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

an initiative of

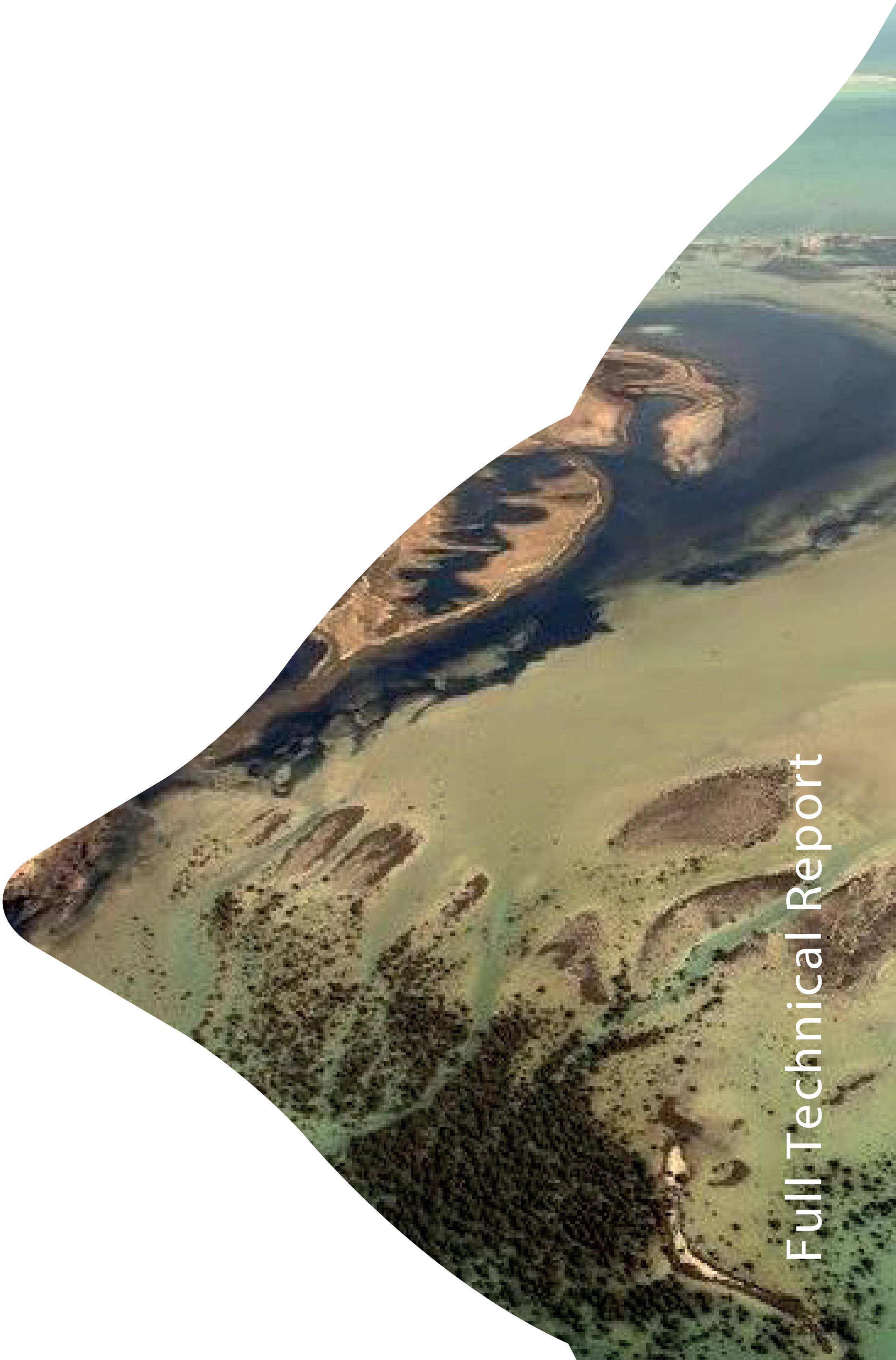
UNEP

هيئة البيئة - أبوظبي
Environment Agency - ABU DHABI

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

COASTAL ZONES: NATIONAL COASTAL VULNERABILITY INDEX

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



Full Technical Report

AGEDI.org

The authors of this report are Gregg Verutes (Principle Investigator), Melissa Rosa, Lauretta Burke and Chris Reed.

Suggested Citation:

AGEDI. 2016. Technical Report, Coastal Vulnerability Index. LNRCCP. CCRG

Climate Change Research Group

Acknowledgments

Many individuals provided invaluable support, guidance, and input to the National Coastal Vulnerability Index (CVI) project. The authors would like to express their sincere and heartfelt expressions of gratitude for their review by providing comments, feedback and /or data towards the multiple deliverables within the project process including:

Mr. Ahmed Al Hashmi, Ministry of Climate Change and Environment (MOCCAE)
Mr. Ashraf Al Cibahy, Environment Agency – Abu Dhabi (EAD)
Mr. David Robinson, Department of Municipal Affairs and Transport
Mr. Fadi Yaghmour, Environment and Protected Areas Authority Sharjah (EPAA Sharjah)
Dr. Frederic Launay, Environment Agency – Abu Dhabi (EAD)
Dr. John Burt, New York University (NYU)
Mr. John Echlin, Abu Dhabi Urban Planning Council (UPC)
Dr. Himansu Das, Environment Agency – Abu Dhabi (EAD)
Mr. Kevin Reid, Abu Dhabi Urban Planning Council (UPC)
Ms. Lisa Hebbelmann, Environment and Protected Areas Authority Sharjah (EPAA Sharjah)
Ms. Manya Russo, Emirates Wildlife Society (EWS) – WWF
Ms. Maria Cordeiro, Environment Agency – Abu Dhabi (EAD)
Ms. Marina Antonopoulou, Emirates Wildlife Society (EWS) – WWF
Mr. Mohammad AbdulRahman Hassan, Dubai Municipality (DM)
Mr. Mohammed Al Darei, Abu Dhabi Urban Planning Council (UPC)
Mr. Obaid Al Shamsi, Ministry of Climate Change and Environment (MOCCAE)
Mr. Oliver Kerr, Emirates Wildlife Society (EWS) – WWF
Mr. Peter Brian Fippinger, Environment Agency – Abu Dhabi (EAD)
Dr. Richard Perry, Environment Agency – Abu Dhabi (EAD)
Dr. Robert Arthur, American University of Ras al Khaimah (AURAK)
Dr. Waleed Al Breiki, Emirates Nuclear Authority
Mr. Winston Cowie, Emirates Wildlife Society (EWS) – WWF

We greatly appreciate the Ministry of Climate Change and Environment (MOCCAE) for partnering and hosting our workshop as well as for their integral role in the project team. We also would like to thank everyone's time and efforts in participating in the workshop and for providing your invaluable expertise.

Stakeholder engagement and directly viewing sites was a critical component of the project. We would like to again thank the Ministry of Climate Change and Environment (MOCCAE) team for arranging for the site visits for each of the Emirates. The onsite knowledge and time of the MOCCAE team, Fadi Yaghmour of EPAA Sharjah and the experts of each of the Emirate Municipalities was incredible and truly appreciated. Thank-you for showing these incredible sites to us.

We are additionally thankful the participation, time and effort that multiple stakeholders across the UAE who participated in the multitude of meetings and dialogue. The authors would like to especially thank the following stakeholders for their particularly involved participation: Abu Dhabi Urban Planning Council (UPC) experts, Dubai Municipality experts, Environment Agency - Abu Dhabi experts, Jason Hale Pandion Saudia, Ministry of Climate Change and Environment (MOCCAE) expert team, Paola Ferreira and the Emirates Wildlife Society – WWF (EWS-WWF) experts.

About this Final Technical Report

In October 2013, the Abu Dhabi Global Environmental Data Initiative (AGEDI) launched the "Local, National, and Regional Climate Change (LNRCC) Programme to build upon, expand, and deepen understanding of vulnerability to the impacts of climate change as well as to identify practical adaptive responses at local (Abu Dhabi), national (UAE), and regional (Arabian Peninsula) levels. The design of the Programme was stakeholder-driven, incorporating the perspectives of over 100 local, national, and regional stakeholders in shaping 12 research sub-projects across 5 strategic themes.[1] The "Coastal Vulnerability & Climate Change" sub-project within this Programme aims to develop a framework to assess the vulnerability of the UAE's coastal environment (both natural and built) to climate change.

The purpose of this "Final Technical Report" is to summarize the analytical inputs and results of the research activities involved in the sub-project. This analysis benefited greatly from the reports and area descriptions provided by a range of UAE stakeholders. It is important to note that the report has not gone through an institutional review at Stanford University and should not be regarded as reflecting the views of the Natural Capital Project. Nevertheless, this report offers the reader a detailed, technical accounting of core default assumptions, analytical approach, analytical framework applied, and updates to previous reports regarding the online visualization of results. Ultimately, this Final Technical Report seeks to provide a detailed, technical synthesis of completed work that can offer a basis for future policymaking to enhance coastal resilience of the UAE under climate change.

[1] For more information on the LNRCC programme, please contact Jane Glavan (lnrclimatechange@ead.ae).

Table of Contents

page

List of Figures

List of Tables

Page

List of Acronyms

AGEDI	Abu Dhabi Global Environmental Data Initiative
°C	degrees Celsius
CCRG	Climate Change Research Group
CO_2	Carbon dioxide
CVI	Coastal Vulnerability Index
DEM	Digital elevation model
EAD	Environment Agency of Abu Dhabi
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic Information Systems
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
km	kilometers
km^2	square kilometers
LNRCCP	Local, National, and Regional Climate Change Programme
mm	millimeters
NCAR	National Center for Atmospheric Research
NGO	Non-governmental organization
SLR	Sea level rise
TNC	The Nature Conservancy
UAE	United Arab Emirates

Glossary of Key Terms

Climate change adaptation	Planned responses to existing or predicted climatic events and effects designed to help humans and environmental systems cope with climate change.
Exposure	Refers to the location of people and property where hazards may occur.
Ecosystem services	If properly managed, ecosystems yield a flow of services that are vital to humanity, including the production of goods such as food and medicine, life support processes such as providing clean and ample water, protection from storms and flooding (the focus of this research), recreational opportunities such as beautiful places to visit, and the preservation of genetic diversity.
Hazard mitigation	Actions taken to reduce the risk to human well-being and biodiversity presented by future destructive climate events.
Resilience	The capacity of a system – be it a city, reef, or economy – to deal with change and continue to develop; withstanding shocks and disturbances (such as climate change) and using such events to catalyze renewal and innovation.
Restoration planning	Ecosystem management plans designed to recover and restore degraded areas.
Risk	Refers to the potential societal consequences of erosion and flooding (e.g., mortality or economic damages).
Social metrics	Measurements of the social and cultural diversity of a landscape or ecosystem
Time horizon	A fixed point of time in the future at which point certain processes will be evaluated. In this report, we refer to near-, mid- and long-term time horizons as planning for climate change impacts by the years 2020, 2050 and 2100, respectively.
Vulnerability	Refers to both social and physical vulnerability. In this research we used a "coastal vulnerability index" to assess the numbers of people and coastal assets with the highest exposure to coastal hazards.

Key Messages and Recommendations

- The of people of UAE depend on coastal-marine biodiversity to sustain and fulfill human life. Mapping and modeling coastal protection services can help highlight these and other benefits provided to people by nature and explore how such benefits might change under different management options.
- It is essential that regional coastal resource management and policy is guided by the best available science and data. Interventions should be evaluated not just based on economic arguments but also considering impacts to local livelihoods and the environment.
- While some natural habitats such as seagrasses provide relatively limited coastal protection services, in combination with other habitats (e.g., coastal sabkha, coral reefs, mangrove forests), they can play an important role in stabilizing the coast as well as supporting ecosystem function and the delivery of socioeconomic benefits, including nursery habitat for fish, water purification, climate regulation and recreation opportunities.
- Local capacity strengthening in science and management can guide regional monitoring programs and the identification of at-risk areas of the UAE coastal zone.
- As part of the Ministry of Climate Change and Environment's (MOCCAE) Natural Capital Mapping Project, we recommend conducting a habitat risk assessment to establish a baseline for identifying future changes in ecosystem service delivery, including coastal protection services.
- Greater collaboration between government and conservation departments will be essential to co-develop locally supported nature-based solutions (e.g., mangrove rehabilitation, coral restoration, etc.) to mitigate the effects of climate change.
- Habitat rehabilitation/restoration strategies that offer co-benefits should be prioritized and coordinated with local and international interests (e.g., MOCCAE, UPC, UNEP, EWS-WWF) to complement ongoing regional conservation efforts.
- National policy opportunities for nature-based strategies should aim to galvanize action from government agencies, coastal managers and developers so the benefits of such interventions are understood across all levels and sectors.
- To inform management interventions related to climate change, spatially-explicit climate projections are needed to move from regional averages to localized estimates of net sea level change. The Center for Climate Systems Research at Columbia University Earth Institute has developed a promising approach to account for several components related to sea level rise, including thermal expansion, local ocean height, land ice melt, and local knowledge.
- The valuation of shoreline protection services should be further explored at the sub-emirate level, including critical infrastructure around Abu Dhabi and offshore islands.

Additional data compilation is needed to capture key ecological and socioeconomic metrics at the municipal/local scale.

1. Background

This Final Technical Report focuses on the UAE and reflects an analysis conducted as part of the Local, National, and Regional Climate Change Programme (LNRCCP) under the auspices of the Abu Dhabi Global Environmental Data Initiative (AGEDI). This analysis benefited greatly from the reports and area descriptions provided by United Arab Emirates (UAE) Ministry of Climate Change and Environment (MOCCAE), environmental authorities and municipalities local NGOs, stakeholders, scientists and academics. In addition, this analysis relied heavily on spatial data assembled by AGEDI and collaborators. Results are being integrated in an online mapping platform called the "CVI Inspector" which currently available at (http://www.ccr-group.org/coastal). All figures were taken directly from the current version of the CVI Inspector, which will be used to generate custom reports from local Emirate to national scales.

This report is organized into four major sections. Section 2 introduces the study and discusses the role of natural systems in the UAE reducing coastal vulnerability. Section 3 describes the methods that are being including, the use of the InVEST model and the range of data inputs to the CVI Inspector. Finally, Sections 4 and 5 provide an overview and discussion of results, respectively.

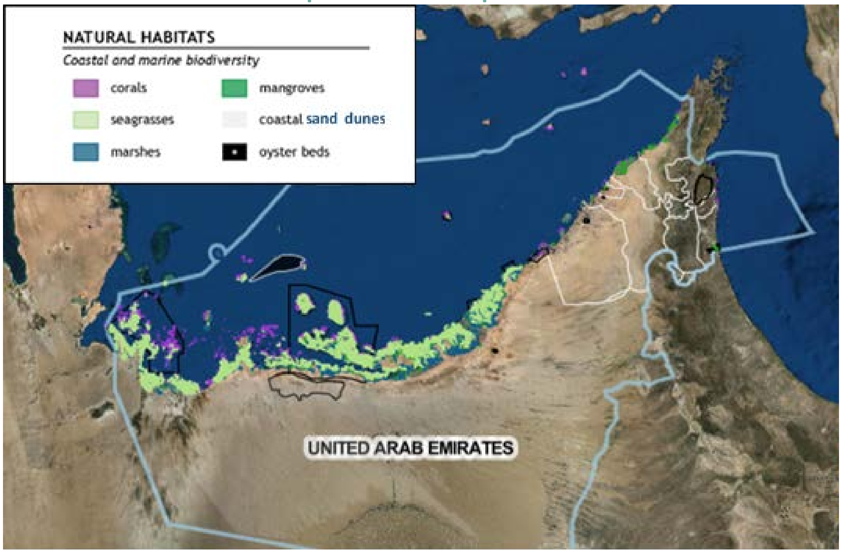
2. Introduction

Globally, natural habitats provide a wide variety of benefits to people, known as ecosystem services, which are estimated to be worth between US$127-145 trillion/year (Costanza et al., 2014). Locally, the value of natural habitats is also recognized as providing important services. Within the emirate of Abu Dhabi, a contingent valuation assessment was undertaken that showed the beach amenity valued between US$8.3 million/ha and US$13.8 million/ha (Blignaut et al., 2016). These ecosystem goods and services are an important natural resource, providing coastal communities with livelihood benefits including provisioning services (e.g., fisheries, aquaculture production), regulating services (e.g., shoreline protection and flood control) and supporting services (e.g., filtration of pollution and habitat for aquatic and terrestrial species). The challenge is also quantifying how these benefits will change under alternative climate and development scenarios and linking these results to the beneficiaries (coastal populations and land holders who demand these services).

Faced with growing intensity of human activities and climate change, coastal communities seek a better understanding of how modifications to the biological and physical environment can affect their exposure to storm-induced erosion and flooding. By analyzing the current distribution of shoreline protection services provided by coastal-marine habitats, we can assess their role in future protection of coastal settlements. This information can be used to assist decision-making from the national level to emirate and local levels. The role of habitats can be useful metric towards designing coastal plans and developing specific recommendations for development, rehabilitation and restoration strategies in the UAE coastal zone.

Figure 2-1 shows the UAE study area. This includes seven coastal emirates and current distribution of six natural habitats: 1) coral reefs, 2) mangrove forests, 3) salt marshes, 4) seagrass beds, 5) coastal sand dunes, and 6) oyster beds. Prior to its constructed islands. the UAE coastline was approximately 2,750 km in length with an exclusive economic zone (EEZ) area of 58,218 km^2 (Sea Around Us, 2016). Within this area of interest, we compiled spatial information to inform an assessment of coastal vulnerability that highlights most exposed areas to impacts from coastal hazards and climate change. Most environmental assessments consider only the economic costs and benefits and ignore their spatial distribution across a land or seascape. Without this spatial information, it is not clear whether the places, habitats, and people put at risk by climate and human activities are also the beneficiaries of these services.

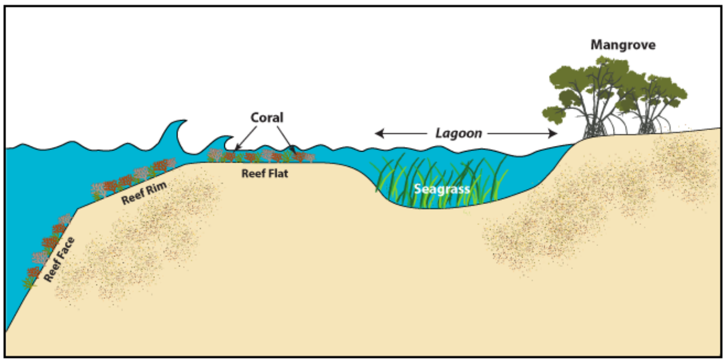
Figure 2-1. Map of UAE study area including the seven coastal emirates (white lines), EEZ (blue lines) and six natural habitats considered in this assessment to provide coastal protection services.



2.1. Biodiversity protects the coastal zone from hazards

Referred to as "nature's shield" by Arkema and colleagues (2013), some coastal and marine habitats, when healthy, buffer the coastal zone from storm-induced erosion and flooding. Through the process of wave attenuation, which varies by habitat type, coastal distance, depth and other factors, a wave's energy can be reduced as it approaches the shoreline (Figure 2-2). Unlike bulkheads and seawalls that increase wave reflection and energy, natural habitats improve wave attenuation, decreasing wave heights from both wind and waves by up to 80% (Bilkovic et al., 2016). Reductions in wave energy increase

Figure 2-2. Diagram of natural habitats known to attenuate waves in the UAE (adapted from Guannel et al., 2016). The coastal protection services provided by oyster beds, marsh and coastal sand dune habitats (not shown) were also considered in this study services.



sedimentation and accretion of marsh, for example, provides further sediment stability and coastal protection (Gedan et al., 2011; Manis et al., 2015).

Coastal development and engineered solutions to protect these assets can erode ecosystem integrity and reduces ecosystem service capacity overall (Bilkovic & Roggero 2008; Long et al., 2011; Patrick et al., 2014). Shoreline armoring structures are fixed on the coast, meaning their effectiveness at preventing erosion is likely to decrease with sea-level rise (Sutton-Grier et al., 2015). Natural habitats, however, can continue to accrete sediment and increase elevation, allowing the shoreline to adapt and maintain its relative position as sea level rises (Gedan et al., 2011, Spalding et al., 2014; Manis et al., 2015; Gittman et al., 2016). Bulkheads and revetments are also susceptible to overtopping (i.e., seawater rising over the top of the barrier) that can cause significant erosion and property damage during storms (Currin et al., 2008; Gittman et al., 2014) while habitats reduce wave energy, storm surge, and flooding (Gedan et al., 2011; Barbier et al., 2013) and maintain or increase elevation under storm conditions (Currin et al., 2008; Gittman et al., 2014). As coastal development increases, habitat conservation and rehabilitation ("nature-based strategies") offer a unique opportunity to ensure shoreline protection through "hard" (e.g., revetments) and "soft" (e.g., dune stabilization) measures, while also maintaining or enhancing coastal habitat and ecosystem services.

2.2. Benefits of and threats to coastal-marine biodiversity

A primary goal of this study is to assess the role that natural habitats play in both current and potential future shoreline protection of people and property in the UAE coastal zone (up to 3 kilometers inland from the coastline). In addition to protection from hazards, coastal and marine biodiversity provide a suite of environmental services to the UAE people. We offer this literature review of six natural habitats known to attenuate waves, including their historic range, threats, and benefits delivered to people (Table 2-1). This research seeks to set the stage for a broader natural capital mapping effort with the goal of making the case for nature-based strategies to support coastal resilience, including shoreline protection and other important ecosystem services.

Table 2-1:
Summary of habitat names, distribution, protective ability, co-benefits, and current/historic threats

HABITAT TYPE	RELATIVE ABILITY TO ATTENUATE WAVES (COASTAL PROTECTION)	POTENTIAL CO-BENEFITS	THREATS TO THESE HABITAT IN THE UAE COASTAL ZONE
Mangrove forests	Highest	Fisheries, blue carbon, water purification, nursery	Hardening of shoreline, dredging of channels
Coral reefs	High	Recreation, habitat for flora and fauna, fisheries	Sedimentation plumes from non-adjacent dredging activities, thermal pollution and coastal development, diseases such as yellow and black band, bleaching and algal bloom events
Salt marshes	Medium-high	Blue carbon, recreation, habitat for flora and fauna,	Coastal development, runoff, desalination, sea level rise
Coastal sand dunes	Medium-low	Habitat for flora and fauna	Coastal development, sea level rise
Oyster beds	Medium-low	Water purification, fisheries	Fisheries extraction, coastal degradation
Seagrass meadows	Lowest	Blue carbon, nursery habitat	Runoff, desalination

2.2.1. Mangrove forests

Mangroves front the largest percentage of overall coastline in Umm Al Quwain and Ras Al Khaimah emirates, followed by Abu Dhabi. In Abu Dhabi alone, the area of mangrove is estimated as 140,000 ha (Spalding et al., 2010). These salt-tolerant trees and shrubs mainly *Avicennia marina* are densely distributed along the southern shores of the Arabian Gulf, confined to low-energy, intertidal areas (Naser, 2014; Saenger, 1997; Dodd et al., 1999). Mangroves provide a host of other ecosystem services, including water quality, amenity services, habitat for a variety of terrestrial and marine fauna, and productivity of the Arabian Gulf (Al-Maslamani et al., 2013), including shelter for commercially and recreationally important fish and shellfish, protecting the broader biodiversity of the coastal ecosystem and community structure of different species of coral reefs (Mumby et al., 2004). The extensive root systems of mangroves anchor soil which can mitigate the effects of wave action during storm events, including shoreline erosion and sedimentation. Mangrove ecosystem services alone, not including carbon sequestration, have been valued at U.S. $193,845 per hectare of intact ecosystem as a global average (De Groot et al., 2012). The belowground, sediment pool is a sink for carbon sequestration (Sifleet et al., 2011). They filter pollutants and improve the quality of coastal and nearshore waters, support the livelihoods of coastal-dependent communities, and are a source of revenue from ecotourism.

At the global scale, mangroves are encountering degradation and decline due to coastal development and many other human-induced impacts (Ellison and Farnsworth 1996). However, it is believed that mangroves of the UAE have experiencing modest growth. The late Sheikh Zayed Bin Sultan Al Nahyan recognized the importance of mangroves and in the 1970s by developing policies that harnessed the cultural value of mangroves. This has been a significant driver for mangrove forest conservation, and over the last 30-40 years, mangroves of the UAE have increased to some extent (Loughland et al., 2007; Howari et al., 2009) due to localized planting activities and increased conservation efforts (FAO 2007; Howari et al., 2009), although most recently mangrove expansion appears to have slowed. Still, coastal vegetated wetlands like mangroves are sensitive to climate change and long-term sea-level change (Fencl and Klein, 2008), including rising water levels, more frequent inundation, and coastal erosion.

2.2.2. Coral reefs

Corals are currently protecting the coastlines of all seven emirates. Corals of the UAE were once extensive in the 1960s and 1970s with *Acropora* dominated reefs extending across most of the Arabian Gulf coast, occupying hundreds of square kilometers of nearshore waters from western Abu Dhabi to Ras Al Khaimah (Burt et al., 2011; Grizzle et al., 2016). In the Arabian Gulf, extremes in temperature, salinity and other physical factors restrict the growth and development of corals to patchy forms (Sheppard et al., 2010). Coral reefs were also widely distributed across the northern emirates and along the east coast in the Sea of Oman. Coral reef ecosystems feature both biological diversity and high levels of productivity, providing a wide range of important habitats for fisheries in the Arabian Gulf (AGEDI, 2013). Additionally, coral reefs can slow incoming waves and protect mangrove and sea grass habitats from strong currents and storms. Coral reefs also provide recreational values and economic benefits such as increased tourism revenues.

About 70% of original Arabian Gulf corals may be considered lost and a further 27% are threatened or at critical stages of degradation (Wilkinson, 2004). The Emirate of Abu Dhabi reefs were impacted in the 1970 and 1980s due to associated channelization, reclamation, and port development during the oil boom (Burt, 2014). Two major thermal bleaching events and a powerful cyclone in the late 90s significantly impacted reefs throughout the southern Arabian Gulf, resulting in the loss of more than 90% of coral in many areas (Burt et al., 2011; Bento et al., 2016). Bauman et al. (2010) report over 90% declines in live coral cover and fish biomass on reefs in parts of the UAE's east coast during the 2007-8 harmful algal bloom. Later work by Bento et al. (2016) has shown that while recovery is in progress, to date these reefs have not yet fully recovered from this event.

Despite recent degradation, many reefs in the UAE contain coral communities with substantial live coral cover and considerable species diversity (Grizzle, et al., 2016). Corals in the Arabian Gulf have been exposed to severe temperature anomalies at a recurrence faster than in any other coral regions in the world (Naser, 2014). Some argue the Arabian Gulf is similar to the thermal environment projected by the IPCC for tropical oceans by 2100 (Riegl & Purkis, 2012) which suggests that further monitoring of corals in the region could serve as a useful indicator of how corals in other areas might adapt to or be impacted by climate change. Still, increases in sea surface temperature of 1 to 3°C could lead to frequent coral bleaching events and widespread mortality, unless corals can acclimate and adapt to the higher temperatures (IPCC 2007). Sea-level rise could have severe impacts on nearshore

Arabian Gulf corals because so much of the southern shoreline is barely above sea level (Riegl, 2003).

2.2.3. Seagrass meadows

Seagrasses front about 30% of segments along the coastline of the Emirate of Abu Dhabi. Three species of seagrass occur in the Arabian Gulf, *Halodule uninervis, Halophila stipulacea and Halophila ovalis* (Phillips, 2002) and are generally tolerant to salinity and temperature extremes. Seagrasses provide important ecosystem services such as stable coastal habitat for many species of fish and invertebrates, and maintain coastal water quality and fisheries production (Naser, 2014; Sheppard et al., 1993). Seagrass habitats serve as a foundation for complex food chains and nursery grounds for certain shrimps, pearl oysters and other organisms of importance to the Arabian Gulf's commercial fisheries (Erftemeijer and Shuail, 2012). They also provide feeding grounds for several threatened species in the Arabian Gulf, such as the green turtle (Abdulqader and Miller, 2012; Preen et al., 2012) and support the largest population of dugongs known outside Australia (Preen, 2004). Furthermore, they supply food and shelter for coral reef associated species (ADEA, 2006) and nutrients and energy to sabkha substrate, which helps stabilize the substrate and minimizes the effect of wind erosion and retains water in coastal soils (Phillips, 2002). Seagrass beds play an important role in climate regulation by typically sequestering as much as twice the carbon per unit areas as that of temperate forest in the tropics (Murray et al., 2011).

Sediment and pollutant runoff resulting from coastal development and dredging activities has degraded seagrass beds of the Arabian Gulf in recent years (Burt, 2014). The distribution and abundance of seagrasses are also susceptible to climate change including sea temperatures, tidal variations, salinity content, water depths, and ocean carbon dioxide content, while sea level rise and an increased water depth can lead to a subsequent reduction in light available for seagrass growth (Short and Neckles, 1999). If permitted to expand inland towards intertidal areas, seagrasses can adapt to climate change (Kentula & McIntire, 1986). Alternatively, a loss in seagrass habitat can be expected where geomorphology or shoreline infrastructure does not permit successful migration.

2.2.4. Salt marshes

Marshes are biologically diverse habitats that continuously accumulate sediment and suited to both fresh and saltwater (AGEDI, 2014). These intertidal ecosystems are primarily found in sheltered regions of the Arabian Gulf coast. Salt marshes are valuable ecosystems that provide habitat for a variety of both commercially and recreationally important marine wildlife, including fish, shellfish and foraging shorebirds (Wildscreen Arkive, 2011). Healthy salt marshes also filter nutrients and sediment from passing water, protect coastlines against wave damage and erosion, mitigating flooding by holding excess storm waters, and regulate water levels during periods of dry weather. The ecosystem services provided by marshes include fisheries production, pasture lands, ecotourism and climate regulation. They inhibit methane creation and contain a range between 900 and 1,700 tonnes of CO_2 per hectare (Sifleet et al., 2011). Salt marshes are typically converted for agricultural use or lost to coastal development, particularly through dredging, filling and draining and from the construction of roads (Burt, 2014; AGEDI 2014). Marshes are also increasingly under pressure from rising sea levels.

2.2.5. Coastal sand dunes

Coastal sand dune habitat currently exists in appreciable quantities in the Abu Dhabi and Ras Al Khaimah emirates. Most of the surface of the present-day UAE is a sand desert. In many areas near the coast, the sand is stabilized by vegetation, although the natural flora has been altered in recent times by extensive grazing of domesticated animals (UAE Interact 2016). Their contribution to coastal protection and tourism has been acknowledged in local coastal plans but the wide range of provisioning, regulatory, cultural and supporting services they provide are often overlooked (Everard 2010). Coastal sand dunes in the UAE are most threatened coastal development activities that include hardening of shoreline for resorts and residential superstructure (Burt, 2014; UAE Interact 2016).

2.2.6. Oyster beds

The Gulf Pearl Oyster traditionally offered a source of local wealth to the region long before the discovery of oil. *Pinctada radiate* and *P. margaritifera* (collectively referred to as 'pearl oysters') are large bivalves that can tolerate a wide temperature range and found on rocks between 5 and 25 meter depths (Carter 2005; Encyclopedia Iranica, 2016). Oysters are currently cultured for pearls in Qatari waters and harvested for their edible flesh and shell on a limited basis. Despite their ability to adapt to subtropical environments and survive in polluted water, globally 85 percent of oyster reefs have been lost due to fisheries extraction, coastal degradation and other anthropogenic pressures (Beck et al., 2011). Like many shellfish species across the globe, the Gulf Pearl Oyster has lost its dominant role as an ecosystem engineer including supporting the historically productive oyster fishery. Smyth and colleagues (2016) observed severe declines in oyster bed occurrence in neighboring Qatar.

3. Methods

The terms *hazard*, *risk*, *exposure* and *vulnerability* are often used interchangeably. For clarity, we define these terms as they apply to this assessment. A *coastal hazard* caused by storms and sea level rise acting upon shorelines can result in flooding and erosion. Erosion and flooding may incur negative consequences for people and property so we refer to them as "hazards". The *risk* is potential societal consequences of erosion and flooding (e.g., mortality or economic damages). We refer to "exposure" as the location of people and property where hazards may occur. Vulnerability can be either social or physical vulnerability. Physically vulnerable populations and property are those that are highly exposed to coastal hazards. We used a "coastal vulnerability index" (or "CVI") to be explicit spatially about coastal areas, people and property most exposed to coastal hazards. Annex C summarizes one commonly used framework to explain climate change and how we can develop resiliency and vulnerability metrics.

The InVEST coastal vulnerability model (naturalcapitalproject.org) **calculates an exposure index based on the distribution of coastal habitats, elevation, wind and wave**

characteristics, shoreline type, relative sea level change and surge potential (Arkema et al., 2013). The index is overlaid with socioeconomic data to identify where populations and critical infrastructure are most vulnerable to storm waves and surge. Model outputs serve to quantify the protective services offered by natural habitats to coastal communities in terms of risk-reduction. Annexes A and B to this report describe in detail the mechanics of the InVEST coastal vulnerability model, as well as data sources and model limitations (Sharp et al., 2015). The following sections describe the CVI model development for UAE, including stakeholder engagement, knowledge co-production, scenario development and expert review and validation.

3.1.Stakeholder Engagement and Knowledge Co-Production

Stakeholder involvement and co-development of knowledge are key steps towards effectively answering the different management questions posed by an ecosystem services assessment (Rosenthal et al., 2014). Stakeholder engagement can improve the quality of decisions (Reed 2008), increase perceptions that decisions are legitimate (Cash et al. 2003), and strengthen stakeholder knowledge and social capita (Chess & Purcell 1999; Blackstock et al., 2012). Engaging stakeholders and decision-makers of the Arabian Gulf was critical to validate preliminary results, improve model inputs, and identify data gaps and relevant metrics. Stakeholder consultations commenced in late 2015, including webinar presentations for local planners, managers and scientists (December 2015). AGEDI organized a two-day stakeholder workshop and site visits in partnership with the Ministry of Climate Change and Environment (MOCCAE) to at-risk coastline (May 2016) and two expert review periods (June and November 2016). Through these consultations both in-person and virtual, the CVI sub-project team was able to:

- Collect and summarize natural capital information for local and national planners to evaluate different coastal protection options in the UAE
- Illuminate choices and consequences for a set of options in each Emirate, including potential impacts to natural capital and coastal protection benefit to people and their property
- Laid the groundwork for a national CVI that includes evaluating alternative future scenarios of human use, risk to habitats and climate change impacts
- Identified data gaps and validated preliminary findings

From October 2015 to June 2016 we acquired and processed data characterizing the biophysical and socioeconomic environment of the UAE coastal zone. This information is provided in Annex A, Table 1. Spatially explicit information describing climatic forcing grid (wind and waves), coastal geomorphology and elevation were collected piecemeal from multiple sources. Initially, we drew on publicly available information, including datasets from the peer-review literature, scanned maps, and reports. For inputs not readily available, including shoreline geomorphology and historical wave data in the Gulf data was obtained from MDA Information Systems (http://www.mdaus.com/) and compiled within the CVI model. Through this process we identified new data sources and model input parameters.

For example, the default input for the storm surge variable is a measurement of each coastline segment to the continental margin. During the May 2016 consultations, this proxy for storm surge potential was flagged as inconsistent with the participant's knowledge of the system. For storm surge and other questionable variable ranks, stakeholders identified alternative data options to improve our preliminary findings. In the following subsections, we outline the two variable ranks that benefited most from this review and subsequent changes in data sourcing.

3.1.1. Climatic Forcing Conditions

In the Arabian Gulf, wind-generated waves can be significant during major storm events. The values of extreme significant wave heights are smaller, however, in the shadow region of Qatar compared to the other parts of UAE territorial waters (Neelamani et al., 2006). We initially relied on wind information from the National Center for Atmospheric Research (NCAR), housed by the LNR Climate Inspector, to summarize top 10% of wind speeds and directions based on observations from 12 locations in the UAE coastal zone.[2] This wind grid was later combined with a 5-year climatologic time series for waves based on ERA-Interim from the European Center for Mid-Range Weather Forecasts. Through a geospatial solutions contractor, MDA Information Systems, we acquired a wave time series at 6-hour intervals from the 2010 to 2015 for two variables: (i) significant wave height and (ii) mean wave period. For a detailed summary of the climatic forcing grid (local and ocean-generated waves) and how each coastline segment was ranked 1 to 5, see Annex B.

3.1.2. Coastal Geomorphology

Many cities in the Arabian Gulf have more than half of their shorelines composed of seawalls, breakwaters, and other artificial structures (Feary et al., 2011; Burt et al., 2012). A national-level classification of coastal geomorphology was conducted to map differences in shoreline composition (soft, mixed and hard) based on the exposure ranking scheme outlined in Annex A, Table 1. We used a combination of Google Earth and Street View imagery as well as ArcGIS mapping software to classify shoreline segments 250m in length. This data product is a critical component of the CVI to incorporate how recent coastal development and engineered structures are being used to protect, or armor, the coastal zone. This layer was derived from recent satellite imagery (2014-2016) and represents we believe the most up-to-date spatial layer characterizing shoreline geomorphology of the UAE. See Annex B for examples of the image analysis and GIS tools used to rank this variable input to the CVI model.

Beaches and other shoreline types are also important components of the InVEST coastal vulnerability model's geomorphology variable because they relate to the importance of natural habitats. In places with soft coastal substrates (e.g., sand, mud, etc.), biogenic habitats such as marshes and seagrasses are more essential because they are less resistant to

---

[2] This information is based on the outputs of the LNRCCP's sub-project #2 entitled: Regional Modeling: Atmosphere" which was focused on future projections of temperature, rainfall, wind speed and other climatic parameters in the Arabian Peninsula under conditions of increased concentrations of greenhouse gases in the atmosphere. Outputs are available at the LNRCCP Climate Change Inspector (www.ccr-group.org/atmospheric).

wave energy and more likely to erode. Where shorelines are hard (e.g., seawalls, rocky intertidal), habitats like seagrass beds may be less important. The coastal vulnerability model not only help users understand why marshes and other coastal habitats are important, but also accounts for the increase in coastal protection provided by multiple, co-occurring habitats.

3.2. Designing Alternative Habitat and Climate Change Scenarios

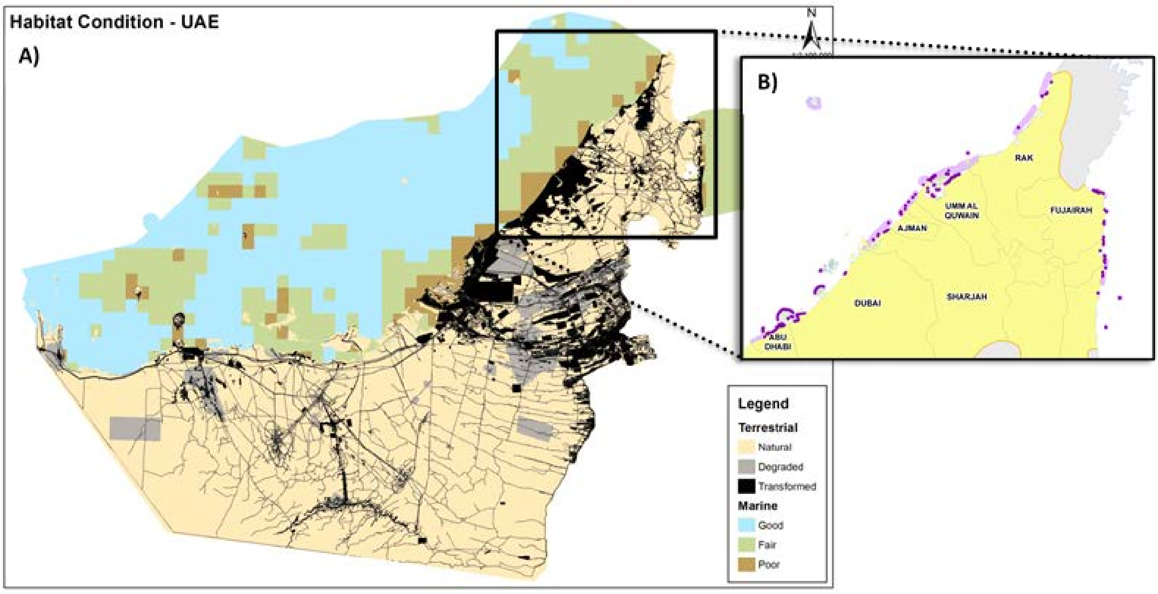
Scenarios are simplified descriptions of possible futures, used to illuminate choices and consequences. Developing a set of alternative scenario options can be useful for examining how actions taken today may play out in the future. The InVEST coastal vulnerability model offers a snapshot of coastal protection services at a given time. We explored alternative futures driven by the effects of climate change and human impacts on habitat quality and function. We began this research with maps of the historic location of coastal and marine habitats based on AGEDI's national track of the Local, National and Regional (LNR) Biodiversity Assessment Project. Each habitat input layer was later refined based on various mapping efforts to characterize threat level to and quality of six habitats known to attenuate waves. Maps of this historic distribution, current habitat quality and a complete loss of habitat function were later combined with near, mid and long-term projections for net sea level rise to create seven plausible habitat/climate change scenarios. The habitat/climate scenarios are snapshots across an 80-year time horizon (2020 - 2100).

3.2.1. Natural Habitats

This assessment made use of threat status information to identify high risk, low functioning habitats that offer less protection than pristine habitats. For example, mangrove ecosystems, relative to other coastal habitats, attenuate waves and dissipate a great deal of this energy. We use a habitat rank of “1” (highest protection) to represent mangroves high protective capacity when healthy and functioning. Maps from AGEDI Ecosystem Threat Level Assessment were then used to map poor condition mangrove areas as rank “3” (less protection). The model will then incorporate this variation in the protective ability of mangrove forests and other habitats to assess coastal exposure and vulnerability throughout the study area (Figure 3-1).

Maps of the historic distribution for six natural habitats represent a ‘best case’ scenario in terms of biodiversity's role in wave attenuation during coastal hazards. We then incorporated maps from AGEDI's Ecosystem Threat Level Assessment and Ecosystem Protection Level (2013) and the University of New Hampshire's Mapping and Characterizing Coral Habitats in the UAE (Grizzle et al., 2013) to account for the current and potential future risk posed by human activities and climate change to these habitats. The assumption being that this risk degrades the quality and function of these ecosystems in delivering coastal protection services. For example, coral reefs of the UAE are living very close to their thermal tolerance limits. Per the recommendation of this CVI sub-project review panel, the thermal effects to habitats and possible decline under various thermal futures was incorporated into the habitat scenarios, including the potential loss of reefs that may occur under a predicted 1

Figure 3-1: A) "Degraded" or "transformed" coastal areas and marine habitats classified as "poor" from the Ecosystem Threat Status Assessment – Initial Ecosystem Threat Status and Protection Level Assessment Layers (October 2012) were used to adjust the coastal protection ranks of the CVI habitat input maps. B) Mapping and Characterizing Coral Habitats in the United Arab Emirates (Grizzle and colleagues from April 2011 - October 2013) shows remaining functional corals (purple) as compared to their historic range (pink).



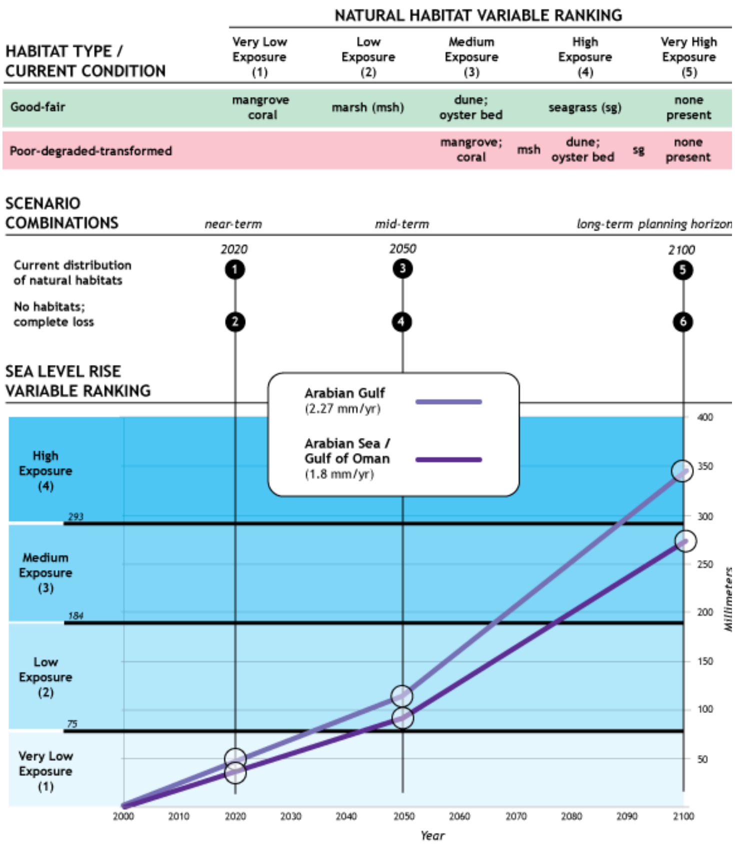
to 2 degree increase in ocean temperatures. This is considered a conservative estimate, as the once extensive range of UAE corals were highly degraded during a 1998 El Nino event and have since shown only modest recovery. Like corals, seagrasses in the region have also been thermally stressed. It is considered likely that mangroves are the least affected of these ecosystems by changes in temperatures based on preliminary field studies. (J. Burt, personal communication, July 25, 2016).

3.2.2. Net Sea Level Change

Coastal planners in the UAE seek to understand near-term impacts from climate change and sea level rise (SLR). We reviewed existing climate change information to determine a suitable approach that accounts for SLR impacts as a variable in the CVI model. For SLR, a "bathtub inundation" model approach that relies on a digital elevation model (DEM) can visualize SLR inundation zones and summarize amount of area flooded by emirate (Fencl and Klein, 2009) as well as impacts to coastal habitats such as mangroves (Taoufik, 2012). Tide gauges for the Arabian Gulf are located near the nations of Iran, Bahrain, and Oman. The National Energy and Water Research Center and Electricity Authority of Abu Dhabi have recently installed tidal gauges at different locations in Abu Dhabi's waters to obtain long-term water level measurements (Mohamed, 2008). Research in Ras Al Khaimah is showing that areas like Al Hamra Village are indeed at risk from predicted flood events and can benefit from the data from such gauges. However, the absence of long-term recording of net sea level change and high-resolution DEMs for the region make it challenging to model SLR impacts. Additionally, we considered recruiting Columbia University's Center for Climate System Research to generate a range of spatially explicit sea level rise projections but given time and resources constraints and a low likelihood that we would see spatial variation across the 50km^2 output grid cells unless there is large land subsidence in the Arabian Gulf region.

The relative net sea level change along the coastline of a given region is the sum of global sea level rise (SLR), local SLR (eustatic rise) and local land motion (isostatic rise). The InVEST CVI model is best suited to use spatially explicit SLR rankings based on long-term observations of sea level change, as demonstrated by Arkema et al., 2013, to incorporate variation in rising seas throughout a study area. SLR averages at the regional scale were used to assess how different sections of the UAE coastline, currently protected by habitats, may become overwhelmed by climate change impacts and transition to the top quartile of coastal exposure risk. We applied the average historical sea level rise rate for the Arabian Gulf and Arabian Sea of 2.27 and 1.8 mm/year, respectively, as a constant rate through 2050 (Ayhan and Alothman, 2009). The year 2050 is the time-period when regional modelers indicate that sea level change rate (mm/yr) diverges relative to the regional climate projections. From 2050 to 2100, we doubled these rates for both regions to get a sea level rise variable rank of '3' for coastline along the Arabian Sea and a rank of '4' for the Arabian Gulf (Figure 3-2).

Figure 3-2: Ranking scheme for natural habitats based on current range (green highlight) and threat status assessments (red highlight); Six plausible habitat and sea level rise scenario combinations, representing the distribution of exposure index scores considered in this study; Sea level rise scenario variable ranking scheme (blue highlight) based on historical rates for the Arabian Gulf and Arabian Sea.



3.3. Applying and Finalizing the InVEST CVI Model

Applying the InVEST CVI Model to UAE conditions helped to identify exposed shoreline and vulnerable coastal communities. In turn, this facilitates the highlighting of areas where natural habitats are reducing the number of people and assets at risk to coastal hazards. Myriad factors contribute to the amount of flooding and erosion damages during storm events, including storm wave height, period, wind speeds and direction along with coastal zone depth profile, substrate type (Ruckelshaus et al., 2016). Given these and other data requirements necessary to model and quantify damages from hazards, we applied a data-light, screening approach to assess factors affecting spatial distribution of vulnerability to hazards. The guiding questions to be addressed by this assessment were:

1. Which sections of the UAE coastline are most exposed to coastal hazards?
2. How will the distribution of risk-reduction provided by nearshore and coastal habitats change under future habitat and climate scenarios?
3. How can these findings inform future planning and management including conservation and restoration of habitats that protect coastal populations, infrastructure and other assets?

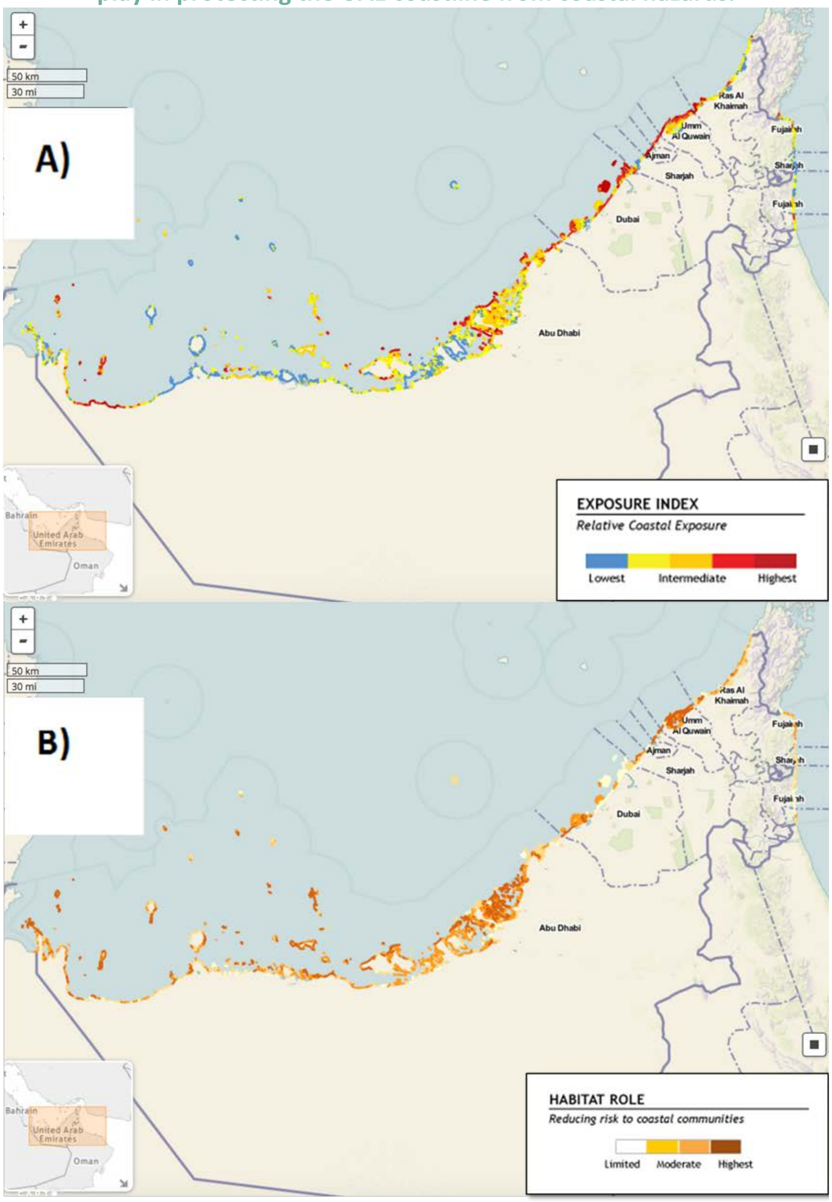
Outputs from the InVEST CVI model were linked to socio-economic and ecological metrics to generate relevant summaries describing coastal protection services and values throughout the UAE coastal zone. Using this methodology, we identified the most exposed coastline and summarized which populations and coastal assets are at reduced risk due to the presence of natural habitats. It is estimated that the UAE population has doubled since 2010 and was 9.16 million people in 2015 (World Bank, 2016). Using a coastal vulnerability index and basic spatial analysis, we highlight where people, property and high value infrastructure are at reduced risk as a result of the protective service provided by natural habitats to quantify the role that natural habitats play in reducing exposure of people and property to coastal hazards.

4. Results

Based on three climate change scenarios for sea level rise, the InVEST coastal vulnerability model classifies between 4 and 32% of the UAE coast (within one kilometer of the shoreline inland) as "highest exposure" areas – currently home to more than 175,000 people and extensive coastal assets.

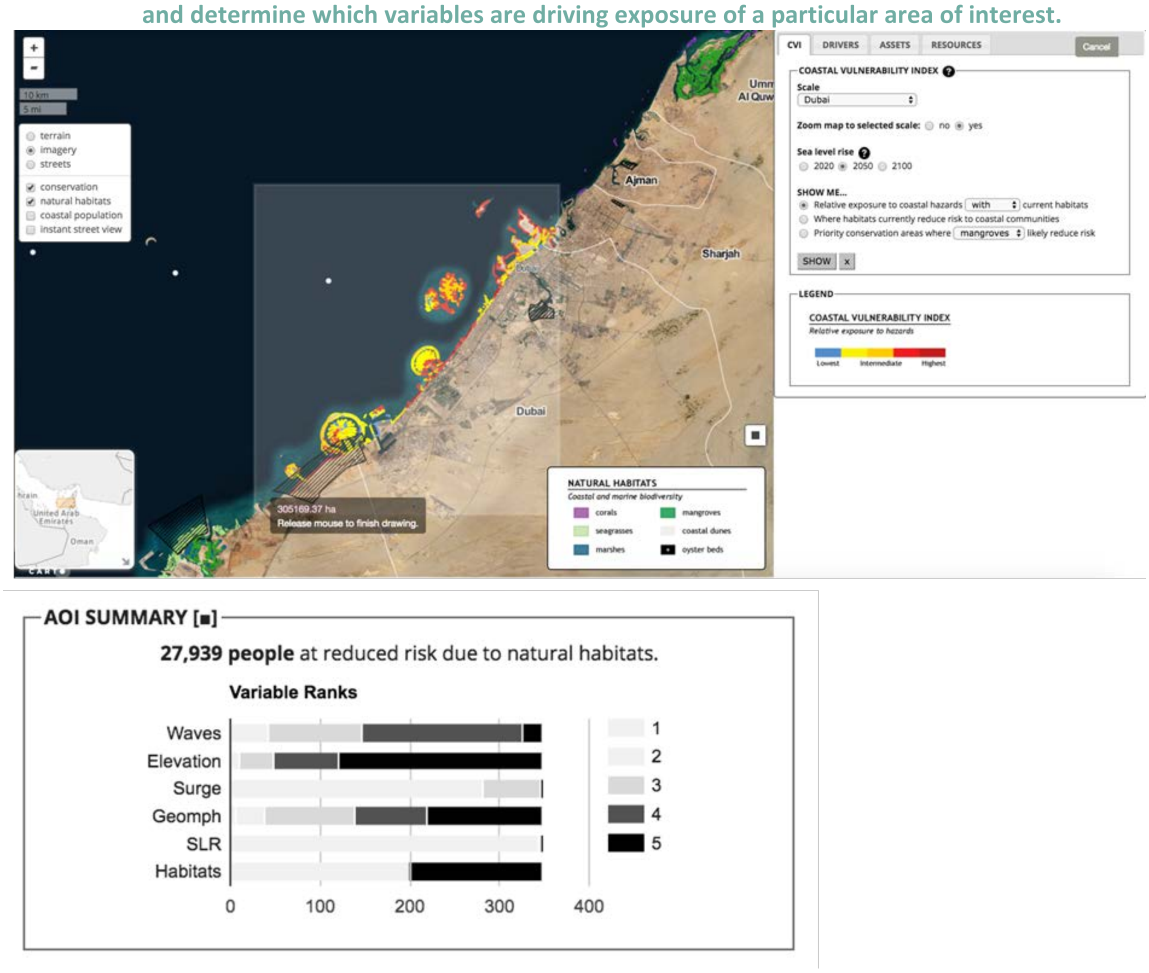
The coastal zones of the Emirates of Ajman and Dubai are most exposed to hazards relative to the other five coastal emirates. As the red areas in Figure 4-1A indicate, more than 75% of Ajman's shoreline will fall in the highest exposure category (top 25th percentile based on a distribution of index scores for nine habitat/climate scenarios) by the year 2050. Dubai is next at 36%, while less than one-quarter of the coastline for the remaining emirates will be highly exposed. The model classifies the Emirates of Abu Dhabi, Fujairah, and Sharjah as least exposed to hazards overall due to elevated coastal areas, lower probability of storm surge, extensive natural habitats, and relatively less exposure from local and ocean-generated waves. Red areas in Figure 4-1A highlight coastline most exposed to coastal hazards. Figure 4-1B identifies coastal segments where the protection provided by the current distribution of natural habitats is the greatest. The combine role of the six coastal and marine habitats considered in this study is greatest in dark brown areas, especially sections of coastline within Abu Dhabi and Umm Al Quwain.

Figure 4-1: A) Most exposed areas (dark red) with the presence of natural habitats for the current scenario and B) Combined role that these habitats play in protecting the UAE coastline from coastal hazards.



To summarize relative risk to coastal populations from storms, we combined exposure index scores with mapped data on population within 1 km of each 250-meter segment. The CVI Inspector calculates the number of people at reduced risk due to coastal protection services and then graphs the six variable ranks within a user-defined area of interest (AOI). At the national level, the Emirates of Abu Dhabi (40,000) and Dubai (25,000) benefit from the largest number of people at reduced risk due to the presence of natural habitats – mostly communities near these urban centers. Approximately 5,000 people are at reduced risk in each of the Emirates of Ras Al Khaimah, Umm Al Quwain and Sharjah. The citizens of Fujairah and Ajman receive the least coastal protection benefits (approximately 500 people at reduced risk each) because there are fewer nearshore habitats and lower population densities along their coastlines. Figure 4-2 shows a screenshot from the Emirate of Dubai. The highly exposed coastline (red line segments) within the selected area (transparent white box) is driven largely by low-lying coastline (elevation), a lack of extensive natural habitats (only patchy corals), and coastal geomorphology variables with the highest exposure rank (5). Wave exposure is also a driving factor as more than 200 km of Dubai's sinuous coastline is ranked 4 or 5 for this input variable.

Figure 4-2: Screenshot from the online CVI Inspector tool showing how a user can "unpack" the CVI model and determine which variables are driving exposure of a particular area of interest.



5. Discussion

As noted earlier, this sub-project of the LNRCCP focused on shoreline protection services provided to people and property by natural habitats. The primary goal was to map near-term coastal vulnerability and prioritize next steps for preserving biodiversity that protects people and property from coastal hazards and other climate change impacts. For example, functioning mangrove forests and coral reefs attenuate waves offer storm surge reduction benefits. We designed a CVI model to identify opportunities for augmenting habitats (e.g., restoration and rehabilitation activities) that maintain shoreline protection services along with other co-benefits. Fishers and divers once thrived in the Arabian Gulf and now tourism development and energy infrastructure throughout the UAE underscore the importance of identifying strategies to promote coastal resiliency to maintain livelihoods and protect these and other assets, as underscored in recent contingent valuation studies in the Abu Dhabi emirate (Blignaut et al., 2016).

While not within the scope of this subproject to assess the suite of ecosystem services and resulting monetary value provided by UAE's natural habitats, this research aims to inform sustainable development planning efforts at the national and emirate-levels. The CVI Inspector maps current and future distributions of habitats and their risk-reduction potential from coastal hazards, including which variables drive this exposure. Users of our tool can inspect an area of interest to identify strategies that can mitigate highest exposure ranks for variables of sea level rise, geomorphology, surge, elevation and wave exposure. The CVI Inspector identifies which habitats are playing the greatest role and where along the UAE coastline and how this service may change under alternative climate and habitat scenarios. This information is intended to assist coastal planners, natural resource managers, landowners, and other stakeholders identify at-risk sections of coast and design ecosystem-based strategies, such as conservation and restoration of coastal habitats, to mitigate exposure risk from hazards.

5.1. Developing Resiliency Metrics

The CVI Inspector is modeled after the work of the Natural Capital Project and collaborators with the Coastal Resilience platform (www.coastalresilience.org). To convert physical exposure to imperiled property and human life, we combined exposure values with mapped data on population. The tool and underlying framework offer users flexibility in their control of model parameters and weights. This enables users to essentially "unpack" the exposure index and investigate *what* is driving coastal exposure and *who* benefits from existing and future protection. Information gaps identified by this sub-project will inform data compilation for the broader natural capital mapping effort, including the supply and beneficiaries of coastal-marine ecosystem services. Table 5-1 outlines a range of social, biological, and ecosystem service metrics that can be linked to the CVI analytical outputs for further examination of risk-reduction provided to exposed sections of coastline, populations and assets. It will be important to further integrate spatial and non-spatial data from various regional mapping efforts, including the 2014-15 Habitat Baseline project, Plan Maritime 2030 for Abu Dhabi and other LNR Climate Change Programme sub-projects.

Table 5-1: Summary of relevant metrics as identified during stakeholder meetings and site visits with key representatives from public and private sectors of the UAE

Socioeconomic
People: Total population, elderly, youths, disadvantaged families Cultural: Archaeological sites, tourism opportunities (malls, hotels, beaches, resorts, cruise ships) Access: Roads, ports, marinas, airports Emergency services: Hospitals, police, fire Subsistence: Fishing communities Critical infrastructure: Oil refineries, storage, wastewater treatment and desalination plants, district cooling and nuclear facilities Industrial and commercial: Aluminum, fish landing and processing, dive operators
Ecological
Conservation: Protected areas, reserves, sanctuaries, heritage sites Ecosystem services: Blue carbon, recreation, fisheries, scenic quality Coastal and marine biodiversity: Sea turtle, dugong, shorebird nesting areas

The data compiled for the CVI subproject represents substantial progress towards the information needs of a broader natural capital mapping project in the UAE. Stanford University and the Natural Capital Project recently concluded a three-year engagement to map, measure and value ecosystem services in collaboration with Belize's Coastal Zone Management Authority & Institute. The team prioritized data compilation at the national and subnational levels to garner information about the range of human activities occurring in Belize's coastal zone along with ecological, biophysical and socioeconomic datasets. By applying the framework described by Rosenthal and colleagues (2014) and building on the outputs of this subproject, researchers could conduct an ecosystem services assessment for the UAE that:

- Delineates the coastal zone, jurisdictional boundaries and the land-sea interface
- Maps the current and future distribution of human uses
- Assesses where and to what extent different ecosystems are at highest risk and could lose the ability to provide important benefits
- Measures key ocean benefits such as coastal protection, fisheries, and tourism opportunities
- Values nature's benefits and potential changes to key ecosystem services in the future. (see Rosenthal et al., 2014, Arkema et al., 2015, and Verutes et al., in review for specifics).

5.2. Geographic Comparisons

There were requests by the Ministry of Climate Change and Environment to compare the CVI results for the UAE with other nations of the Arabian Peninsula. While this is possible, it would require a substantial extension to this scope of work including costly re-acquisition of 4 out of the 6 CVI variables. Another option could be to compare the UAE outputs to other counties where similar analyses have been conducted. To date, the Natural Capital Project and collaborators have applied the CV model in more than ten countries, including tropical locations in the Caribbean, southeast Asia and Africa. We encourage readers of this report to look at online map showcase tools from The Nature Conservancy for the Gulf of Mexico, and Natural Capital Project in The Bahamas (The Nature Conservancy, 2016; Natural Capital Project, 2016).

5.3. Development Impacts to Coastal Processes of Waves, Tidal Currents and Sediment Transport

Across the emirates, there are several ongoing coastal engineering and nearshore mega-projects, such as the Palm Islands and Khalifa Port, that are impacting coastal dynamics. For example, the satellite image in Figure 5-1 shows massive changes in beach accretion/erosion after construction of Palm Jumeirah, where the direction of longshore drift has reversed in large areas of Dubai after the construction of The World Islands. We highlight these areas because shamals typically blow directly towards Dubai rather than towards Abu Dhabi.

Figure 5-1: Satellite image of erosion and accretion zones in the Dubai emirate

Marine dredging activities may contribute to and accelerate the impact of coastal erosion over time. Since erosion tends to be accentuated on the downdrift side of coastal structures, we can see that the beach has eroded at the bottom of the picture of Figure 5-1 and accreted sand at the top of the picture, which also happens to be the base of Palm Jumeirah. This has had significant economic impact, as these beaches now require continuous ongoing maintenance and are being lost to groin fields (i.e., rigid coastal protection structures built from the ocean shore that interrupts water flow and limits the movement of sediment) or detached breakwaters (J. Burt, personal communication, July 25, 2016).

Engineered solutions to protect these developments have claimed to consider sea level rise. However, it is unclear whether they also account for storm surge and local hydrodynamics, including overtopping risk and severe erosion events caused by the funneling of water around these structures during current storm events and future storm events under climate change. The major changes caused by offshore development to beach profiles, longshore drift and erosion/accretion have been documented through the Dubai Coastal Zone Monitoring Programme (Smit et al., 2013), including high frequency radar to monitor surface currents of wave height, wave period, wave direction and wind direction every 10 to 30 minutes.

Figure 5-2 also shows patterns of accretion and erosion, highlighting the typical pattern of longshore drift in Dubai. The general flow of wind/wave activity is blowing onshore and the resulting wave action pushes sediment in a northeasterly direction. The satellite image shows an after snapshot of a longshore drift reversal phenomenon, which is essentially an eddy caused by The World Islands blocking the typical coastal flow to the northeast. Wind and waves coming from the north hit the angled shoreline. The refraction of energy will force a current along the shoreline, to the northeast. The eddy causes the currents to reverse in a southwesterly direction to the lee of the structure. Notice the saw tooth pattern of the groin-sheltered beaches is reversed in the yellow highlighted areas at the top of Figure 5-2 compared to the bottom of the same figure. This is because the longshore drift is reversed in these areas and moving sediment in opposite directions.

Figure 5-2: Satellite image of longshore drift in the Dubai emirate

This example from Dubai is emblematic of rapid development occurring in coastal zones worldwide and how it can often outpace national and subnational policies designed to safeguard coastal communities and resources. It is recommended that outputs of this research be used to screen future development proposals along UAE's coastal zone. The CVI Inspector can serve as a decision-support tool that highlights the suite of benefits that nature provides to the people of UAE and how coastal protection services, in particular, may be impacted by additional coastal development or management actions. This research aims to support the environmental impact assessment (EIA) process and compensation discussions with the goal of identifying opportunities for climate-compatible coastal development, restoration planning, and to evaluation nature-based strategies for more a resilient UAE coastal zone.

5.4.Limitations and Simplifications

The CVI model relies on a "protective distance" parameter to estimate the minimum coastal distance needed for a habitat type to be classified as offering protection. Few field or lab experiments have documented the distance over which different natural habitats effectively attenuate waves and reduce energy as they approach the coastal zone. A sensitivity analysis of varying coastal distance ranges was conducted to strengthen our confidence in the protective distance parameters used for this assessment.

We applied an index-based model to map the spatial distribution of coastal protection services provided by natural habitats along the coast of the UAE. A CVI serves as a screening tool to home in on at-risk locations without the extensive data compilation necessary to parameterize a complex equilibrium beach profile model. Through this research, our team identified particular segments of coastline were it may be worth the effort to collect detailed, site-level information necessary to quantify coastal protection services provided by natural habitats, including metrics describing the amount of land protected and avoided damages during a storm event (e.g., 100-year storm). See Table 2 in Ruckelshaus et al., 2016 for a detailed listing of factors affecting flooding and erosion damages in a specific location along a coastline. The InVEST Nearshore Waves & Erosion model developed by the Natural Capital Project (Guannel et al. 2014, 2016) is one such tool that can be used to assess erosion and flooding at the site level. Building on the inputs collected by the UAE CVI project team, a more resolute bathymetric grid of ocean depths, beach surveys of sediment size, slope, and berm height, storm surge model outputs, and localized sea level rise projections are all likely data requirements to take the next step from a index to a process-based approach for quantifying coastal protection services.

The InVEST coastal vulnerability model is constrained by the quality and accuracy of spatial input variables that comprise the index and the limitations of applying a simple, index-based approach to model exposure to coastal hazards. In other words, uncertainty comes from both the data inputs and the model itself. Empirical (observed) data on coastal erosion and inundation can help to validate this tool and resulting assessment of coastal protections services in the UAE. InVEST coastal vulnerability model assumptions and limitations include:

- The model does not account for processes that are unique to a region, nor for interactions between the six variables.
- The model does not predict changes in shoreline position or configuration.
- The model does not consider any hydrodynamic or sediment transport processes.
- The model assumes that the habitat data reflect the current or a snapshot of past/future distributions of coastal habitats, and that habitat distribution and abundance are constant.

Through this research and the resulting decision-making tool, we aim to support national and local agencies in the UAE to manage future conflicting interests and make defensible, enduring decisions for the management of coastal resources. Our primary objective was to map exposure at the national scale across a range of plausible climate change scenarios and enable users to drill into relevant hotspots at the Emirate-level. For the purpose of developing a national-level CVI Inspector tool, we only utilized data layers that were national in coverage. At the subnational scale, some variable ranks may seem questionable. This indicates a limit has been reached regarding what these national-level input data and the CVI model can tell us. The authors of this report and the CVI Inspector tool are open to ideas for incorporating new approaches, tools and information sources towards the refinement of the input variable ranks and improvement of the model outputs at subnational scales.

6. List of References

Abdulqader, Ebrahim AA, and Jeff Miller. (2012). Marine turtle mortalities in Bahrain territorial waters. *Chelonian Conservation and Biology* 11.1: 133-138.

ADEA (2006) "Marine and Coastal Environment Sector Paper." Abu Dhabi Environment Agency.

AGEDI. (2013). Systematic Conservation Planning Assessments and Spatial Prioritizations for the Emirate of Abu Dhabi, the United Arab Emirates and the Arabian Peninsula. Supporting Technical information: MU945_F11_02_01_UAE.

Al-Maslamani, I., Walton, M. E. M., Kennedy, H. A., Al-Mohannadi, M., & Le Vay, L. (2013). Are mangroves in arid environments isolated systems? Life-history and evidence of dietary contribution from inwelling in a mangrove-resident shrimp species. *Estuarine, Coastal and Shelf Science*, 124, 56-63.

Arkema, K. K., Guannel, G., Verutes, G., Wood, S. A., Guerry, A., Ruckelshaus, M., et al. (2013). Coastal habitats shield people and property from sea-level rise and storms. *Nature Climate Change*, 3(10), 913-918.

Arkema, K. K., Verutes, G. M., Wood, S. A., Clarke-Samuels, C., Rosado, S., Canto, M., et al. (2015). Embedding ecosystem services in coastal planning leads to better outcomes for people and nature. *Proceedings of the National Academy of Sciences*, 112(24), 7390-7395.

Arthur, R. and Garland, G., 2016. "Predicting the Extent of Inundation due to Sea-Level Rise: Al Hamra Development, Ras Al Khaimah, UAE. A Pilot Project", MISCELLANEA GEOGRAPHICA – REGIONAL STUDIES ON DEVELOPMENT, Vol. 20 • No. 2 • 2016 • pp. 25-31

Ayhan, M. E., & Alothman, A. (2009). Sea level rise within the western Arabian Gulf using tide gauge and continuous GPS measurements. Geophys Res Abs, 11, EGU General Assembly: 6006–1.

Barbier, E. B., Georgiou, I. Y., Enchelmeyer, B., & Reed, D. J. (2013). The value of wetlands in protecting southeast Louisiana from hurricane storm surges. *PloS ONE*, 8(3).

Bauman, A. G., Burt, J. A., Feary, D. A., Marquis, E., & Usseglio, P. (2010). Tropical harmful algal blooms: an emerging threat to coral reef communities? *Marine Pollution Bulletin*, 60(11), 2117-2122.

Beck, M. W., et al. (2011). Oyster reefs at risk and recommendations for conservation, restoration, and management. *Bioscience*, 61(2), 107-116.

Bento, R., Hoey, A. S., Bauman, A. G., Feary, D. A., & Burt, J. A. (2016). The implications of recurrent disturbances within the world's hottest coral reef. *Marine Pollution Bulletin*, 105(2), 466-472.

Bilkovic, D. M., and Roggero, M. M. (2008). Effects of coastal development on nearshore estuarine nekton communities. Marine Ecology Progress Series, 358, 27-39.

Blackstock, K. L., Waylen, K. a., Dunglinson, J., & Marshall, K. M. 2012. "Linking process to outcomes - Internal and external criteria for a stakeholder involvement in river basin management planning." *Ecological Economics*, 77, 113–122.

Blignaut, J., Inglesi-Lotz, R., Mander, M., Glavan, J., and Parr, S., (2016). The amenity value of Abu Dhabi's coastal and marine resources to its beach visitors, Ecosystem Services, Vol 19, Pages 32-41.

Burt, J. (2014). The environmental costs of coastal urbanization in the Arabian Gulf. City: analysis of urban trends, culture, theory, policy, action, 18(6), 760-770.

Burt, J. (2016, July 25). Personal interview.

Burt, J., Al-Harthi, S., & Al-Cibahy, A. (2011). Long-term impacts of bleaching events on the world's warmest reefs. *Marine Environmental Research*, 72(4), 225-229.

Burt, J., Bartholomew, A., & Feary, D. (2012). Man-made structures as artificial reefs in the Gulf. In B. Riegl & S. Purkis (Eds.), Coral reefs of the Gulf: adaptation to climatic extremes (Vol. Coral Reefs of the World 3, pp. 171-186): Springer Science+Business Media B. V.

Carter, R. (2005). The history and prehistory of pearling in the Persian Gulf. *Journal of the Economic and Social History of the Orient*, 48(2), 139-209.

Cash, David W., et al. (2003). Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences* 100.14: 8086-8091.

Chess, C., & Purcell, K. (1999). Policy analysis public participation and the environment: Do we know what works? *Environmental Science & Technology*, (732), 2685–2692.

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S. J., Kubiszewski, I., et al. (2014). Changes in the global value of ecosystem services. *Global Environmental Change*, 26, 152-158.

Currin, C. A., Delano, P. C., and Valdes-Weaver, L. M. (2008). Utilization of a citizen monitoring protocol to assess the structure and function of natural and stabilized fringing salt marshes in North Carolina. *Wetlands Ecology and Management*, 16(2), 97-118.

De Groot, R., et al. (2012). Global estimates of the value of ecosystems and their services in monetary units. *Ecosystem services*, 1(1), 50-61.

Dodd, R.S.; Blasco, F.; Rafi, Z.A., and Torquebiau, E. (1999). Mangroves of the United Arab Emirates: Ecotypic diversity in cuticular waxes at the bioclimatic extreme. *Aquatic Botany*, 63(3–4), 291–304.

Fencl, A., and Klein, R. (2008). CLIMATE CHANGE, Impacts, Vulnerability & Adaptation – Coastal Zones. Environment Agency - Abu Dhabi.

Ellison, A. M., & Farnsworth, E. J. (1996). Anthropogenic disturbance of Caribbean mangrove ecosystems: past impacts, present trends, and future predictions. *Biotropica*, 549-565.

Encyclopedia Iranica (2016). Pearl – Islamic Period. Available from http://www.iranicaonline.org/articles/pearl-ii-islamic-period.

Erftemeijer, P. L., & Shuail, D. A. (2012). Seagrass habitats in the Arabian Gulf: distribution, tolerance thresholds and threats. *Aquatic Ecosystem Health & Management*, 15(sup1), 73-83.

Everard, M., Jones, L., & Watts, B. (2010). Have we neglected the societal importance of sand dunes? An ecosystem services perspective. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 20(4), 476-487.

FAO. (2007). The World's Mangroves, 1980–2005: A Thematic Study in the Framework of the Global Forest Resources Assessment 2005. Rome, Italy: FAO, 77p.

Feary, D., Burt, J., & Bartholomew, A. (2011). Artificial marine habitats in the Arabian Gulf: review of current use, benefits and management implications. *Ocean & Coastal Management*, 54, 742-749.

Gedan, K. B., Kirwan, M. L., Wolanski, E., Barbier, E. B., & Silliman, B. R. (2011). The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Climatic Change*, 106(1), 7-29.

Gittman, R. K., Peterson, C. H., Currin, C. A., Joel Fodrie, F., Piehler, M. F., and Bruno, J. F. (2016). Living shorelines can enhance the nursery role of threatened estuarine habitats. *Ecological Applications*, 26(1), 249-263.

Grizzle, R. E., Ward, K. M., AlShihi, R. M., and Burt, J. A. (2016). Current status of coral reefs in the United Arab Emirates: Distribution, extent, and community structure with implications for management. *Marine pollution bulletin*, 105(2), 515-523.

Guannel, G., Arkema, K.K., Ruggiero, P., Verutes, G. (2016). The Power of Three: Coral Reefs, Seagrasses and Mangroves Protect Coastal Regions and Increase Their Resilience. *PLoS ONE* 11(7).

Guannel, Greg, et al. (2014). Integrated modeling framework to quantify the coastal protection services supplied by vegetation. *Journal of Geophysical Research: Oceans*

Howari, F.M.; Jordan, B.R.; Bouchouche, N., and Wyllie-Echeverria, S. (2009). Field and remote sensing assessment of mangrove forests and seagrass beds in the northwest part of the United Arab Emirates. *Journal of Coastal Research*, 25(1), 48–56.

IPCC (2007a). Climate Change 2007: Impacts, Adaptation and Vulnerability. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, eds. Cambridge, UK: Cambridge University Press.

IPCC (2007b). Summary for policymakers. In: Solomon, S.; Qin, D.; Manning, M.; Chen, Z.; Marquis, M.; Avery, K.B.; Tignor, M., and Miller, H.L. (eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press, pp. 1–18.

Kentula, M. E., & McIntire, C. D. (1986). The autecology and production dynamics of eelgrass (Zostera marina L.) in Netarts Bay, Oregon. *Estuaries*, 9(3), 188-199.

Long, W. C., Grow, J. N., Majoris, J. E., and Hines, A. H. (2011). Effects of anthropogenic shoreline hardening and invasion by Phragmites australis on habitat quality for juvenile blue crabs (Callinectes sapidus). *Journal of Experimental Marine Biology and Ecology*, 409(1), 215-222.

Loughland, R.A.; Saenger, P; Luker, G.; Siddiqui, K.; Saji, B.; Belt, M., and Crawford, K. (2007). Changes in the coastal zone of Abu Dhabi determined using satellite images (1972–2003). *Aquatic Ecosystem Health and Management*, 10(3), 301–308.

Manis, J. E., Garvis, S. K., Jachec, S. M., and Walters, L. J. (2015). Wave attenuation experiments over living shorelines over time: a wave tank study to assess recreational boating pressures. *Journal of Coastal Conservation*, 19(1), 1-11.

Mohamed, K., 2008. Long-Term Tidal Water Level Measurements in Abu Dhabi Emirate, ASME 2008 27th International Conference on Offshore Mechanics and Arctic Engineering, Volume 4: Ocean Engineering; Offshore Renewable Energy, Estoril, Portugal, June 15–20, pp. 937-944; 8 pages

Mumby, P. J., et al. (2004). Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature*, 427(6974), 533-536.

Murray BC, Pendleton L, Jenkins WA, Sifleet S. (2011). Green Payments for Blue Carbon: Economic Incentives for Protecting Threatened Coastal Habitats. Nicholas Institute for Environment, Duke University, Durham, North Carolina.

Naser, H. A. (2014). Marine ecosystem diversity in the Arabian Gulf: Threats and conservation. Biodiversity-The dynamic balance of the planet, 297-327.

Natural Capital Project (2016). Hazard Viewer: The Bahamas. Available from: http://marineapps.naturalcapitalproject.org/bahamas/

Neelamani, S., Al-Salem, K., & Rakha, K. (2006). Extreme water waves in the UAE territorial waters. *Emirates Journal for Engineering Research*, 11(2), 37-46.

Patrick, C. J., Weller, D. E., Li, X., and Ryder, M. (2014). Effects of shoreline alteration and other stressors on submerged aquatic vegetation in subestuaries of Chesapeake Bay and the Mid- Atlantic coastal bays. *Estuaries and Coasts*, 37(6), 1516-1531.

Phillips, R. (2002). Seagrasses of the Arabian Peninsula Region, with particular reference to mineralizsation in Sabkhat , in Barth and Böer (eds) Sabkha Ecosystems, pp. 299-302.

Preen, A. (2004). Distribution, abundance and conservation status of dugongs and dolphins in the southern and western Arabian Gulf. *Biological Conservation*, 118: 205-218.

Preen, A., Das, H., Al-Rumaidh, M., Hodgson, A. (2012). Dugongs in Arabia; In: E. Himes, J. Reynolds III, L. Aragones, A. Mignucci-Giannoni, M. Marmontel (Eds.) Sirenian conservation: Issues and strategies in developing countries. University Press of Florida, Gainesville.

Reed, Mark S. (2008). Stakeholder participation for environmental management: a literature review. Biological conservation 141.10: 2417-2431.

Riegl, B. (2003). Climate change and coral reefs: different effects in two high-latitude areas (Arabian Gulf, South Africa). *Coral reefs*, 22(4), 433-446.

Riegl, B. M., & Purkis, S. J. (2012). Coral reefs of the Gulf: adaptation to climatic extremes in the world's hottest sea. In Coral Reefs of the Gulf (pp. 1-4). Springer Netherlands.

Rosenthal, A. et al. (2014). Process matters: a framework for conducting decision-relevant assessments of ecosystem services. *International Journal of Biodiversity Science, Ecosystem Services & Management*: 1-15.

Ruckelshaus, Mary H., et al. (2016). Evaluating the Benefits of Green Infrastructure for Coastal Areas: Location, Location, Location. *Coastal Management*.

Saenger, P. (1997). Biogeography of mangrove species. In: Spaulding, M.; Field, C., and Blasco, F. (eds.), The World Atlas of Mangroves. Cambridge, U.K.: Samara Publishers, 319p.

Sea Around Us. (2016). Catches by Taxon in the waters of United Arab Emirates, Available from: http://www.seaaroundus.org/data/#/eez/784

Sharp, R. et al. (2014). InVEST User's Guide: Integrated Valuation of Ecosystem Services and Tradeoffs (Stanford, CA: The Natural Capital Project). Available from: http://data.naturalcapitalproject.org/nightly-build/release_default/release_default/documentation/coastal_vulnerability.html

Sheppard, C. R. (1993). Physical environment of the Gulf relevant to marine pollution: an overview. *Marine Pollution Bulletin*, 27, 3-8.

Sheppard, C., et al. (2010). The Gulf: a young sea in decline. *Marine Pollution Bulletin*, 60(1), 13-38.

Short, F. T., & Neckles, H. A. (1999). The effects of global climate change on seagrasses. *Aquatic Botany*, 63(3), 169-196.

Sifleet, S., Pendleton, L., & Murray, B. C. (2011). State of the Science on Coastal Blue Carbon. A Summary for Policy Makers. Nicholas Institute Report, 11-06.

Smit, F., Mocke, G. P., & Al Zahed, K. (2003). Dubai Coastal Zone Monitoring Programme. COPEDEC.

Smyth, D., Al-Maslamani, I., Chatting, M., & Giraldes, B. (2016). Benthic surveys of the historic pearl oyster beds of Qatar reveal a dramatic ecological change. *Marine Pollution Bulletin*.

Spalding M.D., Kainuma M., Collins, L. (2010). World Atlas of Mangroves. Earthscan, London, UK

Spalding, M. D., Ruffo, S., Lacambra, C., Meliane, I., Hale, L. Z., Shepard, C. C., and Beck, M. W. (2014). The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards. *Ocean and Coastal Management*, 90, 50-57.

Sutton-Grier, A. E., Wowk, K., and Bamford, H. (2015). Future of our coasts: the potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environmental Science and Policy*, 51, 137-148.

Taoufik Saleh, K. (2012). Sea level rise and Abu Dhabi coastlines: an initial assessment of the impact on land and mangrove areas. *Journal of Ecosystem & Ecography*.

The Nature Conservancy (2016). Coastal Resilience. Available from: http://www.coastalresilience.org

UAE Interact (2016). Natural UAE. Available from: http://www.uaeinteract.com/nature/geology/geo02.asp

Verutes, G.M., et al. (In review). Integrated Planning that Safeguards Ecosystems and Balances Multiple Objectives in Coastal Belize.

Wildscreen Arkive. (2011). Jewels of the UAE: Saltmarsh. Environmental Agency Abu Dhabi, Available from: http://www.arkive.org/uae/en/saltmarsh

Wilkinson C. (2004). Status of coral reefs of the world: 2004. Australian Institute of Marine Science, Townsville

World Bank, 2016. Total population tables. Available from: http://data.worldbank.org/indicator/SP.POP.TOTL?locations=AE

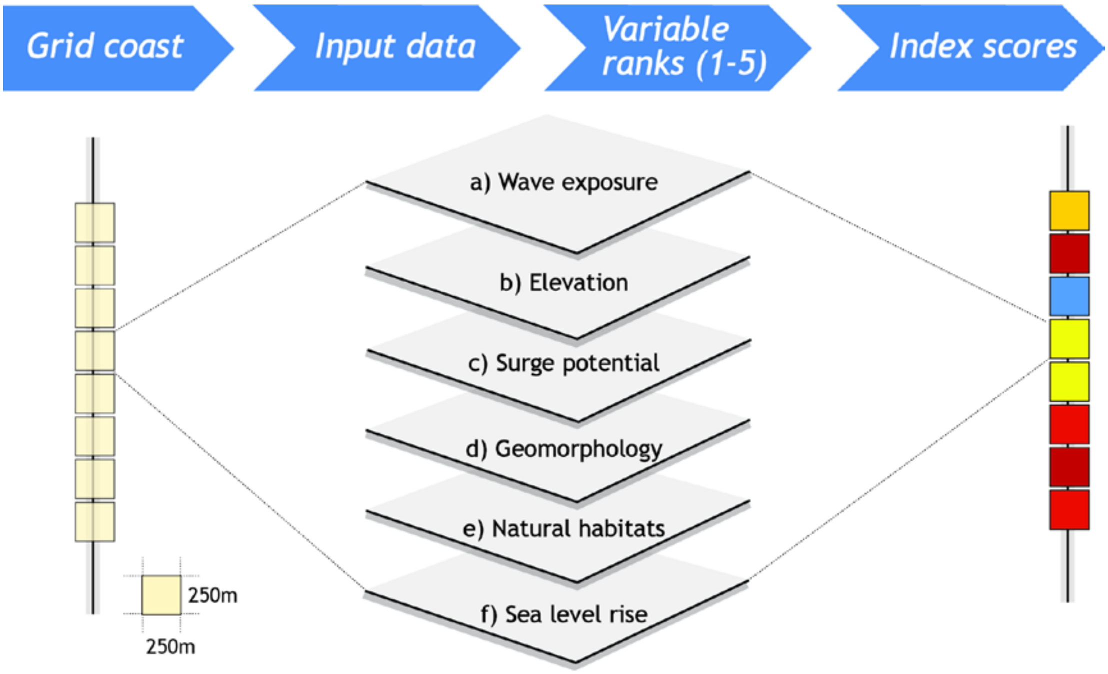
Annex A: Coastal Vulnerability Index (CVI)

The InVEST coastal vulnerability model estimates relative exposure to storms and sea level rise within a user-defined study area and then enables users to combine this output with social metrics to map socially and physically vulnerable people and property. Model inputs, summarized in Table 1, serve as proxies for various complex shoreline processes that influence susceptibility to erosion and flooding. Inputs include information about climatic forcing (wind and wave activity, storm surge potential), shoreline type (geomorphology), presence of natural habitats, elevation and rates of observed sea-level change. The resultant exposure index ranks shoreline segments from 1 to 5, with 1 representing the lowest relative risk of exposure to coastal hazards and 5 representing the highest relative risk. We used the following steps to conduct a coastal vulnerability assessment using InVEST: (a) assess current physical exposure, (b) examine how this exposure and the resulting risk might change as a result of alternative future scenarios (ecosystem threat level, climate, etc.), and (c) highlight high-value habitat areas that provide the greatest reductions in risk to coastal assets ("habitat role" metric).

To estimate the relative exposure of each 250 m^2 segment of coastline, we calculated an index for coastal exposure. Coastal vulnerability model outputs were compared across the seven coastal emirates, island groups and the urban centers of Abu Dhabi and Dubai to identify areas where the role of habitats are the greatest in reducing risk to people and critical infrastructure within one kilometer of each coastline segment. Using observed and modeled data, we generated absolute values for each variable for each 250 m^2 segment of coastline. We then ranked each variable for each segment from low to high exposure (1 to 5). The coastal exposure index (EI) incorporates five variables representing the biological and geomorphic characteristics of the region: natural habitat, geomorphology, elevation, wave exposure, and surge potential.

$$\text{Exposure Index} = \left(R_{\text{Habitats}} R_{\text{SeaLevelRise}} R_{\text{Geomorphology}} R_{\text{Elevation}} R_{\text{Wave}} R_{\text{SurgePotential}}\right)^{\frac{1}{6}}$$

where R is rank and subscripts for each rank indicate one of the six variables.



Annex A, Figure 1: Conceptual diagram of the InVEST coastal vulnerability model.

Table 1 summarizes the individual variables included in the model, each representing unique input data. As with the final exposure index, each individual variable is ranked from 1 (lowest risk) to 5 (highest risk), using a combination of absolute and relative values. The geometric mean of the individual inputs below was used to calculate the final exposure index scores.

Annex A, Table 1: Biophysical variables and ranks for the coastal vulnerability model. Ranks for relief, wave exposure, and surge potential are based on the distribution of values for these variables for all 250 m^2 coastal segments.

	Contribution to Coastal Exposure				
Variable Rank	**Very Low Exposure Rank** (1)	**Low Exposure Rank** (2)	**Moderate Exposure Rank** (3)	**High Exposure Rank** (4)	**Very High Exposure Rank** (5)
Geomorphology	Rocky; high cliffs; seawalls	Medium cliff; bulkheads and small seawalls	Low cliff; alluvial plain; revetments, rip-rap walls	Cobble beach; estuary; lagoon; bluff	Barrier beach; sand beach; mud flat; delta
Elevation (meters)	14.1 – 290 (< 20^{th} percentile)	11.3 – 14.1 (20^{th} to 40^{th} percentile)	10 – 11.3 (40^{th} to 60^{th} percentile)	8.5 – 10 (60^{th} to 80^{th} percentile)	8.5 – 0 (>80^{th} percentile)
Natural habitats	Coral reefs; mangroves	Marshes	Sand dunes; oyster beds	Seagrasses	No habitat
Sea level change (region: year)	Near term (UAE: 2020) (< 33^{h} percentile)	Mid term (UAE: 2050) (33^{th} to 66^{th} percentile)	Long term (Sea of Oman: 2100) (66^{th} to 90^{th} percentile)	Long term (Arabian Gulf: 2100) (>90^{th} percentile)	-
Wave Power (kW/m)	< 0.001 (< 20^{th} percentile)	0.001 – 0.007 (20^{th} to 40^{th} percentile)	0.007– 0.025 (40^{th} to 60^{th} percentile)	0.025 – 0.200 (60^{th} to 80^{th} percentile)	0.200 – 22.35 (>80^{th} percentile)
Storm surge height (meters)	-	1.79 – 2.13 (< 25^{th} percentile)	2.13 – 2.15 (25^{th} to 50^{th} percentile)	2.15 – 2.37 (50^{th} to 75^{th} percentile)	2.37 – 2.63 (>75^{th} percentile)

Table 2 outlines the spatial database and inputs to the CVI model along with planned additions and improvements.

Annex A, Table 2: Inputs, sources, and how these data were used by the InVEST coastal vulnerability model

INPUT	SOURCE	HOW THESE DATA WERE USED IN THE MODEL
Physical Exposure These data were used by the coastal vulnerability model to assess the relative exposure of UAE's coastline to six factors that mitigate or enhance the effects of coastal hazards.		
Land mass line	OpenStreetMap	The model differentiates sheltered from exposed coastline and fetch. This determines whether the model calculates wave rank from oceanic or local (wind) generated waves.
Bathymetry	General Bathymetric Chart of the Oceans (GEBCO)	
Elevation (topographic relief)	ASTER Global Digital Elevation Model Version 2 (GDEM v2)	The model determines the average elevation (height in meters) of all DEM cells on land within a 3-km search radius. The resulting distribution is classified using percentile breaks to produce relative ranks of 5 through 1.
Geomorphology	Landsat 8, Google Earth and Street View imagery	This input data layer will include five geomorphology classifications of each 250-meter shoreline segment ranked from 1 to 5.
Natural habitats (coastal dunes, mangroves, corals, marshes, seagrasses, oyster beds)	LNR Biodiversity Assessment for the UAE (AGEDI); Mapping and Characterizing Coral Habitats in the United Arab Emirates (Grizzle, Ward and Burt); Gazetteer of the Persian Gulf (John Gordon Lorimer)	The model computes a habitat rank from 1 to 5 based on the presence or absence of habitats along each shoreline segment. See Table 1 for ranking scheme.
Wave exposure (local and oceanic waves)	National Center for Atmospheric Research (NCAR); ERA-Interim from European Center for Mid-Range Weather Forecasts (ECMWF)	The model computes relative wave exposure for each coastline segment using time series data (2010-2015) of wind speeds and associated direction, above the 90th percentile value, and fetch distance.

INPUT	SOURCE	HOW THESE DATA WERE USED IN THE MODEL
Surge potential	DIVA database model v1.0 (Hinkel and Klein 2004)	Surge potential was estimated using DIVA model output variable "S100" which represents 1 in 100 year surge height. The resulting distribution is classified using percentile breaks (25/50/75) to produce relative ranks of 5 through 2 respectively.
Sea level rise	Average historical sea level rise rate of 2.27 mm/year for the Arabian Gulf and 1.8 mm/year for the Arabian Sea (Ayhan and Alothman 2009)	The relative net sea level change along the coastline of a given region is the sum of global sea level rise (SLR), local SLR (eustatic rise) and local land motion (isostatic rise). Regional rates were assumed to be constant through the year 2050 and then doubled through 2100.
Social Exposure These data were combined with physical exposure outputs from the InVEST coastal vulnerability model and used to assess where habitats are most critical for protecting coastal assets and how the vulnerability of coastal communities varies for different scenarios.		
Coastal population	WorldPop 2014	Calculate total population within the coastal zone and how many of people are at reduced risk as a result of the protection provided by coastal-marine habitats.
Conservation	UAE Ministry of Climate Change & Environment and IUCN World Database on Protected Areas (WDPA) 2015	Maps the location of important ecological assets including protected areas, reserves, sanctuaries, and heritage sites
Geopolitical boundaries	Global Administrative Areas (GADM v2.8)	Administrative boundary lines for the seven coastal emirates

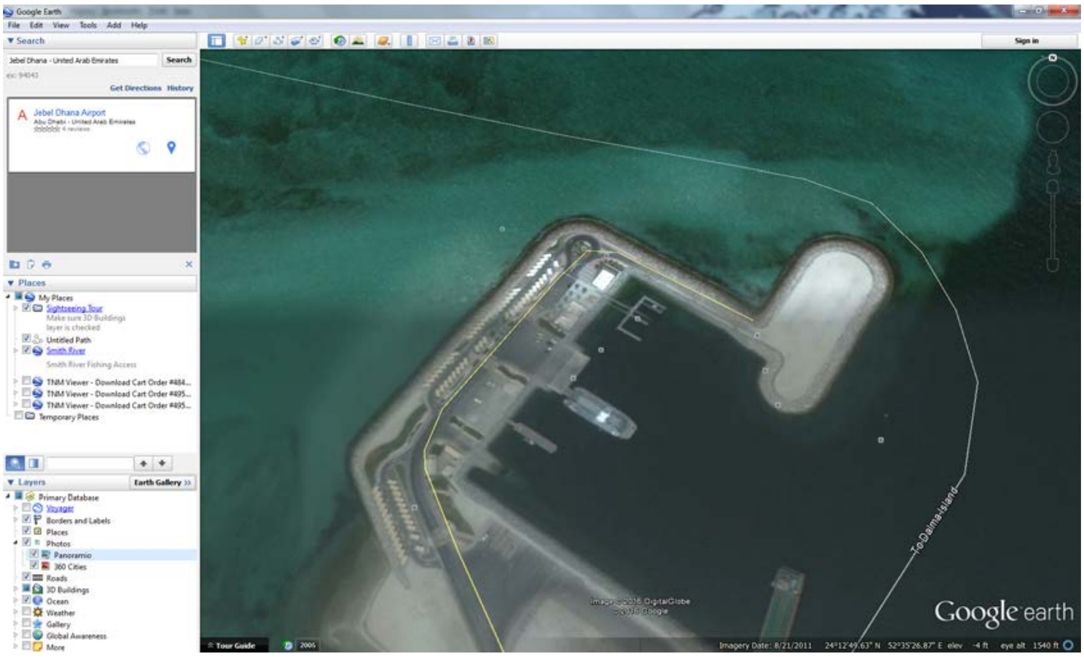
INPUT	SOURCE	HOW THESE DATA WERE USED IN THE MODEL
Critical infrastructure	AGEDI spatial database of select infrastructure	Tabular information with GPS coordinates and values of built infrastructure, including hotels, residential properties, ports, tourism and other coastal assets.
Social, economic and ecological assets	Multiple sources cited in Table 2	As identified by stakeholders, these data can be used as metrics to quantify the risk reduction provided by natural habitats.

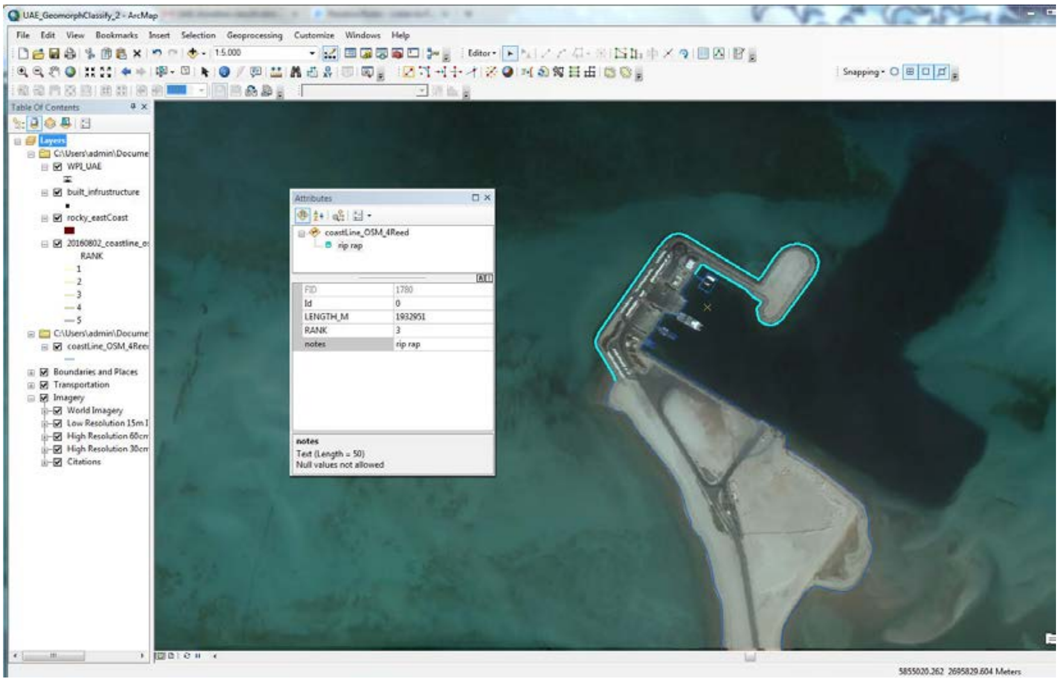
Annex B: Geomorphology and Wave Exposure Variable Ranks

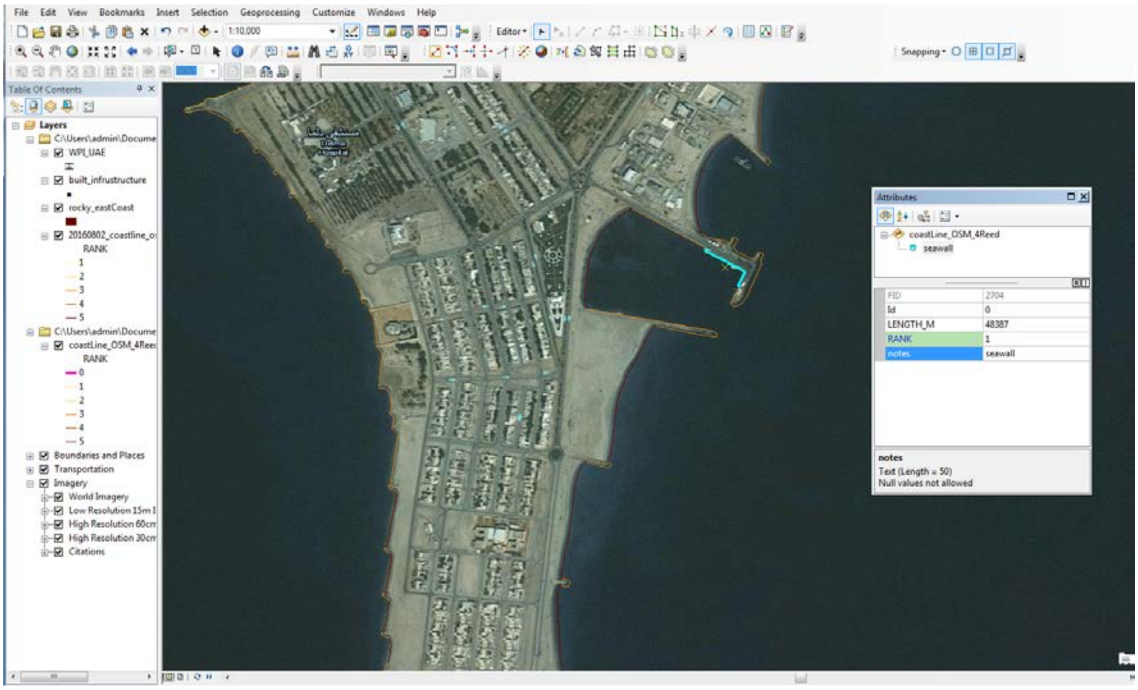
Coastal Geomorphology

Sources: Landsat 8, Google Earth and Street View imagery

The OpenStreetMap landmass line for the UAE coast was segmented into segments at 250 meter intervals. A combination of supervised classification using Landsat 8 along with manual classification based on Google Earth and Street View (orthogonal and oblique imagery) were used to rank the segments based on the categories outlines in Annex B, Table 1. The following figures show the Google Earth and ArcGIS interfaces used in this ranking for Delma Island and Jebel Dhana Port.




UAE_GeomorphClassify_2 - ArcMap
File Edit View Bookmarks Insert Selection Geoprocessing Customize Windows Help
Table Of Contents
Layers
WPI_UAE
built_infrustructure
rocky_eastCoast
RANK
coastLine_OSM_4Reed
Boundaries and Places
Transportation
Imagery
World Imagery
Citations
Attributes
coastLine_OSM_4Reed
rip rap
FID 1780
Id 0
LENGTH_M 1932951
RANK 3
notes rip rap
notes
Text (Length = 50)
Null values not allowed


File Edit View Bookmarks Insert Selection Geoprocessing Customize Windows Help
Table Of Contents
Layers
WPI_UAE
built_infrustructure
rocky_eastCoast
RANK
coastLine_OSM_4Reed
RANK
Boundaries and Places
Transportation
Imagery
World Imagery
Citations
Attributes
coastLine_OSM_4Reed
seawall
FID 2704
Id 0
LENGTH_M 48387
RANK 1
notes seawall
notes
Text (Length = 50)
Null values not allowed

Wave Exposure

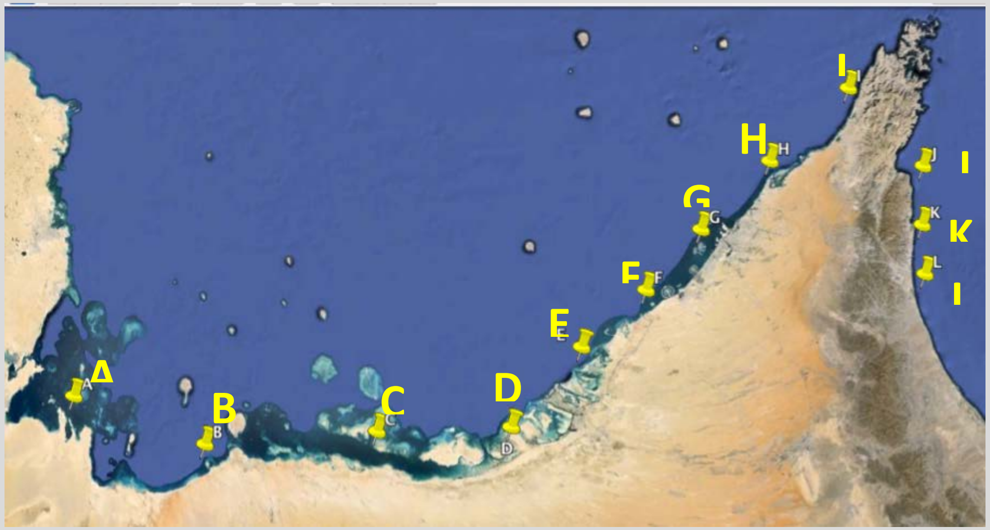
Wind
Sources: National Center for Atmospheric Research (NCAR) - Regional Atmospheric Modeling Under Climate Change; available on Climate Inspector at https://uae.rap.ucar.edu
Temporal resolution: January 1986 through December 2005; readings at daily intervals
Spatial resolution: 12 readings (A-L) at approximately 25km intervals
Units: direction (degrees), mean speed (meters/second),

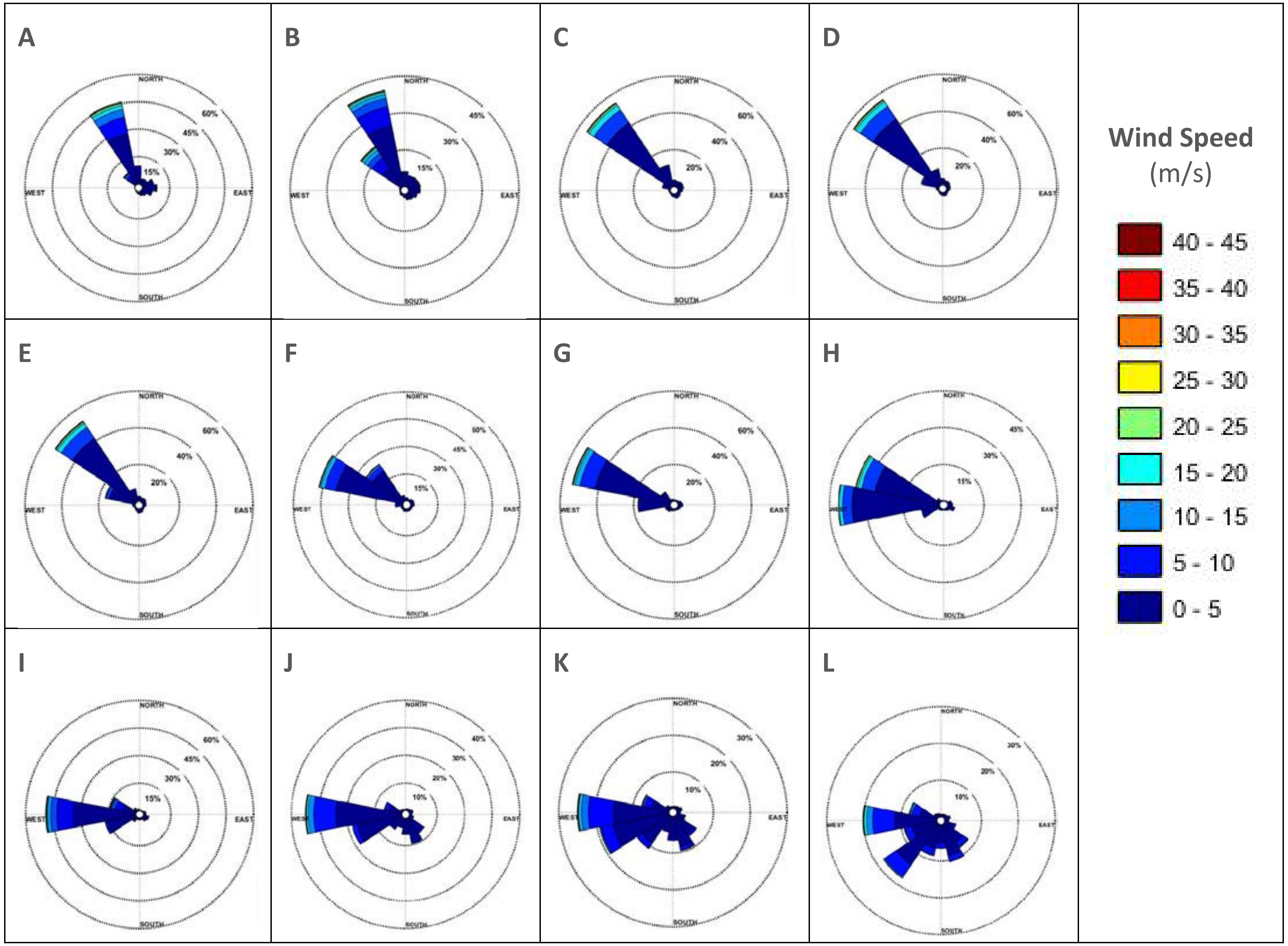
Waves
Sources: ERA-Interim from European Center for Mid-Range Weather Forecasts (ECMWF)
Temporal resolution: January 2010 through April 2016; readings at 6-hour intervals
Spatial resolution: 12 readings (A-L) at approximately 25km intervals
Units: direction (degrees), wave period (seconds), significant wave height (meters)

To estimate the importance of wind exposure and wind-generated waves, wind and wave statistics were used to generate a climatic forcing grid for the UAE coastal zone. Coastline segments that are exposed to the open ocean generally experience a higher exposure to waves than sheltered regions because winds blowing over longer distances generate larger waves. Each 250-meter coastline segment was classified as exposed to either oceanic or locally-generated wind-waves. The InVEST coastal vulnerability model then estimates the relative exposure of a shoreline segment to waves by assigning it the maximum of the weighted average power of oceanic waves and locally wind–generated waves. More information can be found in the coastal vulnerability chapter of the InVEST user's guide: http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/coastal_vulnerability.html

The following table and graphics summarize the climatic forcing grid and wind statistics that served as input to the CVI model for UAE:

Point	Latitude	Longitude
A	24.37	51.66
B	24.14	52.40
C	24.22	53.36
D	24.25	54.10
E	24.66	54.49
F	24.94	54.84
G	25.25	55.19
H	25.60	55.54
I	25.97	56.01
J	25.57	56.41
K	25.27	56.40
L	25.02	56.41




A
B
C
D
E
F
G
H
I
J
K
L
Wind Speed
(m/s)
40 - 45
35 - 40
30 - 35
25 - 30
20 - 25
15 - 20
10 - 15
5 - 10
0 - 5

Annex C: Urban Resilience to Climate Change

The following excerpt is from an internal document produced by the World Resources Institute (2015), entitled "A Handbook on Urban Climate Resilience".

What do we mean by climate change?

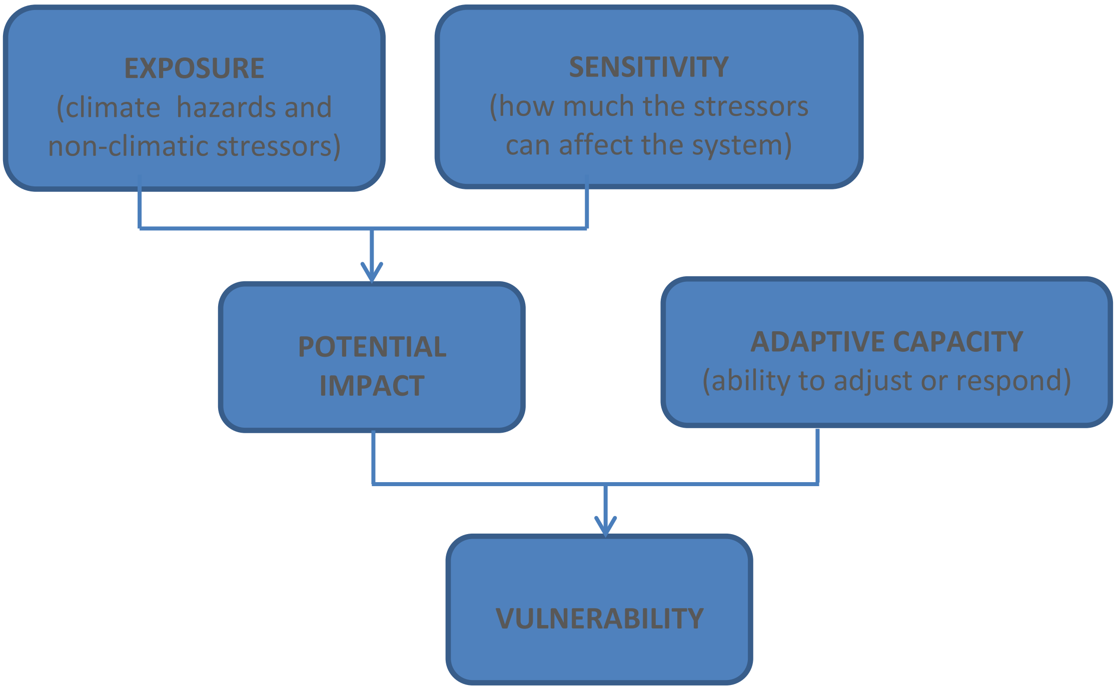
Current and future climate change **hazards** (such as storms and droughts) will have **impacts** on human and natural systems (such as the flooding of subway tunnels and the destruction of crops). Although climate models have helped us understand potential future climate change **risks** better (risk is the probability of a hazard multiplied by the impact of the hazard if it occurs) there is still **uncertainty** about exactly what impacts climate change will have, as well as where, when, and how severe they will be.

It is worth noting that adaptation to climate change comprises two related challenges: adaptation to current climate variability and to future climate change. **Adapting to climate change** confronts both an intensification of existing climate variability, and wholly new, transformational phenomena such as sea level rise and glacial loss. Many cities, especially in developing countries, are not fully prepared to contend with even current levels of climate variability.

Uncertainty is an important concept to keep in mind when making choices about how to reduce vulnerability and increase resilience to climate change. Since the projections about climate change are still uncertain, it is important to plan for a range of various scenarios. Adaptation efforts that are successful under several scenarios, not just one optimal scenario that may or may not manifest, are known as **robust efforts** (see Wilby and Dessai, 2010 for more).

Individuals, communities and countries with high **vulnerability** to climate change are those that have high exposure (to hazards) and sensitivity (the degree to which they are affected by climate change) and low adaptive capacity (their ability to adjust or respond to consequences of climate change). In order to prepare for climate change, individuals and systems can build **resilience** which is broadly defined as the capacity to cope with a hazardous event in a way that maintains essential functioning and capacity.

Annex C, Figure 1: Relationship between climate change concepts



an initiative of

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

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

AGEDI .org

LNRClimateChange@ead.ae