenity, forestry, and agriculture) all water demand growth is attributable to M&I demand. Climate warming induces a 4.3% in total water demand, with increased, intensive outdoor water demand.

The Middle of the Road Scenario (3) puts the

Future Water Demand by Sector

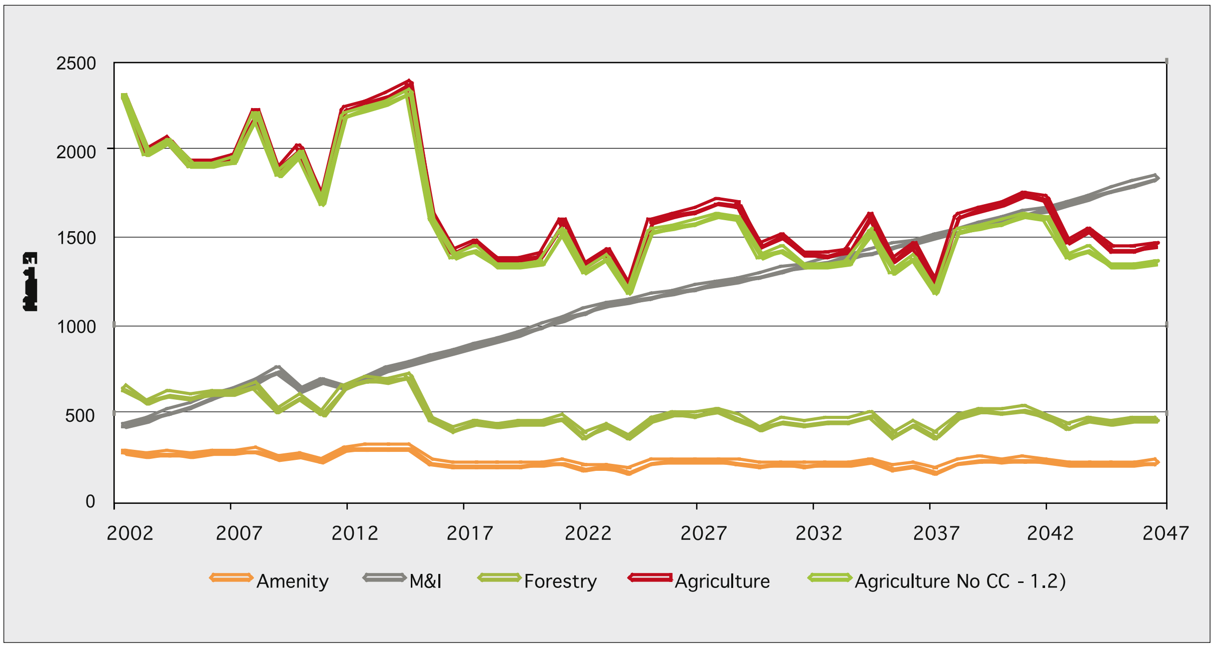


Figure 5-2. Water demands by sector for the Optimistic Scenario with Adaptation and climate change (1.1). The plot includes future agriculture water demands without climate change (1.2), suggesting an approximate 7% increase in agriculture demands due to climate warming alone by 2050.

total water demand estimate at about 7,000 Mm³, which is more than double the current estimate, with nearly all the demand growth occurring in the M&I sector. Comparing the two MOR Scenarios (with and without climate change) suggests that warming leads to a marginal increase in total water demand by 2050 of less than 5%.

Not surprising, all Scenarios suggest that future population, per-capita water use, and future decisions about outdoor irrigation of the agriculture, forestry and amenity sectors will most likely dominate total water demand. Climate change, manifesting itself primarily as climate warming, will likely increase demand by less than 5%, which is small relative to the changes from the other factors. The water demand estimates just presented are based on the assumption that there is water available to meet those demands, with the demands computed from assumptions that include population, per-capita use, climate, and the irrigation strategy for each outdoor use. Since WEAP tracks both the demand and supply sides of the water accounting ledger, we now investigate these Scenarios from the supply side of the equation.

5.2. Water Supply

In WEAP water demand is computed as a total requirement based on the given assumptions, but this requirement does not necessarily reflect the amount of water delivered to meet those demands. To supply the computed water needs, water infrastructure is represented in the model that includes desalinization plants, pumps, treatment facilities, groundwater aquifers with a assumed capacity, a distribution network, etc. Certainly in the UAE, water supply capacity and availability constrains the amount of water delivered to the various end-uses. Quantifying this "unmet demand" is of course subjective. For example, in the agriculture, amenity and forestry sector, the vegetation and crops that have been planted could most certainly use more water to be healthier and more vibrant, but in the hyper-arid environment of the ADE, it makes sense to deficit irrigate, as water is simply to precious (and expensive). In WEAP, the difference between the computed "demand" and the model based allocation of supply to meet those demands (e.g. "Supply Delivered") is referred to as "Unmet Demand" or the supply deficit (Figure 5-3). Since the M&I sector is nearly 100% reliant on desalinized

Future Water Supplies

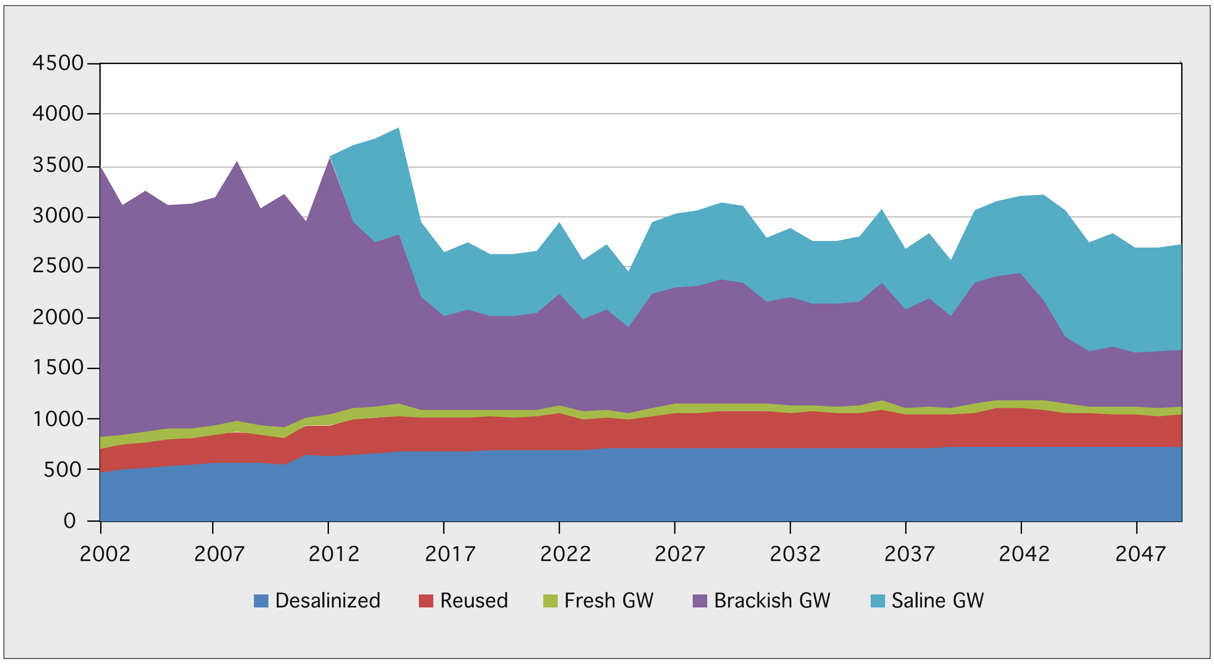


Figure 5-3. Supply allocation for Optimistic Scenario with Adaptation-

water to meet its demands, Unmet Demand for this sector can be thought of as "additional desalinization capacity needed". For the forestry and agriculture sector that rely on groundwater, "unmet demand" suggests the non-sustainability of the water use activity and/or the overdrafting of groundwater aquifers.

For the analysis of water supply, we will focus on the Optimistic with Adaptation (1.1) and the Pessimistic with Adaptation (2.1), where both include their respective climate change forcing. From this analysis, it is very apparent that unless future per-capita water use is not substantially curtailed, future demands will only be met through increased desalinization capacity, while the agriculture and forestry sectors would increasingly need to turn to more saline groundwater to meet irrigation requirements. Renewable freshwater resources in the eastern portion of the ADE are simply not substantial enough to be considered a major contributor to the future water resource portfolio on the ADE.

In Figure 5-3, desalinzed water supply grows up to its currently installed capacity but then capacity does not change over study horizon. Fresh groundwater resources remain constant. To continue to support irrigated agriculture where brackish groundwater sources are inadequate, irrigation requirements are made-up through pumping of saline groundwater supplies. Fresh groundwater supplies remain nearly constant, as they have been constrained to make up only 10% of the total groundwater supply in WEAP, otherwise the alluvial, freshwater aquifers in the western portion of the ADE would be quickly overdrafted. Once this 10% of demand is met through the fresh groundwater resource, brackish and then saline groundwater sources can supply the remaining irrigation needs.

WEAP assumes that all sources can adequately supply crop water requirements, as WEAP makes no distinction between water supply type, except the distinction of preference from which supply to draw from first (e.g. first brackish and if there is an inadequate supply, then draw from the saline groundwater). The supply allocation for the Pessimistic with Adaptation (2.1) Scenario is nearly identical to Scenario 1.1 because we have constrained supply to current levels (e.g. no change in desalinized water or waste water treatment expansion).

Figure 5.4 shows the estimated unmet demands

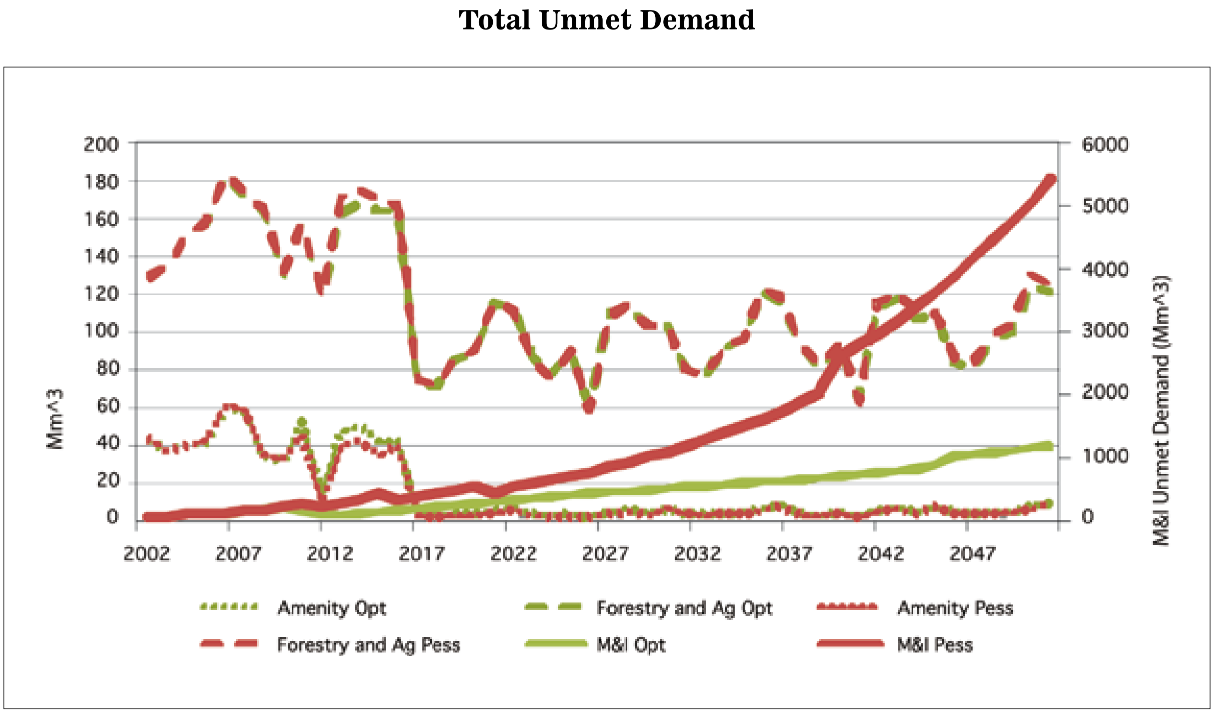


Figure 5-4. Total unmet demand for the Optimistic and Pessimistic Scenarios with Adaptation.

for the Optimistic and Pessimistic Scenarios with Adaptation (1.2 and 2.2, respectively). Both Scenarios suggest substantial unmet demand for the M&I sector, which can be used to quantify the amount of desalinization capacity that would be necessary to meet future demands. These Scenarios imply a need for additional desalinization capacity of more than 5,000 Mm3 and 1,000 Mm3 for the pessimistic and optimistic Scenarios, respectively.

Unmet demand in the amenity sector drops to near zero after 2016 in response to the reductions in summer-time irrigation and reductions in planted area. While there is less shortage in the agriculture and forestry sector, demands still go unmet. Renewable freshwater resources in the eastern portion of the ADE are simply not substantial enough to be considered a major contributor to the current or future water resource portfolio on the ADE. The only way to continue to supply irrigation water to the agriculture and forestry sector at current levels would be to increase the use of more saline groundwater or perhaps bank unused, desalinized water that would normally be wasted to the ocean in an aquifer storage and recovery (ASR) scheme in well suited alluvial deposits interspersed throughout the ADE.

5.3. Groundwater Supplies

In the WEAP model it is necessary to define the initial storage state of each of our aquifers at the start of the simulations. We have represented the alluvial fresh and brackish aquitards of both the eastern and western regions, and it is our understanding that different organization and research groups over the years have drawn different conclusions regarding the available volume of fresh and brackish groundwater. No one debates, however, that the groundwater being used, whether fresh or brackish is effectively being mined as there is no substantial, modern-day recharge of the groundwater systems of the ADE except for a small amount in the extreme eastern region, as groundwater throughflow from the Oman Mountains. Brooks et al reported a mean annual total of 31 Mm^3/yr estimate of groundwater entering the Emirate as groundwater, with the largest contribution occurring within Wadi Dank catchment, benefiting the area around Al Quaa. Recall that the current water demand for the ADE is more than 3000 Mm3/yr, so only about 1% of current demand is supplied with a "renewable" supply.

Our analysis has assumed that for the year 2002, there is about 350 Bm3 of brackish and fresh

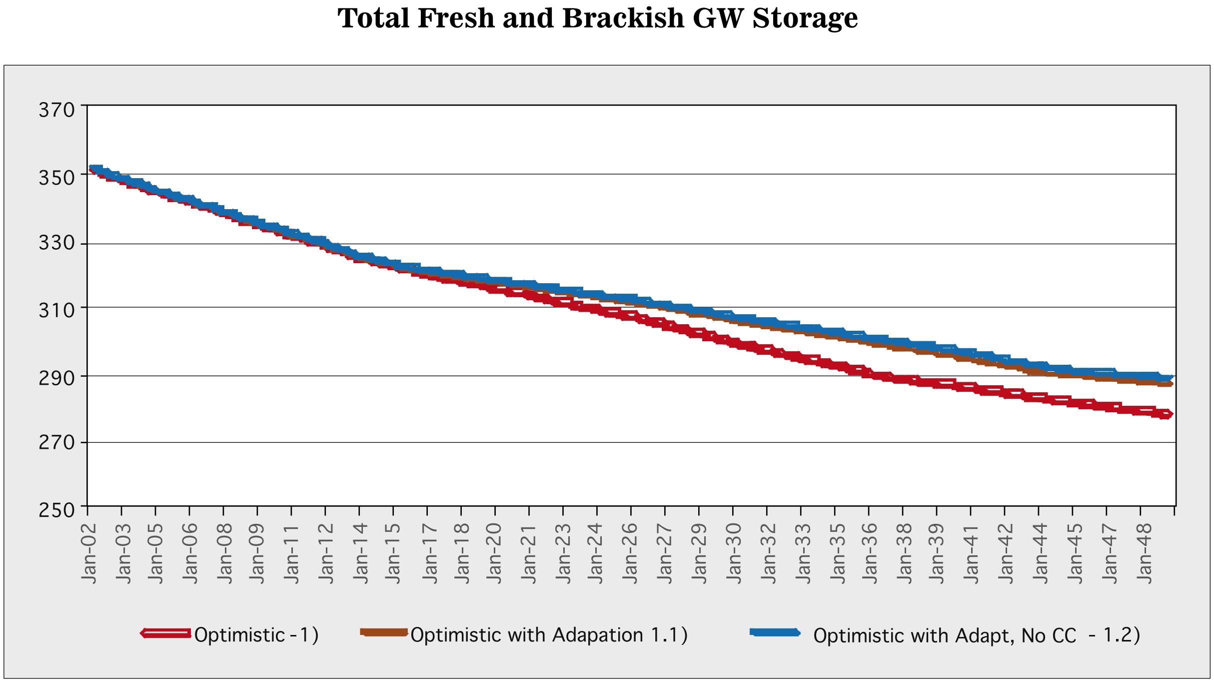

Total Fresh and Brackish GW Storage

Figure 5-5. Fresh and brackish groundwater storage over the study horizon for all three Optimistic Scenarios.

groundwater available, excluding an assumed fresh groundwater source in the western region of the country, near Liwa and Madinat Zayed. This number is higher than the estimate reported in Table 2.1, but research by GTZ suggests a substantial freshwater lens in the western region that is partially taken to account here. Future analysis could, of course, modify this assumption. Brooks et al. note that "the GWRP calculated a total groundwater reserve of 253 Km^3 (7% fresh, 93% brackish) and the GWAP total estimate of 640 Km^3 (2.6 % fresh, 18.1 % brackish, 79.4% saline) is much larger since groundwater of salinity of up to 100,000 mg/l TDS was included, whereas the GWRP included groundwater with less than 15,000 mg/l TDS". The GWRP assessment (USGS, 1996) projects that the fresh and brackish groundwater resources will be depleted in 50 years at current groundwater abstraction rates. Their analysis does not include the freshwater sources in the western region. Given our initial estimate of fresh and brackish groundwater, these resources would be depleted in about 150 years given current extraction rate from the agriculture and forestry sectors of about 2,500 Mm^3/year. This variance highlights the importance of the assumptions regarding the current fresh and brackish groundwater supplies in determining their long-term availability.

Figure 5-5 shows the total storage of the fresh and brackish groundwater for the three Optimistic Scenarios. In the analysis, only the agriculture and forestry sectors are depending on groundwater as their supply source. Interestingly, the relative difference between the Optimistic Scenario with adaptation and No Climate change (1.1) and the same Scenario that assumes no climate change (1.2) are only slightly different, suggesting the marginal impact that climate change would have on groundwater resources. The Optimistic Scenarios (1) does not include any reductions in agriculture or forestry demand over the study horizon and also imposes the moderate climate change forcing. However, as was just stated, the relative impact of climate change on groundwater storage is quite small, so all of the decline in groundwater storage is attributable to the continued high demand from the agricultural and forestry sectors. Since the Pessimistic Scenario is really only concerned with growth in the urban sector, the groundwater storage results for all three of those Scenarios are nearly identical to the Optimistic Scenarios results just presented.

5.4. Adaptation and Mitigation to Climate Change: Hand-in-Hand

The analysis just presented suggests the likely range that climate change and other socio-economic factors will have on the water supply-demand balance in the ADE. Given the current state-of-the science with regards to future climate, the analysis reports assumptions about future per-capita demand and population growth, and the priorities and policies associated with agricultural production and development will overwhelm the impacts of climate change on the water resources sector. While this likely the case, the analysis drives home the point that serious consideration should be given to the long-term goals and sustainability of the agriculture and forestry sectors. If these sectors continue to use water at their current rate, they will continue to strain a limited resource. Climate change will only hasten that position.

On the M&I side, "if freshwater supply has to be replaced by desalinated water due to climate change, then the cost of climate change includes the average cost of desalination, which is currently around US\$1.00/m^3 for seawater and US\$0.60/m3 for brackish water (Zhou and Tol, 2005). The cost for freshwater chlorination is approximately US\$0.02/m^3" (IPCC SRES, 2008). Water conservation will be needed to avoid the continued expansion of desalinization capacity, since increased dependence on desalinized water is sub-optimal.

Increasing desalinization capacity would seem to be a quick and easy adaptation to future demand, but it does not come without a cost from both a financial and environmental perspective. Increasing, to achieve water resource reliability, the water resources management strategy has essentially been in investing in more energy to produce more water. But this option must acknowledge that desalinization and the distribution of water accounts for a significant share of total energy consumption, as power plant emissions account for a significant share of Green House Gases (GHGs). Desalinization is not a "Green" solution. Moreover, the latest report of the IPCC holds out hope that global warming can indeed be mitigated through GHG reductions. The key for sustainable adaptation to climate change for the ADE should fully incorporate the objective of reducing their overall GHG emissions (i.e., reducing their "carbon footprint") as an additional objective within their long-range water resource planning strategy. Thus adaptation to climate change and mitigation of climate change must go hand-in-hand. Perhaps the rising cost of electric power will motivate ADE natural resource planners to re-examine their long-range objectives, particularly in the forestry and agricultural sectors, and continue to encourage water conservation. Likewise, the ADE is awash in renewable energy potential through solar or wind-powered pumping, that would be both fuel cost savings and would avoid GHG emissions. The challenge is to integrate such strategies within the water resource planning process to produce the best operating outcomes for the system as a whole in terms of cost, reliability and social/environmental consequences.

6. Conclusions

Figure 6-1 summarizes the current average annual water demand estimates (2003 through 2008), and for four future Scenarios, averaged over 2045 through 2050. A comparison of the Optimistic and Pessimistic Scenarios highlights the need to curtail per-capita use in the M&I sector. The Optimistic Scenarios indicate increases in water use driven primarily by the M&I sectors, but also points to the fact that reductions in the agriculture and forestry sectors could keep future water use at near current levels. Without strong reductions in per-capita water use and reductions in outdoor irrigation in the forestry and agriculture sectors, the Pessimistic Scenarios suggest that future water demand could jump nearly three-fold by 2050, even with reductions in the agriculture and forestry sectors. While some gains could be made in reducing demands in the amenity sector, this sectors water use relative to the others becomes even smaller by 2050.

Given that the amenity, forestry, and agriculture sectors are very water use intensive, the question of long-term sustainability of groundwater resources is critical. Current irrigation practices in these sectors suggest that non-renewable groundwater supplies could be pumped dry through the next few decades. To reduce the rate of groundwater depletion, the agriculture sector could consider adaptations such as maintaining the culturally important date palm orchards and keeping some Rhodes grass for livestock feed, but fallowing field crops. The forestry sector could realize substantial reductions in a real extent of irrigated trees, with the sector focusing on those stands with the highest aesthetic and social service (e.g. trees near public spaces and those close to roadways). For the amenity sector, there could there be substantial reductions in green space watering during the summer months, and the planting of species that can tolerate longer spells or go dormant without water.

While the Arabian Gulf seems to be a source of unlimited water, pollution by land-based activity could increasingly impair the quality of coastal water bodies that serve as feedwater for desalination plants. 'Hot spots' of marine pollution are typically near centers of more intense human activity such as the cities, harbors and industrial areas of the ADE, which are also the areas where desalinated water is most needed for socio-economic development. Desalinization has been proven to be technically

Total Water Demand- 2045 - 2050 Average

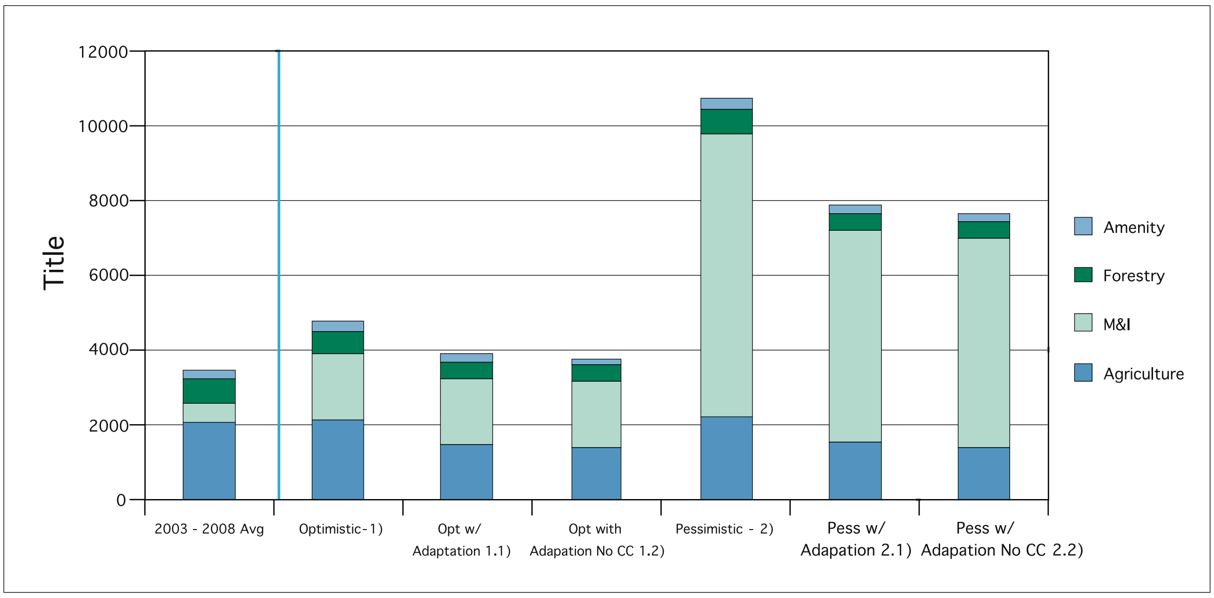


Figure 6-1. Summary of total water demand for the Optimistic and Pessimistic Scenarios, compared with simulated current water demands averaged over the period 2003 through 2005.

Table 6-1. Adaptation options for water supply and demand.

Supply-side	Demand-side
Prospecting and extraction of groundwater	Improvement of water-use efficiency by recycling water
Increasing storage capacity by building reservoirs and dams	Reduction in water demand for irrigation by changing the cropping calendar, crop mix, irrigation method, and area planted
Desalination of sea water	Reduction in water demand for irrigation by importing agricultural products, i.e., virtual water
Expansion of rain-water storage	Promotion of indigenous practices for sustainable water use
Removal of invasive non-native vegetation from riparian areas	Expanded use of water markets to reallocate water to highly valued uses
Water transfer	Expanded use of economic incentives including metering and pricing to encourage water conservation

feasible, but it is expensive from cost, energy, and ecological perspectives. The process of desalination is not environmentally friendly and seawater desalination plants also contribute to the wastewater discharges that affect coastal water quality. This is mostly due to the highly saline brine that is emitted into the sea, which may have higher temperatures, contain residual chemicals from the pretreatment process, heavy metals from corrosion or intermittently used cleaning agents. The effluent from desalination plants is a multi-component waste, with multiple effects on water, sediment and marine organisms. It therefore affects the quality of the resource it depends on. Table 6-1 suggests some general adaptation strategies that have been identified by Working Group II of the IPCC in the Fourth Assessment Report (IPCC, 2007).

The challenge, however, is that demand-side management options may lack practical effectiveness because they rely on the cumulative actions of individuals. On the M&I side, public education of water seems paramount to achieve the kinds of per-capita water use rates that are comparable to other countries of the world.

Supply-side options generally involve increases in storage capacity or abstraction from water courses and therefore may have adverse environmental consequences. Demand-side options may lack practical effectiveness because they rely on the cumulative actions of individuals. Some options may be inconsistent with mitigation measures because they involve high energy consumption, e.g., desalination, pumping, and have so far been implemented infrequently. Climate change may be only one of many drivers affecting strategies and investment plans (and it may not be the most important one over the short-term planning horizon), and partly due to uncertainty in projections of future hydrological changes. (IPCC SR Water, June 2008)

Practices that increase the productivity of irrigation water use – defined as crop output per unit water use – may provide significant adaptation potential for all land production systems under future climate change (as well as in the instance of heightened agricultural or domestic demand). At the same time, improvements in irrigation efficiency are critical to ensure the availability of water both for food production and for competing human and environmental needs (IPCC, 2007).

There is high confidence that adaptation can reduce vulnerability, especially in the short term. Water management in the face of climate change therefore needs to adopt a scenario-based approach (Beuhler, 2003; Simonovic and Li, 2003) as we have in our study. This is being used in practice in countries such as the UK (Arnell and Delaney, 2006) and Australia (Dessai et al., 2005). A second approach to coping with uncertainty, referred to as 'adaptive management' (Stakhiv, 1998), involves the increased use of water management measures that are relatively robust to uncertainty. Integrated water resources management should be an instrument to explore adaptation measures to climate change, but so far it is in its infancy (IPCC SR, 2008).

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Annex 1: Data sources and key assumptions

Spatial Data Sources And Assumptions

Figure A1-1 is a general overview of the country, including elevation data, Emirate capital city points, and three regions used in discussion used throughout the report as based on a delineation in an existing Environment Agency (EA) Reports[1]. We brought these EA maps as .pdfs into GIS, geo-referenced them, and then created a separate 'regional' file for use when calculating hectares per region of irrigated areas.

Figure A1-2 conveys the Abu Dhabi Emirate, alone, a data layer that also includes the previously mentioned regional divisions within the Emirate. It also includes a simplified depiction of the irrigated areas, farms, and forests layers provided by the Environment Agency.

Figure A1-3 is a map from the Environment Agency. We used this as a base for placing Desalination Plants and Waste Water Treatment Plants (WWTPs) in our WEAP schematic. The map can be found in an existing Environment Agency (EA) Report (Brook, n.d.).

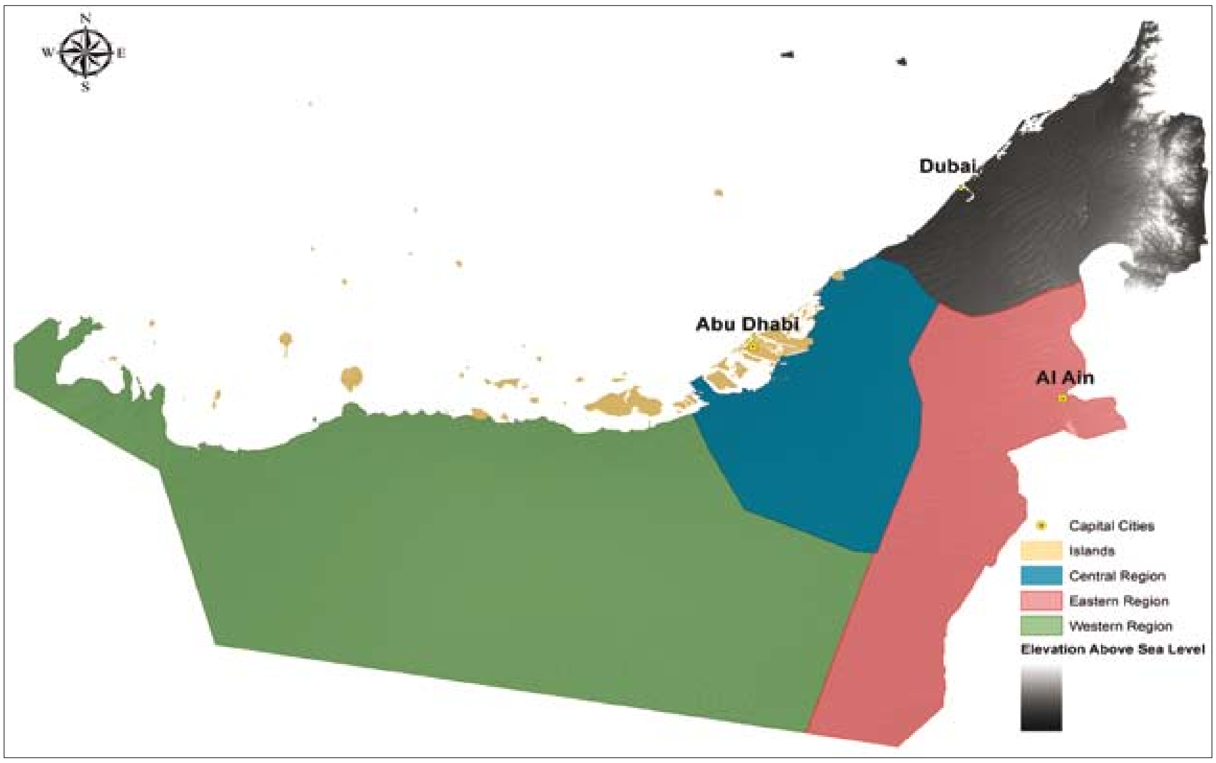

Figure A1-1. Overview Map

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[1] Combined from Figure 31:Location of water sources and users in Abu Dhabi Emirate (2003) [Brook et al., 2005], and Figure 1: General Location Map for the Study Area [Dawoud et al.,] An ArcGIS Database for Water Supply/Demand Modeling and Management in Abu Dhabi Emirate, UAE

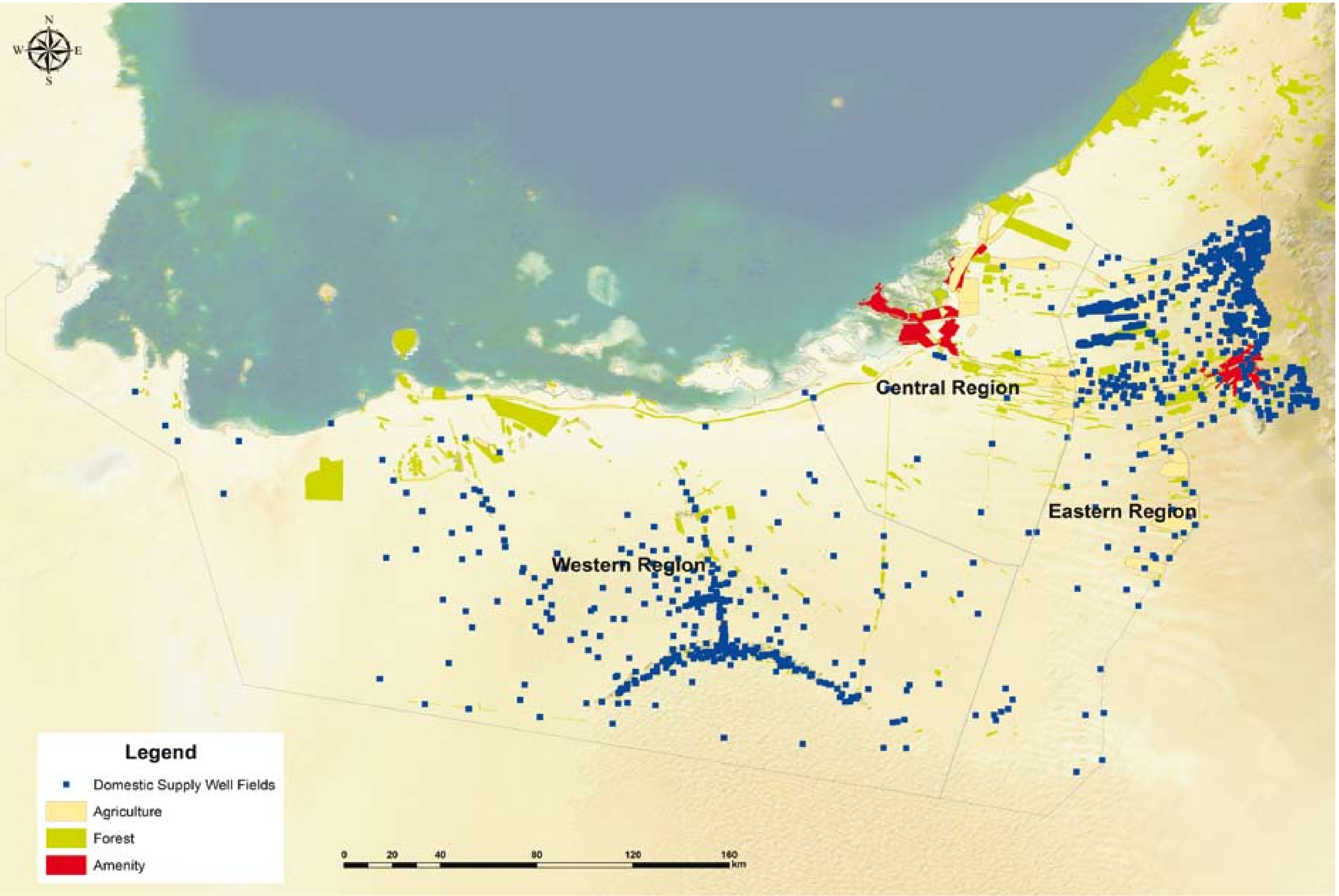


Figure A1-2. Map of Abu Dhabi key Water Supply / Demand

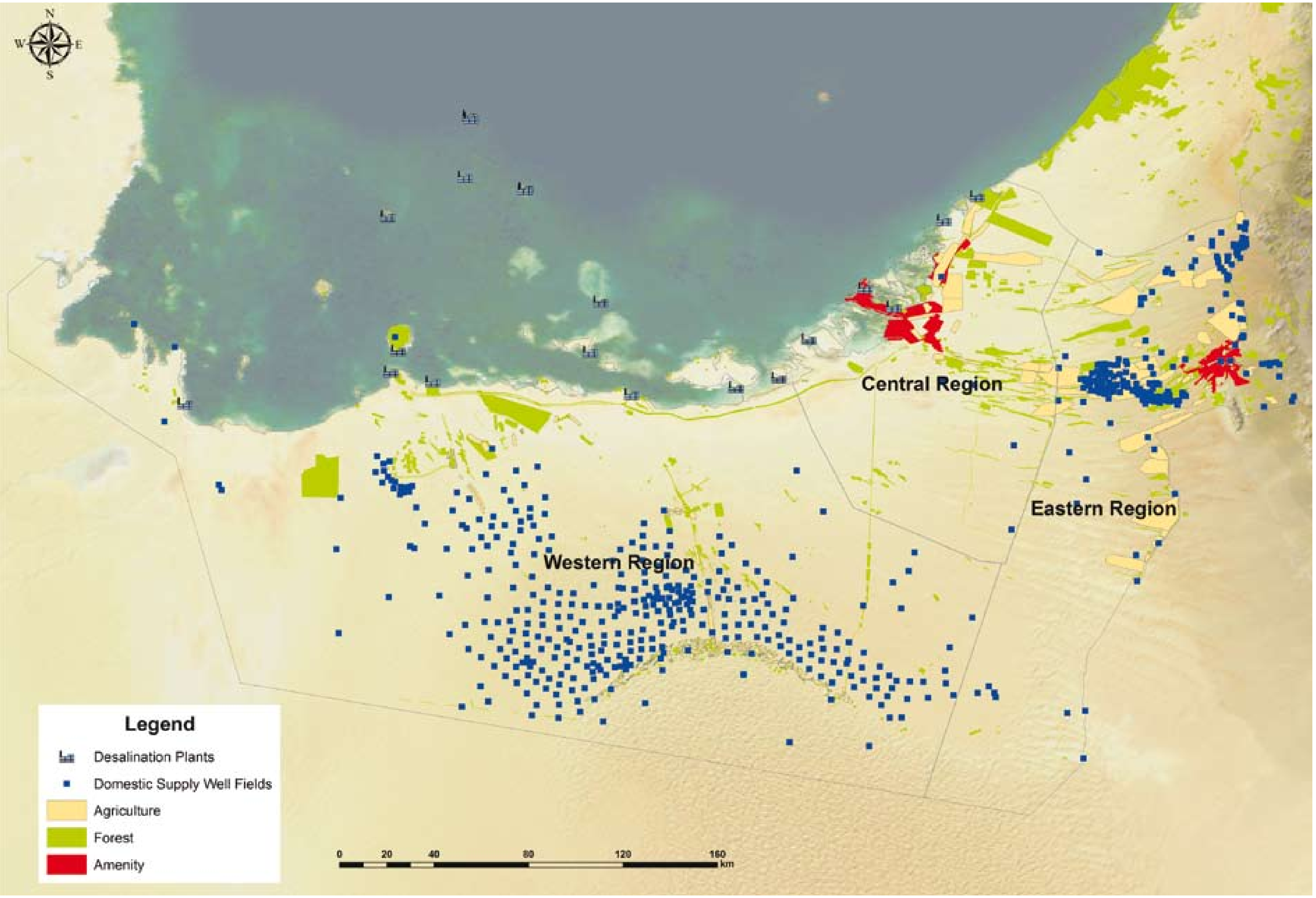


Figure A1-3. Sources and Users of Water in Abu Dhabi Emirate.

Data Sources And Assumptions

We relied predominantly on the data provided to by the Environment Agency. Including the following spreadsheets (See table):

- 2002 water resources statistics
- 2003 water resources statistics
- 2006water resources statistics-English
- Additionally, water resource-specific spreadsheets on Desalination and Wastewater Treatment Facilities, e.g. 'Water Information of Existing Desalination Plants in Abu Dhabi Emirate' from AADC Wellfields 2005.xcl

These are summarized in the tables bellow.

Table A1-1. Abu Dhabi Emirate groundwater reserves estimate from GWAP (GTZ, 2005a).

	Volume of Drainable Groundwater (km^3)			
	Total	**Fresh**	**Brackish**	**Saline**
Upper Aquifer (West)	221	12.5	70	138.5
Shallow Aquifer (East)	58	4	10.25	43.8
Western Aquitard (WA)	326.7	0	9.9	316.8
Eastern Aquitard (UF)	35.2	0	25.7	9.5
Sum (km^3)	640.9	16.5	115.8	508.6
Percentage of Total GW:	100.0%	2.6%	18.1%	79.4%
Sum West (km^3)	547.7	12.5	79.9	455.3
Percent West	85.5%	75.8%	69.0%	89.5%
Sum East (km^3)	93.2	4.0	35.9	53.3
Percent East	14.5%	24.2%	31.0%	10.5%

Table A1-2. Demand site assumptions.

DEMAND SITES	City Name	Population (2001) Growth(Key\Annual Population Growth Rate[%]/100)	Transmission Link à	Return Flow à
Central/East	Abu Dhabi	527000	Um Al Naar Desal Taweelah Desal Mirfa Desal	Mafraq WWTP
West	Madinat Zayed settlements	17869	Mirfa Desal	Madinat Zayed WWTP
East	Al Ain	328000	Taweelah Desal Qidfa_Fujirah Desal	Al Ain WWTP
East	Khazna	102500	Eastern Aquifer (BR) Um Al Naar Desal	Al Khatim/Al Khazna WWTP
East	Swehan	102500	Eastern Aquifer (BR) Um Al Naar Desal	Three Northern WWTP
West	Ghayahti Sett.	11377	Shuweihat_Ruwais Desal Ghayahti WWTP	Ghayahti WWTP
West	Al Mirfa	12325	Mirfa Desal	Mirfa WWTP
West	Ruwais	19925	Shuweihat_Ruwais Desal	Ruwais
West	Islands	13768	Shuweihat_Ruwais Desal	Islands
West	Liwa Settlements	Other Western Pop'n 34456 Muzayrah 4147 Liwa 13799	Mirfa Desal	Liwa WWTP
East	Al Shoosh		Qidfa_Fujirah Desal Shallow East Aquifer (FR)	Three Northern WWTP

Table A1-3. Catchment site assumptions

CATCHMENTS[7]	Sub Sector	Area (Ha)	Transmission Link à	Return Flow à
Al Khanza Agriculture	Amenity		Al Khatim_AlKhazna WWTP	Eastern Aquifer (BR), Al Khazna Wadi
	Forests	15691.89*Key\Irrigation\Planted\Forests; 11000		
	Farms- Total	23000*Key\Irrigation\Planted\Farms; 34000		
	Farms- Rhodes Grass	40%	ShallowEast (FR)	
	Farms- Date Palms	25%	ShallowEast (BR)	
	Farms- Other	25%	ShallowEast (SA)	
	Farms- Fallow	10%		
Al Ain Irrigated Areas	Amenity	4652.77+551.55*Key\Irrigation\Planted\Amenity	Al Ain WWTP	Eastern Aquifer (FR), Al Khazna Wadi
	Forests	1735.9+9711.52*Key\Irrigation\Planted\Forests		
	Farms- total	4000.37*Key\Irrigation\Planted\Farms		
	Farms- Rhodes Grass	40%	Eastern Aquifer (BR)	
	Farms- Date Palms	25%	ShallowEast (FR)	
	Farms- Other	25%	ShallowEast (BR)	
	Farms- Fallow	10%	ShallowEast (SA)	
Abu Dhabi Irrigated Areas	Amenity	11000	Um Al Naar Desal	Al Wathba discharge
	Forests			
	Farms- total	3100		
	Farms- Rhodes Grass	40%		
	Farms- Date Palms	25%	Mafraq WWTP	
	Farms- Other	25%		
	Farms- Fallow	10%		
Al Shoosh Irrigated Areas	Amenity		ShallowEast (BR)	Eastern Aquifer (BR), Northern wadi
	Forests	12856.1*Key\Irrigation\Planted\Forests		
	Farms- Rhodes Grass			
	Farms- Date Palms		ShallowEast (FR)	
	Farms- Other			
	Farms- Fallow			
Madinat Zayed Irrigated Areas	Amenity		Western Aquifer (FR)	Madinat Zayed wadi
	Forests	43949*Key\Irrigation\Planted\Forests		
	Farms- total		Western Aquifer (BR)	
	Farms- Rhodes Grass	40%		
	Farms- Date Palms	25%		
	Farms- Other	25%	Western Aquifer (SA)	
	Farms- Fallow	10%		

Table A1-3. continued

CATCHMENTS[7]	Sub Sector	Area (Ha)	Transmission Link à	Return Flow à
Ghayathi Irrigated Areas	Amenity		Upper West (FR)	Ghayathi Wadi
	Forests	38999*Key\Irrigation\Planted\Forests		
	Farms- total			
	Farms- Rhodes Grass	40%	Upper West (BR)	
	Farms- Date Palms	25%		
	Farms- Other	25%	Upper West (SA)	
	Farms- Fallow	10%		
Wagan Qua Irrigated Areas	Amenity		Eastern Aquifer (FR)	Wadi Dank
	Forests	7186*Key\Irrigation\Planted\Forests		
	Farms- total	32000*Key\Irrigation\Planted\Farms		
	Farms- Rhodes Grass	40%	Eastern Aquifer (BR)	
	Farms- Date Palms	25%		
	Farms- Other	25%	Eastern Aquifer (SA)	
	Farms- Fallow	10%		
Shwaib, Hayer, Sweihan Irrigated Areas	Amenity		ShallowEast (BR)	Shallow East Aquifer (FR), Northern wadi
	Forests	15600*Key\Irrigation\Planted\Forests		
	Farms- total	19500*Key\Irrigation\Planted\Farms		
	Farms- Rhodes Grass	40%		
	Farms- Date Palms	25%	ShallowEast (FR)	
	Farms- Other	25%		
	Farms- Fallow	10%		
	Natural	3500 * 100 ; 3500 km2 * 100ha/1km^2		
Ghantoot Samba Irrigated Areas	Amenity		Taweelah Desal	Al Wathba Discharge
	Forests	5000*Key\Irrigation\Planted\Forests		
	Farms- total	3000 * Key\Irrigation\Planted\Farms		
	Farms- Rhodes Grass	40%		
	Farms- Date Palms	25%		
	Farms- Other	25%		
	Farms- Fallow	10%		
Al Wathba Forest		38999*Key\Irrigation\Planted\Forests	Um Al Naar Desal Mafraq WWTP	Al Wathba Discharge
Liwa- Hammim Irrigated	Amenity		Western Aquifer (FR)	Western Aquifer (SA), Liwa wadi
	Forests			
	Farms- total			
	Farms- Rhodes Grass	40%	Western Aquifer (BR)	
	Farms- Date Palms	25%		
	Farms- Other	25%	Western Aquifer (SA)	

Annex 2: Climate projections

GCM outputs for 2050 and 2100

The climate projections used in the Water Sector Report were based on a Climate Change Projections study that SEI prepared for the Climate Change Executive Committee of the UAE in April 2006. For that study, the authors used the climate projection tools MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) and SCENGEN (A Regional Climate SCENario GENerator) to establish the regional climate baseline (1960-1991) and project future regional temperature and rainfall. MAGICC and SCENGEN are coupled, interactive software tools that can be used to examine future climate change and its uncertainties at both the global-mean and regional-mean levels. The report provided a summary of climate change projections for selected urban areas of the UAE. The focus was on four climate indicators, as follows:

- average temperature and precipitation over the 1961-1990 period (annual and monthly)
- average temperature and precipitation for the year 1990 (annual and monthly)
- average temperature and precipitation under climate change conditions (annual and monthly values for the years 2050 and 2100)
- average change in temperature and precipitation under climate change conditions relative to the 1961-90 baseline (annual and monthly values for the years 2050 and 2100)

There are a total of 36 IPCC emission Scenarios included in MAGICC/SCENGEN See Table A2-1. These IPCC emission scenarios are grouped into four major categories, each with its own "storyline" of how global development paths could unfold and each with their resulting annual emission levels (IPCC, 2000). A brief overview of each Scenario storyline is as follows:

- **A1 storyline:** corresponds to a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. When considering non-fossil intensive scenario subgroups, future carbon emissions are among the midrange of the four storylines.
- **A2 storyline:** corresponds to a very heterogeneous world with a strong underlying theme of self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in a continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and not as fast-paced as in the other storylines. Future carbon emissions under this scenario are among the highest of the four storylines.
- **B1 storyline:** this corresponds to a convergent world in which global population peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of a widespread clean and resource-efficient technologies that lead to a reduction in energy and material use. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives. Future carbon emissions under this scenario are among the lowest of the four storylines.
- **B2 storyline:** corresponds to a world in

which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels. Future carbon emissions under this scenario are among the midrange of the four storylines.

Additionally, there are a total of 17 General Circulation Models (GCMs) included in MAGICC/SCENGEN. Each GCM represents the main components of the climate system in three dimensions as simulated in computer modeling experiments, yet are differentiated by a range of underlying assumptions they use. The models are named relative to the institution where the experiments have been conducted (e.g., HAD295 and HAD300 are GCMs developed at the Hadley Centre for Climate Prediction and Research, which is part of the Meteorological Office of the United Kingdom).

Table A2-1. Summary of 36 emission scenario and 17 GCM options.

IPCC Emission Scenario				
A1	A2	B1	B2	GCM
A1ASF	A2-ASF	BA-IMA	B2-MES	BMRC98
A1B-AIM	A2A1MI	B1AIM	B2AIM	CCC199
A1B-NEW	A2AIM	B1ASF	B2ASF	CCSR96
A1CAI	ASGIM	B1HIME	B2HIMI	CERF98
A1CME	A2MES	B1HIMI	B2IMA	CSI296
A1CMI	A2MIN	B1MES	B2MIN	CSM_98
A1FI-MI		B1MIN		ECH395
A1GAI		B1TME		ECH498
A1GME				GFDL90
A1IMA				GISS95
A1MES				HAD295
A1MIN				HAD300
A1T-MES				IAP_97
A1TAI				IMD_98
A1V1MI				MRI_96
A1V2MI				PCM_00
				WM_95

Each Scenario-GCM combination provides a different estimate of projected temperature and rainfall due to the fact that underlying assumptions are different. A driving concern in using MAGICC/SCENGEN results was to be able to adequately represent a plausible range for the UAE regarding future temperature and rainfall levels. For this reason, it was important that the analysis consider a sufficient number of Scenario-GCM combinations that could provide a robust and defensible indication of future climatic conditions. For this analysis, one Scenario from each of the four storylines was considered, and were each analyzed by the five different GCMs, as summarized in Table A2-2. Hence, the resulting scenario-GCM combinations come to a total of twenty.

The Scenario-GCM combinations can also be represented spatially using Geographic Information Systems (GIS) software. Below we include four maps depicting average change in temperature (AT) and precipitation (AP) across the country based on A1B-AIM-HAD295 Scenario-GCM outputs see Figures A2-1 to A2-4.

The results in the Tables A2-3 and A2-4 provide the maximum and minimum projected change in temperature & precipitation for Abu Dhabi city in 2050 and 2100 that our model was based upon. The projected maximum/minimum changes are for reported for the 4 scenarios (A1, A2, B1, and B2). For each of the 4 scenarios

Table A2-2. Emission scenarios and GCMs used for the UAE.

IPCC Emission Scenario				
A1	A2	B1	B2	GCM
A1B-AIM	A2-AIM	B1AIM	B2AIM	CCC199
				CSI296
				ECH498
				GFDL90
				HAD295

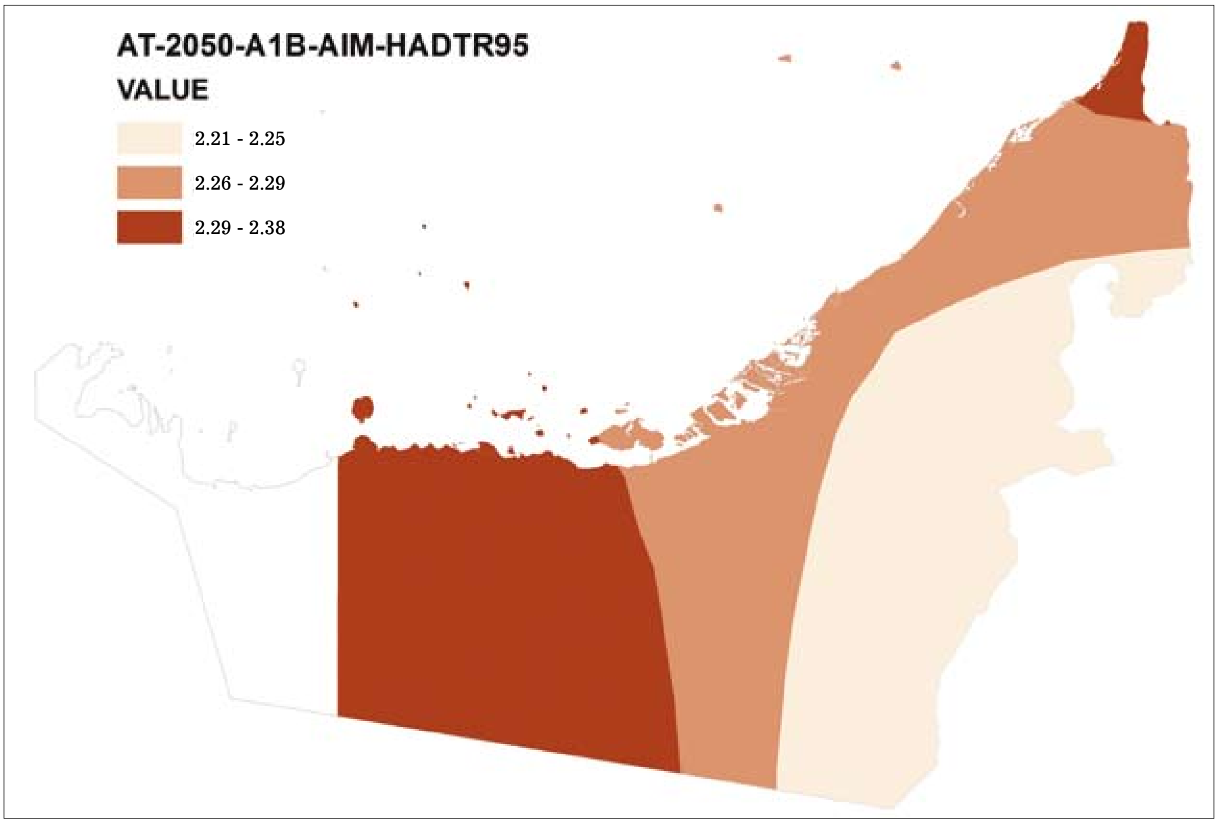


Figure A2-1. Temperature change (ºC) in 2050

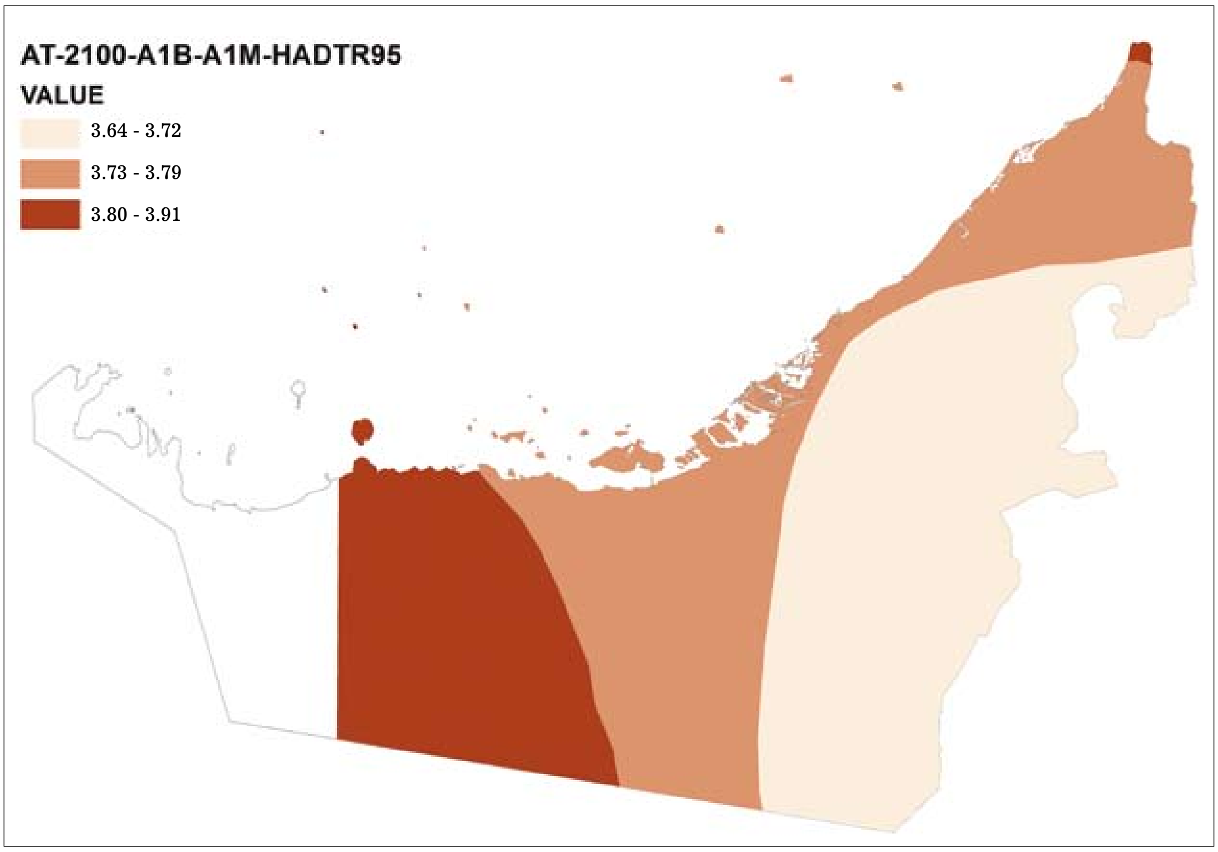


Figure A2-2. Temperature change (ºC) in 2100

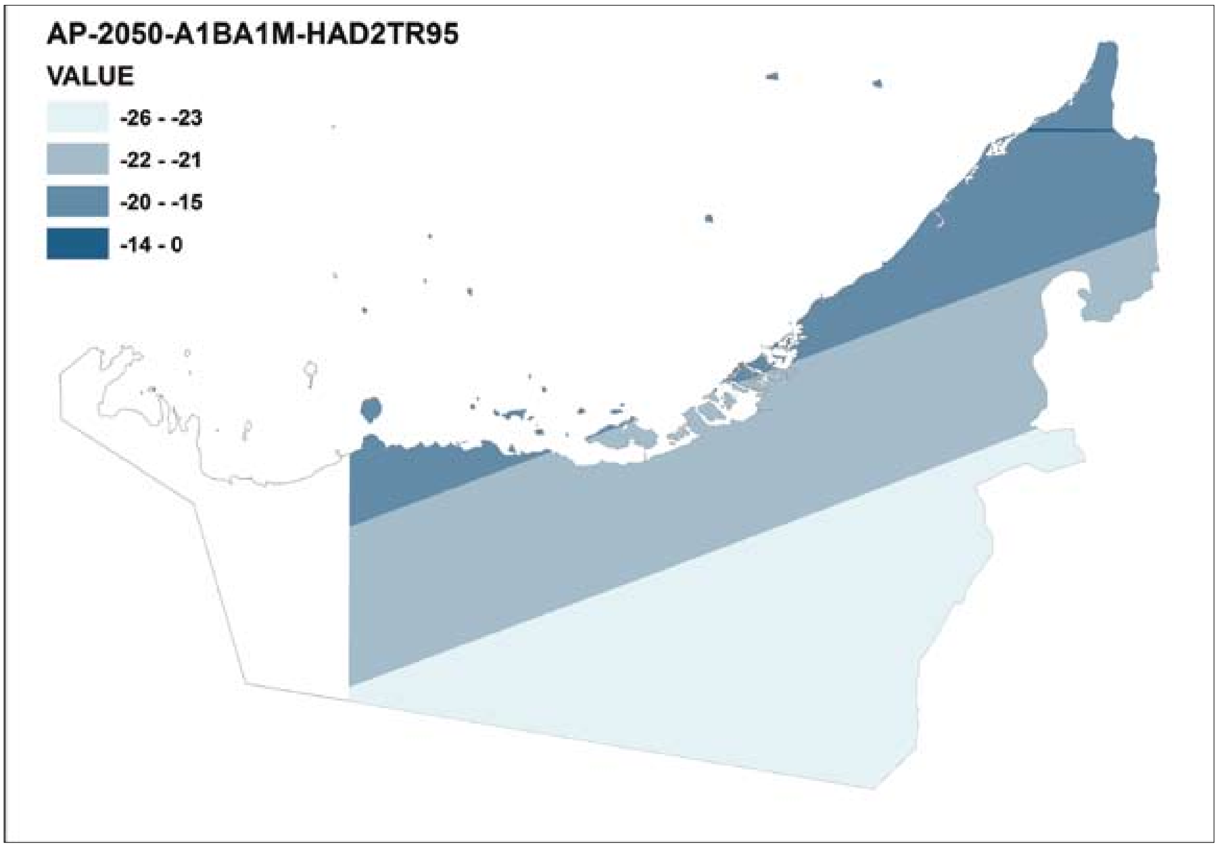


Figure A2-3. Precipitation change (ºC) in 2050

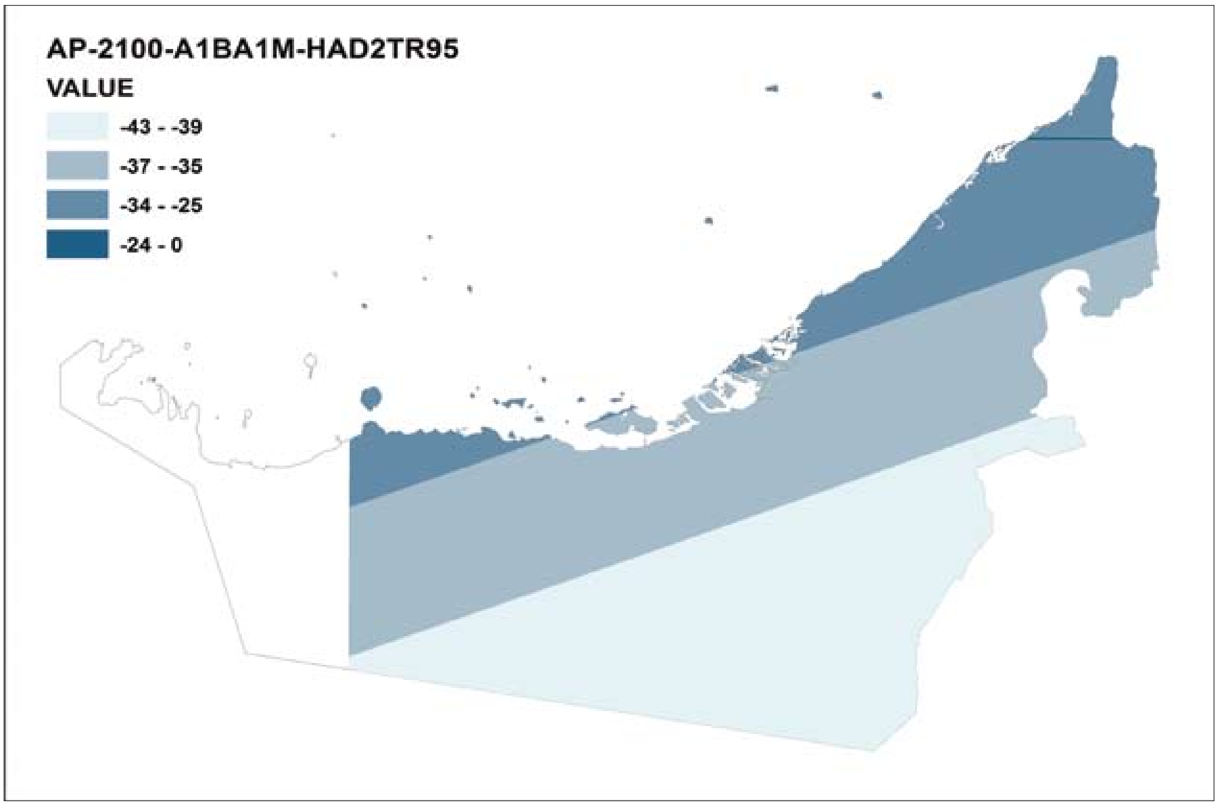


Figure A2-4. Precipitation change (ºC) in 2100

(A1, A2, B1, and B2), the projected maximum/minimum changes are based on 5 GCM outputs (CCC196, CSI296, ECH496, GFDL90, and HAD2TR95). [Maximum/minimum changes are yellow-shaded and dark blue font].

From these tables we derived two summary tables to capture first the range of potential changes, as suggested by the scenario-GCM combinations chosen and second, the average projected change based on the range.

Table A2-3. Annual average maximum change, 2050 and 2100.

	MAXIMUM PROJECTED CHANGES IN ABSOLUTE VALUES							
	Temperature (degrees C)				Precipitation (%)			
Year 2050	B2-AIM	B1-AIM	A2-AIM	A1B-AIM	A1B-AIM	A2-AIM	B1-AIM	B2-AIM
Abu Dhabi	2.57	2.46	2.73	2.90	11.25	10.57	9.53	9.94
Year 2100	Temperature (degrees C)				Precipitation (%)			
Abu Dhabi	4.73	3.50	6.02	4.79	18.55	23.29	13.53	18.32

Table A2-4. Annual average minimum change, 2050 and 2100.

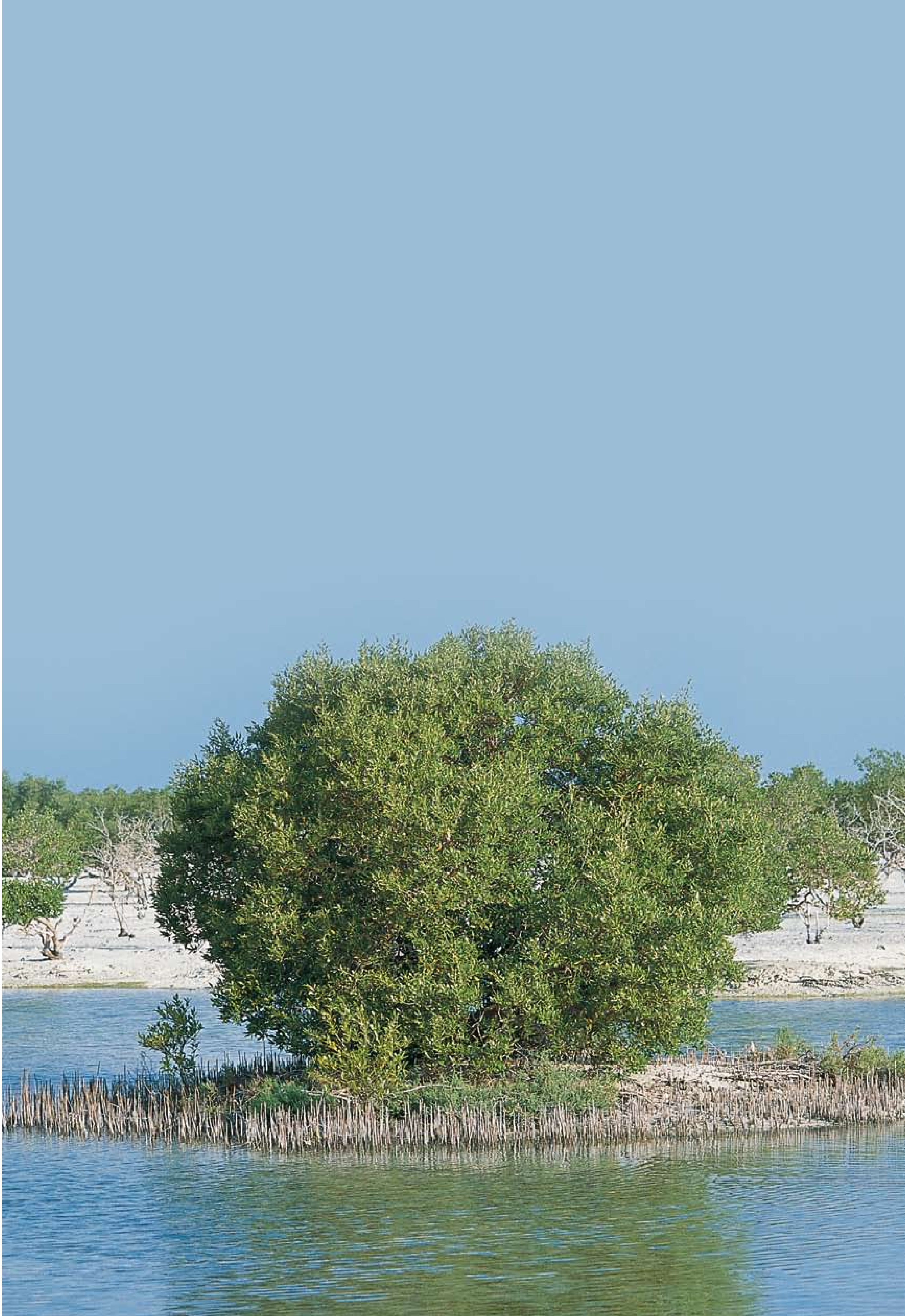
	MINIMUM PROJECTED CHANGES IN ABSOLUTE VALUES							
	Temperature (degrees C)				Precipitation (%)			
Year 2050	B2-AIM	B1-AIM	A2-AIM	A1B-AIM	A1B-AIM	A2-AIM	B1-AIM	B2-AIM
Abu Dhabi	1.68	1.61	1.78	1.90	-23.09	-21.71	-19.58	-20.41
Year 2100	Temperature (degrees C)				Precipitation (%)			
Abu Dhabi	3.10	2.28	3.93	3.13	-38.09	-47.81	-27.77	-37.61

Table A2-5. Summary of GCM Output Range for Abu Dhabi

Temperature	**Precipitation**
+1.74 to 2.67°C (2050)	-21.20% to +10.33% (2050)
+3.11 to 4.76 ° C (2100)	-37.82% to +18.42% (2100)

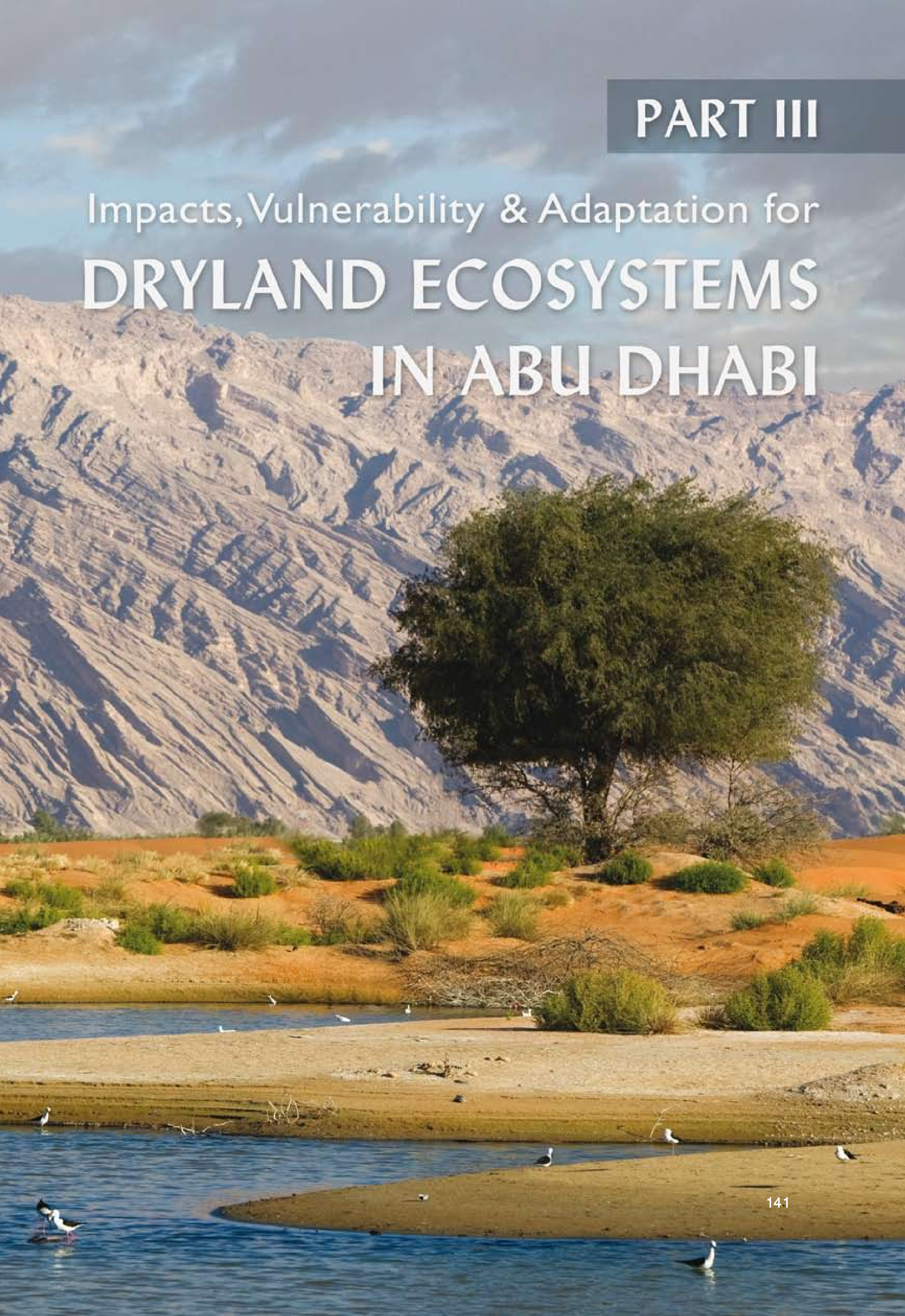
Table A2-6. Summary of climate changes included in WEAP modeled scenarios

	Climate Changes over 1961-90 baseline	
Climate Outcome	Temperature Change	Precipitation change
1) Optimistic	+ 1.7oC	+10%
2) Pessimistic	+ 2.7oC	-20%
3) Middle of the Road MOR)	+ 2.2oC	+5%



PART III

Impacts, Vulnerability & Adaptation for DRYLAND ECOSYSTEMS IN ABU DHABI



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List of Acronyms

Asl	Above sea level
CO_2	carbon dioxide
EN	endangered species
FAO	United Nations Food and Agricultural Organization
GCM	general circulation models
GEF	Global environment facility
GHG	green house gas (emissions)
GIS	Geographical Information System
Ha	hectare
IBAs	Important Bird Areas
IIED	International Institute for Environment and development
IPCC	Intergovernmental Panel on Climate Change
Km	kilomter
Km^2	square kilometer
MEA	Millennium Ecosystem Assessment
m	meters
mm	millimeter
NARS	National Agricultural Research Systems
NT	near-threatened species
PET	potential evapotranspiration
Ppm	parts per million
SRES	Special Report on Emissions Scenarios
UAE	United Arab Emirates
UKCIP	United Kingdom's Climate Impacts Programme
UNCDD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
VU	vulnerable species

1. Introduction

Abu Dhabi is one of seven emirates that together comprise the United Arab Emirates (UAE). The UAE has a total area of 83,600 km^2 (8,360,000 ha), with Abu Dhabi being the largest, occupying an area of 67,340 km^2 and representing 86.67% of the total UAE area. The UAE is situated in the Eastern corner of the Arabian Peninsula, between latitudes 22 degrees and 26.5 degrees north and longitudes 51 degrees and 56.5 degrees east. It is bounded by the Gulf of Oman to the East and the Persian Gulf to the North Sultanate of Oman and Saudi Arabia to the south, and Qatar and Saudi Arabia to the west.

The climate of the UAE is characterized by high temperatures (up to 49˚C in July), high humidity and low rainfall. The average, annual rainfall in the mountain region (140-200 mm) and along the east coast (100-140 mm) is generally higher compared to the gravel plains (100-120 mm), with the west coast receiving the lowest average of less than 60 mm (Boer 1997). The population of the UAE has been growing very fast from 2.41 million in 1995 to 3.77 in 2000 (Ministry of Planning, 2005)

The term drylands is used to define the hyper-arid, arid, semi-arid and dry subhumid ecosystems. Aridity zones as mostly used in the scientific literature are derived from the area's mean annual precipitation (p) and the mean potential evapotranspiration (PET), i.e. given as P/PET. This ratio is referred to as aridity index and is used to classify dry lands as hyper-arid (ratio less than 0.05), arid (0.05 to 0.20), semi-arid (0.20 to 0.50) and dry subhumid areas (0.50 to 0.65).

Drylands are particularly vulnerable to climate change because of their inherent fragility that makes small changes in temperature and rainfall patterns a serious threat to their biodiversity. According to the IIED (2008), dryland regions are expected to undergo significant climate changes, but there is considerable variability and uncertainty in these estimates between different scenarios. The IPCC (2007), projected that dryland, particularly the deserts are going to become hotter and drier. Based on UNEP (2007), these changes are expected to impact plant life and productivity through changing growth conditions and increasing the risk of wildfires, which could change the species composition and decrease biodiversity.

Drylands occupy some 40% of the Earth's terrestrial surface, extending over a variety of terrestrial biomes which are extremely heterogeneous with wide variations in topography, climatic, geological and biological conditions (MEA, 2005). They are found on all continents in both the northern and southern hemispheres and are home to more than 2 billion people or about one quarter of the earth's population as well as many agricultural and wild crops centres of origin. They include important ecosystems rich with unique and diverse communities of animals and plants. Some dryland ecosystems are exposed to a range of climatic and non-climatic factors and stresses that threaten their existence such as drought and desertification, land degradation, pollution, competition with invasive species and climate change (UNCCD, 1997).

Inspite of the many variations between drylands in terms of level of aridity, elevation, geological and biological conditions, etc., they share many common characteristic including; the low and erratic precipitation and high diurnal temperature variability. Moreover, dryland species and ecosystems have generally developed distinct coping mechanisms to cope with the harsh climatic conditions (low and erratic rainfall and high temperature).

People living in drylands, particularly rural communities, often rely on a combination of rain-fed agriculture, livestock raising and other income generating activities that are extremely vulnerable to the climate change impacts anticipated under most models. In some regions and due to the frequent and severe rainfall fluctuations soil formation and water supply have already reached unsustainable levels (IIED, 2008). Dryland people historically managed to maintain and sustain their livelihoods under the very difficult conditions of the drylands, by developing very unique coping strategies under both farming and pastoral systems. These systems are known by their instability and high resilience and are in harmony with the basic properties of drylands which used to support the continued practice of transhumance and of nomadism. Nomadic people adopt mobility and dispersion over wide grazing as coping mechanisms. Currently there is a greater appreciation of the efficiency of traditional pastoral systems based on mobility and the exploitation of extensive resources (Niamir-Fuller, 2000).

2. Potential risks to dryland ecosystems

The predicted global climate warming resulting from the build-up of greenhouse gases in the atmosphere is expected to have profound impacts on global biodiversity at levels that may compromise the sustainability of human development on the planet.

Species and ecosystems prevailing in drylands are generally more resilient and have capacity to recover from the many stresses to which they are frequently exposed e.g. climate variability, drought, fires human-related pressures etc. (Edouard G, 2001). Inspite of this high adaptive capacity, but many studies have indicated that the on-going and projected climatic changes could have significant impacts on the drylands biodiversity and related ecosystems.

Climate warming will cause, inter alia, higher evaporation rates and lower rainfall both of which are major determinants of dryland ecological processes (IPCC, 2007). Significant changes in precipitation patterns and in local or regional temperatures are expected to threaten dryland biodiversity. Simulation models of climate change predict shifts in species distribution and reduced productivity in drylands. Each one-degree rise in temperature is expected to displace terrestrial species some 125 km towards the poles, or 150 meters in altitude. Simulation models by Sala and Chapin (2000) to assess biodiversity change over the next 100 years predict that dryland biomes such as savannahs, grasslands and Mediterranean ecosystems will be among the biomes experiencing the largest biodiversity change, and will be affected significantly by a combination of land use change and climate change.

Drylands are currently witnessing the combined impacts of climate change and human induced pressures. According to the UNCCD (2005b), seventy per cent of the world's drylands, including arid, semi-arid and dry sub-humid areas, are degraded, directly affecting more than 250 million people and placing 1 billion people at risk. The Millennium Ecosystem Assessment has also noted that the projected impacts of climate change on biodiversity across all ecosystems will increase very rapidly (MEA, 2005).

The MEA report also indicated that many factors could interact to increase the impacts on dry land with climate change being a major factor capable of increasing drylands vulnerability significantly. In an assessment of 29,000 observed changes in terrestrial biological systems, more than 89 percent of the significant changes were consistent with the direction of change expected as a response to global warming (IIED, 2008). The IPCC (2007) stated that, among the most significant observed changes in drylands is; an increased extinction risk for 20–30 percent of plants and animals (5 out of 10 chance), and major changes in ecosystem structure and function, (8 out of 10 chance). A recent study suggest that 15–37% of a sample of 1,103 land plants and animals would eventually become extinct as a result of climate changes expected by 2050 (Nature, 2004).

3. Terrestrial Ecosystems of the UAE

The terrain of Abu Dhabi is generally dominated by low-lying, sandy desert and salt flats (sabkhas). In the eastern side there are the Hajar Mountains which rise to more than 2,000 meters. Satchell (1978) describes the UAE as having two distinct regions:

- **An eastern mountain region:** with a sub-montane zone of outwash plains characterised by Acacia tortilis. In the eastern region, the barren, jagged mountains form part of the Hajar range in neighbouring Oman; they rise rapidly to 1,300m and then descend to a narrow coastal lowland plain along the Gulf of Oman. The northern ridges of these mountains, known as the Ruus al Jibal or Musandem, face the Strait of Hormuz and are in an enclave of Omani territory. The highest peak is 2,087m, and the slopes drop precipitously, creating a highly irregular coastline with spectacular valley sand;
- **Western desert region:** divided into a coastal belt and inland desert and scrub characterised by ghaf (Prosopis cineraria) trees.

The natural landscape in both of these regions includes wide range of terrestrial habitat types, which can be broadly classified as:

- inland sand sheets and dunes, piedmont alluvial and interdunal plains,
- mountains and wadis,
- coastal sand sheets with dwarf shrub vegetation,
- coastal and inland sabkha.

Other important man-made habitat types, such as cropland, planted forests, oases and urban areas represent a relatively small area (see Table 3-1). These major habitat types (see box 2 on % of ecosystem types) could be subdivided into more specialized ones with unique abiotic features, flora and fauna. The total protected area of 14 sites in UAE is 25,000 Ha, representing 0.3% of total land in 2003. And the total number of breeding mammals during 1992-2002 is 34 with 8 threatened species.

According to Country Report for the Central Asian Flyway Overview, UAE is an important area for the wintering, breeding and staging waterbirds and conservation of the waterbirds and their habitats is an important element in the conservation of overall biodiversity of the country.

The Arabian Peninsula serves as a staging post between Africa and Asia for migratory species, and the many lagoons, mud flats, khors and mangrove stands found along the Persian Gulf and the Gulf of Oman provide ideal nesting and feeding sites. With nearly 50% of all the bird species on the Central Asian Flyway and covered under the Central Asian Action Plan to conserve migratory waterbirds and their habitats found in the UAE, the region presents a bird watchers paradise, with over 400 bird species recorded.

Land type	Share of Abu Dhabi Emirate (%)
Shrub, savanna grass land	8%
Barren or sparse vegetation	90%
Wetlands and water bodies	1%
Urban and built up area	0.1%

Table 3-1: Major land types in the Abu Dhabi emirate (Environment agency).

The country assumes much greater significance to conserve waterbirds and their habitats (UAE, 2006) see also Annex 5 on wintering birds). An inventory of Important Bird Areas (IBAs) in the Middle East showed this ecoregion to contain 14 out of 33 areas identified in Oman, and 11 out of 20 areas in the UAE (Evans, 1994). Khor Khalba on the UAE's east coast, bordering Oman, contains an endemic subspecies of the white-collared kingfisher *(Halcyon chloris ssp kalbaensis)*, which is endangered, with only 44-55 pairs remaining at the site (Aspinall, 1996). Thirteen IBAs have been identified in the UAE, almost all concerning island seabird colonies and intertidal feeding sites for shorebirds (Evans 1994). The UAE contains a significant population of the Socotra cormorant (*Phalacrocorax nigrogularis)* a species endemic to the Arabian Peninsula and listed as endangered on the IUCN Red List (IUCN, 2001). The UAE has six of the fourteen known breeding colonies in the world.

4. Major terrestrial ecosystems in Abu Dhabi

The Abu Dhabi emirate has a variety of habitats, ranging from the coastal zones, flat inlands to mountains. Researchers have identified seven major zones with distinct habitat and ecosystems. This section will provide information on the characteristics and biodiversity situation for each of these major ecosystems.

4.1. Coastal Zones

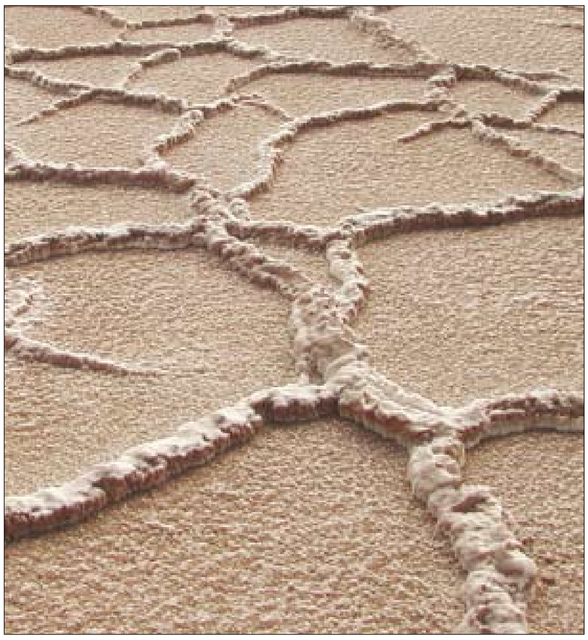
The coastline of mainland UAE extends for about 650 km, and comprises the Arabian Gulf coast in the north, and the Gulf of Oman coast to the east. Two separate coastal areas are identified, namely the sandy and low Arabian Gulf coast (600 km long), and the rocky and sometimes steep Gulf of Oman (Indian Ocean) coast (approximately 75 km long).

Main habitats of the coastal zone include mangroves, salt marsh, tidal flats with cyanobacterial mats, sandy and rocky beaches, coastal flats and low sand dunes, sabkha, cliffs and rocky headlands. Compared to other terrestrial habitat in UAE, coastal vegetation is more productive as it presents a habitat to a relatively high number of species with some individual stands dominating over different areas. Among the main factors that determine the abundance and distribution of specific plant species along the coast are: the water or substrate salinity, frequency and extent of inundation and the water-holding capacity of the substrate layers. A visual inspections readily shows that mangroves are flourishing along the UAE coasts in many sites including Abu Dhabi Island. Other dominant species in the coastal zone is the *Halophytic perennials* beside some annuals such *Biernertia cycloptera*, *Suaeda aegypti-aca and Zygophyllum* (see Annex 6 for a listing of important Flora of the UAE).

In more saline coastal habitats Chenopods constitute the main dominant species. Towards the inland, with less influence of sea the species *Zygophyllum qatarense* are frequently found over wide areas. The white dunes of the coast are home to a high diversity of plants, including a large amount of annuals that appear after the winter rains, but in general terms, the vegetation is dominated by Dwarf shrubs and perennial grasses.

4.2. Coastal and Inland Sabkhat

Sabkha' is an Arabic term referring to flat, salt-encrusted desert that is usually devoid of any significant plant cover (Aspinall, n.d.). Due to the high concentration of salts on the sabkha surface formed by means of tidal action of the sea– it can not support any type of vegetation. The accumulation of salt is profound in areas where the water table lies close to the surface. Inland sabkha, formed from periodic floorings that result come after occasional rainfall events.



Plant species particularly halophytes found in the sabkha could only be found in the margins are restricted mainly to the margins. Other species could grow only after heavy rainfall which dilute the concentration of salts. e.g *Zygophyllum qatarense*.

4.3. Sand Sheets and Dunes

The majority of land in UAE is covered by sand sheets and dunes particularly the southern areas. Two types of sands are identified a) white coastal sands originated from marine sediments. b) The yellowish to grey siliceous sands found mainly in large tracts of the inland and are produced from the weathering of quartz. Coastal white sands are derived from recent marine sediments and are rich in carbonate. Generally sand sheets absorb rain water and act as reservoirs for water in the short to medium term. The most dominant plant species in the sand of UAE is the *Cyperus conglomeratus*.

Other associated perennials include *Dipterygium glaucum* and *Limeum arabicum*. *Cyperus* being unplatable, was able to survive the heavey grazing better than other species, such as *Centropodia forskaolii, Panicum turgidum* and *Pennisetum divisum*. Observations in one of the protected ares (Al Wathba) have shown that good germination of Cyperus occurs after incidents of heavy rainfall in the late spring, when temperatures are already quite high again. It also indicated the occurrence of many premature death of seedlings under insufficient rainfall during the sensitive early stages of its growth. South of Abu Dhabi City, some stands of shrubby tree *(Haloxylon persicum)* ('ghada'), are found, mainly in the form of poorly established plant community.

4.4. Piedmont Alluvial and Interdunal Plains

The alluvial plains are found along the western edge of the Hajar Mountain range. They consist of pebbles and coarse rock detritus at the foot of mountains and sand and finer gravel further west, plus interstitial alluvium. Small trees, dwarf shrubs and succulents are the dominant plants in the alluvial plain. The north-eastern part of the UAE is dominated by *Acacia tortilis* ('samr')-the classic species of rocky and gravelly plains. In the Madam Plain of East Coast a vegetation type similar to open Acacia woodland is observed. The acacia is found in association with shrubs such as *Lycium shawii* and *Gaillonia aucheri* (= *Jaubertia a.*), as well as the succulent cactus-like *Euphorbia larica* and semi-succulent *Ochradenus arabicus*.

Other species found in the alluvial plains are the *Prosopis cineraria* and *Acacia ehrenbergiana* along with *A. tortilis*/ Scattered in a few localities in the east of Abu Dhabi *A. ehrenbergiana* is found in sandy to silty interdunal plains. The toxic species of Rhazya stricta ('harma') which is generally regarded as a gravel plain species is usually found in the east of the country. Its toxicity derived animals to shrink from grazing it, giving it the chance to increase and dominate – to the extent that its presence is usually regarded as a sign of land degradation that dominate after the disappearance of other species such as *Acacia tortilis* and *Haloxylon salicornicum*. Both *Haloxylon salicornicum* and *Aerva javanica* are often associated with Rhazya.

The other species that also indicate land degradation from heavy human disturbance is *Calotropis procera* (ushar), an extremely fast-growing tree that can begin producing flowers at an early age and found in the alluvial plains and low dunes. Species like *Haloxylon salicornicum* is only slightly tolerant of salt and could be replaced by other species like *Zygophyllum qatarense* as soil salinity increases. Other regular associates on interdunal plains include the perennials *Fagonia ovalifolia*, a small woody plant, *Heliotropium digynum*, found mainly on sandy interdune corridors, and *H. acciferum*, a plant that tolerates more saline, gravelly substrates.

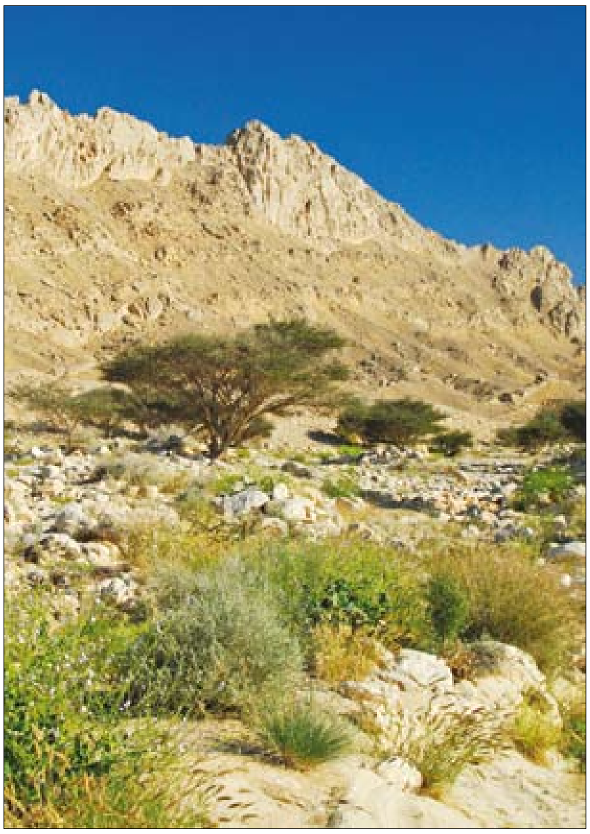
The interdunal plain which is already species-poor, is dependent on winter rainfall and in years of low precipitation its seedlings may not be able to germinate. Another factor that limits the growth of annual plant is the high soil salinity. Inland sabkha is frequently developed in the interdunes, and vegetation may be completely lacking there.

4.5. Mountains and Wadis

The Hajar range is the major mountain system of south-eastern Arabia, about 20-50 kilometers wide dissected by numerous wadis, and reaches elevations of more than 1000 m. The mountain extends some 700 km from the Musandam

Peninsula in the north to close to the Wahiba Sands (eastern Oman) in the south-east. The mountain contains one of the highest diversity of plant life compared to other habitat types in the UAE, with composites (*Asteraceae*), grasses (*Poaceae*) and umbellifers (*Apiaceae*) represented by a relatively high number of species (UAE, 2005).

A wadi is a depression in the mountains - or in gravel plains or dune areas - caused by natural processes such as the movement of the earth's surface and weathering. Water from the surrounding areas runs into these wadis and, being the course of least resistance, they carry the water to wherever they lead, be it sea, lake or plain. In other words, wadis are watercourses - according to the Westernised version of the word. According to the literal translation from the Arabic, however, wadis are valleys. Another traditional use of the wadi is as a travelling route, whether through dunes or mountains, between towns and villages, or even between countries. Wadi Al Qawr, for instance, is used as a route between the UAE and Oman. Some wadis were originally river beds stretching to the sea. Over time, and through lack of water and flooding, some wadis have dried, been silted up by moving sand and become disconnected from their original destination. Others, however, still flow into the sea after heavy flooding,



Boer (1999) noted that large numbers of species are restricted to Hajar Mountains in the eastern parts of the emirates. Important and dominant species in the lower mountain slopes include the *Acacia tortilis* and *Euphorbia larica* accompanied by a number of perennials such as *Gaillonia aucheri, Lycium shawii, Pulicaria glutinosa, Ochradenus aucheri, Physorrhynchus chamaerapistrum* and *Tephrosia apollinea. Capparis cartilaginea and C. spinosa. Acacia* species gradually disappears with increasing elevation, and is rarely encountered above 500 m, although *Euphorbia* remains common at much higher altitudes. On rock debris, especially near wadis, trees like *Moringa pere-grina* and *Ficus cordata ssp. salicifolia* become more dominant. Common throughout the mountains is the shrub *Dodonaea viscosa*, often reach up to the summits. In the far north-east of the country, the Arabian almond *(Amygdalus arabica)* is an important constituent of the vegetation above 1000 meters elevation. Further south, olive trees (*Olea europaea*) are locally common in high mountain situations.

In general terms, the vegetation in mountains and wadis zone is determined by precipitation and temperature, as increasing precipitation and decreasing temperatures provide more favourable climatic conditions for the growth of plants at higher altitudes. The presence of poikilohydric plants, in particular lichens and bryophytes and the wide spread of the mountain fern *Onychium* divaricatum are indicators for the presence of such favourable climatic condition. Wadi beds are always characterized by being rich in biodiversity particularly in the lower fringes. *Acacia tortilis* dominates the edges of many wadis and is frequently accompanied by *Lycium shawii* and *Gaillonia aucher.*

At lower altitudes, in wadis and on rocky slopes *Zizyphus spina-christi* (Christ's Thorn), is found as a common tree ascending to about 1500 m. In wet winters, the wadis flourish with a large amount of annuals, and particularly common, even in drier years, is *Asphodelus tenuifolius*, a lily-like plant with numerous small white flowers. The only known species of orchid in the UAE, *Epipactis veratrifolia*, thrives in moist shady conditions along the banks of wadis and artificial watercourses, typically accompanied by the fern *Adiantum capillus-veneris*.

4.6. Freshwater Habitats and Oases

Natural fresh water habitat is very rare in UAE and is restricted to the permanent streams and pools present in the mountains. In such habitat with highly moist conditions some aquatic plants are found such as *Potamogeton lucens, P. pectinatus, Najas marina* and *Zannichellia palustris. Arundo donax* and *Juncus*. Heavy rain conditions could also lead to formation of temporary streams with wadis carrying flowing water.

Freshwater Oases exist throughout the UAE on e.g. the plains on either side of the Hajar Mountains, and in many desert sites of Abu Dhabi Emirate. The largest desert oasis is located in the Liwa Crescent. It consists of a series of individual oases spanning over more than 100 km. Oases in coastal plains are usually irrigated by a 'falaj' system where the underground water is tapped from the edge of the mountains and then diverted along open channels to the oasis. This a 3000-year old system used in UAE.

In case of 'ghayl' system in the mountains, water is extracted from the upper reaches of the wadi bed to be fed along open watercourses built into the sides of the wadi and then directed to terraced fields. The field in the mountain is very rich in wild species beside date palm plantations. In places with abundant water supply, farms have been established (e.g. Liwa), and fields of *Chloris gayana* (Rhode's grass) are spread around the country. Typical wildflower species of the agricultural areas include *Anagallis arvensis, Chenopodium murale, Eruca sativa, Euphorbia peplus, Fumaria parviflora, Melilotus indica, Portulaca olereaca, Oxalis corniculata, Rumex dentatus, Sida urens, Sisymbrium erysimoides, S. irio, Sporobolus spicatus,* and *Vicia sativa* (Brown and Sakkir, 2004).

4.7. Urban Environments

The vast urban developments in UAE have largely impacted the natural vegetation cover. However, a number of new species have started to appear, making use of the inductive environment brought about by the afforestation programs and available irrigation water. Some of these plants are indigenous to the UAE, including *Aeluropus lagopoides* and *Sporobolus spicatus* (both common in irrigated urban areas), others could be exotic such as *Cressa cretica* (garden beds), *Coronopus didymus* and *Fimbristylis sp.* (both locally abundant in lawns in Abu Dhabi), *Euphorbia prostrata*, E. serpens and *Sonchus oleraceus* (Brown and Sakkir, 2004).

5. Important flora in Abu Dhabi

Abu Dhabi has a remarkable number and variety of habitats, plant and animal species. Many habitats and species have come under severe threat, primarily due to the rapid rate at which the emirate has developed, and continues to develop. According to Kürschner and Boer (1999), the flora of the UAE contains more than 630 species, and comprises elements from both Asia and Africa. In addition to about 20 bryophyte species, they highlighted that the greatest number of species recorded in the UAE are therophytes. The therophytes appear after rains and disappear in dry periods. In general terms, the natural UAE flora could be classified according to the following ecological categories: seagrass, mangrove, salt marsh, reed swamp, sand dune, gravel plain, desert wadis, and rocky-mountainous vegetation.

Apart from these, there are several oases with date palm vegetation, and urban green areas within the UAE. Because of the prevailing desert like conditions, the flora of the UAE is widely scattered across different habitat types e.g. coastal, mountain, wadis etc. Moreover, the soils of the UAE are characterized by their aridity, sandy nature, low water retention capacity, nutrients and organic matter (Boer and Sargeant, 1998). The arid environments have their impact on the plant structure and life, as the flora of the UAE mainly comprises thorny shrubs, therophytes (ephemerals, annuals, biennuals), xerophytes, psammophytes and halophytes.

Also, there are some hygrophytes growing in the shaded humid wadis of the mountains, and some hydrophytes in the inundated ecosystems of the UAE. A recent study in Abu Dhabi (UAE, 2008) indicated that Abu Dhabi is a home to approximately 400 species of vascular plants, 50 species of mammals, 416 bird species, 55 species of reptiles, and between 4,000 and 5,000 species of invertebrates. More details on some floral and faunal types is given in the subsequent sections.

5.1. Mangroves

Walsh (1974) defines mangroves as a woodland formation below the high-tide mark. They exist in coastal ecosystems in a transitional environment between land and marine, characteristic of tropical regions subject to the action of tides. It is constituted of woody tree species and many micro and macroalgae adapted to fluctuations in water salinity, shifting sediments with low levels of oxygen and naturally occur in the intertidal zones (Chapman, 1976).

Mangroves require a fine-grained alluvial substrate and shores that are not exposed to strong wave activity that could otherwise wash the seedlings away by the action of currents. It is also widely known that, coastal processes such as tidal mixing and coastal currents may also influence mangrove distribution through affecting dispersal ability (McLeod *et al*., 2006). Climatic factors such as temperature and moisture affect mangrove distribution (Duke, 1992; Saenger, 1993). Temperatures above 35°C have led to thermal stress affecting recovery rates following the disturbance. (Ning *et al.*, 2003).

Mangroves are known to be important biomass producers and exporters to coastal environments (Dahdouh-Guebas *et al.* 2000). They provide protection and refuge for juvenile fish and are important in increasing fishery production on the coastline (Laegdsgaard and Johnson, 2001). Only one species of mangrove, *Avicennia marina* occurs naturally in the UAE, possibly due to the harsh summer climate, although there is speculation that in the past, a second species, *Rhizophora mucronata*, also thrived in some areas.

In Abu Dhabi Emirate, the main strands of mangroves are found east of Abu Al Abyad island, with isolated occurrences further to the west (for instance, just west of Jebel Dhanna). The trees rarely exceed 3 to 4 m in height. The stands are much denser than any mainland vegetation type in the Emirate, and are extremely important habitats for marine life and many species of bird. The roots anchor the trees firmly in the mud, and the upper parts of the roots grow out of the water as characteristic ‘pneumatophores’. Their primary function is to absorb air and transport it to the roots beneath the water. *Avicennia marina* is a C3 species and transpires large amounts of water. Since the uptake of dissolved salts cannot be reduced to any significant degree, the accumulation of toxic concentrations of salt in their aerial organs is potentially a serious problem for the plants.

This problem has been overcome by the presence of salt-excreting glands on the leaf surface, which results in the plants often coated in a whitish layer of salt. Climate change is expected to impact the mangroves and the destruction of mangroves could also exacerbate the negative impacts of climate change on coastal ecosystems and infrastructure based on a paper by IUCN (2006). Climate change impacts on mangroves will not occur in isolation; the response of mangroves to climate change will be a result of these impacts acting synergistically. The paper stressed that the damage caused by the tragic 2004 Asian tsunami was exacerbated by over clearing of mangroves and other coastal “bioshields”, inappropriate coastal development and inadequate information and preparedness.

5.2. Mountain and Jebel vegetation

Jebel Hafit, which is part of the Hajar mountain range, is considered as the only true mountain in Abu Dhabi Emirate, although part of it is located in Oman. It stands high above the surrounding plain to over 1000 m asl. Jebel Hafit is characterized by a least developed virgin soil very rich in humus. The mountain is considered as the most important site within Abu Dhabi Emirate due to a number of characteristics, as briefly described below:

- highly rich floristic diversity, representing

over a one third of the known species in Abu Dhabi (approx. 380 sp.) exist within a very small area which represents less than 0.002% of the total area of the UAE

- this mountain is the only habitat to many of these species and not to any other area or ecosystem; and
- the site represents the western limit for the distribution of many global taxa.

Acacia tortilis and *Euphorbia larica* are widespread in the lower slopes of Jebel Hafit, often accompanied by perennials such as *Gaillonia aucheri* and *Lycium shawii*. With increasing elevation, *Acacia* becomes less frequent, but still occurs close to the summit. *Euphorbia,* though, remains common at all altitudes, but is often found along natural drainage channels. *Haloxylon salicornicum* is a common dwarf shrub on the exposed mountain slopes. Other species identified are *Salsola rubescens*, which is fairly widespread, occurring locally in large populations and *Capparis cartilaginea*, a species with large, leathery leaves, detected by the roadside up to the summit, and ascending rocky cliffs.

Other shrubs occurring on the mountain include *Periploca aphylla*, *Grewia erythraea* and *Rhanterium epapposum*, a species otherwise characteristic of sandy habitats. In Wadi Tarabat, a small group of *Acridocarpus orientalis* trees were observed. The dwarf palm *Nannorrops ritchieana* which is a rare species in the UAE, occurs locally on the mountain, as well as the *Ficus johannis ssp. johannis*.

Tertiary jebels are found along the coast in more western parts of the Emirate as prominent features. They are mostly surrounded by barren sabkha. These rocky exposures with flat tops vary in both area and height, but are typically up to about 5 to 10 m high, with the largest up to 60 m. Jebels represent typical island habitats and are thus of considerable research interest. A number of plant species occur on the jebels, including halophytes such as *Seidlitzia rosmarinus* and *Salsola spp*. The salinity is presumably due to the windblown saline dust from the surrounding sabkha.

Also present are a number of nonhalophytic species that are otherwise absent from the surrounding area. These plants grow in small pockets of soil that accumulate behind rocks or in gullies on the smaller jebels, as well as on the plateaux of the larger ones. Among the plants are a number of desert annuals, such as *Savignya parviflora, Eremobium aegyptiacum* and the bristly, facultative perennial Arnebia hispidissima. Furthermore, the lily *Dipcardi erythraeum* appears abundantly on the flanks of some jebels after heavy rainfall. *Salsola drummondii* can be dominant on the tops of some larger jebels, often accompanied by *Calligonum comosum, Indigofera sp. Panicum* turgidum and *Pennisetum divisum*.

5.3. Wadi beds vegetation

Wadi beds are recognized for their biodiversity rich vegetation, particularly the lower ends due to the existence of different types of substrate; presence of significant spatial heterogeneity in microtopography and microclimate; light availability; and regular access to water. All these conditions combine to create a mosaic of favourable microhabitats. The climate variability and extremes such as the seasonal severe flooding influence the wadi beds creating within it highly dynamic habitats, in terms of their physical characteristics as well as their floral composition. Floods can wash

away many plant species and at the same time bring the seeds of new plants to grow in these unique microhabitats. Important grasses of wadi beds are *Cymbopogon commutatus* and C. schoenanthus, as well as *Cenchrus ciliaris*.

5.4. Flora of the oases

The natural oases at Al-Ain and Liwa, which were the habitat for the earliest agricultural settlements in Abu Dhabi, are the largest in the emirate, and they continue to expand with irrigation. Some of the oases are naturally occurring, while others are man-made; however, generally they have similar wild and domestic flora as they provide good environment for date plantations together with other agricultural crops (Brown 2004). Date palm plantations provide habitats for a number of wild plant species. Farms have sprung up in desert areas where there is a sufficient supply of water (e.g. Liwa), and fields of *Chloris gayana* (Rhode's grass) are dotted around the country. Typical wildflower species of the agricultural areas include *Amaranthus spp., Chenopodium murale, Emex spinosa, Eruca sativa, Euphorbia prostrata, Launaea procumbens, Melilotus indica, Phyllanthus rotundifolius, Portulaca olereaca, Sisymbrium erysimoides, Sporobolus spicatus and Trigonella hamosa.*

6. Fauna of the terrestrial ecosystems in Abu Dhabi

Forty-eight species of terrestrial mammals have been recorded in the UAE. These mammals exist within 18 Families of 8 Orders (Carnivora, Artiodactyla, Perissodactyla, Rodentia, Hyracoidea, Lagomorpha, Insectivora and Chiroptera). Of these 48 species, 7 species (*Oryx leucoryx, Capra aegagrus, Capra ibexnubiana, Canis lupus arabs, Hyaena hyaena, Panthera pardus nimr, and Hystrix indica*) are known to be extinct in the wild. From the remaining 41 species, 11 species have been introduced in UAE under recent geological times, either accidentally or as domesticated animals, and can be found in the wild.

6.1. Birds

Birds constitute nearly 81% of overall higher vertebrate biodiversity (reptiles, birds and mammals) in the Abu Dhabi Emirate. Various species of birds are identified in Abu Dhabi, mostly desert-adapted species such as the hoopoe lark, the cream-coloured courser and the black-crowned finch lark. Buzzards and desert eagle owls are also known to maintain small breeding populations in the desert, so are brown-necked ravens. Land birds constitute the majority of species in Emirates, reaching to about 65% with around 35% of water birds. Of the 271 identified land birds 18% are resident while 82% are migratory.

A number of birds' surveys have been undertaken recently by the Environmental Agency - Abu Dhabi (formerly ERWDA) and also by members of various natural history groups in the country. It indicated the presence of 416 species of birds in Abu Dhabi Emirate alone, representing almost 96% of all the birds recorded in the United Arab Emirates. The relatively high number of species recorded from Abu Dhabi Emirate related to the diversity of habitats from the coastal to mud flats, mountains and inland wetlands.

Abu Dhabi Emirate is a breeding habitat of regionally and globally important seabirds. This makes it particularly important in terms of conservation. Moreover, and beside the seabirds breeding colonies, it hosted the wintering of houbara bustard *Chlamydotis macqueenii*, one of the highly valued bird species in the Arab world, and because of it some significant conservation measures have been taken to protect the avifauna of the Emirate. Most of the bird species breed during summer (May-August), but still some species like Osprey *(Pandion haliaetus)*,Socotra Cormorant *(Phalacrocorax nigrogularis)*, Red-billedTropicbird *(Phaethon aethereus)* and Brown-necked Raven*(Corvus*

ruficollis) breed during winter (November-April) months. Seven habitat types are identified as birds' habitat in Abu Dhabi, mainly green areas with artificial plantations, gardens/parks and wetlands. These habitats present the grounds for feeding, resting and breeding of different species of birds. 16% of the total bird species are found in the mountains, rocky habitats and wadis and 5% are found in the desert habitat.

6.2. Threatened bird species

Several species found in the Emirate are regarded as internationally important or priority species, meaning they are [rare, threatened (globally or nationally) and have restricted breeding range]. Of the 15 species listed as 'Globally Threatened' by the BirdLife International in the UAE, four (4) are water birds and rest are terrestrial species. Of the 11 terrestrial only the Saker Falcon *(Falco cherrug)* is listed as endangered (EN), while species such as Houbara *(Chlamdydotis macqueeni)*, Imperial Eagle *(Aquila heliaca)*, Greater Spotted Eagle *(Aquilaclanga)*, Lesser Kestrel and Lappet Faced Vulture are listed as vulnerable (VU). Five species are listed as near-threatened (NT), includes Pallid Harrier *(Circus macrourus)*, European Roller and Cinereous Bunting *(Emberiza cineracea)*.

The main threatening factors identified

include the urban development and industrial infrastructure which have directly or indirectly impacted the natural ecological habitat. Other expected threats identified include disease transmission such as Avian Influenza by other wild migratory birds of introduced species (IUCN, 2004) and the shooting or hunting of birds with certain predators species such as eagles and falcons, including the important Sooty Falcon, are particularly vulnerable to such practices. Climate change has been mentioned among the factors that could potentially impact the presence and distribution of birds and their habitats.

6.3. Mammals

The most common fauna in Abu Dhabi are camels and goats. Several species of animals have suffered extinction in the desert over the last decades. These include the wolf, oryx, striped hyaena and jackal. Two species of gazelle survive in Abu Dhabi – the sand and mountain gazelle. Some of the nocturnal species are found in the Western region of the Abu Dhabi such as the sand cat, Rueppell's fox, cape hare and even the jerboa and several species of the hedgehog.

6.4. Reptiles

Reptiles are widely known in deserts. They are dominated by the lizards, amphisbaenids and snakes. There is also a new record of the Golden Skink (Mabuya aurata septemtaeniata) which is a new record for the UAE and was discovered on Jernain Island in 2004 (Soorae, 2005).

7 Vulnerability assessment of Drylands ecosystems

This section will attempt to assess the vulnerability and impacts of drylands ecosystems with focus on Abu Dhabi emirates. It will present information on climatic changes, potential impacts and adaptation measures for the drylands ecosystems.

7.1. Observed Climatic changes in dryland ecosystems

An assessment by the IPCC of long-term trends in precipitation amount over many large regions for the period 1900-2005, indicated that drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. The report has also indicated that more intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics (IPCC, 2007). These observations are linked to higher temperatures, decreased precipitation; changes in sea surface temperatures, wind patterns, and decreased snow cover.

More relevant to dryland regions is that areas affected by drought have and will continue to increase (IPCC, 2007). Little was reported in the IPCC Working Group 2 report regarding the observed impacts on crops and livestock in drylands or other developing country regions (Rosenzweig *et al.* 2007). A study had shown that very dry land areas across the globe (defined as areas with a PDSI of less than –3.0) have more than doubled in extent since the 1970s, and this was associated with an initial precipitation decrease over land related to the El Niño-Southern Oscillation and with subsequent increases primarily due to surface warming (IIED, 2008).

7.2 Projected climatic changes in dry land ecosystems

The IPCC (2007) has left no doubt that global warming is occurring and that climate change is human-induced, concluding that “warming of the climate system is unequivocal” and stating with 90 percent confidence that the net effect of human activities on Earth since 1750 has been warming. The report emphasized the high uncertainties in prediction of arid ecosystem responses to elevated CO_2 and global warming. However, it projected a generalized warming of over 3°C and a 100% increase in frequency of extremely warm years and the likely reduction in rainfall in Southern Africa, Sahara & Central Asia and likely increase in West Africa, East Africa and South Asia (IPCC, 2007).

7.3. Current climate and expected climatic change in the UAE

The climate of the UAE is characterized by high temperatures (up to 49°C in July), high humidity and low rainfall. The average annual rainfall in the mountain region (140-200 mm) and along the east coast (100-140 mm) is generally higher compared to the gravel plains (100-120 mm), with the west coast receiving the lowest average of less than 60mm (Boer, 1997).

The IPCC groups the Saudi peninsula into the Asian division, a region expected to undergo a wide range of climatic changes over the next century. An assessment by the IPCC of trends in precipitation for the period extending from 1900-2005 indicated that drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia, regions with similar climate characteristics to the peninsula. The IPCC reported that more intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics, but may have increased slightly in the Arabian Peninsula (IPCC, 2007).

A recent consortium of climate scientists from the Middle East recently compiled a database of climate observations over the last half century, and reported that both maximum and minimum temperatures in the region have shown a statistically significant increase and the number days exceeding the 90th percentile have increased throughout the region (Zhang *et al.*, 2005). However, the report indicates that there have been no coherent trends in precipitation

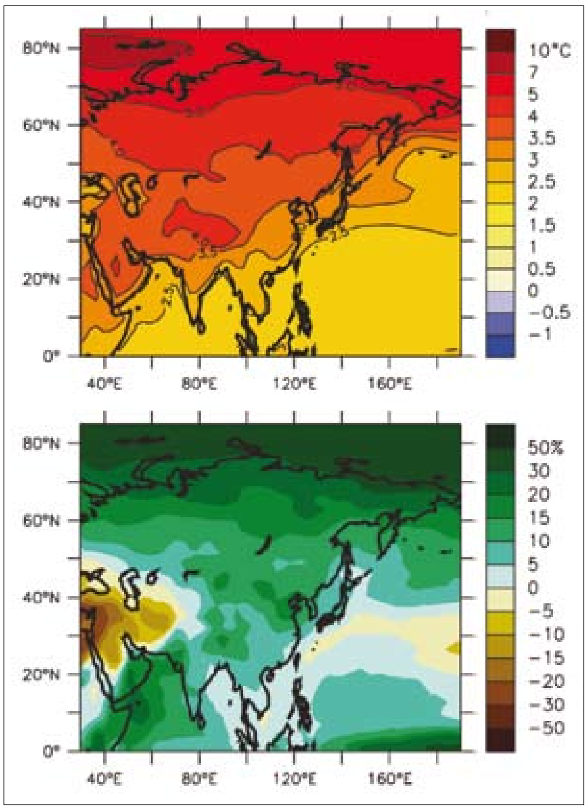


Figure 7-1: Expected changes in a) annual temperature and b) precipitation in the period 2080-2099 relative to 1980-1999, ensemble average. Source: IPCC (2007) WG 1.

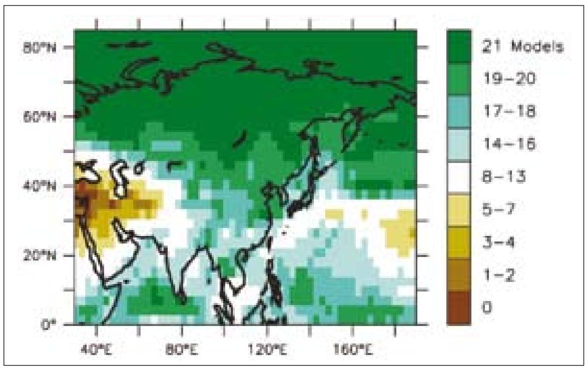


Figure 7-2: Number of climate change models in the IPCC report which indicate an increase in precipitation out of 21 independent models. Source: IPCC (2007) WG 1.

patterns thoughout the region.

Climate models project that the Arabian peninsula will experience increasing temperatures from 3-5ºC over the next century (see Figure 7-1a), and may possibly see decreases in its already low precipitation (see Figure 7-1b), leading to reduced runoff and water availability (Arnell, 1999; Milly *et al.*, 2005).

While these same conclusions are repeated throughout the literature, the most recent IPCC report indicates that there is relatively high uncertainty in expected climate change in the Arabian peninsula (IPCC, 2007), and the region is rarely explicitly addressed in either models or the literature (i.e. Bou-Zeid and El-Fadel, 2002). For example, the IPCC report suggests that the Indian summer monsoon is very likely to increase in intensity over the Arabian Sea (IPCC, 2007), and that severe droughts are expected in the Mediterranean, but indicates that approximately half the models disagree on the direction of change for precipitation trends over the Arabian peninsula, and the UAE in particular (see Figure 7-2). It appears as if many of the models disagree if the shifts in climate over this region will be linked to the Arabian Sea and Indian Ocean, or the Intertropical Convergence Zone (ITCZ) over Africa, which show opposite directions of change.

7.4. Vulnerability of terrestrial ecosystems of Abu Dhabi

Vulnerability of terrestrial ecosystems in Abu Dhabi is a function of exposure to multiple climatic and non-climatic stresses. The fast development and land use change are identified among the major factors that have significantly impacted the natural systems. This section will consider the vulnerability to these different sources of stresses.

Although most of the available national literature identify human interference as the major threat to biodiversity and dryland ecosystems in the Emirates, many other national and international assessment reports highlighted climate change as a major threat to drylands ecosystems (IPCC, UNEP, IUCN, UNFCCC-NCs). UNEP, 2007 noted that small changes in temperature and rainfall patterns can have serious impacts on the biodiversity of dry and sub-humid lands and that rising temperature could increase the risk of wildfires, which could change the species composition and decrease biodiversity. In areas where water is a limiting factor, changes in rainfall patterns could have serious impacts on biodiversity as any changes in water availability could disproportionately affect human livelihoods.

Moreover, the impacts of climate change on drylands may have significant repercussions on populations and economies particularly in areas where people are highly dependent on drylands biodiversity. In general terms, the faster the climatic changes, the greater will be the impact on people and ecosystems (UNEP, 1997). Heat and water are limiting factors in the dryland of the Abu Dhabi Emirate, and changes in temperature or water availability can have disproportionate effect on its biodiversity. UNEP also highlighted the fact that higher temperatures could threaten organisms that are already near their heat-tolerance limits.

Decreasing precipitation could impair the growth of annual and perennials species in Abu Dhabi, on which a large number of human and animals depend. This link between rainfalls and plant growth in Abu Dhabi Emirate was illustrated by the observation that increase in rainfall, over the spring of years 1982, 1983, and 1987 has been associated with the appearance of a greater number of perennials. This was further demonstrated by the wide spread of *Zygophyllum hamiense* along the Abu Dhabi to Al Hair road. Adverse impacts are observed during severe flooding where patches of eroded desert are exposed, linked to an increase in waterborne particles and the disappearance of some species of the natural vegetation, which relies on a minimum soil depth (Western, 1988).

Floral and faunal biodiversity in Abu Dhabi is expected to be affected by impacts on water resources. A low rainfall future, would lead to lower levels of surface runoff and less soil moisture that will impact the germination of many plant species that are not particularly adapted to drought, such as the wadi plants. The scarcity in plant species will affect the existence of animals that feeds on them and thus the whole food chain.

Decreasing precipitation could also lead to less recharged water and less available groundwater. The increasing temperatures associated with climate change would also reduce water availability through increasing potential evapotranspiration. Sea level rise associated with climate change is expected to lead to inundation and intrusion of salt water into important coastal ecosystems and aquifers. This will have implications on the growth of important species and threaten their existence.

Non-climatic stressors can increase vulnerability to climate change by reducing resilience (IPCC, 2007) e.g. human-induced degradation of ecosystems may increase vulnerability to climate extremes. The MEA demonstrated how drylands are challenged by the major drivers of ecosystem services change – habitat change.

Many non-climatic factors are identified as threatening the biodiversity in Abu Dhabi. There is a general agreement that in addition to natural causes like drought, the main threats are coastal development and urbanization where 40% of the population is concentrated in the two main coastal cities of Dubai and Abu Dhabi, accounting for about 60% of the population (Ministry of Information and Culture, 2006). Overexploitation of natural resources (fishing, hunting, over-grazing and water extraction) that are linked with the vast population increase and changes in lifestyle have also been identified as a significant threat to biodiversity.

The fast economic growth without consideration to the natural environment has been identified as one of the most important factors contributing to destruction of biodiversity. Toreng *et al.,* (2008) elaborated on the importance of biodiversity in UAE and the threats it faces. They highlighted that, despite being regarded as a vast deserted and unfertile area with one of the lowest human populations in the world, the UAE hosts a unique and remarkably adapted fauna and flora. (Boer, 1999), on the other hand, listed domestic pollution, eutrophication, reclamation, landfill and sedimentation, hunting, persecution, and unsustainable harvesting, alien introductions including predators on islands, disturbance, mismanagement and development as among the main factors leading to habitat and species loss.

Overgrazing

Excessive grazing by camels is rated among the greatest threatened factors to the inland desert ecology of the UAE (Hellyer *et al.,* 2001). Their severe impact was attributed mainly to the rapid increase in their number since the unification of the Emirates. Although the ecology of the region included grazing by camels and other large herbivores in previous centuries, camels are the only domestic animals that are currently allowed to move and graze freely through out the desert. Social and cultural considerations for camels have been behind the lack of regulations controlling their movement (Gallacher *et al,* 2008).

Some evidence supports the camel grazing for replenishing the ecology of the desert, indicating that some grazing may be required to maintain plant biodiversity and maximize biomass production (Oba *et al.,* 2000; Zaady *et al.,* 2001). The study further indicated that grazing is unlikely to significantly impact annual or perennial plants within the season of germination, due to the short exposure time to herbivores. And that the growth of perennial species is reduced only by heavy grazing which could also lead to loss of habitat, while moderate grazing could provide a chance for the species to survive and to compensate for the loss in numbers.

A report by ICAEDA, stated that nomadic grazing systems in arid and semi-arid regions have evolved over many centuries into a complex set of practices and knowledge that has permitted the long-term maintenance of a sophisticated "triangle of sustainability" that includes plants, animals, and people as a rational response to erratic climates with limited annual precipitation. The report added that socio-economic changes involving livestock subsidies and the introduction of water tankers increased herd sizes manifold to suit the new economic conditions.

Desertification and land degradation

The UNCDD defines desertification as the degradation of land in arid, semi-arid, and dry sub-humid areas. It is caused primarily by human activities and climatic variations. It occurs because dryland ecosystems, which cover over one third of the world's land area,

are extremely vulnerable to over-exploitation and inappropriate land use.

Land degradation reduces natural vegetation cover, and affects productivity. According to a study conducted by ICARDA Arabian Peninsula Regional Program, working in collaboration with the National Agricultural Research Systems (NARS), and other institutions over 90% of the total area now suffers from some sort of overgrazing, and 44% is severely or very severely degraded. The loss of biodiversity likewise undermines the environmental health of drylands and makes them more prone to further degradation.

According to IIED (2008) the major threat to dryland biodiversity is land degradation resulting from climate variability coupled with human induced factors like urbanization and overgrazing, it is upon this bio-physical and socio-economic base that climate change impacts will unfold. Andrea (2006) stated that recently, land degradation in more arid regions of the world such as the Arabian Peninsula coupled with progressive population growth has become a serious concern. Andrea (2006) also stressed the potential impacts of deforestation and other forms of land resource exploitation, in particular oil and gas surveys, on biodiversity.

Other factors

Hunting and trapping of large mammal species has resulted in very low population levels of Panthera pardus ssp. nimr and Hemitragus jayakari. Over the last few decades, the UAE has lost most of its big fauna such as the Arabian leopard, Mountain Gazelle, Arabian Tahr, Development for tourism and recreation is threatening habitats in and around Jebel Hafit, which is Abu Dhabi's only mountainous area. Habitat degradation and destruction are almost inevitably accompanied by threats to individual plant and animal species. The risk is that habitats are degraded to such an extent that they no longer provide the means of support to specific species. Examples of species that have become extinct in the wild in Abu Dhabi include the Arabian leopard, the Arabian wolf and the striped hyena (Drew & Tourenq, 2005).

Oil spills are a threat to the entire coastline of this ecoregion. Large vehicles and trucks cause damage to bird and turtle nesting sites. Off-road driving inland causes much damage to the vegetation, which is slow to recover due to the limited annual rainfall.

8. Biodiversity, ecosystem thresholds, and climate change

There are a wide range of drivers which may change ecosystem structure and function, including human influences such as land use and pollution, shifts in climate patterns, and alterations to physical or chemical balances. One key element of ecosystem health is its biodiversity, a metric of how many different distinct types of flora and fauna interact in the same space. An ecosystem with high biodiversity is highly resilient to damage and disturbance, and is able to resist change.

Losses in biodiversity leave key ecological niches unfilled, and may promote instability or catastrophic change in an ecosystem. Like a well-balanced portfolio, a highly biodiverse ecosystem is less likely to collapse or be adversely affected by disturbances over long periods (such as shifts in climate) or short periods (such as wildfires, pathogen or disease outbreaks, or flooding); each element of the ecosystem is susceptible to some type of damage, but resilient to other forms – as a whole, an ecosystem with high biodiversity can function well even in the face of adverse conditions. As we look to assess the potential impact of climate change on the UAE, biodiversity and ecosystem function will remain a key concept.

It is important then, to understand not only the role of biodiversity on ecosystem function, but the role of anthropogenic (human) and climate change on biodiversity. Generally speaking, researchers agree that the last two centuries have seen an extraordinary loss of biodiversity (Ceballose and Erlich, 2002; Hughes, 1997), rivaling (if not exceeding) the extinction rates of geologic historic mass extinctions (Balmford, 2003). Researchers have attributed much of this biodiversity loss to:

- over-harvesting of both predator and prey species (e.g. overfishing and hunting);
- habitat destruction (e.g. deforestation, overgrazing, or pollution); and
- climate change.

Over-harvesting of species can lead to critical shortages in breeding populations, meaning that a population is not large enough to re-

populate itself, and imbalances in the food-web, meaning that there is either not enough food for top predators or there are too few predators to control the population of prey species. In these circumstances, the imbalances can quickly stack up synergistically in a positive feedback cycle: for example, as top predators dwindle, prey species multiply quickly and begin to deplete food sources for other species or change the physical or chemical properties of their ecosystem. For example, overfishing of Codfish in the rich kelp (seaweed) forests of the Gulf of Maine allowed sea urchins to prosper, which in turn destroyed the kelp habitat (Jackson *et al,* 2001). Cod is now extinct in the North Atlantic, and the habitat has, for all intensive purposes, changed permanently.

Habitat destruction results in the loss of ecosystem area or an impedance in ecosystem function, and is, by far, the most pressing threat to biodiversity worldwide. Pollution and habitat misuse can destroy or impede key elements of an ecosystem, lending to severe imbalances and loss of ecosystem functionality. For example, overgrazing in arid ecosystems commonly leads to the trampling of biogenic crusts and the loss of critical vegetation cover, which, in turn, leads to increased runoff and erosion, nutrient losses, and can promote invasive species.

The direct loss of habitat by land use change can also result in the loss of biodiversity as parts of an ecosystem are transformed for another use, there is less area for the native ecosystem to use. The relationship between species diversity and area has been recognized since at least the early 20th century, and was formalized by Williams (1964) and, later, Rosenzsweig (1995) as a logarithmic curve. In numerous studies, as larger areas are examined, the number of species increases (i.e. from a small plot to a continent). Geographical constraints, the ability to move, migrate, and compete, and the ability to escape small-scale disturbances all govern the relationship between area and speciation.

Within a specific type of biome or ecosystem, as the physical size of the ecosystem is reduced, the number of species which can be supported in the ecosystem is also reduced. Expansion of urban areas, deforestation, sedimentation, and agricultural expansion are all mechanisms of direct habitat destruction. Fragmentation restricts the ability for species to migrate or expand. Thus, even if total habitat space is large, but is subdivided into small fragments, the net effect results in small, non-diverse (and often functionally deficient) ecosystems.

Finally, climate change may already be responsible for some species losses and threatens to lead to rampant reductions in biodiversity globally. Climate change shifts the basic substrates upon which ecosystems rely: as temperatures increase and precipitation patterns are altered, ecosystems which used to thrive in one region may be displaced to other areas or disappear altogether. For many biomes around the world, this shift may look like a mass movement of ecosystems towards the poles or higher elevations, while ecosystems already near the poles or at high elevation may be lost completely.

While the story is both complicated and uncertain, it is likely that many sedentary or non-migrating species will be unable to move at the pace of climate change, and even migratory species may find their migratory routes falling out of synchrony with weather and food patterns. For all of these reasons, it is likely that climate change alone will lead to significant biodiversity losses (Sala *et al.*, 2000), and the effect will be compounded where there are already significant environmental stresses, such as those described previously (Thomas *et al*, 2004).

8.1. Biodiversity and ecological thresholds

In 2000, Sala and others predicted that "Mediterranean climate and grassland ecosystems likely will experience the greatest proportional change [loss] in biodiversity" by 2100 due to the combined influence of climate change, land use change, changes in atmospheric CO_2, and introduced (invasive) species. Except for far northern and southern latitudes, where climate change is expected to have the most significant impacts, changes in land use are expected to be responsible for the heaviest toll on biodiversity. According to the Sala *et al.* (2000) analysis, if we assume that interactions amongst the drivers of biodiversity change are synergistic and multiplicative,

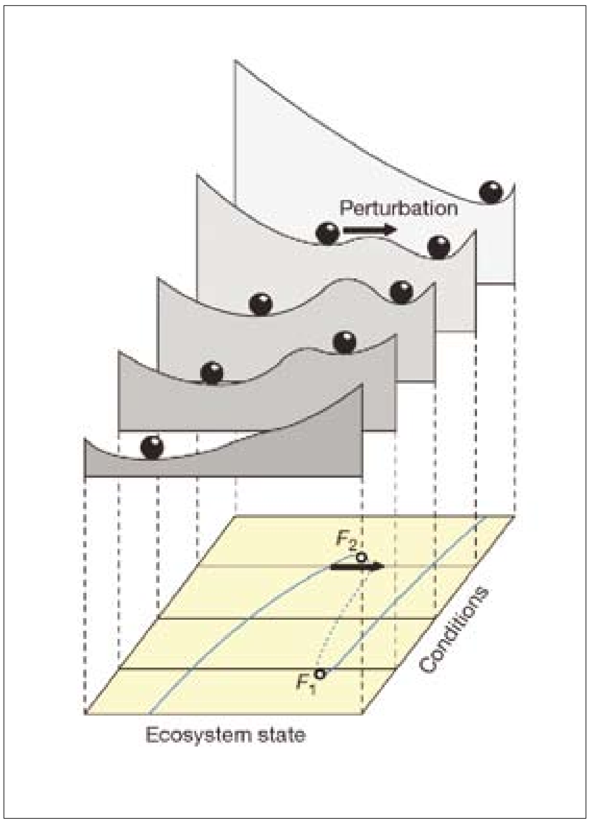


Figure 8-1: The multiple state ecosystem representation, Source Scheffer et al., 2001.

then Mediterranean, grassland, and savanna ecosystems may be exposed to the most severe losses due to the wide array of change factors. By the definitions used in this analysis, hot deserts are expected to see a relatively small change.

There are two important caveats to the Sala assertion. First, the nature of interactions amongst the drivers of biodiversity change are poorly understood and biodiversity may be shifted by only the most powerful driver amongst many, a combination of particular drivers, or a synergistic combination of many of the above. Secondly, it is feasible that a single driver of change could reach a critical tipping point, or threshold, and shift an ecosystem into a completely different functional type. The theory of a climate or disturbance induced threshold could be of particular importance in the UAE.

An ecological threshold has been defined as an “abrupt change in an ecosystem quality, property or phenomenon, or where small changes in an environmental driver produce larger responses in the ecosystem” (Groffman, *et al.*, 2006). The IPCC 4th Assessment report considers that "there may be critical thresholds beyond which some systems may not be able to adapt to changing climate conditions without radically altering their functional state and system integrity" (IPCC, 2007). Practically speaking, defining the criteria to reach a threshold is very difficult to determine: either it requires empirical evidence from similar systems which have undergone some threshold change, or a nearly flawless mechanistic model (a potentially unachievable gold standard).

The theory of whether distinct, quantifiable thresholds exist in complicated, natural ecosystems continues to be debated in the literature (Burkett *et al.,* 2005; Briske *et al.*, 2006; Groffman *et al.,* 2006), but there is general agreement that the concept is at least illustrative, if not functionally applicable in many circumstances. To be susceptible to threshold behavior, an ecosystem must have the potential to obtain multiple stable states. Ecosystems of all sizes are always in a state of flux, with various components continually recovering from disturbances; therefore, ecosystems do not simply obtain a 'climax', but may reach a stable equilibrium, in which the functional state of the system remains essentially the same despite disturbances. Some have described the steady state as a suite of positive and negative feedback loops, which balance to keep ecosystem function relatively constant (van de Koppel *et al.*, 1997).

In some cases, either extreme disturbances or (more often) chronic disturbances may be enough to either enhance a positive feedback cycle or attenuate a negative feedback cycle, and the state of the ecosystem shifts dramatically. The shift from one stable state to the next requires that the system be pushed past a particular threshold before settling into a new steady state (Scheffer *et al.*, 2001).

Current ecosystem theory suggests that multiple steady states can be envisioned in a three dimensional space (see Figure 8. 1) representing the ecosystem state and conditions on a flat plane, and a measure of ecosystem stability in the vertical plane (Scheffer *et al.*, 2001). The "ecosystem state" is simply the functional form of an ecosystem under a certain set of conditions. The conditions may include climate, chemical, and physical properties of the area. The line represented on the flat plane traces the region of maximum ecosystem stability, with two areas of "attraction" (labeled as F_1 and F_2).

Along the solid line, as conditions change smoothly, the state of the ecosystem changes smoothly. However, a significant perturbation in either the state or the ambient conditions may be enough to push the ecosystem into a new steady state. This shift could be both perceived and labeled as a catastrophic change. In this representation, the depth of the wells is a measure of the ecosystem's resistance to change (its intrinsic stability at particular conditions), while the steepness of the well walls represents the resilience of the ecosystem (given a disturbance, how likely is the ecosystem to return to its initial state).

In this case, resilience can be envisioned as the magnitude of a disturbance required to push the ecosystem into a new steady state (Carpenter *et al.*, 2001). In the context of climate change and biodiversity, climate change would be a shift in ambient conditions, driving the ecosystem through a smooth transition along a steady-state line. However, if land use change, habitat destruction, or pollution weakens resilience, it may be trivial to push an ecosystem into a new steady state.

A threshold could be crossed by stressing multiple state variables, or even a single important state variable such as climate change or precipitation availability. Changes in critical loadings, such as nutrients, temperature, or water availability can trigger a catastrophic change, and external anthropogenic forcing can also push a threshold envelope.

The concept of a threshold is a useful concept, yet may lack a specific application in real world management. Ecosystem models have been built to explore the nature of ecosystem equlbria, and in these process-based models, it is relatively trivial to simulate threshold behavior. Since even process-based models inevitably rely on some degree of empirical numerical estimations, thresholds are, to some degree, built into these models. However, in practice, it is difficult to define the boundaries of a natural ecosystem state and the contributing conditions such that a threshold can be quantitatively defined. To define a threshold effectively, either the behavior has to have been observed already in a similar ecotype, or the understanding of the

system across multiple spatial scales has to be so comprehensive that it is reasonably certain a threshold exists (Scheffer, 2001).

It is worth noting that in the literature, although ecosystems are described as having multiple steady states in almost all circumstances the alternative state is one of severe degradation relative to the original condition. So, for example, while a lake ecosystem can either persist as a clear water system with a diverse range of invertebrates, benthic life, and fish, or as a eutrophic, nutrient overloaded pool with heavy algal cover, clearly the original condition is preferred for biodiversity, function, and environmental quality.

8.2. Implications of climate change on UAE dryland ecosystems

The implications of climate change for the arid ecosystems of the UAE are several fold, and we explore several case examples in the next section. However, we can potentially state several widely applicable principles for ecosystem changes in hot, arid regions.

- **Increases in aridity and reductions in soil moisture:** In general, if precipitation remains low but both daytime and evening temperatures increase in the UAE, we would expect that soil moisture will decline significantly. The amount of moisture available to plants is a function of precipitation, infiltration into soils, and evapotranspiration, or the amount of water which evaporates from surfaces or is released by the stomata of plants. As temperatures increase, evapotranspiration rises, and soil moisture declines (Xu *et al.*, 2004). If precipitation events are more severe yet less frequent, we would expect more water to run off soil surfaces and thus remain unavailable to plants.

- **Narrower margin of semi-arid grasslands and scrublands:** The shift towards more arid soils will render it increasingly difficult for even highly drought-adapted plants to survive along desert margins. In the African Sahara, extended drought periods (decade-length, or longer), regularly extend sandy desert margins into previously productive landscapes (ref).

- **Mountaintop and wadi ecosystems reduced or disappear:** Similarly to desert margin ecosystems, both natural and managed ecosystems in Wadis and on mountains are at risk as temperatures rise and precipitation patterns change. In many parts of the world, species which survive on the mountains of arid regions persist because the mountains receive either marginally more precipitation, or have slightly cooler temperatures than lowlands. These so-called “sky-islands” are able to support a higher diversity of both plant and animal species, and many will be threatened by changes in climate. As global temperatures increase, the only available climatically acceptable area for these species will be at higher elevations, which almost always have less area available; if temperatures increase as dramatically as expected in some scenarios, many of these ecosystems will be displaced altogether (i.e. made locally extinct; Halpin, 1994). In seasonally moist wadis, a similar balance could be threatened by more intermittent runoff. Plants which require continual soil moisture could be exposed to extended droughts, and experience elevated rates of erosion as heavy precipitation floods these ecosystems.

- **Drylands shift towards invasive annuals or shrubby perennials:** Dryland ecosystems are highly responsive to the frequency and magnitude of rain pulses (Xu *et al.*, 2004; Huxman *et al.*, 2004; Sponseller, 2007). At the smallest of precipitation pulses, infiltration may not extend more than several millimeters into the soil, and can stimulate photosynthetic activity in biological soil crusts (an important micro-ecosystem of fungi, bacteria, and algae discussed in more depth later) while remaining ineffective in triggering growth in vascular plants. Annual grasses with dormant seed bank may germinate with heavy early-season precipitation, while the growth of perennial shrubs can be enhanced by sufficient mid-season rainfall (Huxman *et al.*, 2004). Shallow-rooting grasses are able to take advantage of short mid-season rain pulses as small as 5 mm (Sala and Lauenroth, 1982), while deeply rooted perennial shrubs rely on low-lying water reserves and larger precipitation events, but are able to withstand extended droughts. Once established, grasslands can become dominant through repeated brushfires, which destroy perennial shrubs.

Alternatively, established shrublands retain ecosystem dominance by using available water resources, and effectively pool nutrient resources in small concentrated areas. Depending on the rainfall regime (evenly distributed low intensity rainfall or infrequent high intensity rainstorms), we may expect to shift the dominance of grasses or shrubs in the semi-arid drylands of the UAE.

- **Shifts in phenology:** Annual patterns in the growth, flowering, and fruiting of flora and foraging, hibernation, and migration of fauna (all called phenology) are governed primarily by seasonal resource availability of light, temperature, and water. In the arid tropics, it is rare that biota are restricted by light availability or cool temperatures, but biotic patterns can often be dependent on seasonal water availability and excessive heat. For many desert plants, phenological cycles are timed to take maximum advantage of water availability and avoid heat stress. It is not uncommon to see short, intense bursts of growth during winter or spring rainy periods, plants distributing seeds or flowers immediately following the period of growth, and near or complete senescence by the onset of intense summer heat. One of the expected impacts of climate change throughout a wide range of biomes will be shifts in phenological cycles. In the UAE, these shifts may materialize in the form of either earlier or delayed spring growth periods as elastic plants adapt to changes in precipitation patterns. Amongst phenological researchers, there is significant concern that these changes in seasonal patterns may disrupt critical synchrony between co-dependent biota (Morisette *et al.*, 2008). For example, as the date of spring has advanced throughout the northern hemisphere due to warmer temperatures (Schwartz and Reiter, 2000), the annual abundance of insects which rely on early vegetation growth has correspondingly advanced as well. However, migratory birds which feed on these insects do not breed earlier, and correspondingly, population abundances have fallen in some species (Visser *et al.*, 1998). There is a significant risk that interdependent biota, particularly in the highly precipitation dependent UAE, will loose synchrony, impacting both local and migratory species.

8.3. Examples of climate change induced biodiversity thresholds in the UAE

There are significant uncertainties in predicting precipitation volumes and patterns with climate change in the Saudi Peninsula in general, and the UAE in particular (see IPCC, 2007). Models predict from 20% less to 10% more by 2050 and a gap as wide as 45% less to 22% more by 2100 (UAE, 2006b). Given the importance of rainfall intensity and timing as an ecological driver, it is unlikely that we can make a definitive assessment of potential environmental consequences due to climate change alone in the UAE.

However, we can explore dryland ecosystem vulnerabilities in the UAE that pertain to climate change, and heed lessons from other similar biomes which have been more extensively studied. In each of the four case studies which follow, we explore the potential for a threshold-type of ecosystem change, and its implications for biodiversity in the United Arab Emirates.

Avian migration and phenological change

Nearly 81% of listed higher vertebrate species in the Abu Dhabi Emirate are birds. Amongst the avian species are insectivores (such as larks), scavengers (buzzards and ravens), predators

and raptors (owls, eagles, and falcons), and a wide variety of herbivorous and wading water birds (ducks, plovers and terns). About 70% (271) of the avian species are land based birds, while the 30% (117) are water-based. Over 80% of the land birds, and 90% of the water birds are migratory.

Migrants in the Central Asian Flyway migrate from the UAE towards northern Central Asia in the spring, breed, and return to the UAE as a winter feeding ground (Central Asian Flyway, 2005). Long-distance migrants in the East African / West Asian Flyway are funneled over the Arabian Gulf and through the UAE as they pass from African wintering grounds to Asian and European breeding grounds. For wading water birds, the many lagoons, mud flats, khors and mangrove stands found along the Persian Gulf and the Gulf of Oman provide ideal feeding sites.

It is known that forage quality in wintering grounds is a critical predictor of survivorship for migratory bird species. In poor conditions, female birds are slow to depart for northern breeding grounds, and may not have enough energy to make the journey or arrive soon enough to breed and reproduce successfully (Marra *et al.*, 1998). Less well studied, but equally important, the quality of forage at stopover sites is critical for migrant's survival. The reproductive success of a migratory birds depends on critical habitat being available at the right time of year, a condition which could quickly be undermined with climatic change.

The phenology[1] of migratory birds is closely linked to the phenology of the sites these birds visit for winter feeding, summer breeding, and interseason passage. For some species, migration appears to be triggered by the state of vegetation at the site they are at (as the vegetation or forage quality declines, the birds depart), while for other species, migration is closely linked to a precise time of year. As the climate changes, there is a distinct risk (already seen in some well-studied species) that bird populations will increasingly migrate asynchronously with their food sources, arriving either well before or after peak available forage. For example, the Great Tit (*Parus major*) in the UK forages on caterpillars during its breeding period; however, caterpillar abundance follows the arrival of spring and has advanced by nearly 15 days over two decades as spring temperatures in the northern hemisphere rise. This migratory species breeds according to a photoperiod (daylength) signal, and appears to now be temporally mismatched, putting the population at significant risk (Visser *et al.*, 1998).

There is not necessarily a clear or predictable pattern to help determine if migrant species will be impacted by these timing changes. For example, Walther and colleagues (2002) found that short-distance migrants tended to trend towards earlier arrivals with changing climate, while late-arriving long-distance migrants either did not change arrival times or even delayed them. These phenological shifts may create a significant mismatch between peak forage availability and food demands. A more recent analysis attempted to generalize the impacts of climate change on multiple types of bird species, both migratory and resident; Sekercioglu and others (2004) suggest that under a business-as-usual climate change and land use practice scenario "by 2100, we expect 6-14% of all historic bird species to be extinct, 7-25% to be functionally extinct, and 13-52% to

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[1] Phenology: seasonal biotic patterns which follow abiotic phenomena

be functionally deficient. We project greater-than-average extinction rates to frugivores, herbivores, nectarivores, piscivores, and scavengers. Specialists are predicted to have more extinctions than average."

In the UAE, overwintering and stopover migrants are particularly at risk for loosing their food sources as climates shift. Species may have to cope with both reduced forage availability as well as reductions in forage area (coastal mangroves, mudflats, and natural dryland ecosystems).

Transitions between shrubs, grasses, invasives, and desert in savanna ecosystems

The low inland regions of the United Arab Emirates are dominated by large tracts of sand sheets and dunes, interrupted by strips of gravel plains and Sabkha salt flats. These dunes support a variety of plants and soil ecologies, which in turn support unique endemic fauna (Drew *et al*., 2003). Brown and Sakkir (2004) note that the arid lowland interior of the UAE can be considered two overlapping biogeographical zones: a narrow coastal belt of Nubo-Sindian (or Sudanian) semi-arid savanna, and an Arabian hyper-arid interior. The Arabian region is sparsely vegetated, but some legumous shrubs (i.e. *Medicago, Ononis*) and flowering annuals and herbs (i.e. *Spergularia, Silene, Astragalus, Calligonum*). The Sudanian belt has a significantly richer flora, including some trees (i.e. *Acacia tortilis, Prosopis cineraria or "Ghaf"*) numerous grasses (*Poaceae, Gramineae*), legumes (*Fabaceae*), sedges (*Cyperaceae*), and flowering annuals and perennials (*Asteraceae, Amaranthaceae*) (Brown and Sakkir, 2004). The boundaries between these zones, and even more subtle boundaries within the Sudanian coastal belt may be broadly attributable climatic differentiations.

Generally, the dominance of a particular community in an ecoregion is governed by the joint influences of climate (precipitation and temperature), light availability, soil substrate and nutrient availability, and land use. In the UAE, the zonal differentiation between the Sudanian coastal belt and the desert interior can widely

be defined climatically (Boer, 1997), although increasingly harsh land use practices along the coast may rapidly overtake contemporary climate as an ecosystem driver. In undisturbed savannas, the frequency and intensity of rainfall and temperature fluctuations drive the distribution of grasses, trees and shrublands. Land uses and disturbances add a level of complexity to the story: Grazing dynamics (both intensity and timing) can quickly shift can force semi-arid grasslands towards either shrub or grassy monocultures; fire frequency alters the balance of shrubs and grasslands; and human disturbances, such as road building and mineral extraction, commonly introduce exotic and invasive species. In the UAE, some exotics have been introduced for horticultural purposes (such as *Prosopis juliflora*, an acacia) and are spreading invasively (Essa *et al.,* 2006).

To date, the most significant threats to the dryland ecosystems of the UAE have been from land use and development practices: camel overgrazing of sensitive vegetation (Gallacher and Hill, 2008), rapid urban development (Brown *et al.,* 2004), and unchecked groundwater extraction (Zoebisch and DePauw, 2004; Brook *et al.,* 2005). However, changes in the already extreme climatic conditions of the UAE could significantly impact the already strained ecosystem. The semi-arid Sudanian coastal belt could see rainfall reductions, or shifts in intensity and timing, which could lead to shifts in the dominance of grasses, shrubs, and trees, or even a loss of biota altogether.

Many researchers (Ogle and Reynolds, 2004; van de Koppel *et al*, 2004; Holmgren, 2006) have found that in desert ecosystems, plant functional types respond to precipitation pulses differently: relatively small amounts of rainfall trigger growth and respiration in biological soil crusts at the top several centimeters of soil, while less common, but larger precipitation events trigger the growth of grasses and sedges. These grasses survive drought years by producing large seed stores in rainy years which then sprout in future rainy years.

Finally, rare heavy rainfall events can migrate through soils into groundwater and contribute to the growth of trees and shrubs with deep taproots. These shrubs survive drought through senesce and dormancy. However, extended droughts can begin to reduce the ability of even the most drought tolerant grasses to survive with no rainfall. Some arid systems (such as soil biota) have been shown to display a heartiness threshold, failing to thrive when temperatures increase without a concurrent increase in precipitation (respiration increases with temperature and a negative carbon balance leads to senescence; Xu *et al.,* 2004). Recent observations show that the Sahara desert was previously a wooded savanna ecosystem, which dried out significantly about 4,300 years ago, and then lost all vegetation cover approximately 2,700 years ago (Claussen *et al.,* 1999; Kröpelin *et al.,* 2008).

Increasing aridity, when coupled with intensive land use, is particularly damaging. In arid regions, herbivores play an important role in maintaining biodiversity and providing nutrients to soils, but in wet years, both native herbivores and livestock can increase dramatically, leading to overgrazing in following years (Holmgren, 2006). The Millennium Ecosystem Assessment on Desertification (MEA, 2005) suggests that transitions from low to high pressure grazing force a rapid transition from grasslands to shrublands, with a subsequent increase in erosion, loss of biodiversity, productivity, and ecosystem services, such as groundwater recharge. A potential climate-change induced threshold then may be induced by either a changing balance of temperature and precipitation, or relatively small changes in climate coupled with increasing land use and grazing pressures in the UAE.

8.4. Adaptation to climate change in drylands

The IPCC defines climate change adaptation as: 'Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities'. An alternative definition is offered in the inter-agency report, *Poverty and Climate Change*, as The ability to respond and adjust to actual or potential impacts of changing climate conditions in ways that moderate harm or take advantage of any positive opportunities that the climate may afford.

Adaptation can be planned or it can occur spontaneously through self-directed efforts (autonomous). Understanding these individual responses to changes in climate is particularly important. This section will cover both autonomous and planned adaptation to climate change.

Autonomous adaptation

Dryland are among the most resilient ecosystems to unfavorable climatic conditions. The seasonal and erratic pattern of rainfall, characterizing the drylands for example, has induced certain characters for dry land species e.g. having large below ground systems to store water and nutrient or corky bark to insulate living cells from desiccation and fire burning (Medina *et al*., 1992; SBSTTA, 1999). In the desert, many plants have developed interesting ways to survive the arid conditions. According to Western (1989), the number of plant species in UAE may range between 450-500 indigenous and introduced species. Many show interesting adaptations to high salt levels, high temperatures and low rainfall.

Plant species in the UAE could have a totally different appearance from plants in temperate countries. There fewer tall trees, some plants appear leafless, hairs and spines and prickles are more numerous, and flowers are often inconspicuous In some areas, dew is the only water that will reach ground level for most of the year and some plants make use of this source, often storing the water in succulent leaves. Other plant species has the ability to develop rapidly and complete their life cycle in a very short period of time. Some plants produce seeds that are able to survive long periods of drought and germinate only after sufficient rain. Some protect their seeds with older plant material and release them only after rain.

Subsequently, these plants develop quickly and their life cycles last only a few weeks and during this time they'll have to produce new seeds that will lie dormant until the next rain. Some 80 per cent of all plant species in the UAE appear to be winter annuals, having adjusted to a life cycle that takes advantage of the winter rain. Some of the perennial plants also depend on the relatively reliable rainfall.

Generally local habitat, especially soil conditions are vital in controlling individual species adaptations. Different parts of the plants have a role to play in adaptation and are specifically designed to make use of scarce water resources and minimize the exposure to high temperature, Examples for adaptation by different plant organs are as follows:

- **Root system:** Woody perennials such as trees usually have deep root systems. This is true of local species such as *Acacia tortilis, Prosopis cinerea* and the date palm *Phoenix dactylifera*. Young plants have longer roots than shoots to reach out for water.
- **Shoot system:** The dryland plants are always characterized by a short shoot, long root pattern – mostly in the ratio of 1: 6. Moreover, the shoot is usually hard and tough and may bear spines or prickles
- **Leaves:** An important adaptation in the dryland plants is the modification of their leaves- many develop very small, needle like leaves to reduce evapo-transpirations, others e.g. Salt-tolerant species, or halophytes, bear leaves which are globular, contain sap that can be used during long, dry summers. Moreover, they some are covered with an outer wax layer to prevent water loss. The amount of stored water varies but can be much more in terms of volume by night than by day. Hence many herbivore species such as camels and hares tend to be largely nocturnal in feeding habits.
- **Stems:** Some stems are much jointed which give much support against the blowing winds. Some Stems may be covered with dense hairs or spines to trap the water and prevent its evaporation.
- **Flowers:** The colour of flowers indicates the method o pollination. Desert plants which flower in the summer or autumn are more likely to be wind-pollinated because of a relative lack of suitable insect agents at that time of year. Exceptions are *Tribulus* species in the sands and *Capparis* species in the mountains, both of which bear large attractively-coloured flowers.
- **Photosynthesis:** A very unique adaptation is observed in some desert plants where the stomata close during day time and open by

night when gas interchanges take place, and water is used much more efficiently. The absorbed carbon dioxide is temporarily stored overnight and then transfused through the plant during the day while the stomata are closed. This phenomenon occurs in several common UAE species including *Portulaca oleracea, Aizoon canariehse* and *Citrullus colocynthis.*

Autonomous adaptation by Fauna

Desert ecosystem is home to a wide range of animals which are biologically adapted to extremely harsh climatic conditions and survive for long periods of time with little or no water. Most of the desert animals have autonomously developed adaptive strategies to their dry environment by e.g. "burrowing or spending long periods resting in holes well below the surface, while others move rapidly beneath the surface of uncompacted sand. Some possess hard or thorny skins. The camel is a typical animal which is the most adapted mammal to the desert conditions. With all his organs modified to store and efficiently utilize the water.

Planned Adaptation Strategies

Although ecosystems have adapted to changing conditions in the past, current changes are occurring at rates not seen historically, consequently, coping with future climate change will require effective adaptation in dryland areas. Throughout the UAE, significant effort has been expended toward afforestation and the construction of green areas. Such green tracts while conserving tree species, they provide shade and evaporative cooling effects, as well as some degree of protection from sandstorms for cities in the UAE (Salloum, 2001).

Adaptation efforts could include the expansion of these afforestation programs, with a significant focus on the more efficient use of water for tree and plant production. While green areas provide an invaluable service to dryland ecosystems and protection of the inhabited areas which they border, it is important to manage their development in a manner integrated with water resources to avoid competition between different uses.

Insitu conservation of species has also been planned in the Emirates. Based on Al-Abed and Hellyer (2001), adaptation efforts in shrubland and woodland areas, could be focused on the restoration and rehabilitation of impacted ecosystems. Currently only two protected areas, one terrestrial, Al Wathba Wetland Reserve, and the second marine reserves, Morrawah Marine Protected area, have been formally established through official decrees. Al Wathba, an inland wetland with an area of 4.9 km^2 was declared as protected area mainly to protect the breeding colony of the Greater Flamingo Phoenicopterus roseus, while the Morrawah Marine protected Areas (MMPA) covers 8 islands and intervening waters covering an area of 4255 km^2 and has been established to protect overall marine biodiversity including birds.

Two more protected areas, the Jebel Hafit National Park with a proposed area of about 96 km^2 and Umm az-Zamul National Park with an area of more than 10000 km^2 have been proposed. To provide protection for resident and migratory species of land birds such as Egyptian Vulture, Sand Partridge, Hoopoe Lark and the Golden Eagle (*Aquila chrysaetos*) and Eagle Owl. The proposed protected areas are expected to provide protection mainly from human interference and disturbance. However, more research and studies are needed to identify the impacts of climate change on different plant and animal species as well as their natural habitat, and to develop the appropriate adaptation measures. IUCN (2006) identified a number of measures that need to be implemented to increase the adaptation of mangroves to impacts of climate change including: restore degraded areas that have demonstrated resistance or resilience to climate change; understand and preserve connectivity between mangroves and sources of freshwater, establish baseline data and monitor the response of mangroves to climate change and to implement adaptive strategies to compensate for changes in species ranges and environmental conditions. According to IPCC-TAR, identifying peripheral species of interest and protecting their habit will likely enhance planned adaptation for natural ecosystems.

9. Modeling climate change impacts in the UAE

9.1 Ecosystem models: limited understanding, limitless possibilities

Much of our understanding of ecosystem structure and function today is derived from ecosystem models, driven by a variety of data types, from remote sensing to field observations to physical first principles, and operating at a wide range of complexities and scales, from global vegetation and climate coupled models to empirical observations of time series or processes at a single field site. Models have provided some of the best insights into how climate change might be expected to impact ecosystem structure and function.

There is no single clear definition for an "ecosystem model", as most are designed with specific questions in mind. For example, coupled climate-ecosystem models arose from the need to more accurately portray generic vegetation characteristics (such as evapotranspiration, albedo, and surface roughness) in global and regional climate models (Hurtt *et al.*, 1998), while empirically-based field models are used to explore explicit relationships such as the impact of changing groundwater or agricultural regimes on vegetation cover (Elmore *et al*., 2003; Elmore *et al*., 2006), the effect of seasonal temperature variations on vegetation phenology (Schaber and Badeck, 2003; Fisher *et al*., 2007), or the impact of rainfall frequency and abundance on carbon flux (Weltzin *et al*., 2003; Sponseller, 2007).

There are fundamental differences between models developed from field-based empirical data and those that attempt to work at larger regional or global scales. It is important to note even before our discussion of model potentials and fundamentals that ecosystem models are intrinsically limited by both available data, computational complexity, and in general by our imperfect knowledge of ecosystem processes. The study of ecology asks biologists to explore and understand data across a vast range of spatial and time scales, from photosynthetic reactions in individual leaf cells, to patterns of water distribution and disturbance across a landscape, to complex feedback cycles between vegetation and the atmosphere.

While there have been great insights at every level of study over recent decades, models still simplify processes by necessity, assuming relationships or causations when possible and not critical to the model outcome. The end result is that ecologists developing or applying ecosystem models usually start a modeling process by determining which fundamental sets of relationships can be fixed, and which need to be variables (and how these variables will be portrayed). Therefore, it has been nearly impossible, to date, to develop models which are both general and accurate across biomes. However, this is not to say that models have not yielded great steps forward in understanding ecosystem function and process.

A reasonably good rule of thumb for applying ecosystem models is that these systems should be used for exploring patterns and dynamics in a biome or region, but should not be counted on to provide predictive capacity in most situations. A model can help a scientist discern critical factors driving ecosystem change such as climate, land use, or disturbance (Veldkamp and Lambin, 2001), or assist a land manager in determining an appropriate timing or intensity of fire or grazing (Anderies *et al.,* 2002). Increasingly, models are being used to explore potential impacts of climate change, ecosystem vulnerabilities, and the developing field of "adaptive management", managing and modeling iteratively to achieve an ecosystem goal. Below, we describe some of the fundamental bounds and constructs of ecosystem models, and explore specific case examples in arid ecosystems.

Empirical or first principles? Top-down versus bottom-up models

Ecosystem models encompass a wide universe of possible model constructs, yet there are some useful first order classifications which can serve to clarify the philosophy behind the model, and how the model is ultimately used and interpreted. One of the most important classifying mechanisms is whether a model is based on a theoretical understanding of system dynamics (bottom-up) or if it is built on empirical observations (top-down).

Models built from the top down are more common, if only because the line between an experimental construct and a model is blurred when using empirical data. Empirical models can be as simple as deriving a function to describe a relationship through a set of variables, or can be as complex a system which predicts spatial patterns of vegetation under changing climate conditions (see the CASA model, below). Empirical models may be methods of interpreting or simplifying datasets with rich temporal or spatial information, such as long time series or satellite data; or may use dense datasets to compile statistical relationships, which may then be used for predictive purposes. The advantages of empirically-based models is that they can be relatively simple to construct and interpret, are often highly explicit in their assumptions, and, most importantly, are based directly on data.

Broadly, the bottom-up modeling approach relies on established theories on how individual components of an ecosystem operate at the micro-scale. These mechanistic models are often built to be as general as possible, such that they are not constrained by data (collected by fallible observers) or limited by the way communities and ecosystems are structured today. The point of these models is to explore relationships between ecosystem components and forcing factors, understand dynamics, and impose conditions on a simulated ecosystem which may not exist today. Some of the most developed versions of these models are able to predict the structure and function of major biomes from first principles (i.e. photosynthesis, respiration, and nutrient requirements), and are now being used to explore how climate change, land use, and disturbance may impact future biomes.

Model limitations

All ecosystem models are severely limited by scale, scope, and assumptions. Key aspects of each are briefly described below.

- **Scale:** The most fundamental processes in an ecosystem occur at micro-scales, where photosynthesis and respiration occur, nutrients are utilized, and water is cycled. There are, however, also important processes which happen at the scale of the leaf (for example, growth, senescence, shading, herbivory), the stem (individual mortality, light and water availability), the patch (disturbances), the community (competition), and the region (climate, light availability). The levels to which these processes are simulated are computationally and data limited, and many processes operate across scales.
- **Scope:** The broader a model strives to be, the more general its assumptions must become. To simulate a single type of biome effectively, one might choose to model or simulate a modest number of individual floristic species with known characteristics; to then include yet more diverse biomes in the model, one often has to reduce the level of detail down to functional plant types rather than individual species. Models which are global in scope often reduce plant types down to simple plant functional types which distinguish between physiognomy (tree or grass), leaf form (broadleaf or needle-leaf), leaf longevity (evergreen or deciduous), and photosynthetic pathway (C_3 or C_4) (i.e. Wang *et al*., 2004). Models which effectively capture global-scale dynamics may be ineffective or irrelevant for studies at the sub-biome scale.
- **Assumptions:** Every form of ecosystem model has (or should have) a well developed list of general assumptions. Empirical models, for example, often assume that relationships between correlated variables are causal, or at least replicable, and rarely model discrete pathways or mechanisms. First-principles (bottom-up) models are rarely entirely mechanistic: at some level, even the most rigorous models simplify processes and mechanisms with empirical relationships.

9.2 Types of ecosystem models

Ecosystem models span a wide range of functions, but several types may be useful for evaluating the impacts of climate change on ecosystems and biodiversity in the UAE.

First principles ecosystem models: potential vegetation and disturbance

Mechanistic models are designed to simulate the structure, function, and (sometimes) dynamics of ecosystems based on a "first principles" understanding of the components of the ecosystem. Exclusively, these models simulate and follow changes in vegetation composition only, and do not consider fauna, except occasionally as numerical agents of disturbance. The bottom-up approach is an effective way of exploring how a biome forms, and which climatic and competitive features drive the equilibrium composition of a biome.

There are no standard structures for mechanistic models, but many do share common features. The mechanistic component is usually a set of equations describing carbon balance (photosynthesis and respiration) with available light and water for a small variety of plant functional types (i.e. grasses, shrubs, trees, and deciduous and coniferous species). Various levels of sophistication in these models may describe important ecosystem components, depending on the question at hand:

- Water availability and transfer: water infiltration into the soil and uptake by roots (CARLUC, Hirsch *et al.,* 2004)
- Physical structures: tall trees deprive shorter shrubs and grasses of light (ED, Moorcroft *et al.,* 2001)
- Disturbances: fires, windstorms, and other destructive events (IBIS, Foley *et al.,* 1998; ED)
- Nutrient dynamics: available nitrogen in soils, roots, stems, and leaves (TEM, Tian *et al.*, 1998)
- Seasonality: changes in leaf density, senescence (CASA, Potter *et al.,* 2004)

These mechanistic models are useful for understanding how large scale changes in climate or other abiotic factors will change biome locations or biomass, or tracing complex feedback mechanisms (such as how shifts in vegetation abundance impact climate patterns, Wang *et al*., 2004). These models, however, are difficult to apply at small scales and lack the ability to discriminate changes in composition more detailed than basic functional types. In addition, mechanistic models can only describe a limited degree of complexity, and may neglect detailed, yet critical, interactions (such as nutrient or water flow between clustered shrubs and grasses in a semi-arid system, or different phenological responses to seasonality and drought).

This class of model may be useful in determining climate impacts on the UAE if the predominant question is in regard to biomass, ecosystem feedback cycles, or how an ecosystem might be structured in the UAE without an anthropogenic influence.

Bioclimatic envelope models

Bioclimatic envelope models are designed to explore how species ranges may shift in response to climate change. It has long been understood that climate (precipitation and temperature) strongly controls the ability of certain species and functional types to survive and thrive (Pearson and Dawson, 2003), and in fact, one of the central tenants of biogeographical niche theory is that an ecological niche can be defined by the environmental variables which affect a species. Major biomes, and even biogeographical boundaries within these biomes, are largely defined climatically. Individual species may have a narrow range of acceptable climates, or an envelope in which they are typically found (the "realized niche") or should be found based on known biological functions (the "fundamental niche"). Bioclimatic modeling asserts that we can anticipate the ecosystem impact of climate change on species ranges (at the regional scale) by determining the new bounds on bioclimatic envelopes.

Bioclimate envelope modeling suffers from at least three shortcomings (see Pearson and Dawson, 2003):

- **Competition:** how a species might thrive in an environment and how it actually interacts in its community can be very different; if a species is non-competitive within its climate envelope, it may not be found in the new environment.
- **Adaptation:** it may be more effective for a

species to adapt to a changing climate than for it to migrate and establish in a new physical location.

- **Species dispersal:** non-mobile species may be unable to migrate or disperse to new climatic zones, even over the course of many generations, while highly mobile species may be able to exploit much more of their fundamental climate range.

Empirically-based bioclimate models share an underlying methodology (Araujo *et al.*, 2005): the physical locations of a species is recorded over a wide range (as presence-absence), and climate variables are derived for all locations. Climate variables may include cooling or warming degree days, average temperature over a time-period, maximum or minimum temperatures during a critical period, number of days over a temperature threshold, volume of precipitation over a time-period, frequency of rainfall, and drought lengths. Using a variety of classification mechanisms (neural networks, statistical clustering, or decision trees), the variables (and their ranges) which best discriminate species presence or absence are determined on a subset of the data and 70% is a standard (Pearson and Dawson, 2003). The remaining data is used to validate the climate envelope assumptions. New climate variables are derived for a climate change scenario, and the derived rules are applied to the new variables to determine the potential species range.

This class of model may be useful in determining the impact of climate change in the UAE if the underlying question is in regard to expected new species ranges or biodiversity. These models require significant field and possibly remote sensing data to run successfully.

Patch structure and spatial distribution models

Patch structure and spatial distribution models have at least two distinct lineages, but have evolved to answer similar questions: how does the spatial structure of an ecosystem (usually at a landscape scale) impact the function and composition of the ecosystem? Similarly to the mechanistic models described above, these models are usually theoretically based and non site-specific, and usually track the dynamics of vegetation, rather than fauna.

Patch structure, or gap, models are derived from forest stand models, developed to estimate the rate of growth and height of trees in dense, light-limited environments (such as rainforests). These models simulate the light and water environment for individual stands of trees, and often explicitly model the shape, size, and leaf cover of each tree in the stand, using allometric equations to estimate leaf density, branch size, and tree height from more simply tracked metrics, such as stem width (Busing and Mailly, 2004). Important questions in these models revolve around how quickly gaps (treefalls) are replaced with new vegetation in certain environments.

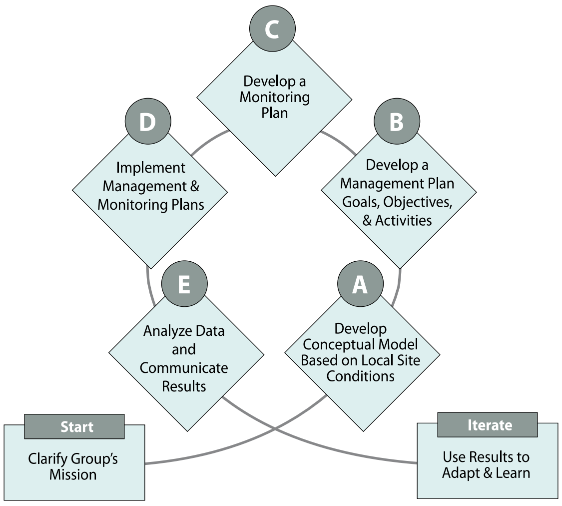
Spatial distribution models are systems developed to explore the dynamic systems in which physical proximity, rather than height, is important. Such models are often seen applied in arid or semi-arid ecosystems where nutrient and water availability are critical limiting factors. The distance between shrubs or clumps of grasses may determine how much water is available to individual plants, how water is transferred between plants, or where pools of nutrients are available. Spatial distribution models may be combined with grazing or fire simulations to determine how herbivory and disturbance changes the structure, health, or composition of sparsely vegetated landscapes (i.e. van de Koppel and Rietkerk, 2004; Adler *et al.*, 2001; Weber *et al.*, 1998; Aguiar and Sala, 1999)

This class of model may be useful in determining the impact of climate change in the UAE in the context of evaluating both precipitation frequency and intensity influence on ecosystem composition, and grazing impacts, primarily by camels, on arid ecosystem health.

Climate / phenology models

Climate-phenology models are a distinct and unique class of model, usually empirically based, which strive to understand the drivers of seasonality of flora and fauna. Many of these models relate various climate factors (temperature, precipitation, and available sunlight at key times of the year) to the timing of leaf development, fruiting, and senescence, or less often, the timing of migration or breeding success for various fauna. In light and temperature limited ecosystems (such as temperate and arctic forests), these models use long time series or large spatial datasets to derive a series of climate forcing factors which appear to trigger changes in phenology (see Schwartz, 1998 and Zhang *et al*., 2003, respectively). These models may be structured similarly to the bioclimatic models described previously, but rather than tracking the spatial presence or absence of a particular species, they track the timing of specific phenological phenomena.

This class of model is widely applied in ecosystems where a gradient of climatic phenomena creates a gradient of ecosystem response (such as in temperate forests in relation to temperature). However, climate-phenology models may prove to be highly important in determining the impact of climate change in the UAE when examining potential asynchrony between symbiotic species (i.e. if insects which feed on developing plants are unavailable as a food source to migrating birds at the time when the birds require it, the bird population could be put at risk; Beaumont *et al*., 2006).



Source: Adapted from Margoluis & Salafsky 1998

Figure 9-1. The adaptive management cycle Source Frankin et al., 2007.

9.3 Examples of applied ecosystem models in arid environments

Modeling for climate change impact assessment

The arid Great Basin in the southwest United States supports extensive perennial grasslands and shrubs, and for decades has provided a rich grazing resource for cattle ranchers throughout the country. In the mid-1800's, Cheatgrass (*Bromus tectorum*) was accidentally introduced from Asia. B. *tectorum* is an invasive species in the Great Basin, and the annual is highly adapted to semi-arid to arid environments. The grass is not palatable to livestock and is able to compete effectively with both native grasses and shrubs. It grows earlier than native grasses, depriving them of nutrients, water, and light. In rainy years, B. *tectorum* can quickly grow several feet in height, after which it is extremely fire prone. Raging brush fires through large tracts of B. tectorum destroy most native shrubs and singe the surface of the soil, inhibiting the growth of other species. It is not uncommon to see large tracts of B. tectorum monoculture throughout the Great Basin.

Bradley and Wilcove (2008) explored the dynamics of B. tectorum in a bioclimatic model. Tracts of cheatgrass were identified using a remote sensing technique, and climatic information was pulled together from a high resolution climate dataset (4.5 km resolution). The researchers used an automated mechanism to determine the smallest set of explanatory climate variables, which ultimately included average precipitation from June to September (summer to senescence), annual average precipitation, precipitation from April to May (spring), and average temperature from December to February (winter). Using a climate model (GFDL2.1) with a CO_2 doubling scenario (720 ppm by 2100, SRESA1B), the researchers determined how the climate variables would change by 2100 and determined if and where B. tectorum would occur in the future climate. The researchers determined that cheatgrass would become less viable in 50% of its current area, but might invade specific new areas north of its current range. As a result, the team suggested that remediation steps begin soon to reduce the invasion probability.

Modeling to understand vulnerabilities

In 1998, a team from the University of Wisconsin demonstrated a successful coupling between a rigorous atmospheric transport model (GENESIS) and an ecosystem model (IBIS) to explore dynamics between vegetation cover and climatic variability (Foley *et al.,* 1998). This effort was a first attempt to create a comprehensive ecosystem model which would come to equilibrium on its own by cycling through feedback loops between vegetation and the atmosphere. Although in error, the model indicated that increasing vegetation throughout the African Sahel and the Arabian peninsula would lead to cooler temperatures, and subsequently more precipitation and denser vegetation.

This observation was further explored by Wang *et al*. (2006) where, using an improved version of the GENESIS-IBIS model, the researchers found that seasonal vegetation dynamics in the Sahel enhance the severity of multi-decadal droughts. The results found that if vegetation was allowed to persist naturally in the Sahel, droughts may be less severe. However, intensive land use and vegetation losses in the African Sahel may have brought about a more persistent drought than would otherwise be expected.

Modeling for adaptive management

Adaptive management is a technique of iteratively managing ecosystems for conservation goals and checking to ensure that benchmarks and goals are met on a regular basis, adjusting management techniques where necessary to achieve the goal. The system incorporates modeling explicitly as a management and benchmarking tool. Franklin *et al.,* (2007) describes the process of creating an adaptive management program and its application to controlling Bromus tectorum in the Western US (see above for details).

An adaptive management program comprises several iterative steps (see Figure 4). First, a conservation goal is set, such as the preservation of a specific species or community, or establishment of a rare species, or the preservation of a certain type of biodiversity in a specific system. Secondly, a detailed model of the specific ecosystem is created which incorporates critical components of both management and naturally occurring processes. Third, a management plan is developed from the results of the model, and a monitoring plan is developed to independently test hypotheses posed in the management plan. The management plan is then implemented, and results are regularly checked against benchmarked goals and hypotheses. New information learned from the management process is incorporated into the next model, and the entire process is iterated. The goal of the adaptive management process is to use the management as a natural experiment, in which a vetted, hypothesized management plan is tested and the results used to craft the next iteration of the management plan.

Frankin *et al*. (2007) describes a case study of an adaptive management program in the state of Wyoming in western United States designed to control B. tectorum. In this program, a non-profit organization developed several “treatments” to control cheatgrass, and designated small portions of a prairie reserve into experimental areas to test the various management techniques, including burning, applying herbicides, grazing, and planting native grasses. In each region, the managers tested for biodiversity, bird density, and habitat use to determine the efficacy of the treatment.

Similarly, a federal program to control cheatgrass in a major US National Park in the arid southwest (Mesa Verde) used modeling to explore how changing fire patterns might either inhibit or enhance the rate of invasion by B. tectorum (Romme *et al.,* 2006). The project employed the SIMPPLLE (Simulating Vegetation Patterns and Processes at Landscape Scales) model to estimate how different fires might change vegetation outcomes. The model results are guiding fire management procedures in the park.

9.4 Next steps for modeling and data collection in the UAE

One of the most promising approaches for comprehensively understanding and then managing for climate change impacts in the United Arab Emirates is to employ the data collection, assessment, management, and monitoring techniques of the adaptive management framework (see Franklin *et al.*, 2007). While not directing a specific course of action, the framework asks for concerned stakeholders to first and foremost identify the goal of both ecosystem study and management, and create a monitoring and assessment system such that both current and future managers can learn from both successes and inevitable failures as the goal is pursued.

Development of baseline datasets

In nearly every circumstance, unless the only goal of ecosystem management is to create an aesthetically pleasing environment, it is critical to lay a foundation of data and basic environmental science in the region. To date, there are few enviromental studies available regarding the UAE's ecosystems, which means that there is little substrate to develop well informed management practices. State agencies have compiled diversity surveys, but there are few comprehensive sources describing such fundamentals as biogeography, species abundance, or biodiversity hotspots. Basic informative and widely accessible datasets would ideally include:

- Species or community maps of ecosystems throughout the UAE and surrounding regions, in a georeferenced digital form;
- Biogeographical surveys describing dominant biomes in the UAE and their basic structures, functions, and vulnerabilities;
- Climatic maps and datasets, indicating patterns of precipitation and seasonal temperatures;
- Soils and groundwater assessments to map surface features and plant-available moisture and groundwater;
- Topographic maps;
- Important migratory routes;
- Land use maps indicating urban and urban-zoned areas, agricultural regions, reserves and parks.

Development of essential environmental studies

From this initial literature survey, it is unclear what, if any, threat climate change poses to the dryland ecosystems of the United Arab Emirates. It is apparent that land use practices, invasive species, intensive grazing, and groundwater extraction may pose a more immediate danger, but the relative magnitudes of these natural and anthropogenic disturbances are unclear. The UAE would benefit from a significant investment in basic ecosystem and climate studies to better understand the various components of change in the region. Potential studies could include:

- Expected climate change in the biomes of the UAE at a fine spatial scale as well as model and data uncertainties;
- Which factors determine biogeographical boundaries in the UAE;
- The impact of grazing pressures on groundwater, soil moisture, and ecosystem structure;
- Expected land use changes and urban development over the next decades, and the effect of various land use practices on landscape health, biodiversity, and species abundance;
- How vegetation responds to interannual variability in the UAE's climate;
- How migratory species respond to interannual variability in the UAE's climate;

The UAE sits at a the confluence of three distinctly different ecoregions. With floral and faunal influences from Africa, East Asia, and the Middle East, the UAE and the Arabian peninsula harbor a unique biodiversity and critical habitats. There is a potential to understand this relatively poorly characterized landscape, to learn about what may be in store for arid regions of the world.

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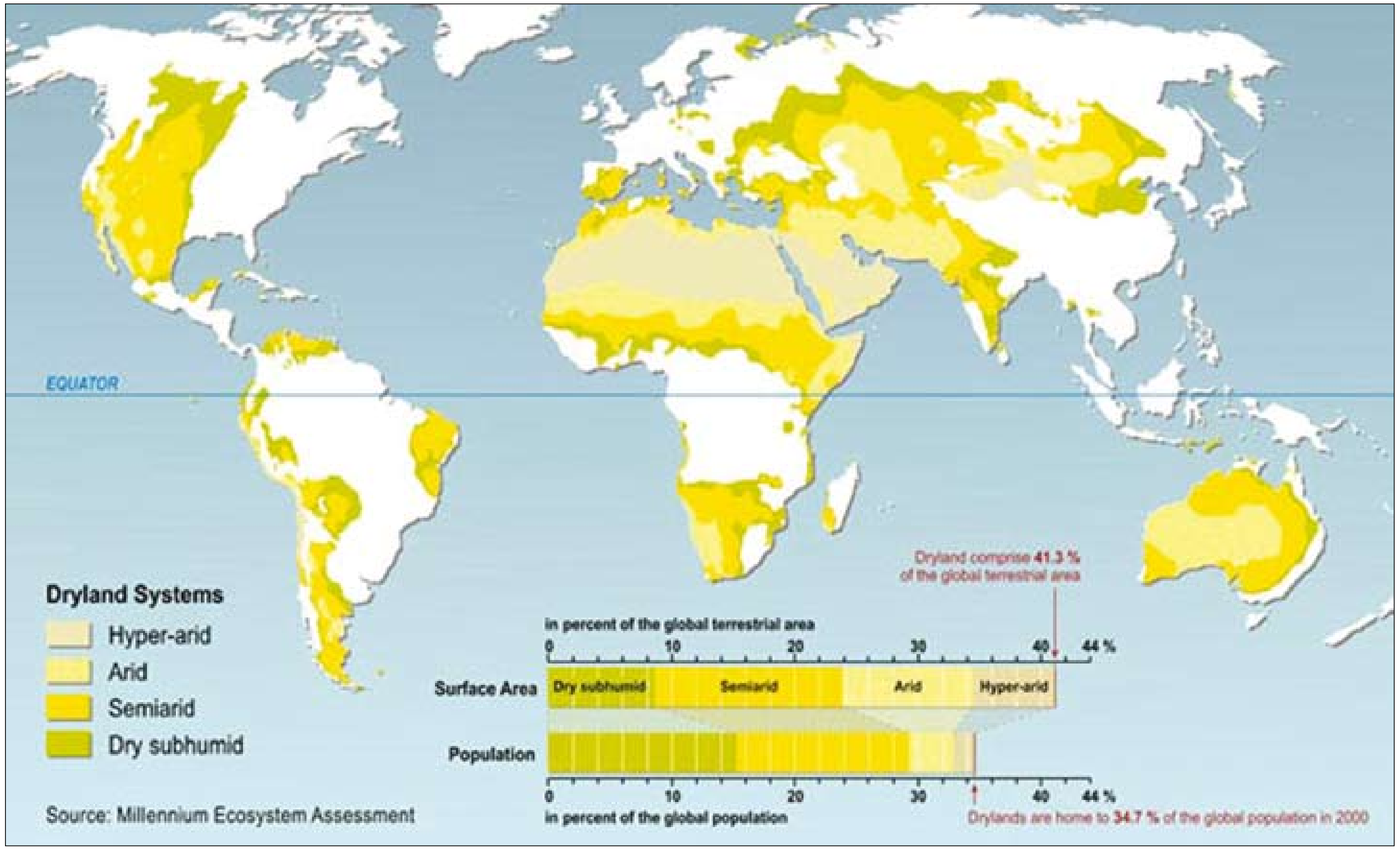
Annex 1: Global vulnerable area

Note that the vulnerable areas are mostly in mid-latitudes near 30 degrees of latitude.

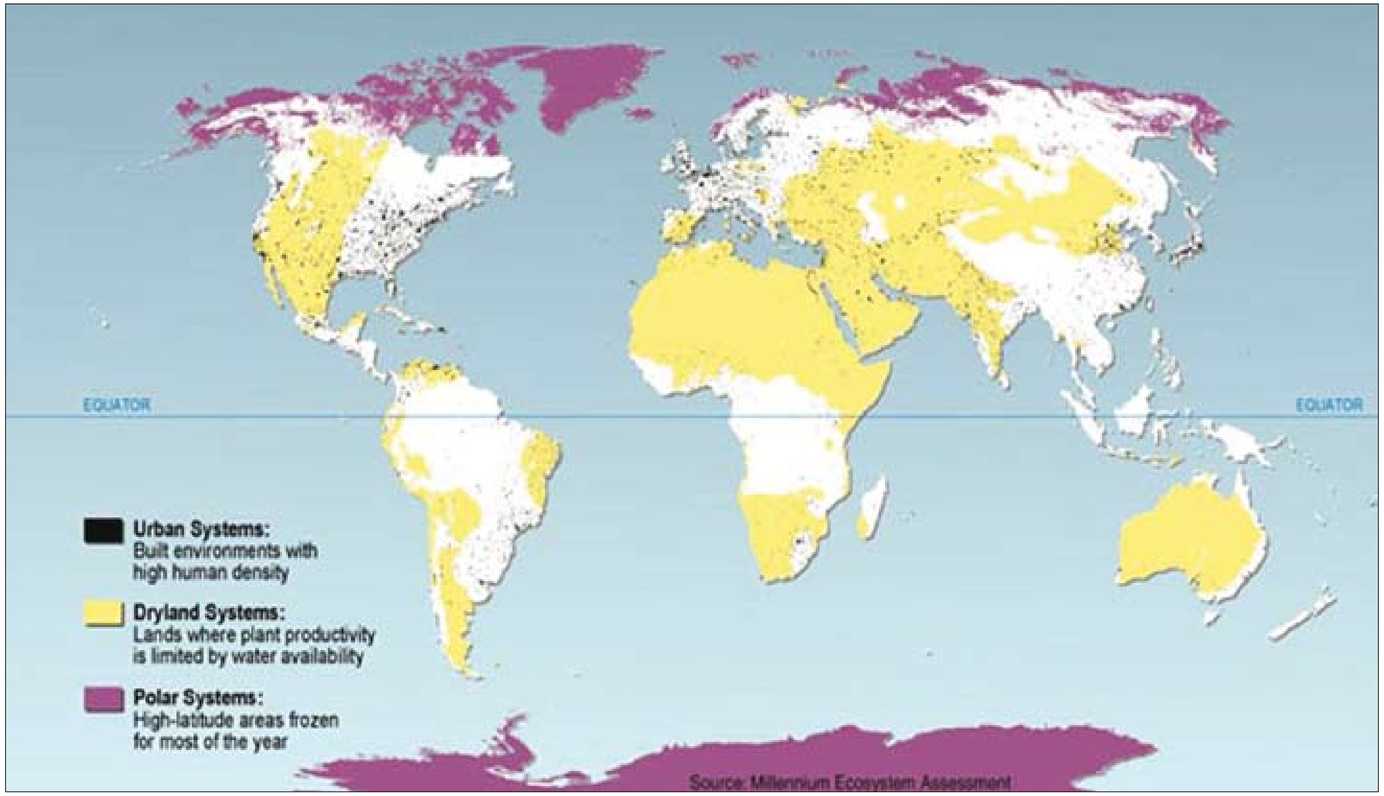


Source: Millennium Ecosystem Assessment

Annex 2: Expected effects of global warming on Asia

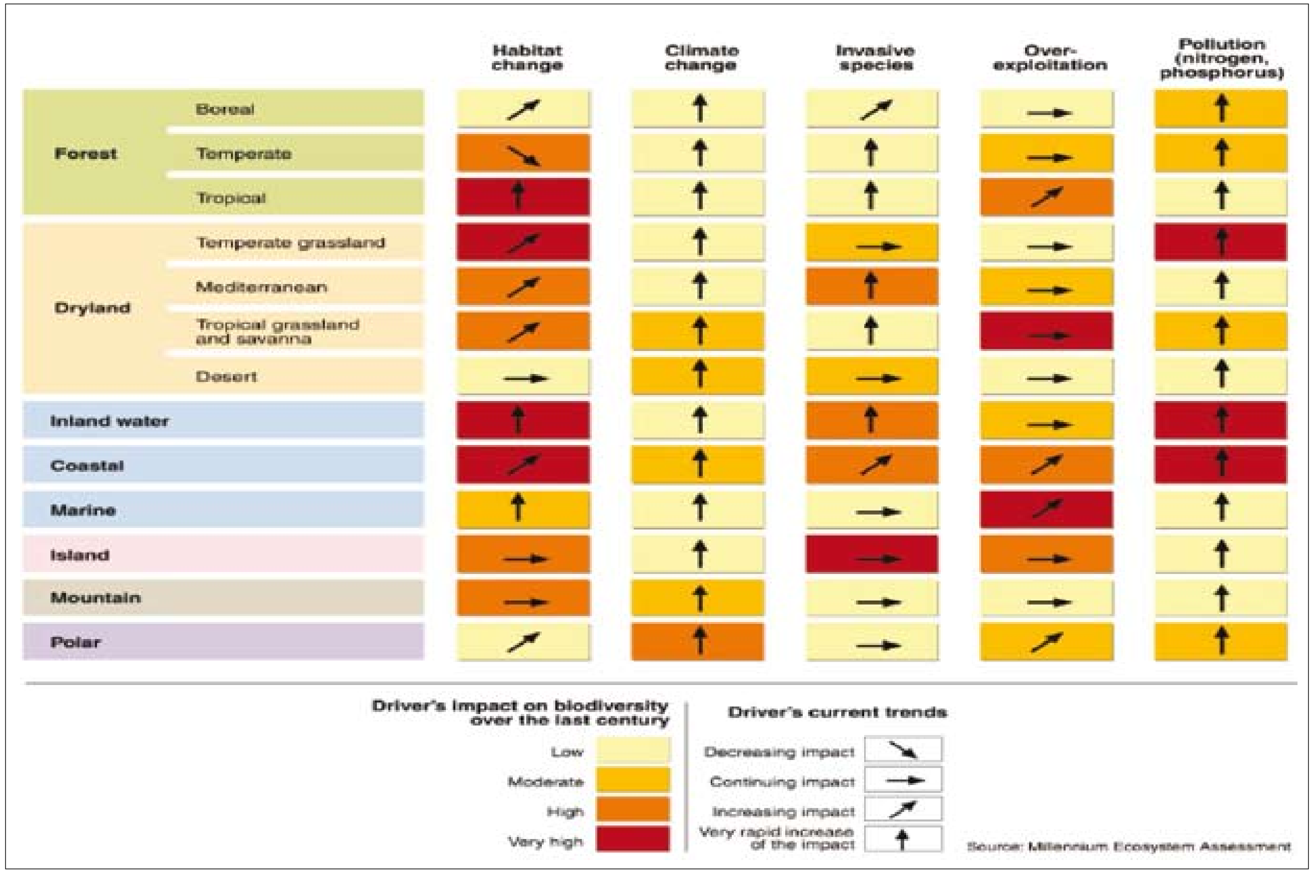
- Glacier melt in the Himalayas is projected to increase flooding, rock avalanches from destabilised slopes, and affect water resources within the next two to three decades. This will be followed by decreased river flows as the glaciers recede.
- Freshwater availability in Central, South, East and Southeast Asia particularly in large river basins is projected to decrease due to climate change which, along with population growth and increasing demand arising from higher standards of living, could adversely affect more than a billion people by the 2050s.
- Coastal areas, especially heavily-populated mega-delta regions in South, East and Southeast Asia, will be at greatest risk due to increased flooding from the sea and in some mega-deltas flooding from the rivers.
- Climate change is projected to impinge on sustainable development of most developing countries of Asia as it compounds the pressures on natural resources and the environment associated with rapid urbanizations, industrialisation, and economic development.
- It is projected that crop yields could increase up to 20% in East and Southeast Asia while it could decrease up to 30% in Central and South Asia by the mid-21st century. Taken together and considering the influence of rapid population growth and urbanization, the risk of hunger is projected to remain very high in several developing countries.
- Endemic morbidity and mortality due to diarrhoeal disease primarily associated with floods and droughts are expected to rise in East, South and Southeast Asia due to projected changes in hydrological cycle associated with global warming. Increases in coastal water temperature would exacerbate the abundance and/or toxicity of cholera in South Asia.

Annex 3: Main urban settlements in dryland areas



Source: Millennium Ecosystem Assessment

Annex 4: Main drivers of ecosystem change



		Habitat change	Climate change	Invasive species	Over-exploitation	Pollution (nitrogen, phosphorus)
Forest	Boreal	🟨 ↗	🟨 ↑	🟨 ↗	🟨 →	🟧 ↑
	Temperate	🔶 ↘	🟨 ↑	🟨 ↑	🟧 →	🟧 ↑
	Tropical	🟥 ↑	🟨 ↑	🟨 ↑	🔶 ↗	🟨 ↑
Dryland	Temperate grassland	🟥 ↗	🟨 ↑	🟧 →	🟨 →	🟥 ↑
	Mediterranean	🔶 ↗	🟨 ↑	🔶 ↑	🟧 →	🟨 ↑
	Tropical grassland and savanna	🔶 ↗	🟧 ↑	🟨 ↑	🟥 →	🟧 ↑
	Desert	🟨 →	🟧 ↑	🟧 →	🟨 →	🟨 ↑
Inland water		🟥 ↑	🟨 ↑	🔶 ↑	🟧 →	🟥 ↑
Coastal		🟥 ↗	🟧 ↑	🔶 ↗	🔶 ↗	🟥 ↑
Marine		🟧 ↑	🟨 ↑	🟨 →	🟥 ↗	🟨 ↑
Island		🔶 →	🟨 ↑	🟥 →	🔶 →	🟨 ↑
Mountain		🔶 →	🟧 ↑	🟨 →	🟨 →	🟨 ↑
Polar		🟨 ↗	🔶 ↑	🟨 →	🟧 ↗	🟧 ↑

Driver's impact on biodiversity over the last century

Low	🟨
Moderate	🟧
High	🔶
Very high	🟥

Driver's current trends

Decreasing impact	↘
Continuing impact	→
Increasing impact	↗
Very rapid increase of the impact	↑

Source: Millennium Ecosystem Assessment

Annex 5: List of regular wintering and breeding water birds in the United Arab Emirates

Sn	Species	Scientific name	Family	Status	Remarks
1	Little Grebe	*Tachybaptus ruficollis*	Podicipedidae	Breeder	Resident breeding species
2	Great Crested Grebe	*Podiceps cristatus*	Podicipedidae	Migrant	Rare Migrant
3	Black-necked Grebe	*Podiceps nigricollis*	Podicipedidae	Migrant	Winter Migrant, Occasional breeder
4	Wilson>s Storm Petrel	*Oceanites oceanicus*	Hydrobatidae	Migrant	Summer & Winter visitor
5	Red-billed Tropicbird	*Phaethon aethereus*	Phaethontidae	Breeder	Localised breeder; post-breeding dispersal
6	Socotra Cormorant	*Phalacrocorax nigrogularis*	Phalcrocoracidae	Breeder	Post breeding dispersal
7	Great Cormorant	*Phalacrocorax carbo*	Phalcrocoracidae	Migrant	Common winter migrant
8	Night Heron	*Nycticorax nycticorax*	Ardeidae	Migrant	Passage / winter migrant; occasional breeding
9	Striated Heron	*Butorides striatus*	Ardeidae	Breeder	Resident
10	Western Reef Heron	*Egretta gularis*	Ardeidae	Breeder	A common resident breeding species
11	Little Bittern	*Ixobrychus minutus*	Ardeidae	Migrant	Regular migrant
12	Bittern	*Botaurus stellaris*	Ardeidae	Migrant	Uncommon winter migrant
13	Squacco Heron	*Ardeola ralloides*	Ardeidae	Migrant	Regular passage migrant
14	Indian Pond Heron	*Ardeola grayii*	Ardeidae	Migrant	Regular non-breeding migrant
15	Cattle Egret	*Bubulcus ibis*	Ardeidae	Migrant	Common winter migrant
16	Little Egret	*Egretta garzetta*	Ardeidae	Migrant	Common passage migrant
17	Great Egret	*Egretta alba*	Ardeidae	Migrant	Uncommon passage migrant
18	Grey Heron	*Ardea cinerea*	Ardeidae	Migrant	Common winter migrant
19	Purple Heron	*Ardea purpurea*	Ardeidae	Migrant	Common passage migrant
20	White Stork	*Ciconia ciconia*	Ciconiidae	Migrant	Uncommon passage migrant
21	Glossy Ibis	*Plegadis falcinellus*	Threskiornithidae	Migrant	Uncommon passage migrant
22	Spoonbill	*Platalea leucorodia*	Threskiornithidae	Migrant	Winter migrant
23	Greater Flamingo	*Phoenicopterus ruber*	Phoenicopteridae	Migrant	Passaga and winter migrant with some resident birds
24	Mallard	*Anas platyrhynchos*	Anatidae	Migrant	Common winter migrant
25	Greylag Goose	*Anser anser*	Anatidae	Migrant	Uncommon winter migrant
26	Ruddy Shelduck	*Tadorna ferruginea*	Anatidae	Migrant	Uncommon winter migrant
27	Shelduck	*Tadorna tadorna*	Anatidae	Migrant	Winter migrant, localised

Sn	Species	Scientific name	Family	Status	Remarks
28	Wigeon	*Anas penelope*	Anatidae	Migrant	Regular winter migrant
29	Gadwall	*Anas strepera*	Anatidae	Migrant	Uncommon winter migrant
30	Teal	*Anas crecca*	Anatidae	Migrant	Common winter migrant
31	Pintail	*Anas acuta*	Anatidae	Migrant	Common winter migrant
32	Garganey	*Anas querquedula*	Anatidae	Migrant	Common passage migrant
33	Shoveler	*Anas clypeata*	Anatidae	Migrant	Common winter migrant
34	Pochard	*Aythya ferina*	Anatidae	Migrant	Localised winter migrant
35	Ferruginous Duck	*Aythya nyroca*	Anatidae	Migrant	Scarce winter migrant
36	Tufted Duck	*Aythya fuligula*	Anatidae	Migrant	Uncommon
37	Moorhen	*Gallinula chloropus*	Rallidae	Migrant	Migrant with some resident breeding birds
38	Spotted Crake	*Porzana porzana*	Rallidae	Migrant	Regular passage migrant
39	Little Crake	*Porzana parva*	Rallidae	Migrant	Rare passage migrant
40	Baillon>s Crake	*Porzana pusilla*	Rallidae	Migrant	Rare passage migrant
41	Corn Crake	*Crex crex*	Rallidae	Migrant	Rare passage migrant
42	White-breasted Waterhen	*Amuarornis phoenicurus*	Rallidae	Migrant	Rare winter migrant
43	Purple Gallinule	*Porphyrio porphyrio*	Rallidae	Migrant	Rare winter migrant
44	Coot	*Fulica atra*	Rallidae	Migrant	Localised winter migrant
45	Red-knobbed Coot	*Fulica cristata*	Rallidae	Migrant	Rare winter migrant
46	Water Rail	*Rallus aquaticus*	Rallidae	Migrant	Scarce winter migrant
47	Black winged Stilt	*Himantopus himantopus*	Recurvirostridae	Breeder	Common resident, some local movement
48	Avocet	*Recurvirostra avosetta*	Recurvirostridae	Migrant	Irregular migrant with some breeding birds
49	Oystercatcher	*Haematopus ostralegus*	Haematopodidae	Migrant	Common winter migrant
50	Crab Plover	*Dromas ardeola*	Dromadidae	Breeder	Resident, post breeding dispersal and winter influx
51	Collared Pratincole	*Glareola pratincola*	Glareolidae	Migrant	Regular autumn migrant
52	Oriental Pratincole	*Glareola maldivarum*	Glareolidae	Migrant	Rare autumn migrant
53	Red-wattled Lapwing	*Vanellus indicus*	Charadriidae	Breeder;	Migrant and some breeding regularly
54	Kentish Plover	*Charadrius alexandrinus*	Charadriidae	Breeder	Common resident; winter migrant
55	White-tailed Plover	*Vanellus leucurus*	Charadriidae	Migrant	Regular winter migrant; occasional breeder
56	Little Ringed Plover	*Charadrius dubius*	Charadriidae	Breeder	Passage migrant; breeding summer migrant
57	Ringed Plover	*Charadrius hiaticula*	Charadriidae	Migrant	Common migrant
58	Lesser Sand Plover	*Charadrius mongolus*	Charadriidae	Migrant	Common winter migrant

Sn	Species	Scientific name	Family	Status	Remarks
59	Greater Sand Plover	*Charadrius leschenaultii*	Charadriidae	Migrant	Common winter migrant
60	Caspian Plover	*Charadrius asiaticus*	Charadriidae	Migrant	Uncommon passage migrant
61	Dotterel	*Eudromias morinellus*	Charadriidae	Migrant	Rare autumn migrant
62	Pacific Golden Plover	*Pluvialis fulva*	Charadriidae	Migrant	Regular winter migrant
63	Grey Plover	*Pluvialis squatarola*	Charadriidae	Migrant	Common winter migrant
64	Lapwing	*Vanellus vanellus*	Charadriidae	Migrant	Rare winter migrant
65	Great Knot	*Calidris tenuirostris*	Scolopacidae	Migrant	Winter migrant
66	Sanderling	*Calidris alba*	Scolopacidae	Migrant	Common winter migrant
67	Little Stint	*Calidris minuta*	Scolopacidae	Migrant	Common winter migrant
68	Temminck>s Stint	*Calidris temminckii*	Scolopacidae	Migrant	Regular winter migrant
69	Long toed Stint	*Calidris subminuta*	Scolopacidae	Migrant	Rare passage migrant
70	Curlew Sandpiper	*Calidris ferruginea*	Scolopacidae	Migrant	Common winter migrant
71	Dunlin	*Calidris alpina*	Scolopacidae	Migrant	Common winter migrant
72	Broad-billed Sandpiper	*Limicola falcinellus*	Scolopacidae	Migrant	Regular winter migrant
73	Ruff	*Philomachus pugnax*	Scolopacidae	Migrant	Common winter migrant
74	Jack Snipe	*Lymnocryptes minimus*	Scolopacidae	Migrant	Rare
75	Snipe	*Gallinago gallinago*	Scolopacidae	Migrant	Common winter migrant
76	Great Snipe	*Gallinago media*	Scolopacidae	Migrant	Rare passage migrant
77	Pintail Snipe	*Gallinago stenura*	Scolopacidae	Migrant	Localised winter migrant
78	Black-tailed Godwit	*Limosa limosa*	Scolopacidae	Migrant	Localised winter migrant
79	Bar-tailed Godwit	*Limosa lapponica*	Scolopacidae	Migrant	Common winter migrant
80	Whimbrel	*Numenius phaeopus*	Scolopacidae	Migrant	Common winter migrant
81	Curlew	*Numenius arquata*	Scolopacidae	Migrant	Common winter migrant
82	Spotted Redshank	*Tringa erythropus*	Scolopacidae	Migrant	Scarce winter migrant
83	Redshank	*Tringa totanus*	Scolopacidae	Migrant	Common winter migrant
84	Marsh Sandpiper	*Tringa stagnatilis*	Scolopacidae	Migrant	Uncommon winter migrant
85	Greenshank	*Tringa nebularia*	Scolopacidae	Migrant	Common winter migrant
86	Green Sandpiper	*Tringa ochropus*	Scolopacidae	Migrant	Common winter migrant
87	Wood Sandpiper	*Tringa glareola*	Scolopacidae	Migrant	Common winter migrant
88	Terek Sandpiper	*Tringa cinerea*	Scolopacidae	Migrant	Common winter migrant

Sn	Species	Scientific name	Family	Status	Remarks
89	Common Sandpiper	*Tringa hypoleucos*	Scolopacidae	Migrant	Common winter migrant
90	Turnstone	*Arenaria interpres*	Scolopacidae	Migrant	Common winter migrant
91	Red-necked Phalarope	*Phalaropus lobatus*	Scolopacidae	Migrant	Common winter migrant
92	Grey Phalarope	*Phalaropus fulicarius*	Scolopacidae	Migrant	Scarce winter migrant
93	Sooty Gull	*Larus hemprichii*	Laridae	Breeder	Common
94	Pomarine Skua	*Stercorarius pomarinus*	Stercorariidae	Migrant	Common passage migrant
95	Arctic Skua	*Stercorarius parasiticus*	Stercorariidae	Migrant	Uncommon passage migrant
96	Great Black-headed Gull	*Larus ichthyaetus*	Laridae	Migrant	Uncommon winter migrant
97	Black-headed Gull	*Larus ridibundus*	Laridae	Migrant	Common winter migrant
98	Brown-headed Gull	*Larus brunnicephalus*	Laridae	Migrant	Uncommon winter migrant
99	Slender-billed Gull	*Larus genei*	Laridae	Migrant	Common winter migrant
100	Common Gull	*Larus canus*	Laridae	Migrant	Rare winter migrant
101	Lesser Black-backed (Baltic) Gull	*Larus fuscus*	Laridae	Migrant	Uncommon winter migrant
102	Siberian Gull	*Larus heuglini*	Laridae	Migrant	Common passage migrant
103	Caspian Gull	*Larus cachinnans*	Laridae	Migrant	Common winter migrant
104	Lesser Crested Tern	*Sterna bengalensis*	Sternidae	Breeder	Summer breeding visitor
105	Caspian Tern	*Sterna caspia*	Sternidae	Breeder	winter migrant; passage migrant; some breed in country
106	Swift (Crested) Tern	*Sterna bergii*	Sternidae	Breeder	Migrant breeder
107	White-cheeked Tern	*Sterna repressa*	Sternidae	Breeder	Migrant breeder
108	Bridled Tern	*Sterna anaethetus*	Sternidae	Breeder	Migrant breeder
109	Saunders> Little Tern	*Sterna saundersi*	Sternidae	Breeder	Migrant breeder
110	Gull-billed Tern	*Gelochelidon nilotica*	Sternidae	Migrant	Common passage & winter migrant
111	Sandwich Tern	*Sterna sandvicensis*	Sternidae	Migrant	Common winter migrant
112	Roseate tern	*Sterna dougallii*	Sternidae	Migrant	Uncommon winter migrant
113	Common Tern	*Sterna hirundo*	Sternidae	Migrant	Common winter migrant
114	Sooty Tern	*Sterna fuscata*	Sternidae	Migrant	Uncommon winter migrant
115	Little Tern	*Sterna albifrons*	Sternidae	Migrant	Regular summer migrant
116	Whiskered Tern	*Chlidonias hybridus*	Sternidae	Migrant	Common passage migrant
117	White-winged Black Tern	*Chlidonias leucopterus*	Sternidae	Migrant	Regular autumn migrant

Annex 6: Important flora of the UAE

Sources:

- adapted from M.V.D. Jongbloed, G.R. Feulner, B. Ber, A.R. Western, 2004. A comprehensive Guide to Wild Flowers of UAE
- Gulf of Oman desert and semi-desert (AT1306), 2008- Peer review in process

Name of species/sub-species	Habitat/location of species	Status/condition
Socotra cormorant (Phalacrocorax nigrogularis)	Endemic to Arabia peninsula	Endangered on the IUCN Red List (IUCN 2001); population numbers around 200,000 individuals, representing 15-33% of the estimated world population (Aspinall 1995).
Zygophyllum qatarense and Salsola imbricata as dominant species, with Heliotropium kotschyi, Fagonia ovalifolia, Suaeda vermiculata and Panicum turgidum mixed in.	sandy coastal strip with tidal lagoons	
mangrove - Avicennia marina - Arthrocnemum macrostachyum dominates the tideline, - various saltbushes such as Halopeplis perfoliata, Suaeda spp., Anabasis Setifera And Salsola imbricata. Cornulaca monacantha, Heliotropium kotschyi and Convolvulus deserti .	Near Abu Dhabi in many inshore islands	
-Halopyrum mucronatum grass -Salsola imbricata.	Further north in the low dunes along the seashore	

Name of species/sub-species	Habitat/location of species	Status/condition
mixed stands of Cornulaca monacantha and Atriplex leucoclada Crotalaria persica and Sphaerocoma aucheri Haloxylon salicornicum with Cornulaca monacantha, Cyperus conglomeratus, Zygophyllum madavillei and Haloxylon salicornicum and grasses such as: Setaria verticillata, Stipagrostis plumosa and Centropodium forskahlii. annuals Cleome amblyocarpa, Eremobium aegyptiacum and Silene villosa	Further inland higher ground in low dunes with deep water table wet springs	
Rhazya stricta and Haloxylon salicornicum Fagonia ovalifolia, Indigofera argentea - Astragalus spp -Cleome amblyocarpa	East of Al Ain the gravel plain In fenced areas	
Acacia tortilis and Haloxylon salicornicum Rhazya stricta	On gravel plains further north around Madam and Dhaid	Dominate
Capparis sinaica and Ochradenus arabica,	. The limestone hills of Jebel Faiya and Jebel Mileiha	Dominates
Tephrosia purpurea and Salvadore persica stands.	Mountain foothills to the east	Dominates
Prosopis cineraria forest and annuals such as Malva parviflora, Sisymbrium and Geranium spp.	the west of Digdaga and Khatt on the fertile Jiri plain	Dominates
Euphorbia larica and Tephrosia Purpurea and bushes such as Gaillonia	The Hajar Mountains	Dominant
Cyperus conglomeratus and Calligonum comosum Tribulus omanense grows along with a sparse Zygophyllum qatarense and Halopeplis perfoliata a Heliotropium digynum and Limeum arabicum	The sand desert In the west mobile dunes sandy plains between the dunes In deep sands	

Annex 7: Recorded mammalian taxa occurring in UAE

Order	Families	Extinct Species	Introduced Species	Total Number of Species
Carnivora	5	3	3	14
Perissodactyla	1		1	1
Artiodactyla	1	3	2	8
Rodentia	3	1	3	11
Hyracoidea	1		1	1
Lagomorpha	1			1

Annex 8: Native species list of terrestrial mammals of UAE

Common Name	Scientific Name
Insectivora	
Ethiopian Hedgehog	Hemiechinus aethiopicus
Brandt's Hedgehog	Hemiechinus hypomelas
Savi's Pygmy Shrew	Suncus etruscus
Chiroptera	
Egyptian Fruit Bat	Rousettus aegyptiacus
Muscat Mouse-tailed Bat	Rhinopma muscatellum
Naked Bellied Tomb Bat	Taphozous nudiventris
Trident Leaf-nosed Bat	Asellia tridens
Persian Leaf-nosed Bat	Triaenops persicus
Sind Serotine Bat	Eptesicus nasutus
Kuhl's Pipistrelle	Pipistrellus kuhlii
Hemprich's Long-eared BAt	Otonycteris hemprichii
Carnivora	
Wolf	Canis lupus arabs
Red Fox*	Vulpes vulpes
Rüppell's Fox	Vulpes rueppelli
Blandford's Fox	Vulpes cana
Honey Badger or Ratel	Mellivora capensis
White-tailed Mongoose	Ichneumia albicauda
Striped Hyaena	Hyaena hyaena
Gordon's Wildcat	Felis silvestris gordoni
Sand Cat	Felis margarita
Caracal	Caracal caracal
Arabian Leopard	Panthera pardus nimr
Artidactyla	
Arabian Tahr	Hemitragus jayakari
Nubian Ibex	Capra ibex nubiana
Wild Goat	Capra aegagrus
Arabian Oryx	Oryx leucoryx
Mountain Gazelle	Gazella gazella cora
Sand Gazelle	Gazella subguttarusa marica
Lagomorpha	
Cape Hare	Lepus capensis
Rodentia	
Indian Porcupine	Hystrix indica
Lesser Jerboa	Jaculus jaculus
Egypian Spiny Mouse	Acomys cahirinus
Wagner's Gerbil	Gerbillus dasyurus
Baluchistan Gerbil	Gerbillus nanus
Cheesman's gerbil	Gerbillus cheesmani
Sundevall's Jird	Meriones crassus
Arabian Jird	Meriones arimalius

Species in Bold are classified as extinct in the wild

The cover picture represents a Bridled Tern's plea for survival as climate change impacts the UAE's coastal zones, salinity and sabkhat areas.