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Sea Level Rise Vulnerability Assessment for Abu Dhabi, United Arab Emirates

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Disclaimer

This research report was prepared by the research scholar - the Author of this thesis- based on the methodology, results and conclusions acquired during the research development phases and does not reflect Abu Dhabi governorate entities or any of its employees.

Abstract

The phenomenon of global warming has become a fact, however; the uncertainty is about the magnitude and acceleration of its manifestations. Global mean sea level rise is one of the results induced by global warming and is happening with an undetectable accelerated pace. The world international organizations and governments are devoting efforts and initiatives in a trial to manage global warming induced impacts. The efforts include: assessment for the potential impacts of risks, mitigation of the risks by trying to decrease its magnitude or acceleration through developing and adhering to environmental policies, and finally adapting our environment to increase its resilience to such risks. On the other hand, governments cannot act solely to mitigate the risks of global mean sea level rise or global warming; only international as well local collaborated efforts can trigger an effective plan to manage such risks.

The goal of this project was to introduce a comprehensive yet simple practice on how the Geographic Information Systems methods and up-to-date technology can be utilized in assessing the potential impacts of sea level rise. This was translated into three main objectives to fulfill: (i) Assess which areas are vulnerable to sea level rise using the best available methods; (ii) Simplify the results of assessments in the form of charts and statistics to enable stakeholders to have a quick insight on the selected sea level rise scenario potential impacts; (iii) Publish the vulnerability assessment results on a sharable platform where multiple organizations/entities can have access.

The first objective was accomplished through developing a configurable geo-processing model that aims to extract the potentially inundated areas using a bathtub-enhanced method with hydrological connectivity evaluation. The model runs on the best free elevation dataset available for the area (SRTM 1arc second - 30 meters), selected possible sea level rise scenarios (1 meter, 2 and 3 meters) and United Arab Emirates boundary. The results were overlaid with multiple datasets representing different domain categories like natural environment (land-cover, natural habitats, protected areas), built up environment (land-use, industrial areas, points of interest), administrative (municipalities, districts, population), transportation and utilities (roads, transportation facilities and utilities). The final output is multiple datasets for each sea level rise scenario representing each domain category vulnerable areas associated with the possible inundation depth in meters.

The second and third objectives were achieved through building a web application summarizing the most vulnerable areas statistics and thus reflecting species/categories at higher risk. The web application is published on an organization ArcGIS Online account, which can be accessed by other permitted organizations/entities. Through this technological approach stakeholders at different entities can have a brief insight on the vulnerability assessment results, to enable them to prioritize the areas at higher risks and develop an effective plan to save the city resources and increase the natural/built environment resilience to sea level rise risk.

Acknowledgements

Accomplishing this research project would not have been possible without the support of:

- Environmental Agency of Abu Dhabi (EAD), by providing me with the necessary environmental dataset that had enabled me to conduct a comprehensive vulnerability assessment on Abu Dhabi Governorate environmental features. My deep gratitude goes to Mr. Anil Kumar – Director of Environmental Information management, EAD.

- Abu Dhabi Department of Municipal Affairs (DMA), for providing me with administrative, land use and population datasets that had enriched the project results and statistics. Many thanks to the DMA team and management.

Furthermore, my deepest thanks would not be enough to show my sincere gratitude to my supervisor Ulrik Mårtensson who had helped me in getting a seat in the LUMA-GIS program at the first place and supported me all the way till here with lots of patience, tolerance and guidance.

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Dedication

To my beloved husband and hero- Yehia- who had always been my infinite support, inspiration and hidden wisdom. Your commitment, hardworking and dedication is a role model for me and our girls.

To my parents who had inherited me and my sister the thirst for knowledge and commitment to consciousness in every act.

To my darling daughters, Sara and Lina who had endured mummy's absence for many hours to fulfill this achievement.

And finally, to a country I love and cherish. To United Arab Emirates people and government…

Preface

This research project originated from my passion towards tackling global warming passive impacts on our planet. Global warming has been considered as an exponential dangerous threat to our planet. And sea level rise comes as one of the earth's responses to the global warming. My passion to act positively regarding this threat led me to the idea of directing my thesis towards studying the sea level rise impact on River Nile Delta in Egypt. However, the fact that I left my home country Egypt – some years back - made it unfeasible to conduct the study there. Yet, because my passion is for the cause of mitigating the impacts of global warming on our planet, I had to redirect my case study area to the country where I live in now - United Arab Emirates. And I shall save no effort to express my appreciation to Abu Dhabi governmental entities that had supported me with essential data to fulfill my project objectives…

Keywords

Sea Level Rise, Vulnerability Assessment, Abu Dhabi, Modelling Sea Level Rise, Impacts Assessment of Sea Level Rise, GIS application in sea level rise, Disaster Risk Reduction (DRR), Geographic Information System (GIS), Information Sharing (IS), Government Information Sharing (GIS), ArcGIS Web App Builder dashboard, Sea Level Rise Story Map

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Glossary

Term	Abbreviation
AAM	Al Ain Municipality
AD	Abu Dhabi
ADM	Abu Dhabi Municipality
ADRM	Al Dhafra Region Municipality
AGEDI	Abu Dhabi Global Environmental Data Initiative
DEM	Digital elevation model
DMA	Department of Municipal Affairs – Abu Dhabi
DTED	Digital Terrain Elevation Data
DTM	Digital Terrain Model
EAD	Environment Agency Abu Dhabi
GHGs	Green House Gases
GIS	Geographic Information Systems
IPCC	Intergovernmental Panel for Climate Change
NASA	National Aeronautics and Space Administration

NIMA	National Imagery and Mapping Agency (NIMA).
NOAA	National Oceanic and Atmospheric
OGD	Open Government Data
PA	Protected Areas
PIA	Potentially inundated areas
POI	Points of interest
SLR	Sea level rise
SLRp	Sea Level Rise projection scenario
SLRv	Sea Level Rise value after adding tidal range
SRTM	Shuttle Radar Topography Mission
UAE	United Arab Emirates
USGS	United States Geological Survey
WGS84	World Geodetic System 1984

1 Introduction

1.1 Background

1.1.1 Global Sea Level Rise Risk

Global Sea level rise is one of the anticipated impacts of the global warming. The sea level rise indicates the increase in global ocean volume that is caused by two main phenomena; the first is the melting of the world's major ice sheets and glaciers while the second is the expansion of ocean water by heat. Both phenomena are results of the global warming, which is caused by the rising concentration of the greenhouse gases (GHGs) - especially the carbon dioxide. (Lindsey, 2016; Kostelnick et al., 2008; Sharma and Dwivedi, 2005; Mao, 2011)

Ice sheets are huge masses of glacial ice with areas exceeding fifty thousand square kilometers (National Snow and Ice Data Center, 2018). The earth current ice sheets are the Antarctica Ice Sheet and Greenland Ice Sheet (Figure 1-1). Both contain more than 99 percent of the freshwater ice on Earth (National Snow and Ice Data Center, 2015).

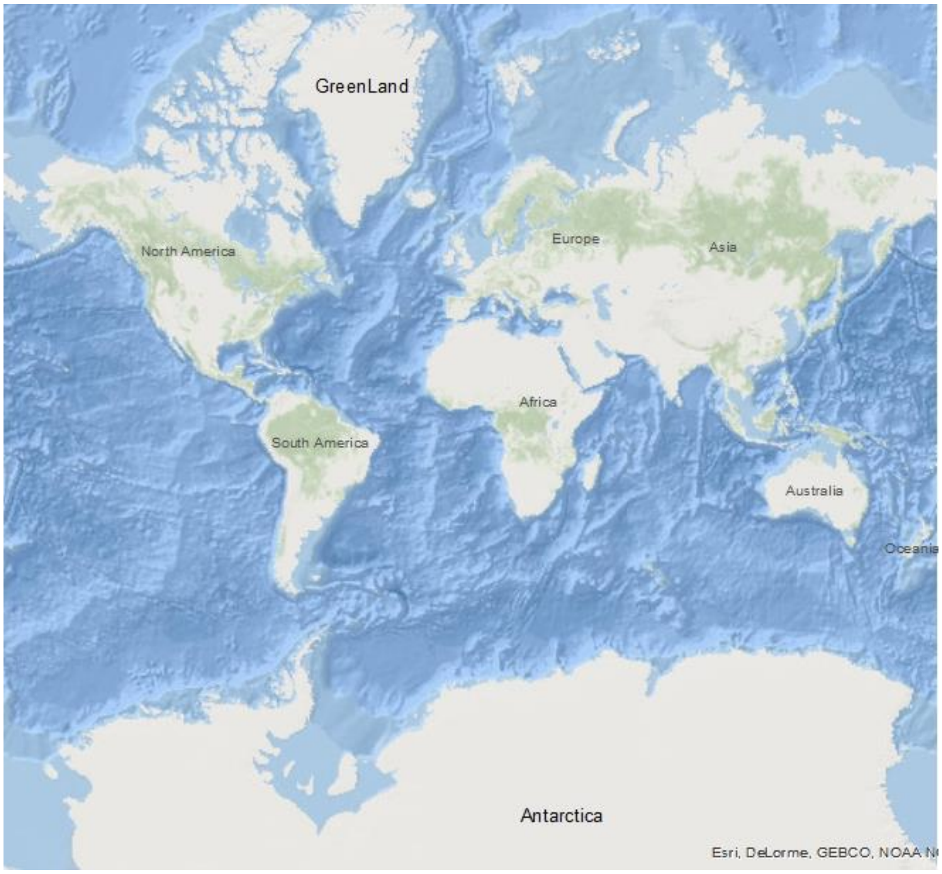

Figure 1-1: Greenland and Antarctica Ice Sheets contain more than 99% of the freshwater ice on Earth - Source: World Ocean Base Map. Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors (updated August 2016)

The Greenland Ice Sheet and the West Antarctic Ice Sheet are currently losing mass at an increasing rate. Ice loss statistics indicate that the rate of ice loss between 1992-2001 and 2002-2011 had raised by six-fold within Greenland Ice Sheet and by four-fold in the Antarctic; if such loss continues the sea level will increase significantly (Li et al., 2009; Lindsey, 2016). While in East Antarctica, no clear phenomena of accelerated ice loss have been proven, despite some stations appear to be partially cooling, yet scientists confirm that Antarctica is starting to lose ice but at a lower rate than Greenland (National Snow and Ice Data Center, 2018).

The Greenland ice sheet contains a volume of water equivalent to that required for 6 m of sea level rise, while the West Antarctic ice sheet contains a volume of 5 m of sea level rise (Mao, 2011).

The Intergovernmental Panel on Climate Change (IPCC) - which is a scientific and intergovernmental body under the auspices of the United Nations- clarified in its 5th Assessment Report that Global Mean Sea Level (GMSL) has risen by an average of 1.7 mm/yr [range: 1.5 to 1.9mm/yr] between 1901 and 2010. Whereas between 1993 and 2010, the rate was very likely higher at 3.2 mm/yr [range: 2.8 to 3.6mm/yr] (IPCC, 2013).

The American scientific agency; National Oceanic and Atmospheric Administration (NOAA) latest Global Sea level rise report indicates that a probable sea level rise scenario by 2100 can have a range of 2.0 meters to 2.7 meters (Sweet et al., 2017), earlier studies points out a range of 0.59 meter by the 2100 (Kostelnick et al., 2008; Usery et al., 2010; Li et al., 2009). The extreme upper limit of 80m, is the theoretical maximum rise in sea level if all icecaps and glaciers melt (Usery et al., 2010).

Mitigating and adapting the sea level rise risks is a global concern due to the huge impact it may have on communities, ecosystems and infrastructures. When the sea level rises, water will reach farther inland and this could have negative impacts on population, natural and built environments especially in coastal areas where coastal ecosystems will be subject to flooding (Sahagian et al., 1999). The severity of impacts depends on the sea level rise value as well as the type and nature of the environment. According to NOAA's report "Constructing Sea-Level Scenarios for Impact and Adaptation Assessment of Coastal Areas" (Nicholls et al., 2011), the main potential physical impacts of relative sea-level rise are listed in Table 1-1: Potential impacts of a change in relative sea level (Nicholls et al., 2011).

Table 1-1: Potential impacts of a change in relative sea level (Nicholls et al., 2011)

Physical Impacts	
1. Inundation, flood and storm damage	a. Surge (sea) b. Backwater effect (river)
2. Long-term wetland loss (and change)	
3. Altered patterns of erosion and accretion (direct and indirect morphological change)	
4. Saltwater Intrusion	a. Surface Waters b. Ground-water
5. Rising water tables/ impeded drainage	

On the other hand, nearly a quarter of the world's population lives at elevations below 100 m above mean sea level and within 100 km from a coast (Li et al., 2009). Mapping the areas susceptible to inundation by sea level rise is complicated because the actual flooding process involves the level of high water, which is linked to tidal patterns and storm surges. Depending on the region, the highest water level can be several meters above mean sea level (Li et al., 2009).

1.1.2 Government Information Sharing Trend

The world governments have been shifting to information sharing and cloud computing during the past decade. Initiatives of Open Government Data and Government Information Sharing are widely spread among developed governments. The initiative's aim is to share and integrate governmental data across governmental entities, private institutions and citizens (Choi et al, 2013). Benefits of information sharing across governmental entities are numerous, starting from sharing service related information to facilitate and promote the service quality as well as resource data sharing to enable proper emergency management and response planning, etc.

With the current frequency of natural disasters worldwide (Yamamoto, 2015), preparedness is a necessity and shall be utilizing the benefits of cloud computing techniques and government information sharing initiatives. This would support the conduction of comprehensive natural disasters assessments and spreading it among concerned authorities to create a "whole government" response. The comprehensive disaster assessments will help ensure each sector preparedness to expected disasters/emergencies, thus enabling them to develop mitigation plans that targets disaster risk reduction by decreasing the disaster impact on natural and built environments as well as the society. On the other hand, concerned governmental parties may start new initiatives or apply regulations within their codes to mitigate natural disasters risks. Moreover, it will help governmental authorities to improve its resources preparedness to respond effectively and timely to disaster/emergencies once it takes place.

1.1.3 Technology Trends

In 2012, ESRI launched ArcGIS online which was considered at that time a new trend in publishing, sharing and utilizing ArcGIS cloud-based services through simple steps. ArcGIS online can be said to be a one-stop destination for published GIS data, maps, services and applications. Through ArcGIS online, authorized users can publish data, create web maps and build customized web applications to share with other users without having any programming background. The variety in applications types and templates available on ArcGIS online made it easy and time efficient for organizations to choose and configure what matches its business needs then share with other organizations or with the public. Moreover, the organization can define, and control users' access to all its ArcGIS online contents (data, services, applications, licenses etc.).

Also, other geospatial companies had introduced web-based GIS services and application like Google Maps, Hexagon (Intergraph previously) and Mapbox. This is to say, that web-based GIS services and application is the current technology trend and leveraging its benefits is becoming prevalent across the world governments.

1.2 Problem Statement (Sea Level Rise in Abu Dhabi)

In 2010, the Environmental Agency of Abu Dhabi (EAD) commissioned the study "Climate Change: Impacts, Vulnerability and Adaptation in the UAE" which stated that 85% of UAE's population are living on the coast and more than 90% of the infrastructure is lying along the seashores, the country's economy and general well-being is at risk even from a one-meter rise in sea level (Todorova, 2010).

The EAD report chose to study 3 scenarios of sea level rise representing possible scenarios over the next century. The variation of scenarios depends on the degrees of warming (2˚C to 4˚C) as well as the impact of global warming on ice caps melt. The report refers to research done by Jim Hansen of NASA's Goddard Institute, that linear projections of sea-level rise are no longer acceptable which give way to abrupt rapid scenarios in the case of arctic melt.

The study expects that by year 2050, the sea levels may rise between 1 and 3 meters, depending on the speed of polar ice melting, while by 2100, the predictions are between 2 and 9 meters causing a maximum loss of 6% of the country's total land area to its populated and developed coastline by the end of the century. (Dougherty et al., 2009)

The modest scenario by 2050 of 1-meter sea level rise would cause a total loss of 344 km^2 to the sea, including extensive mangrove areas, more than 100 km^2 of urban green spaces as well as 10 km^2 of built-up area and roads. While the direst scenario of 3 meters in Abu Dhabi by 2050, would cause flooding causing loss of more than 800 km2 under water (Todorova, 2010; Radan, 2010). On the other hand, the direst scenario of 9 meters by 2100 would submerge all of Abu Dhabi and much of Dubai city causing a loss of 5,000 km^2. The shore would migrate south by up to 30km, and Jebel Dhanna and Al Mirfa would become islands (Todorova, 2010).

Another report conducted by UAE Ministry of Energy in 2010: *The United Arab Emirates Second National Communications to the Conference of the Parties of United Nations Framework Convention on Climate Change* stated that downscaling climate projections were developed using UAE-specific meteorological data from 1995-2004. The downscaling study results showed that annual mean temperatures by 2050 in UAE will rise by 2.1- 2.8 °C and by 2100 could be 4.1°C to 5.3°C while the IPCC estimates for the Middle East was 2.6°C to 5.4°C warmer in the 2080-2099 (Ministry of Energy, 2010). The IPCC 4th Assessment Report (2007) expects that range of sea level rise- not considering glacier melting- is between 0.37 and 0.59 meters by 2100 while its 5th Assessment Report (2013) indicates that the sea level rise may reach 0.98 cm. If glacier melting is included, the IPCC notes that 10 meters or more in climate change-induced sea level rise is possible beyond 2100 (IPCC, 2007).

Both reports warn that some of the Emirate's most biologically-productive ecosystems, like mangrove forests and flagship species like marine turtles, are highly vulnerable to climate change (Dougherty et al., 2009 and 2010 and Ministry of Energy, 2010).

For an instance, sabkhas/ salt flats exists few meters above sea level, which make them highly vulnerable to sea level rise and salinity alteration. Qurms/ mangrove forests are sensitive to sea temperature, water depth, and salinity. Mangrove roots should be totally exposed for certain periods of time, otherwise if they are submerged all the time then the trees will not survive. Sea level rise can also erode grass habitats, which are a vital nutrition for some species. Also, the rise in seawater temperature can damage the coral reefs and adversely affect the marine ecosystems. (Ministry of Energy, 2010)

While sea level rise projection scenarios are variable due to the fact that it is a non-linear phenomenon resulting from climate change complex aspects, there is an urge to simulate and identify the impact of different sea level scenarios on the environment. Moreover planning for adoption to sea level rise risk should be based on a whole of government approach to empower city's preparedness and ensure vulnerable areas are considered in city's plan to avoid severe economic loss. This shall basically start by facilitating government information sharing principles the web-based technology features and capabilities where governmental and planning entities can have access to varying outputs of the simulation and assessment exercise instead of reports that may not reflect the currently sea level rise probability nor contain data layers that can be used in overlaying with urban or environment features for planning purposes.

Ideally the exercise should be flexible enough to adopt changing sea level rise values according to climate change scientific projection and the output inundation boundaries should be shared as datasets with planning and governmental entities. An essential initial step would be implementing a scalable flexible model that can assess the impact of different sea level rise scenarios. The model should be able to simulate the impact sea level rise on natural and built up environment. Then the output datasets should be shared with stakeholders, planning departments and governmental entities to help them realize the potential risk impact on coastal populations, economies, infrastructure, and ecosystems and identify vulnerable areas. With these guiding inputs, mitigation and adoption plans can take place which shall aim to increase the environment resilience and direct future development wisely.

1.3 Research Aim and Questions

1.3.1 Research Aim

This project aims to introduce a comprehensive practice that tackles the risk of long term sea level rise, through the following aims:

A. ***Simulating different sea level rise scenarios:***

- Examining different spatial analysis methods and tools to identify the best methodology to extract potentially inundated areas.

- Developing a sea level rise simulation model that accommodate the divergence in sea level rise by in-taking the sea level rise value from the user and simulating the inundation areas according to the input.

B. Assessing sea level rise scenarios impacts:

- Simulating 3 different sea level rise scenarios impact on the natural and built up environment, communities, population and facilities to identify the most vulnerable domains, sub types, or environment features (land types).

C. Disseminating and sharing results :

- Introduce a practical up-to-date methodology to share the results with concerned authorities while incorporating governmental data sharing initiatives. This study model/methodology proposed one entity to conduct the sea level rise impact assessment and share the assessment results with all related parties through its web-based platform. This in turn will help governments to establish a Risk Reduction Plan to mitigate the cost of sea level rise impact on environments and increase the environments resilience to such risk.

1.6.1 Research Questions

To fulfill the above aims, the research will address the below questions;

– What are the geoprocessing methods and tools used to extract sea level rise inundation areas using a bathtub hydrological connectivity model?

– For each environmental (natural or built environment) category;

  - What is the impact of selected sea level rise scenario?
  - Where are the Potentially Inundated Areas (PAs)?
  - What are the most vulnerable classes to sea level rise?
  - How deep will this category be potentially inundated?

– Which administrative territories (districts and municipalities) are more vulnerable to sea level rise according to the size of potentially inundated area in each territory?

– With regard to the current technology trends, how can the study results be distributed and shared among concerned parties?

1.4 Study Area

The study area of this project is Abu Dhabi (AD) Governorate / Emirate, which is largest of the seven emirs that comprise the country of United Arab Emirates (UAE). UAE is located in southwest Asia by the southeastern side of the Arabian Peninsula (Figure 1-2). The country coastlines spread along the south and southeastern shores of the Arabian Gulf in addition to a part on the western shores of the Gulf of Oman. (Ministry of Energy, 2010)

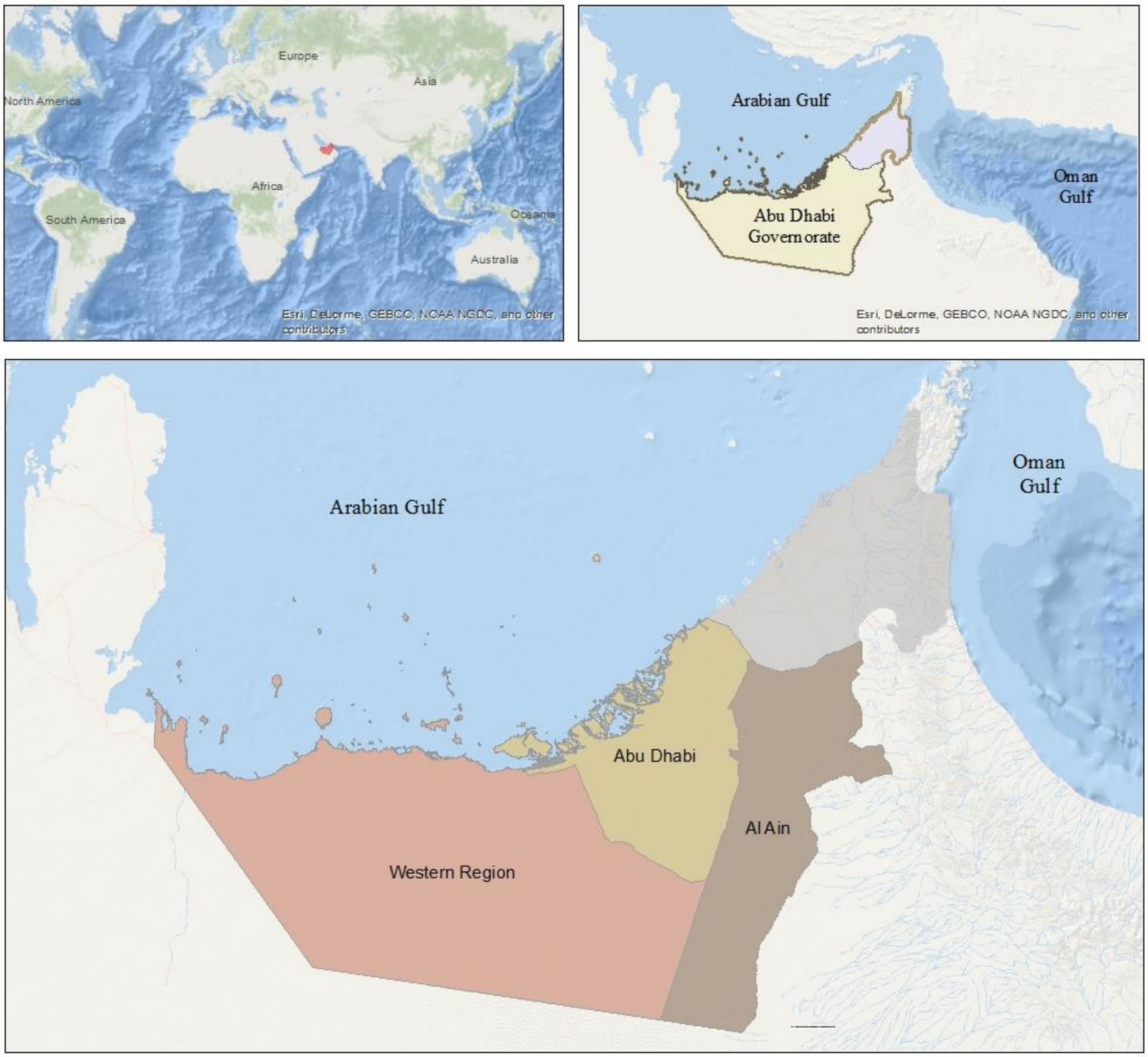

Figure 1-2: Study Area Definition- Top left: UAE on World Map, Top Right: Abu Dhabi Governorate Location, Bottom Center: Abu Dhabi Governorate Municipalities

Abu Dhabi Governorate / Emirate occupies around 80% of the UAE's total area. The governorate capital is Abu Dhabi City, which is the country capital as well and is the second largest city in the United Arab Emirates after Dubai. Abu Dhabi Governorate is divided into 3 municipal subdivisions which are within the study area's scope: Abu Dhabi Municipality

(Central Capital District), Al Ain Municipality (Eastern Region), and Al Dhafra Region Municipality (earlier Western Region Municipality).

1.4.1 Population

Abu Dhabi Governorate had a population of more than 2.7 million in 2015 (SCAD, 2016), which marks it as the governorate of highest population in UAE. The population distribution among the 3 municipalities showed that Abu Dhabi Municipality population is around 1,720 200 persons, Al Ain Municipality is 738,500 persons, and Al Dhafra Municipality population 325,800 persons.

1.4.2 Topography

Abu Dhabi governorate has a low lying coastline that extends for more than 400 km (AGEDI, 2011). The governorate is home for around 200 islands with variable sizes, some of which are open to visitors and tourists (AGEDI, 2013). Most of Abu Dhabi City area lies on a T-shaped island jutting into the Arabian Gulf (Figure 1-3, but it has many suburbs on the mainland and other smaller islands. The island is less than 250 meters away from the mainland and is joined to the mainland by bridges.

Tidal inlets/lagoons ('Khors') and creeks are very common in the Arabian Gulf (Figure 1-3: Abu Dhabi main districts showing Abu Dhabi T shape main island and Khors (Tidal Inlets/Lagoons). Source: Esri). Those with appropriate size are mostly modified into waterways and sheltered harbors. The khor-side mangrove woodland can be considered essential to sustainable fisheries. Khors, coastal areas and other UAE inter-tidal areas are a visited by millions of birds during the migration periods (Scott, 1995). These khors connect to the open sea by relatively shallow and narrow tidal channels (AGEDI, 2008).

Figure 1-3: Abu Dhabi main districts showing Abu Dhabi T shape main island and Khors (Tidal Inlets/Lagoons). Source: Esri

The UAE 3rd National Communication under the United Nations Framework Convention on Climate Change report states that the region enjoys a rich biodiversity in a hyper arid environment. It also states that UAE main terrain types are: low-lying coastal plains along the Arabian Gulf shore, rugged mountains along the border with Oman, and flat desert and sand dunes of the Earth's largest sand desert: The Empty Quarter or Rub al-Khali desert, of which Abu Dhabi governorate includes its northwestern part. However, massive forestry operations are underway to green the UAE's deserts like the mangroves planting projects taking place on the shoreline.

1.4.3 Ecosystems

The report UAE 3rd National Communication report states that the region enjoys a rich biodiversity in a hyper arid environment. The report describes the natural ecosystems within the area to be composed of a variety of habitats occurring in the marine and terrestrial environment of the UAE. The common coastal ecosystems in Abu Dhabi governorate include beaches, islands, salt pans/flats ('sabkhas' in Arabic) mangrove stands (‘qurms’ is arabic), seagrass beds, salt marshes, intertidal areas, khors and coral reefs, (Figure 1-4Also, despite permanent freshwater is scarce in the UAE, some running water persists through the year within the mountain deep gorges of valleys ('wadis' in Arabic).

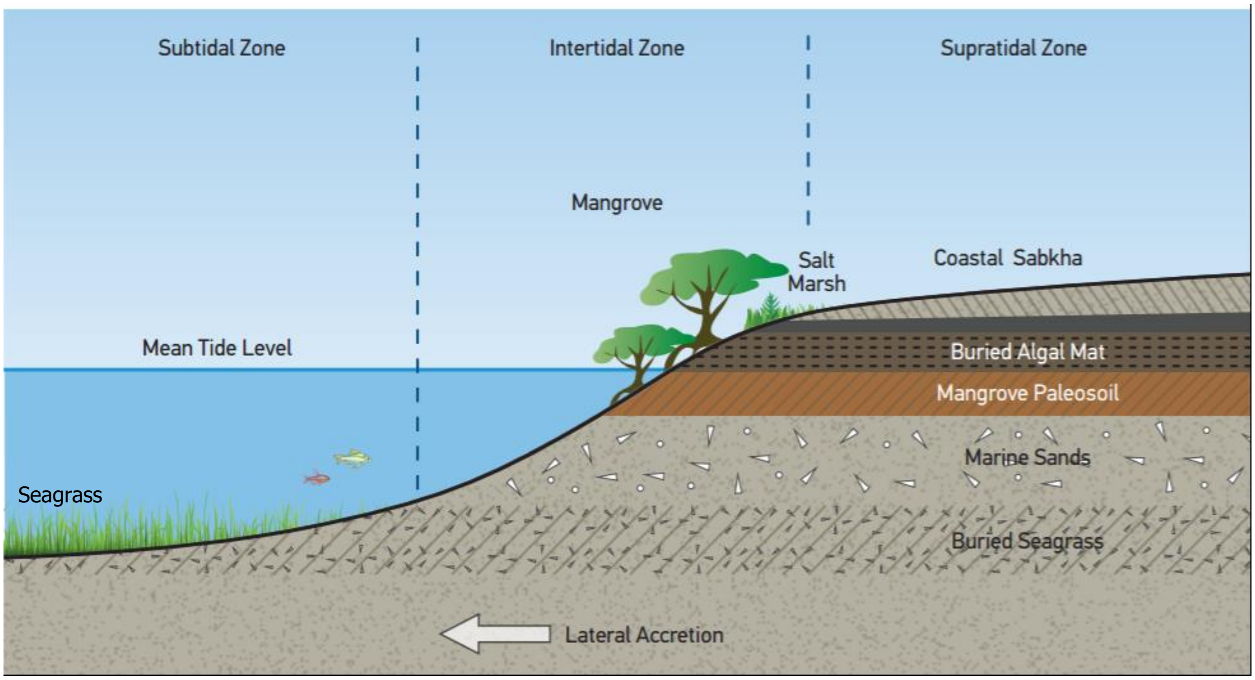

Figure 1-4: Abu Dhabi Coastal Ecosystems of Interest (AGEDI, 2013)

Salt pans/flats ('sabkhas') are present where rainwater may sometimes stagnate (EWS-WWF, 2015). *Sabkhas* are one of the most important ecosystems in Abu Dhabi (Figure 1-5), and are likely to play an important role in preventing soil carbon from being released into the atmosphere (AGEDI, 2013). They are low-lying, sand and salt flats that stand only a few centimeters above high-tide mark and are created from the interplay between seasonal inundation of Gulf water, rainwater and sandstorm deposits during the hot-dry season.

By contrast the Arabian Gulf littoral of the UAE is an exemplary development of active coastal sabkha, which is recognized as among the biggest and most unique in the world due to their vastness and completeness; and the early investigation conducted by geologists (MCKD, 2018). It is around 300 km long and of variable width but extending continuously 20 km or more inland in places. It is said by geologists to be less than 7,000 years old and is continuing to grow seaward (Scott, 1995).

The coastal sabkha, is inundated with marine tides, and its ecosystem is highly influenced by geo-ecological factors of the surrounding areas (Dougherty et al., 2009).

Figure 1-5: Abu Dhabi Coastal Sabkha (AGEDI, 2013)

Another ecosystem of interest is Algal Mats *(also known as* cyanobacterial mats *or* microbial mats*) which is known of its ecological importance in the carbon cycle*

Figure 1-6: Abu Dhabi Algal Mats (AGEDI, 2013)). Algal Mats in Abu Dhabi, lies along tidal margins of coastal sabkha and covers an estimated area of 109 km^2 throughout Abu Dhabi governorate (AGEDI, 2013).

Figure 1-6: Abu Dhabi Algal Mats (AGEDI, 2013)

An iconic ecosystem in Abu Dhabi is the *Mangroves (qurms)* which occupies about 141 km^2 of the area around the margins of khors and mud banks behind the Abu Dhabi islands (Figure 1-7 Figure 1-11) A single species, the grey mangrove (*Avicennia marina*), is found in Abu Dhabi (AGEDI, 2013). Mangroves are defined as woodlands formation below the high-tide mark (Welsh, 1974). They provide protection and refuge for juvenile fish and are important in increasing fishery production on the coastline (Laegdsgaard and Johnson, 2001).

Figure 1-7: Abu Dhabi Mangroves (AGEDI, 2013)

Seagrass meadows are a very valuable element ecologically as they host a combination of unrelated species (Scott, 1995) and are an important feeding, breeding and nursery ground for many marine species (AGEDI, 2013). They grows readily in water up to a depth of 10 meters, thus Abu Dhabi coastal water -where the depth are less than 10 meters- providing a large area of suitable habitat (Scott, 1995). It's estimated to have a coverage of 1582 km^2 in Abu Dhabi extending around the islands and along the near shore coastal plain (Figure 1-11: Sea Grass, Mangroves and Coral Reefs Distribution on the north shore of Abu Dhabi. Credits: Abu Dhabi Urban Planning Council (UPC). Abu Dhabi hosts one of the world's most expansive complex of seagrass meadows, supporting the second largest population of dugongs as well as other ecosystems of recognized value, like the coral reefs and it also provides critical foraging habitat for sea turtle species (Figure 1-8). The meadows within Abu Dhabi are populated by mosaics of three seagrass species. (AGEDI, 2013)

Figure 1-8: Seagrass Meadows on the leftside, dugong in the middle (AGEDI, 2013), sea turtle on the rightside (AGEDI, 2011)

Salt marshes are found in Abu Dhabi at high tidal elevations behind mangrove stands and along the fringe of coastal sabkha, covering an area of about 47 km^2 (Figure 1-9). It consists of salt tolerant shrubs and other types of plants include some of traditional medicinal benefits.

Mangrove, seagrass, salt marsh, and to some extent algal mats play a role in maintaining coastal water quality. (AGEDI, 2013)

Figure 1-9: Salt marshes, Abu Dhabi. (AGEDI, 2013)

Coral Reefs in Abu Dhabi are present in 34 different species of hard corals which have a role in enhancing fish productivity, protecting shorelines against storms and erosions (Figure 1-10)

Figure 1-10: Coral Reefs, Abu Dhabi. (AGEDI, 2013)

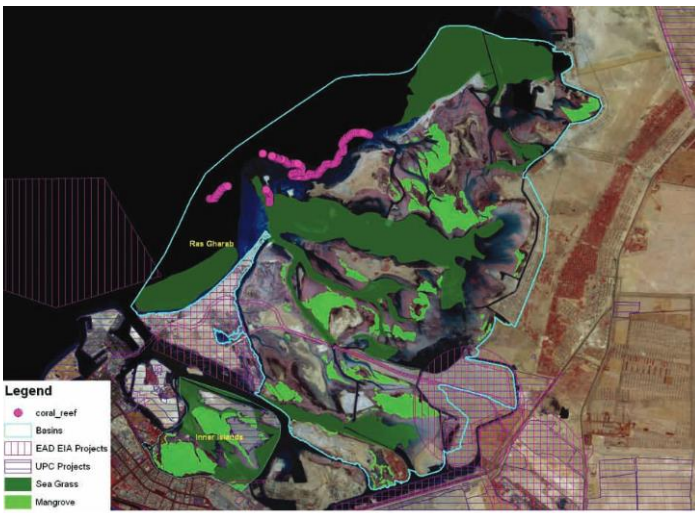

Figure 1-11: Sea Grass, Mangroves and Coral Reefs Distribution on the north shore of Abu Dhabi. Credits: Abu Dhabi Urban Planning Council (UPC).

Low lying *inter-tidal flats* are spread widely in Abu Dhabi up to few kilometers from the shoreline, in some cases due to the gradual slope of the Gulf area, as well as the shallow water depth, which is usually around 6 meters in the low tide season. Tidal flats, khors, and sand dunes, decline gradually into the offshore waters of the Arabian Gulf, forming several types of coastal landforms as a result of tidal action. These include coastal terraces, wave-formed bars, and flood deltas (Figure 1-12). Those areas are usually of vital importance to many marine species as well as shorebirds. (Scott, 1995)

Figure 1-12: Example of Coastal landforms resulting from tidal action : Coastal terraces on the left, flood deltas in the middle, wave formed bars on the right (AGEDI, 2011)

1.4.4 Economy and industries

Abu Dhabi governorate is the largest emirate of UAE seven emirates in terms of land area, economic activity accounting for more than 50% of UAE GDP and oil producer controlling more than 85% of UAE total oil output capacity (UPC, 2010). Oil Industry is the backbone of Abu Dhabi economy. Most oil extraction is done offshore by the oil companies (AGEDI, 2008). Upon the oil discovery in 1960s, the UAE oil-based revenues have been re-invested to sprint the country into modernism, with a focus on the development of healthcare, education, industry and infrastructure (UPC, 2010). Following the oil and gas industries that started in the 1970s, the petrochemical industry began producing a variety of products and later more initiatives started, including steel and aluminum industries and vehicles assembly. (AGEDI 2011)

Another large industry in Abu Dhabi is shipping, which is the means of export for the oil industry and the way in for imported products. There are plenty of marinas and harbors in Abu Dhabi and port development is a major industry. (AGEDI 2011)

The fishing industry is source of income in Abu Dhabi as well, it provides employment and recreation as well, and is a part of Abu Dhabi’s cultural heritage. (AGEDI, 2008)

1.4.5 Urban concentration

During the past three decades, vast development took place in the industrial, recreation, transportation, residential and tourism sectors, the latter of which relies basically on the coastal and marine attractions. The development mainly took place in the coastal areas. Accordingly, most of the industrial and residential infrastructure is concentrated within urban centers along the coast (Figure 1-13).

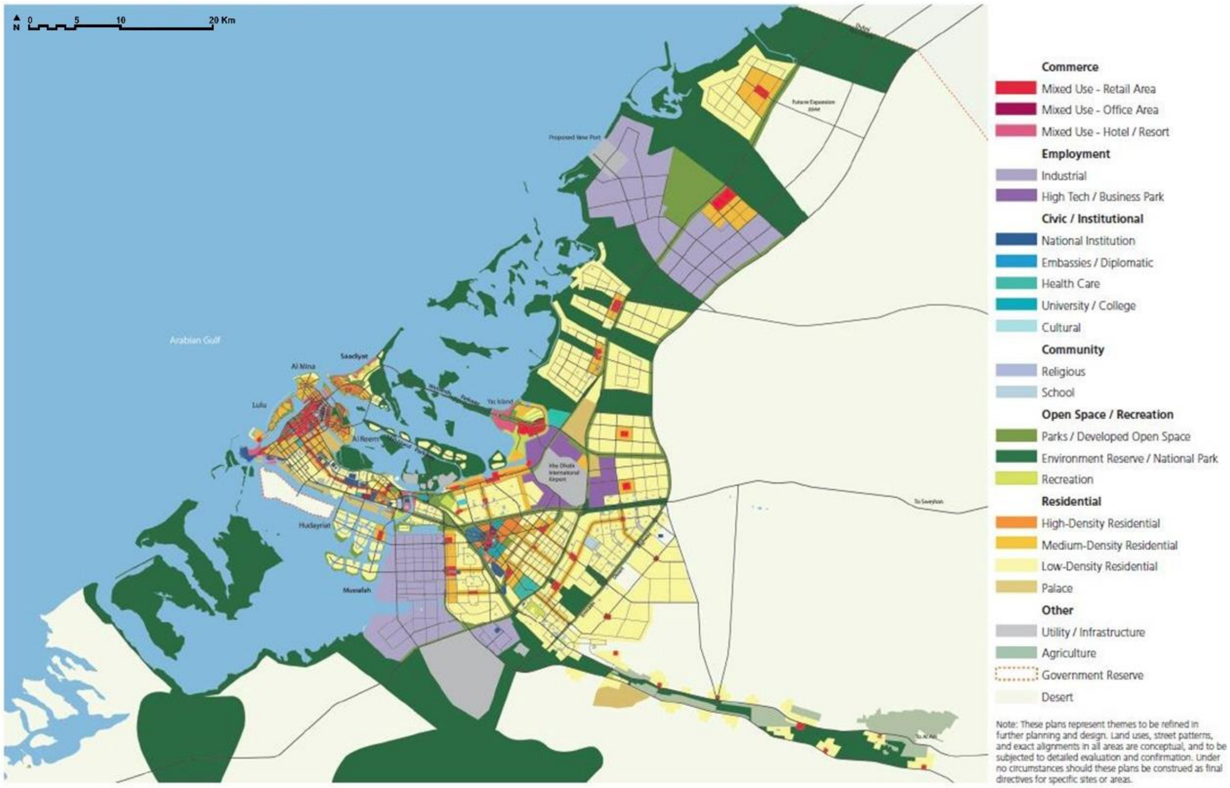

Figure 1-13: Abu Dhabi 2030 Urban structure framework plan demonstrating the distribution of land use on the coastal areas (UPC, 2007)

1.4.6 Water Supply

As a desert governorate, Abu Dhabi is facing a resource challenge related to water. Abu Dhabi, is one of the highest per capita consumers of water in the world, is consuming groundwater reserves much faster than rainfall recharges them. UAE has created several desalination plants – which convert seawater into fresh water- to provide for the water requirements of the various municipal sectors. While desalination is an evident solution to resolving water needs in UAE, it's a costly solution in terms of finance, energy and environment. The desalination process requires electrical energy and fuel burning, beside the costs associated with disposing of the salt (brine concentrate) produced during the process (AGEDI, 2011 and UPC, 2007). Currently Abu Dhabi draws 61% of its water from groundwater, 31% from desalination plants and 8% from recycled water (EAD, 2015) (**Error! Reference source not found.**. Agriculture depends mainly on ground water and consumes around 70% of all water, while desalinated water supplies the domestic & industrial sectors (EAD, 2015).

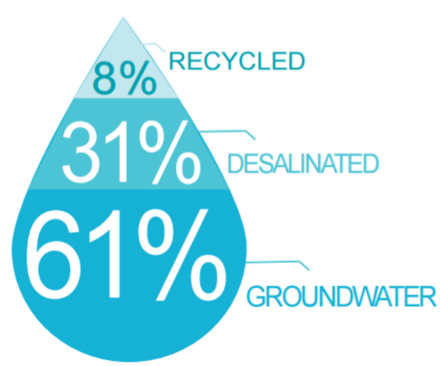

Figure 1-14: Water supply resources in ADE (EAD, 2015)

2 Data

2.1 Elevation Data

2.1.1 Digital Elevation Model Dataset (Ellipsoidal Model vertical datum)

A digital elevation model (DEM) is the source for the ground elevation used to derive sea level rise potentially inundation surfaces according to the sea level rise projections. The inundation analysis results are highly dependent on DEM accuracy as well as the modeling approach. On the other hand, while most DEM vertical resolutions range from 1.5 to 10 to 100 meters, these resolutions cannot accurately simulate fraction scenarios or < 1 m sea level rise scenarios.

The National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission (SRTM) developed global elevation data at; 30-meter (1 arc second) resolution and vertical accuracy of 16 meters absolute/ 10 meters relative accuracy, which is considered to be the best publicly available DEM data. However a study about vertical accuracy assessment for SRTM and ASTER Digital Elevation Models in the Gulf region proved that the vertical accuracy of SRTM and ASTER elevations data is ±6.87 m and ±7.97 m, respectively indicating that the absolute vertical accuracy of SRTM ver3 data to be two to three times higher than the value of ±16 m presented in the original SRTM requirement specification (Elkhrachy, 2017).

Within this research, the NASA Version 3 SRTM Global 1 arc second dataset is used for the inundation analysis. The main characteristic of Version 3.0 that distinguishes it from previous versions is the elimination of gaps and voids from the SRTM DEM. (LP DAAC, 2015)

2.1.2 Tidal Datum and tidal range

The tidal datum is a standard elevation used to measure water levels based on measures taken during tide phases. For example, the Mean Sea Level (MSL) tidal datum is the average level of the sea's surface over long periods (usually over the 19 year long lunar cycle). MSL changes on a seasonal basis, not to mention the increase in MSL over years due to climate change. To baseline sea level elevation and compute sea level trends, Monthly Mean Sea Level (MMSL) is used. While the Mean Higher High Water (MHHW) mainly represents the spring high tide, which is the highest sea level during the year. Thus the MHHW is commonly used while assessing seal level rise impacts to determine the worst-case scenarios (NOAA, 2012).

A tidal range is the difference between the highest high tide and the lowest low tide. The tidal range in southern Arabian Gulf barely exceeds 2 meters. (EAD, 2010; Windfinder, 2017)

Unfortunately, Abu Dhabi MHHW data was not available at the consulted authorities, so the tidal range will be used in this report's inundation analysis instead. To map sea level rise inundation, sea level change projections shall be added to the tidal datum; in other words, the tidal datum shall be a constant offset to the sea level change projections.

2.2 Datasets Listing

Data used in this research was collected from different sources that included NASA's Shuttle Radar Topography Mission, United States Geological Survey (USGS), and Esri ArcGIS online services for the elevation datasets and satellite imagery. While the vector data sources for the local administrative boundaries, natural and built up environment datasets, it was acquired from 2 governmental entities which are Environment Agency of Abu Dhabi (EAD) and Department of Municipal Affairs (DMA). In addition, few open source data was also used for the points of interest, roads and countries boundaries.

The section below lists summary of datasets used in the research further information on datasets in Appendix A – Datasets Details.

Table 2-1: Datasets Listing

Dataset Name	Description	Category	Source	Data type	Extent
SRTM	- NASA's Shuttle Radar Topography Mission (SRTM) - Version: 3.0 - Resolution: 30 meter - Vertical error: absolute 16m; relative 10m - Horizontal error (CE90): absolute 20m; relative 15m	Elevation Data	NASA's Shuttle Radar Topography Mission (SRTM)	Raster Data – DTED format	15 tiles downloaded to cover U.A.E extent
Landsat 8	Landsat 8 OLI-TIRS - Resolution: up to 30 meters in most bands and	Satellite Imagery	United States Geological Survey (USGS)	Raster Data	U.A.E

	panchromatic band is 15 meters.				
World_Imagery (MapServer)	ArcGIS online service. Resolution: starts from 15 meters then goes as high as 15cm with a sub-meter resolution in the Middle East area	Satellite Imagery	ArcGIS online	Satellite Imagery Service	Globe Extent
Country Borders	UAE country border	Administrative Dataset	Global Administrative Data (GADM)	Polygon Feature Dataset	UAE
Abu Dhabi Governorate	Abu Dhabi governorate borders	Administrative Dataset	Extracted from EAD dataset	Polygon Feature Dataset	Abu Dhabi Governorate
Abu Dhabi Governorate municipalities	Abu Dhabi Governorate municipalities borders (Abu Dhabi Municipality, Al Ain municipality, and Al Dhafra Region Municipality).	Administrative Dataset	Extracted from DMA administrative dataset.	Polygon Feature Dataset	Abu Dhabi Governorate
Abu Dhabi Municipalities Districts	Abu Dhabi governorates districts	Administrative Dataset	DMA	Polygon Feature Dataset	Abu Dhabi Governorate
Land-use	Usage of all Abu Dhabi governorate	Built-up Environmental	EAD	Polygon Feature	Abu Dhabi Governorate

	land areas	Dataset		Dataset	
Land-use plots	Plots usage mainly in urban areas	Built-up Environmental Dataset	DMA	Polygon Feature Dataset	Abu Dhabi Governorate Urban Areas
Points of interests (POIs)	Points of Interests dataset (POIs) within Abu Dhabi Governorate	Built-up Environmental Dataset	MapCruzing.com	Point Feature Dataset	Abu Dhabi Governorate
Industrial Areas	Industrial plots	Built-up Environmental Dataset	DMA	Polygon Feature Dataset	Abu Dhabi Governorate
Roads	Roads lines	Transportation Network Dataset	DMA	Line Feature Dataset	Abu Dhabi Governorate
Streets	Street lines	Transportation Network Dataset	MapCruzing.com	Line Feature Dataset	Abu Dhabi Governorate
Transportation facilities	Contains airport, bus stations, marines features	Transportation Network Dataset	DMA	Polygon Feature Dataset	Abu Dhabi Governorate
Sea Shoreline layer, creeks & islands	Represents the borders lines of seashore, creeks and islands	Environmental Dataset	EAD	Line Feature Dataset	Abu Dhabi Governorate
Protected Areas (PA)	Represents National protected areas, national parks, biosphere reserves	Environmental Dataset	EAD	Polygon Feature Dataset	Abu Dhabi Governorate

Land cover layer	Satellite derived habitat mapping of land cover categories. Contains 27 different land cover categories.	Environmental Dataset	EAD	Polygon Feature Dataset	Abu Dhabi Governorate
Terrestrial Habitat layer	Satellite derived habitat mapping of terrestrial areas classification. Contains 41 terrestrial habitats.	Environmental Dataset	EAD	Polygon Feature Dataset	Abu Dhabi Governorate
Marine Habitat layer	Satellite derived habitat mapping of marine areas classification. Contains 13 marine habitats.	Environmental Dataset	EAD	Polygon Feature Dataset	Abu Dhabi Governorate
Population dataset	Includes the total population of each district and the total number of males and females as well.	Demographic Dataset	DMA	Polygon Feature Dataset	Abu Dhabi Governorate

2.3 Datasets Preparation

2.3.1 General Data Preparation

The below section documents briefly the data preparation procedures that were applied on the datasets prior to proceeding to data analysis.

Create workspace: A file geodatabase was created with 5 feature datasets for administrative, natural environment, built-up environment, demographic, transportation and utilities as well as DEM mosaic dataset.

Assign projection: The datasets were assigned Universal Transverse Mercator (UTM) (WGS_1984_UTM_Zone_40N) which is the popular projection for Abu Dhabi Municipality and Al Ain Municipality. The UTM system is a conformal projection divides Earth into sixty zones, where each zone represents a 6 degrees of longitude, and uses a transverse Mercator projection in each zone preserving areas and minimizing distances distortion at this zone.

***Adjust land border with coastline*:** As mentioned earlier, Abu Dhabi governorate morphology is composed of plenty of islands, generating a long complex shoreline with many creeks in-between.

While the EAD datasets represents the land and shoreline accurately, other data sources failed to provide the same accuracy. In other words, the non-EAD datasets simplifies the morphology, causing a loss of representation of small islands and creeks.

To resolve this issue, the EAD land use layer was merged to a single polygon presenting Abu Dhabi governorate land, and then all non-EAD datasets were clipped using this layer.

Merging land-use layers: Two different land-use layers were collected from DMA and EAD (refer to dataset listing in: Appendix A – Datasets Details). While the DMA land-use layer delineated plot scale land-use accurately in the main urban areas within the three municipalities, it lacked data in deserted and rural areas. On the other hand, the EAD land-use layer represents the land usage over the whole governorate.

- So the two layers were merged together, maintaining the high accuracy data of DMA land plots and appending to it the missing land areas which were provided by the EAD land-use layer through the following steps: EAD land-use layer was updated to erase all area that intersect with DMA land-use using the ArcGIS erase Tool.
- The results after applying this erase operation were added to the DMA land use plots to create a comprehensive land-use layer covering the whole governorate.

Merging roads layers: The two roads layers provided by DMA and Mapcruzing.com had the same comprehensiveness issue as the land-use (refer to dataset listing Appendix A – Datasets Details). Thus, both layers had to be merged to cover the whole governorate. The Mapcruzing data was chosen to be the main dataset, and the missing features were added to it after removing duplicate streets that are delineated in both layers using the following steps:

- Spatial selection was applied on the EAD roads layer to select features that have centroids that lie within 300 m of the Mapcruzing layer features. (i.e. this is to select roads in EAD that are duplicated in Mapcruzing)
- The selected features were excluded from the final dataset using switch selection.
- Then the selected roads features from EAD were added to Mapcruzing roads layer.

2.3.2 Elevation Data preparation

The DEM data source collected was provided as 15 tiles stored in the DTED format. To combine these and prepare them for analysis, a mosaic raster dataset was created with a projected coordinated system WGS 40N (Abu Dhabi municipality preferred projection), and pixel type of 16 bit signed. The compression type used to transmit the mosaicked image to display was LERC, which is a loss efficient compression method recommended for terrain models. The mosaic dataset default interpolation method to resample pixels in order match the resolution of the user's displaywas bilinear interpolation, which smooths the elevation surface without changing the value range.

SRTM version 3 was processed by National Geospatial-Intelligence Agency (NGA) to fill the voids using interpolation algorithms in conjunction with other sources of elevation data (LP DAAC, 2015). Thus, there was no need to fill the voids on the elevation dataset.

2.4 Data Assumptions

2.4.1 Sea Level Rise Projections (SLRp)

With reference to the Problem Statement section above, and to accommodate the modest and direst scenarios, the projection scenarios selected to map and assess the impacts of sea level rise in this research are: 1 meter, 2 meters, and 3 meters.

3 Methodology

While assessing environment vulnerability to sea level rise risk, there is no certainty about the precise amount of sea level rise nor its likely timing. For this reason, the best practice is to develop a functional model that can run using a user provided sea level rise value. Also, to increase the scalability of its usage, all layers are set as model parameters so that it can be substituted with similar layer types, but for different regions, to assess their vulnerability to sea level rise.

The methodology practiced in this study started by incorporating sea level rise projection values with tidal range values, then moved to modelling the potentially inundated areas (PIAs) considering their hydrological connectivity to Gulf waters. The final PIAs boundaries are then used to assess the vulnerability of natural environment and built environment to sea level rise and depict the possible impacted population count (Figure 3-1).

Upon the completion of the vulnerability assessment, the next step should be visualizing, publishing and sharing the results on a platform where all concerned authorities can have a view on it.

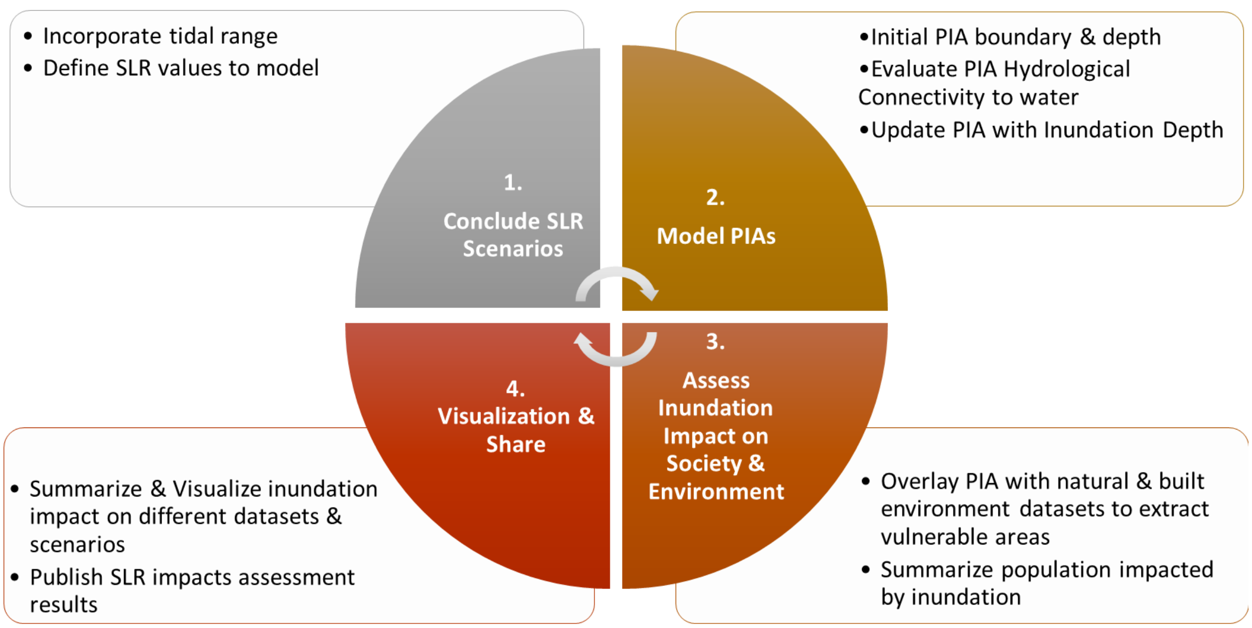

Figure 3-1: Research Methodology Sequential Workflow

3.1 Define Sea Level Rise Scenarios Values to Model

3.1.1 Incorporate the tidal range value

To start the analysis, the sea level rise scenario must incorporate the tidal range (or tidal datum if available). With reference to Tidal Datum and Tidal Range section, the tidal range in southern Arabian Gulf barely exceeds 2 meters, so the research will use 2 meters as the tidal range to raise the basic DEM before adding the sea level rise projection scenario. This aims to shift the sea level rise scenarios to start from an existing high tide as elaborated in the below equation;

- SLRv = Tidal Range + SLRp (1, 2, or 3 meters SLR)
- SLRv = 2 meters + SLRp meters

Where:

- SLRv is the final sea level rise value to use in mapping inundation,
- SLRp is the sea level rise projection scenario (1 meter, 2 meters, or 3 meters).

3.1.2 Define the Sea Level Rise (SLR) values to model

Next the SLR projection scenarios defined in DATA ASSUMPTIONS (1 meter, 2 meters, 3 meters) together with the tidal range, will be used to produce an initial water surface layer on top of mean sea level value:

- SLRv1 = Tidal range + SLRp1
  = 2 meter + 1 meter = 3 meters
- SLRv2 = Tidal range + SLRp2
  = 2 meters + 2 meter = 4 meters
- SLRv3 = Tidal range + SLRp3
  = 2 meter + 3 meter = 5 meters

While many areas in Abu Dhabi governorate are low rising areas, with DEM values much less than 0, the results of sea level rise will be much more than the sea level rise value. For instance, if the combination of a low rise area with a DEM value of negative 9 (below sea level) and the sea level rise scenario with value 1 meter took place, then the negative 9 land area will be filled with 9 meters of water to reach the resulting sea level of + 1 meter, so in total there will be 10 meters inundation depth at such a location.

3.2 Extract Potentially Inundated Areas (PIAs)

3.2.1 Create Initial Inundated boundary and Inundation depth layers

This step aimed to produce an initial inundation layer representing water levels for the sea level rise scenarios using the bathtub approach, where all cells in DEM less than or equal to the SLR projection values would be extracted to 2 new raster grids, as follows:

- In the first raster grid all cells less than or equal SLRv value will be extracted from the DEM and given a value that represents the depth of innundation through the expression : SLRv – DEM value (Figure 3-2)

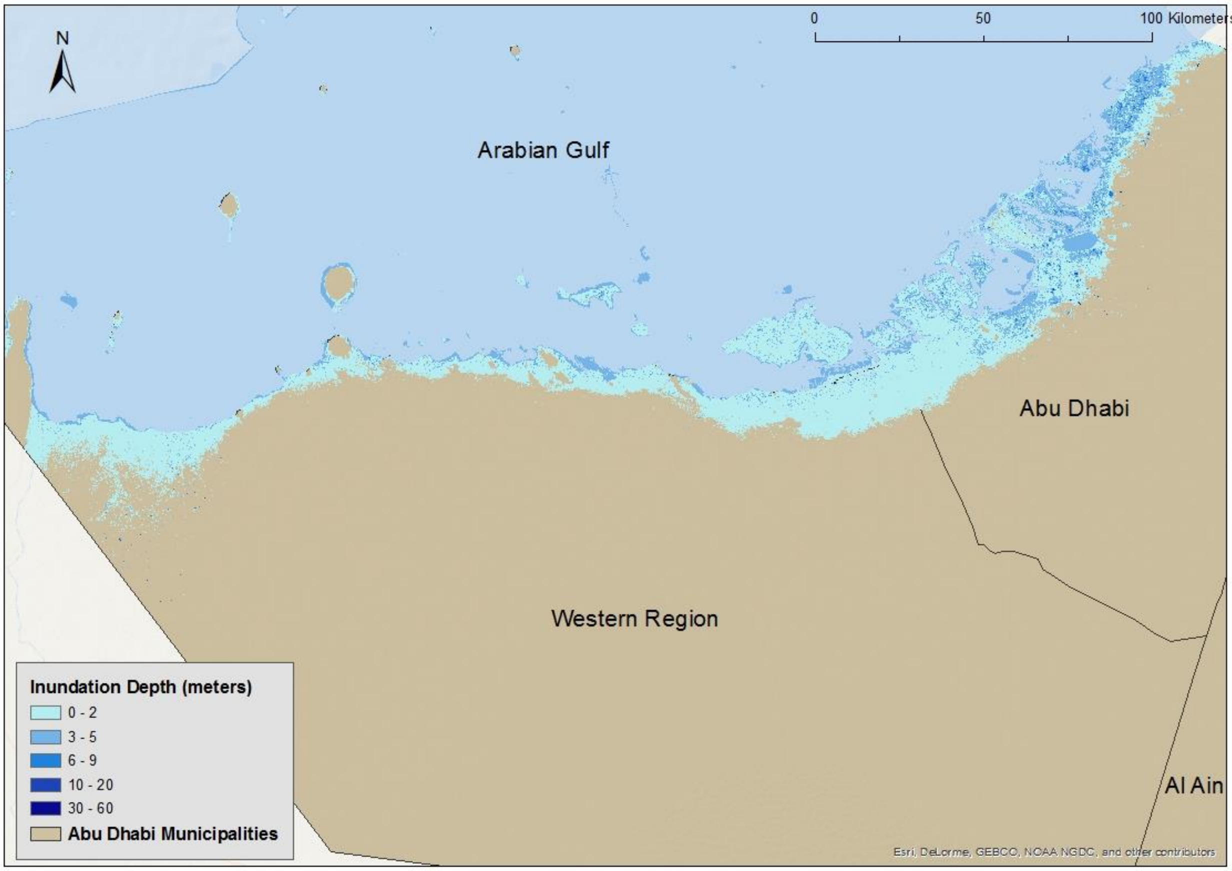

Figure 3-2: Potentially Inundated Areas with metric inundation depth values using basic bathtub approach(SLRv1), where lightest blue areas are inundated with 0-2 meters and darker blue areas have greater inundation depth value due to their low DEM values

- In the second raster grid, all cells with elevation value less than or equal SLRv were extracted from the DEM and assigned a value of 1. (Figure 3-3: Potentially Inundated Areas in darker blue color (using basic bathtub approach)- SLRv1)

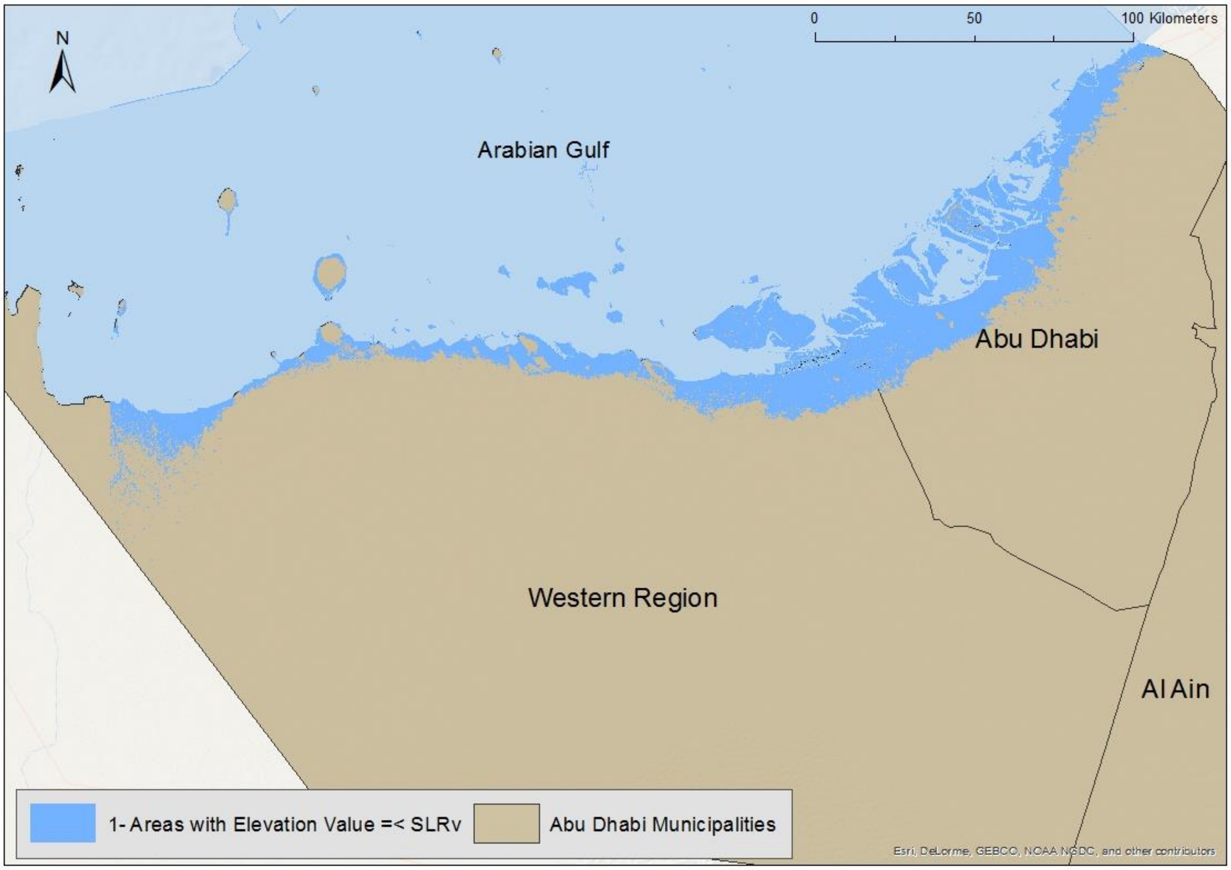

Figure 3-3: Potentially Inundated Areas in darker blue color (using basic bathtub approach)- SLRv1

3.2.2 Evaluate Inundation Areas Hydrological Connectivity to Gulf / Creek water

Two approaches were examined while evaluating the hydrological connectivity of low lying areas to Gulf / Creek water. The first one aimed to group connected cells into regions then overlay the regions with the land/water layer to identify which regions intersects with the bathtub inundation boundary created in the above step decribed in section *3.2.1*.

The second approach utilized surface characteristics analysis to identify cells from the bathtub inundated boundary grid that are connected directly or indirectly to the Gulf water layer.

First Approach details :

- The Generalization method "Region Group" was used to group connected cells in the bathtub inundation boundary layer, whose height is within the SLR value, into regions. The output raster grid had groups of cells that were located in the same region with the same value (in this case all innundated values has value of "1").

- Then the output regions were overlaid with the *"Land0_ Sea1"* layer (were Gulf water value = 1 while land value = 0, *Figure 3-4*) to identify regions that intersect with water. The method used for the overlay was zonal statistics "Zonal Statistics - Maximum value". The output of this zonal statistics operation retrieves the maximum value each region overlaps with; this means that regions that overlaps with the Gulf water pixels will be returned with a value of 1, while those which overlap with land will return with a value of 0.

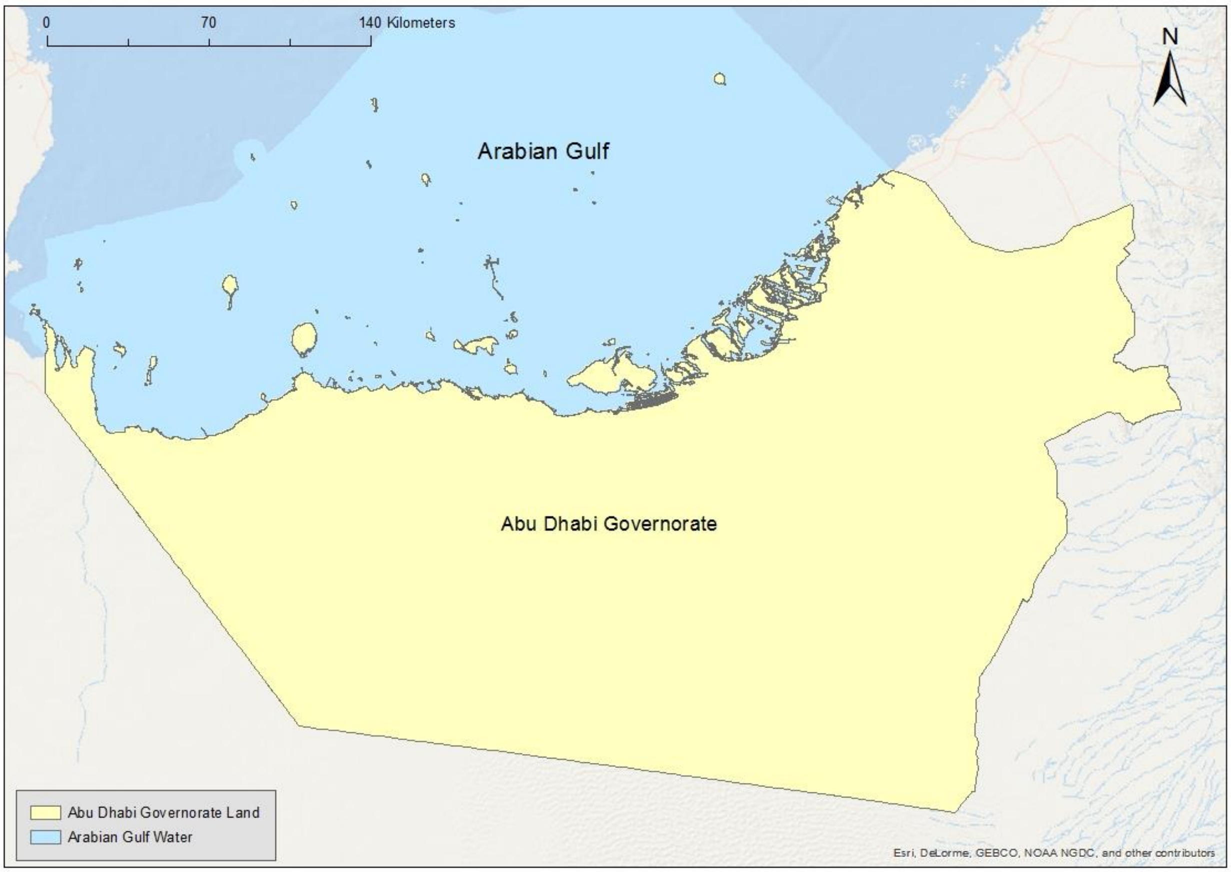

Figure 3-4: Raster Layer representing Land and Gulf/creeks water in UAE

- The last step needed to create the Hydrologically Connected Inundation layer extent is to extract the regions that overlap with the Gulf water layer (with value = 1) resulting from the zonal statistics operation using the extraction method "Extract by Attribute" and thus remove isolated areas with elevations lower than or equal to the SLRp value (Figure 3-5).

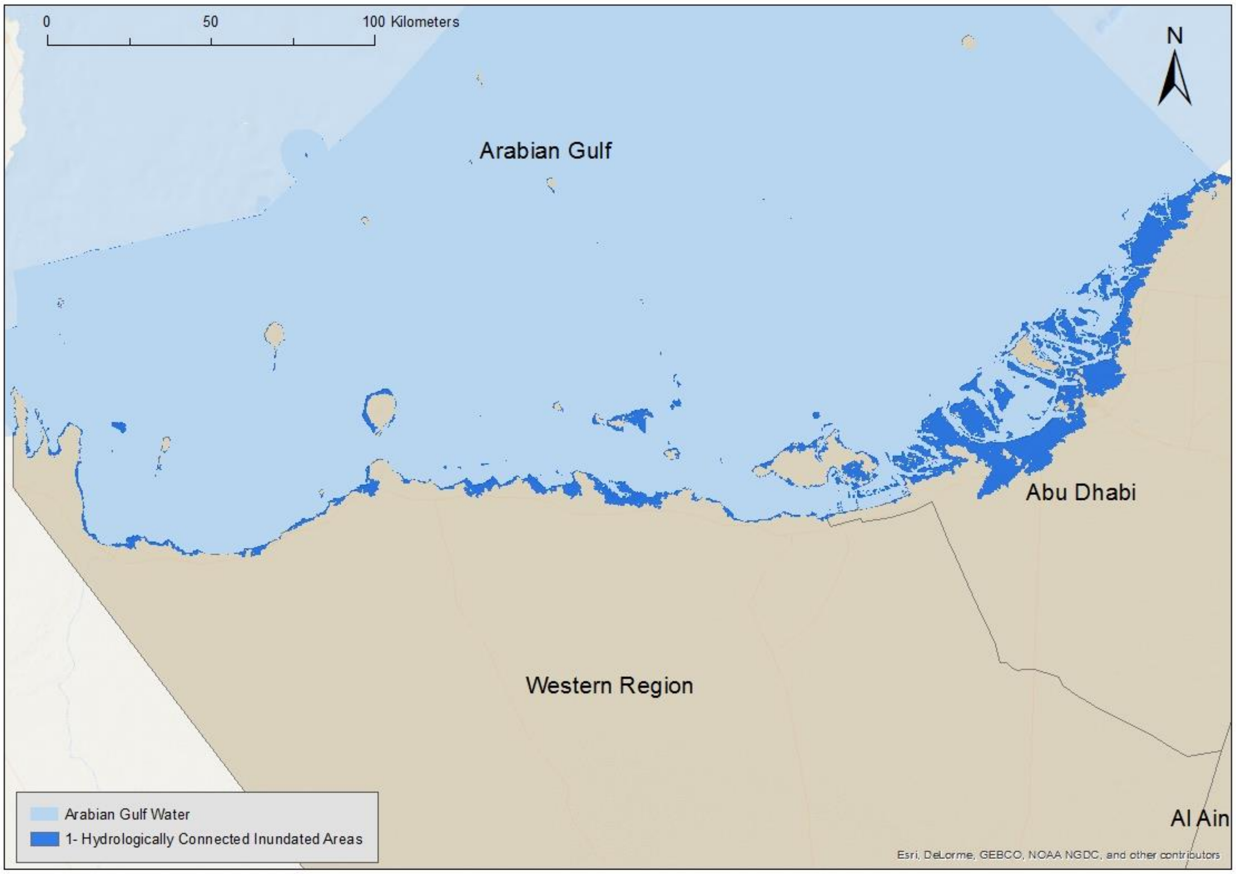

Figure 3-5: Results of Extract by Attribute function represents in dark blue potentially inundated areas that are hydrologically connected to Gulf / Creek water boundaries

Second Approach details :

This approach used the Raster Distance analysis tools named the Cost Distance method, where the Gulf water layer was used as the source layer and the cost layer was the bathtub inundation single value layer. So the output represents the connected areas to the water whose height is less than or equal to the SLRp value.

In this way the bathtub / initial inundated layer cells were hydrologically evaluated to extract only the cells that are connected to the Gulf water layer to a new raster grid layer.

3.2.3 Update Hydrologically Connected Inundation Areas with Inundation Depth

Finally, the bathtub inundation depth layer boundary (created in the first step) will be updated with the two outputs of Hydrological Connectivity evaluation using the Extraction tool "Extract by Mask". The extraction outputs will only represent the hydrologically connected PIAs with the inundation depth value incorporated in the cell value (*Figure 3-6: Final output for* hydrologically connected *potentially* inundated areas with metric inundation depth value (for SLRv1).

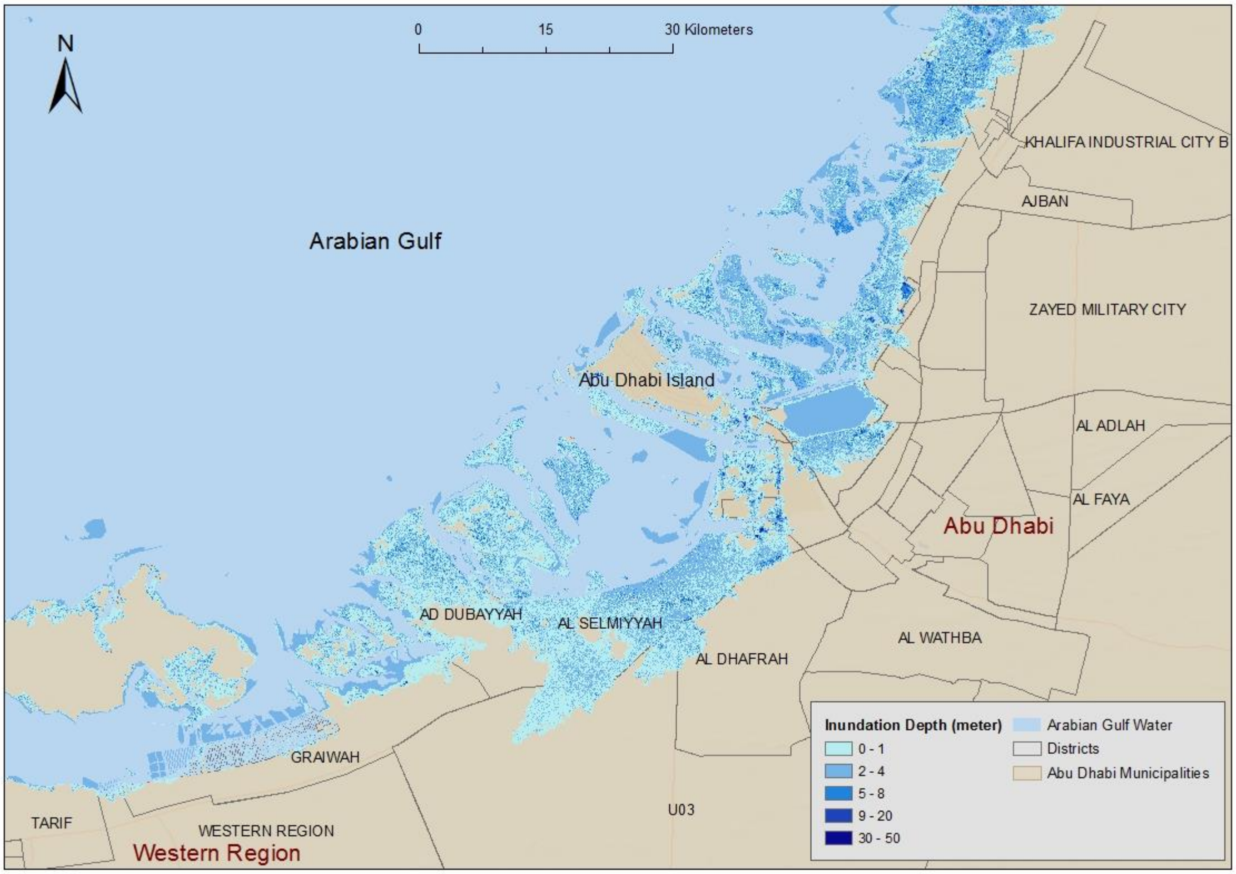

Figure 3-6: Final output for hydrologically connected potentially inundated areas with metric inundation depth value (for SLRv1), where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth value due to their low DEM values

3.2.4 Convert final inundation raster layer to polygon layer

As a preparatory step to the inundation impact assessment part of this study, the final PIA raster layer shall be converted to a polygon feature class, and then all polygons in the new feature class are dissolved into a single polygon to facilitate the overlaying processes which will be used to assess the inundation impacts on natural and built environments.

3.3 Assess Inundation Impact on Natural and built Environment and Population

3.3.1 Overlay inundation layers with natural and built environments datasets

The first step to assess and summarize possible inundation impacts is to clip the built and natural environments feature datasets with the final inundation boundary (hydrologically connected inundation polygon) using the Overlay tool, Intersect. The output feature class will contain a features subset from built / natural environments that will intersect with the inundation boundary.

Then to summarize inundated natural and built environments features according to their sub types and inundation depth, the generalization method, Dissolve was used. This method grouped features according to their sub types or inundation depth into one group.

3.3.2 Summarize population subject to inundation

Next the population layer will be overlaid with inundation layer using the Tabulate Intersection tool to compute the intersection between two feature classes and cross-tabulates the population count of the intersecting features based on ratio of intersecting area to the whole feature.

3.4 Visualize, Publish and Share Results

3.4.1 Abu Dhabi Sea Level Rise Vulnerability Dashboard

The web application Abu Dhabi Sea Level Rise Vulnerability Dashboard was developed to organize, summarize and present the assessments results of Abu Dhabi vulnerability to sea level rise exercise.

The preliminary design/mock up design of the Dashboard (*Figure 3-7: Preliminary design/mockup*) aimed to display summarized statistics and charts for each domain and sub domain highlighting the top impacted categories, sub categories, maximum inundation depth as well as other characteristics according to the sub domain.

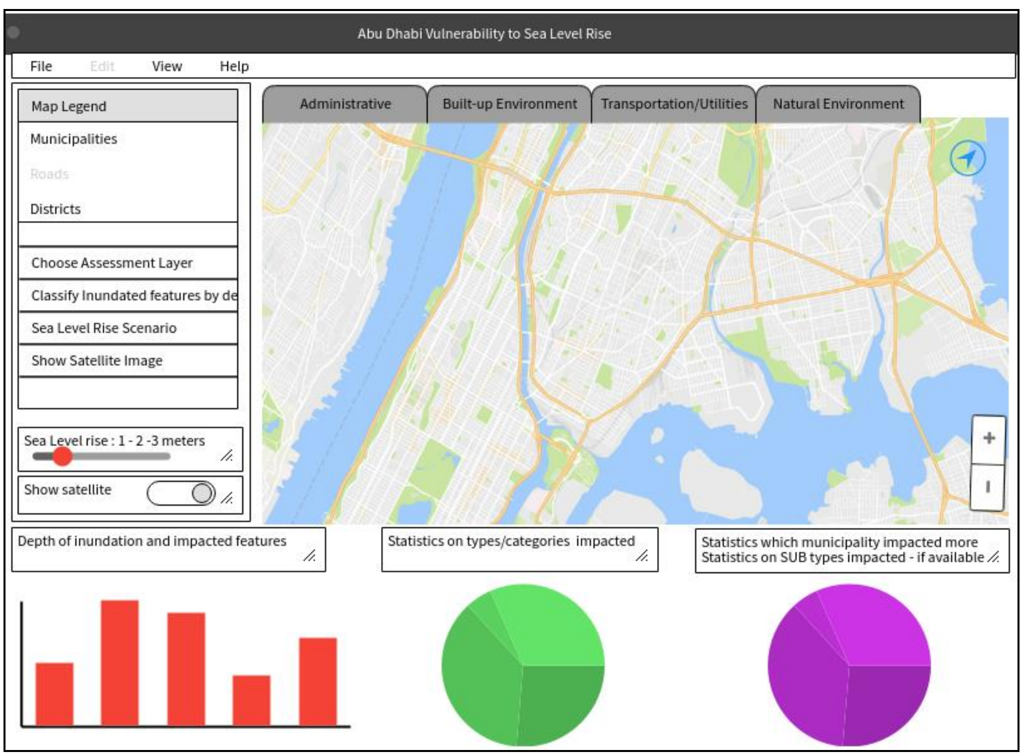

Figure 3-7: Preliminary design/mockup of the Abu Dhabi Sea Level Rise Vulnerability Dashboard web application showing the main domains on top of the map; main feature on the right and basic statistics to be displayed for each sub-domain at the lower banner

The application has four main tabs, representing the four main domains assessed and under each domain, its sub domains are listed on separate pages as elaborated in Figure 4-2.

The implementation workflow of Abu Dhabi Sea Level Rise Vulnerability Dashboard (Figure 3-8) included data preparation, cartography tasks and web map creation, creation of a web app dashboard for each sub domain (like terrestrial habitats) and a story map for each domain containing all dashboards for a selected domain (for example Natural Environment domain story map contains Terrestrial Habitat Dashboard, Marine Habitat Dashboard, Land-Cover Dashboard, Protected Areas Dashboard, and Coastline Dashboard).

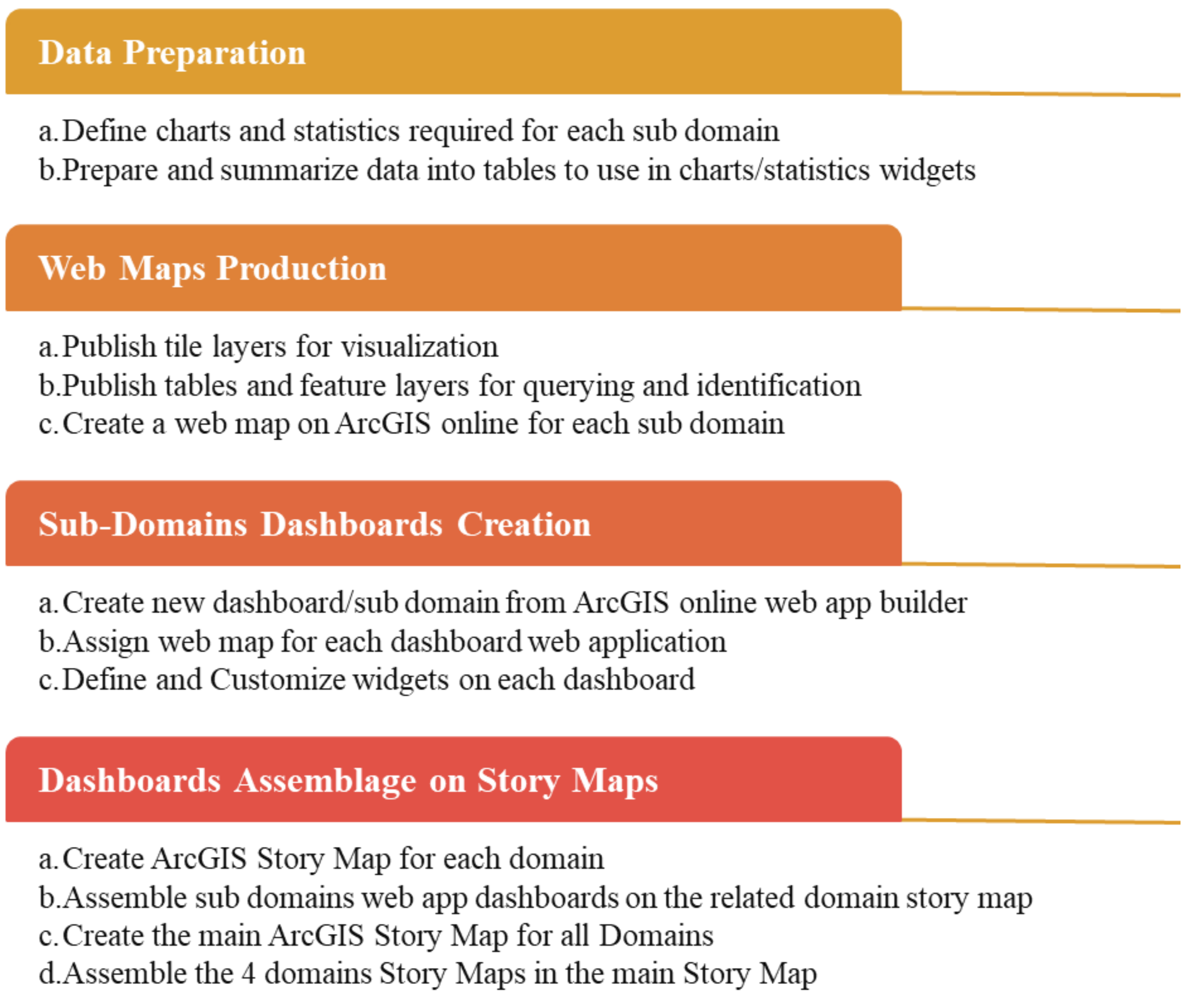

Figure 3-8: Abu Dhabi Sea Level Rise Vulnerability Dashboard implementation steps.

It is worth mentioning that the configuration of the web application did not require any further software installation or programming. However, it was built using the Lund University ArcGIS online account, through creating a web application from the web app builder on ArcGIS online, assigning a web map, then selecting widgets to configure according to the required chart type.

As for viewing the web application, no specific requirements were needed other than an Internet connection and web browser. On the user side, the web application dashboard requires only basic technical expertise to use.

3.5 Software used

The GIS related software/technologies used throughout the whole project are:

- ArcGIS Desktop 10.5
- Spatial Analyst Extension
- ArcGIS Pro 2.0.1
- WebApp Builder for ArcGIS
- ArcGIS Online
- ArcGIS Story map

4 Results

The results of the thesis project can be sorted into 3 main outputs;

i. Potentially Inundated Areas (PIAs) Extraction Model
ii. Abu Dhabi Sea Level Rise Vulnerability Dashboard
iii. Natural/Built up environment Vulnerability Results and Statistics

4.1 Potentially Inundated Areas Extraction Model (a geoprocessing model)

Sea level rise projections change with scientific observation, so solutions / practices that assess long term sea level rise impacts should be developed to be scalable, reusable and configurable. In this thesis project, the extraction of potentially inundated areas was done by developing 2 ArcGIS models with the same objective: to extract low rising areas – within SLR value- then evaluate those areas' hydrological connectivity to sea water (details in section *5.2 Potentially Inundated Areas Extraction Methods*). The outputs of the models define the PIAs that are low rising hydrological connected areas to sea water.

To ensure scalability and flexibility of the PIA extraction method, the model input parameters required to run it included (Figure 4-1, details on: Appendix B – Analysis steps, Figure 8-1 and Figure 8-3):

- The DEM layer;
- The sea level rise projection value

The outputs of the 2 models included:

- A standard bathtub PIA boundary (representing areas with SLR value);
- PIAs boundary refined with hydrologic connectivity filter run;
- PIAs boundary associated with inundation depth value.

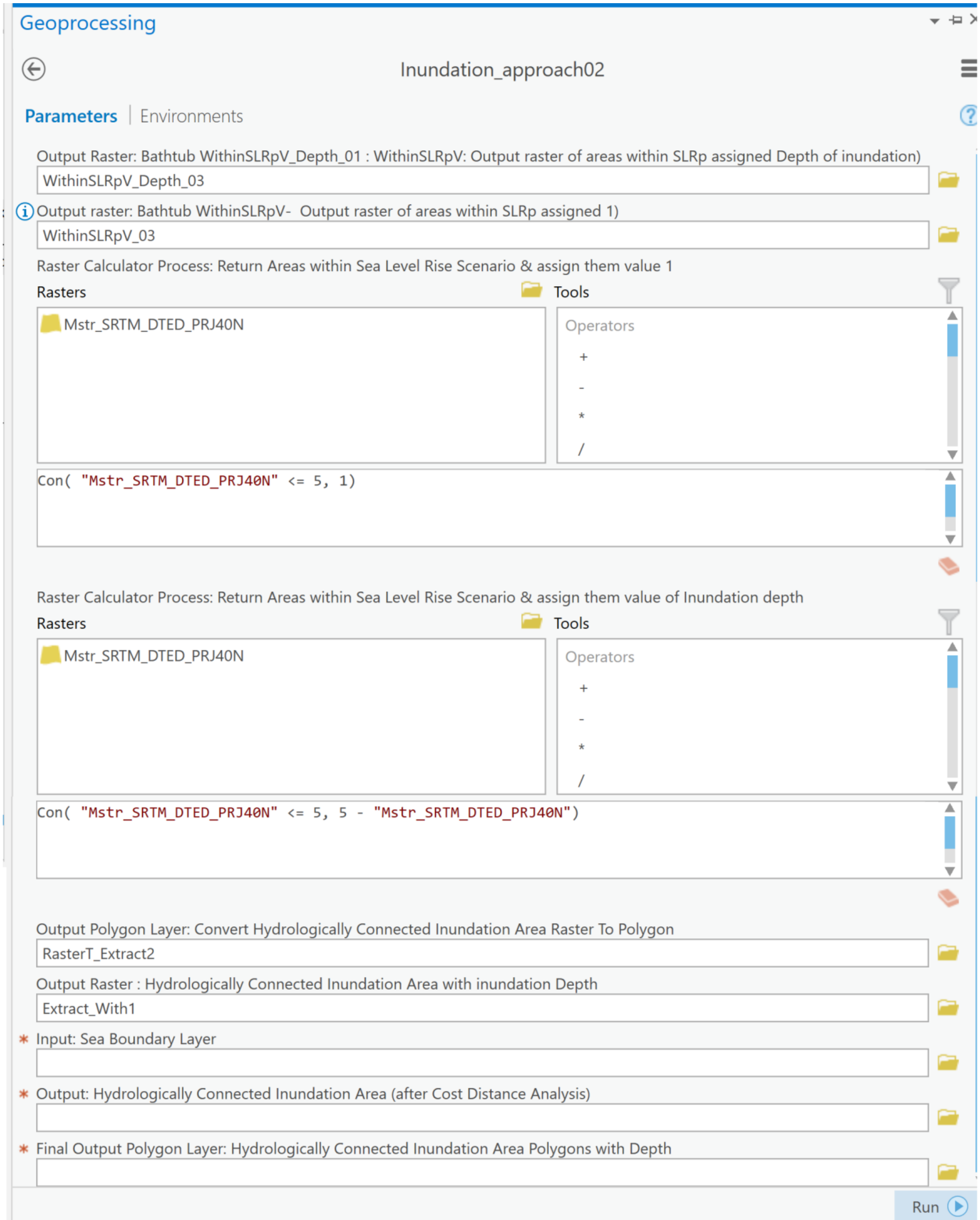

Figure 4-1: Potentially Inundated Areas Extraction Model using Cost Distance Analysis in the run time where the analyst can define the SLR value, select Sea Boundary Layer, DEM layer and define outputs names and paths

4.2 Abu Dhabi Sea Level Rise Vulnerability Dashboard (a web application)

The vulnerability dashboard "Abu Dhabi Sea Level Rise Vulnerability Dashboard" has a dual aim: (1) To introduce a practical up-to-date methodology to share the results of vulnerability assessment exercise with concerned authorities and thus help governmental parties in developing SLR Risk Reduction Plan and increasing the environments resilience to such risk and (2) To summarize the potentially inundated areas in different domains on the sharable platform and enable viewers to navigate easily between results of the three selected sea level rise scenarios.

The dashboard highlights the most impacted sub types in each domain/category, helping concerned parties to prioritize resources at higher risks, which shall eventually support the development of an effective mitigation plan.

The vulnerability dashboard consists of 15 separate dashboards consolidated using a single web application. The dashboards were grouped according to their nature and the domain they belong to (Figure 4-2: The Structure of Domains and Sub-Domains presented on Abu Dhabi Sea Level Rise Vulnerability web application dashboard). The dashboards were developed using ArcGIS Web App Builder Dashboard. Then an ArcGIS Story Map was created for each domain: Administrative, Natural Environment, Built Environment and Transportation/Utilities domains. Next, each story map was assigned 3-5 sub domains dashboards links. Finally, the 4 domains story maps were imbedded on 1 main story map called "Abu Dhabi Sea Level Rise Vulnerability Dashboard".

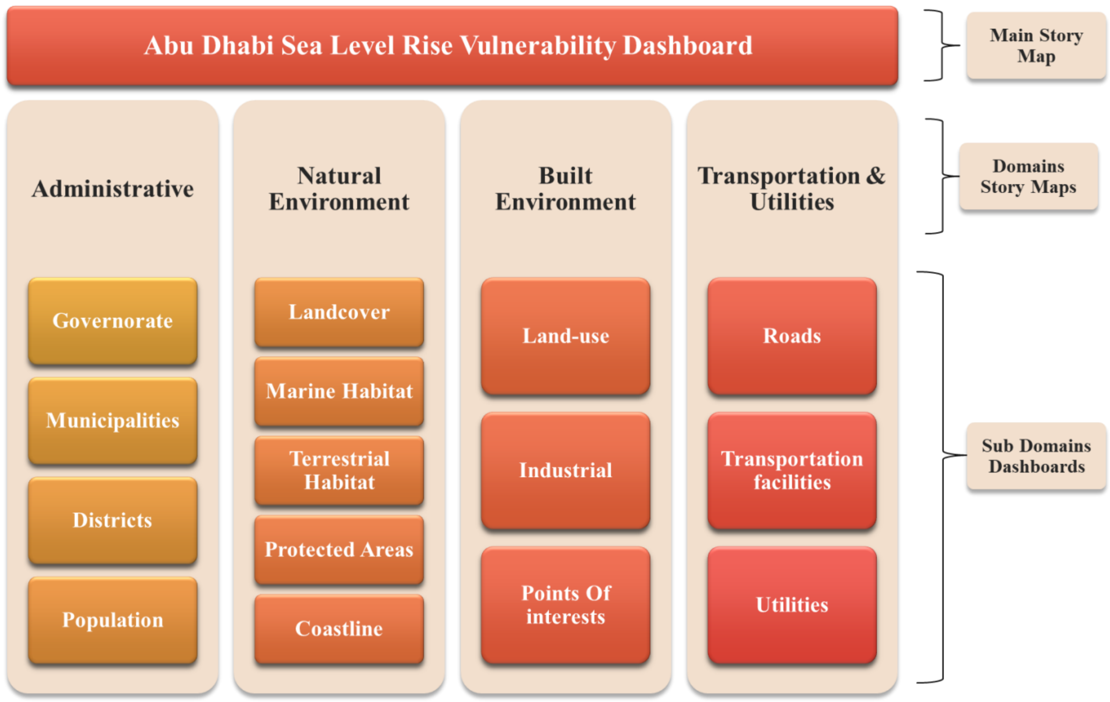

Figure 4-2: The Structure of Domains and Sub-Domains presented on Abu Dhabi Sea Level Rise Vulnerability web application dashboard where each sub domain had a designated dashboard displaying and summarizing potential impact of 3 SLR scenarios and each Domain story map, has the sub domain dashboards included on it.

To implement the web application dashboard, the workflow passed by four main steps illustrated in *Figure 3-8: Abu Dhabi Sea* Level Rise *Vulnerability* Dashboard implementation steps. Each sub domain dashboard contains diverse types of data statistics, charts and gauges displayed with its map (details in section 4.3, Figure 4-4). The selection of the statistical indicators was tailored for the data characteristics of each sub domain.

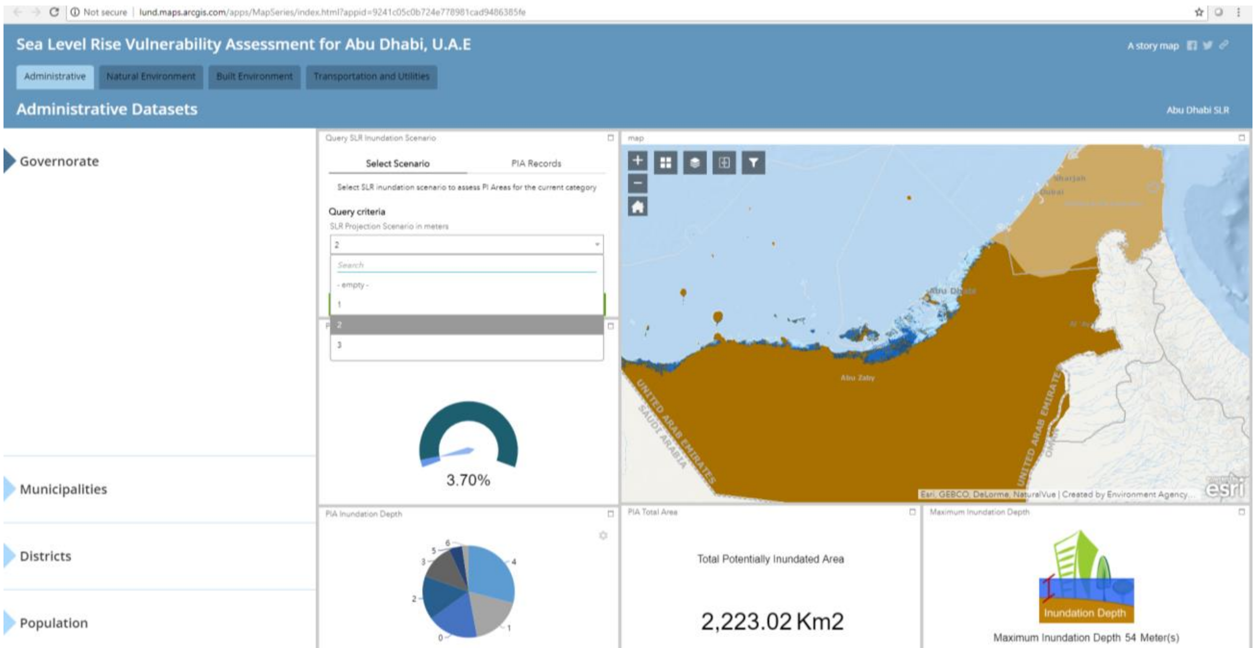

Figure 4-3: Abu Dhabi Sea Level Rise Vulnerability Dashboard- showing Administrative Domain Story map > Governorate Sub Domain Dashboard where the user can select the Sea Level Rise Projection (1-meter, 2 meters or 3 meters) to map and summarize the anticipated inundation results on Governorate dashboard (a sub domain of Administrative domain)

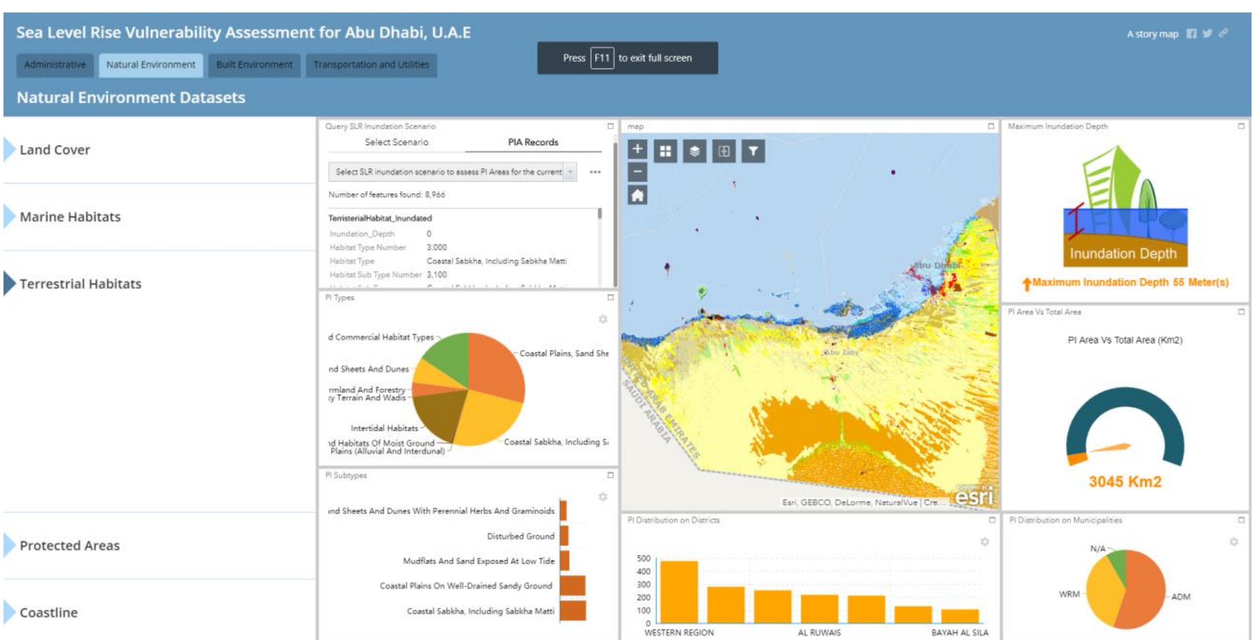

Figure 4-4: Abu Dhabi Sea Level Rise Vulnerability Dashboard- showing – on map, charts and graphs- anticipated1 meter SLR impact on Terresterial Habitats (a sub domain of Natural Environment Domain)

4.3 Vulnerability Assessment Results (data layers and statistics)

4.3.1 Data Layers

The output of PIA extraction model and inundation impact assessment analysis on natural / built environments included:

– Potentially inundated boundaries for each SLR projection scenario associated with inundation depth.

– Potentially inundated areas/features from natural / built environments datasets.

The analysis of natural / built environments extracted and clipped all features / feature parts that intersect with the PIA boundaries. However, due to the size and complexity of resulting geometries, together with the need for simple data to provide acceptable performance on the web application, the datasets representing inundated areas / features from natural / built environments were exported as tables before publishing as web services to be used in the charts and statistics. Still, their corresponding layers are also available on web upon user selection to view on the map and are also available for download to carry on further analysis using their corresponding services.

4.3.2 Statistics & Charts

The inundation impact assessment datasets contained numerous data and attributes. Specific factors and attributes were selected to be summarized on charts / graphs, giving at-a-glance insights on the impact assessment results.

The statistics/charts focused on reporting the following indicators for each subdomain/category:

– Ratio of Potentially Inundated Area (PIA) versus Total area of the selected subdomain/category.

– Total square area of PIA for the selected sub domain.

– PIA in the selected subdomain sorted by inundation depth (height of water covering the subdomain/category PIA).

– Maximum inundation depth threatening the subdomain PIA.

– Top subdomain/category classes and sub classes at risk (for example: districts with largest PIA contribution or land cover types at highest risk…etc.).

– PIA in the selected subdomain sorted by their administrative distribution on municipalities/districts.

In the below sections, the results of vulnerability assessments were extracted from Abu Dhabi Sea Level Rise Vulnerability Dashboard pages and listed according to their category grouping.

A. *Administrative*

– *Governorate*

Table 4-1: Potentially Inundated Governorate Areas Summary & Statistics

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
PIA vs. Total Area	PIA represents 2.61% of total governorate area	PIA represents 3.7% of total governorate area	PIA represents 5.07% of total governorate area
PIA Total area	1,568 km^2	2,223 km^2	3,045 km^2
PIA by Inundation Depth	<1 m: 16.69% 1 m: 17.73% 2 m: 15.66% 3 m: 39.87% 4 m: 6.01% 5 m: 3% 6 m: 1.44%	<1 m: 17.92% 1 m: 18.05% 2 m: 15.47% 3 m: 12.59% 4 m: 29.04% 5 m: 4.62% 6 m: 2.31%	<1 m: 17.46% 1 m: 18.74% 2 m: 16.11% 3 m: 12.62% 4 m: 9.83% 5 m: 21.69% 6 m: 3.54%
PIA Maximum Inundation Depth	53 meters	54 meters	55 meters

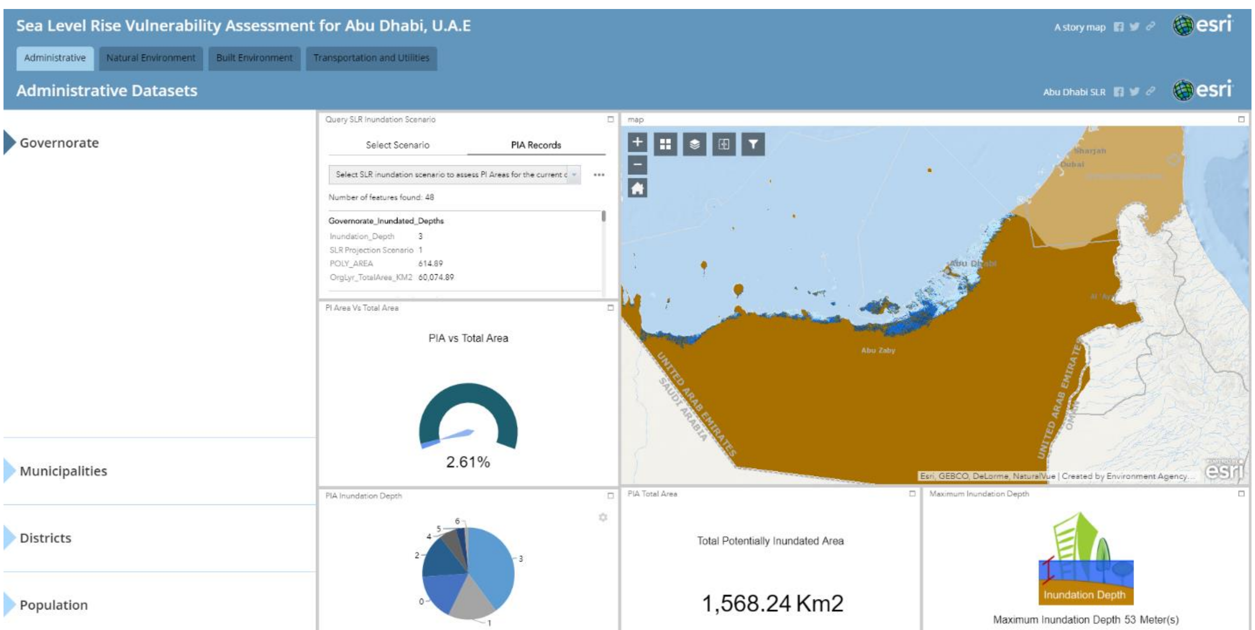

Figure 4-5: Governorate Vulnerability Dashboard summarizing anticipated impact of1 meter sea level rise scenario on Abu Dhabi governorate (Graphs showing size of PIA as a percent total governorate area; PIA distribution by inundation depth; total PIA in sqkm; maximum inundation depth. Map showing hydrologically connected PIAs with metric inundation depth value, where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth.

– ***Municipalities***

Table 4-2: Potentially Inundated Municipalities Areas Summary & Statistics

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
PIA Distribution on municipalities	1. ADM 77.5% 2. ADRM 22.5%	1. ADM 71.4% 2. ADRM 28.6%	1. ADM 54% 2. ADRM 36%
PIA Total Area per Municipality	1. ADM 1,215 km^2 2. ADRM 353 km^2	1. ADM 1,588 km^2 2. ADRM 635 km^2	1. ADM 1,951 km^2 2. ADRM 1,094 km^2
PIA Total Area by Inundation Depth	<1 m: 257 km^2 1 m: 267 km^2 2 m: 242 km^2 3 m: 615 km^2 4 m: 93 km^2 5 m: 46 km^2 6 m: 22 km^2	<1 m: 389 km^2 1 m: 392 km^2 2 m: 336 km^2 3 m: 273 km^2 4 m: 630 km^2 5 m: 100 km^2 6 m: 50 km^2	<1 m: 513 km^2 1 m: 551 km^2 2 m: 473 km^2 3 m: 371 km^2 4 m: 289 km^2 5 m: 637 km^2 6 m: 104 km^2
PIA Maximum Inundation Depth	53 meters	54 meters	55 meters

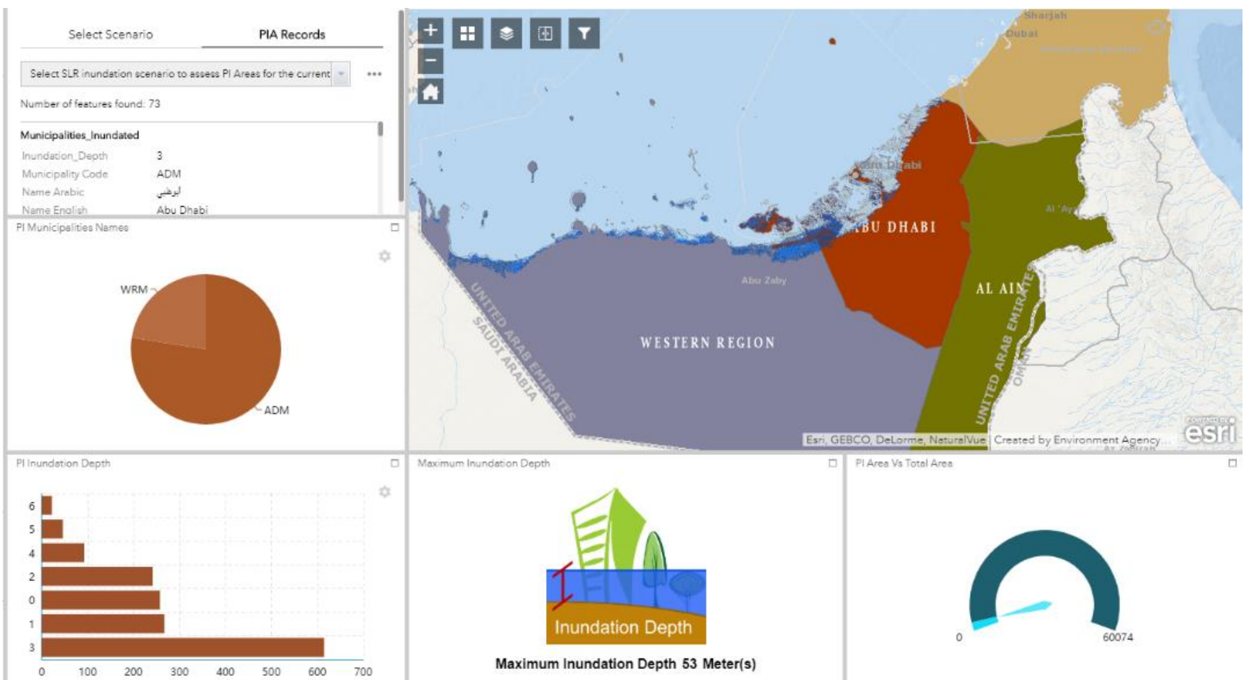

Figure 4-6: Municipalities Vulnerability Dashboard summarizing anticipated impact of 1 meter sea level rise scenario (graphs showing distribution of PIA on the municipalities of Abu Dhabi governorate, size of PIA by inundation depth value; maximum inundation depth; size of PIA versus total municipalities area. Map showing hydrologically connected PIAs with metric inundation depth value, where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth)

– *Districts*

Table 4-3: Potentially Inundated Districts Areas Summary & Statistics

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
Top 5 PI Districts	1. AD Dubayyah 2. Musaffah south 3. Al Ruwais 4. Al Selmiyyah 5. Garaiwah	1. AD Dubayyah 2. Al Ruwais 3. Abu Al Abyad Island 4. Garaiwah 5. Western Region	1. Western Region 2. Abu Al Abyad Island 3. Garaiwah 4. AD Dubayyah 5. Al Ruwais
PI Districts Municipal location	1. Abu Dhabi Municipality 81% 2. Al Dhafra Region Municipality 19%	1. Abu Dhabi Municipality 73% 2. Al Dhafra Region Municipality 27%	1. Abu Dhabi Municipality 65% 2. Al Dhafra Region Municipality 35%
Total area of PI Districts	1,298 km^2	1.918 km^2	2,713 km^2
PIA Maximum Inundation Depth	53 meters	54 meters	54 meters

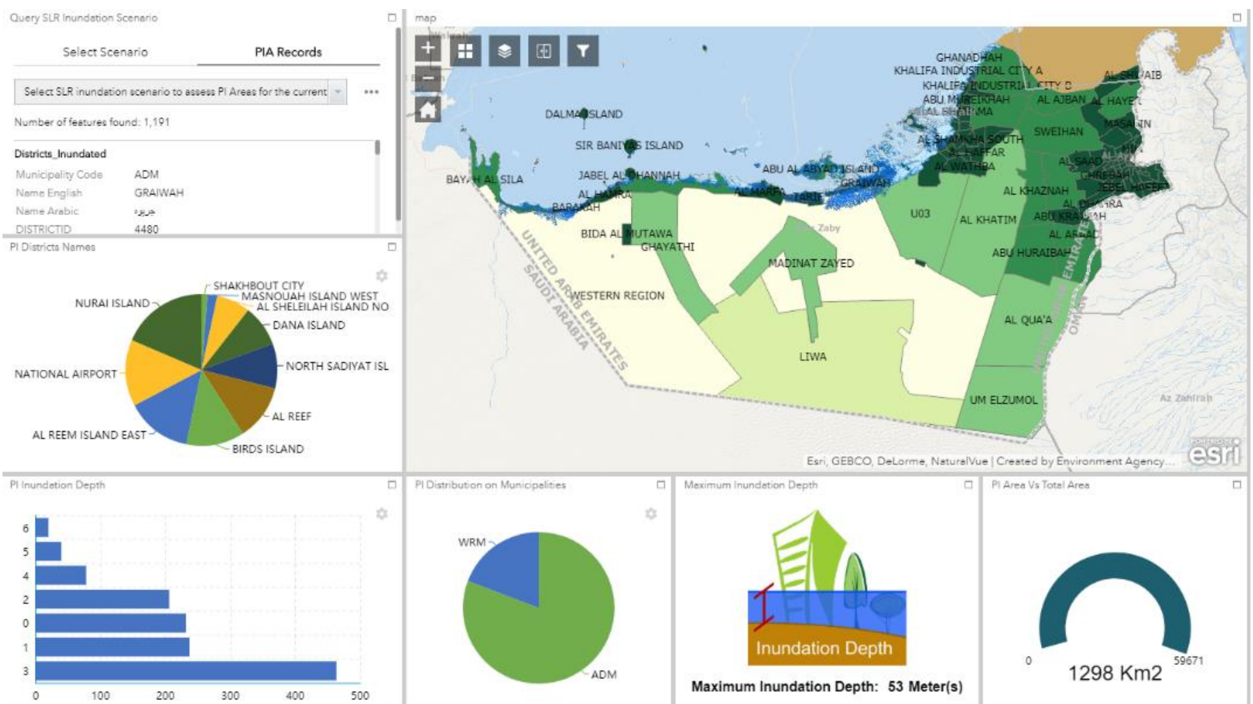

Figure 4-7: Districts Vulnerability Dashboard showing – on map, charts and graphs- anticipated 1 meter SLR impact on Abu Dhabi Governorate districts (Graphs showing distribution of PIA by : district name, inundation depth value; municipality; as well as size of PIA versus total district area and maximum inundation depth. Map showing hydrologically connected PIAs with metric inundation depth value, where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth)

– ***Population***

Table 4-4: Potentially Inundated Population Areas Summary & Statistics

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
Potentially Impacted Population District allocation	1. Abu Dhabi Island 2. Musaffah 3. Khalifa City 4. Abu Dhabi Industrial City 5. Yas Island 6. Mohamed Bin Zayed Island 7. Al Reem Island	1. Abu Dhabi Island 2. Musaffah 3. Khalifa City 4. Abu Dhabi Industrial City 5. Mohamed Bin Zayed Island 6. Yas Island 7. Al Reem Island	1. Abu Dhabi Island 2. Musaffah 3. Mohamed Bin Zayed Island 4. Khalifa City 5. Abu Dhabi Industrial City 6. Al Ruwais 7. Yas Island
Potentially Impacted Population Municipal allocation	1. ADM 298,306 Capita 2. ADRM 8,280 Capita	1. ADM 417,679 Capita 2. ADRM 14,931 Capita	1. ADM 527,480 Capita 2. ADRM 22,680 Capita
Potentially Impacted Population	16% of total population	23% of total population	30% of total population

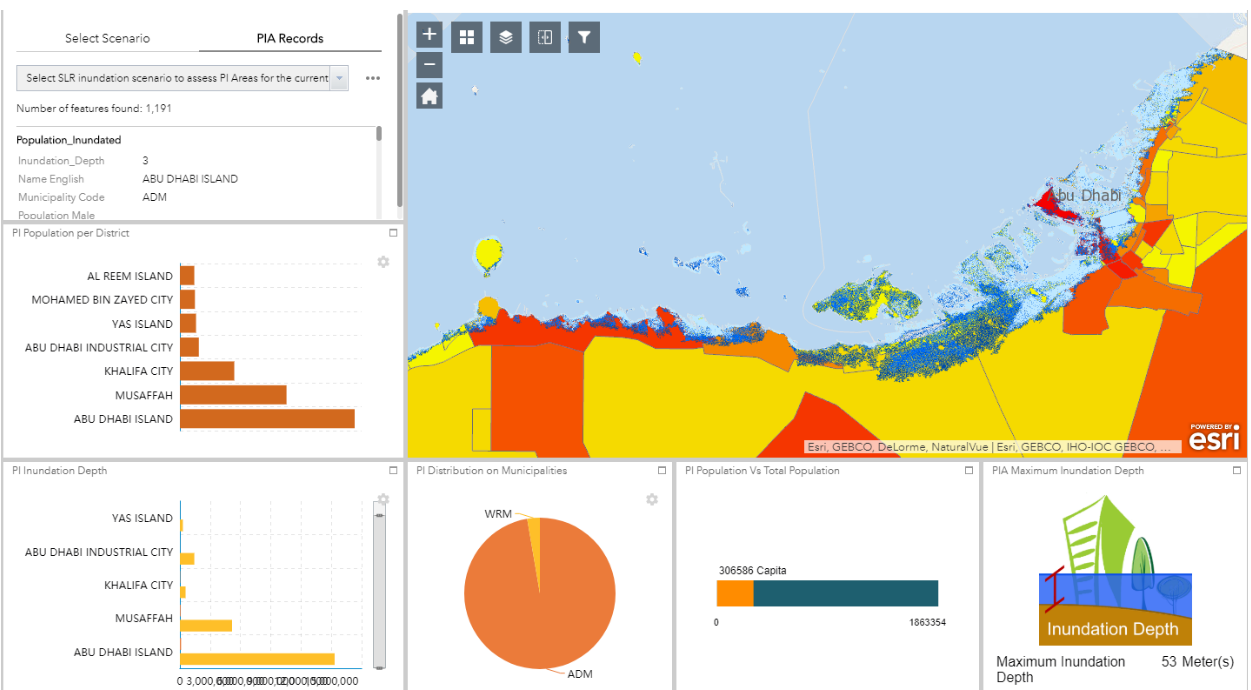

Figure 4-8: Population Vulnerability Dashboard showing – on map, charts and graphs- anticipated 1 meter SLR impact on Abu Dhabi Governorate Population (graphs showing distribution of potentially impacted population by: district, inundation depth value, municipality; as well as count of potentially impacted population versus total governorate population and maximum inundation depth for populated

areas. Map showing hydrologically connected PIAs with metric inundation depth value, where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth)

B. ***Natural Environment***

– ***Land Cover***

Table 4-5: Potentially Inundated Land Cover Areas Summary & Statistics

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
Top PIA by Type	1. Sand Dunes, 2. Vacant, 3. Coastal Sabkhas, 4. Mangroves 5. Mixed Urban	1. Sand Dunes, 2. Vacant, 3. Coastal Sabkhas, 4. Mangroves 5. Mixed Urban	1. Sand Dunes, 2. Vacant, 3. Coastal Sabkhas, 4. Mangroves 5. Mixed Urban
Top PIA by District(s)	1. Abu Dubayyah 2. Al Ruwais 3. Al Selmiyyah 4. Abu Al Abyad Island 5. Ghanadhah	1. Abu Dubayyah 2. Al Ruwais 3. Western Region 4. Abu Al Abyad Island 5. Garaiwah	1. Western Region 2. Abu Dubayyah 3. Al Ruwais 4. Abu Al Abyad Island 5. Garaiwah
Top PIA by Municipality	ADM	ADM	ADM
Total area of PI land cover areas	1, 56835 km^2	2,161 km^2	2, 950 km^2
PIA Maximum inundation depth	13 meters	14 meters	15 meters

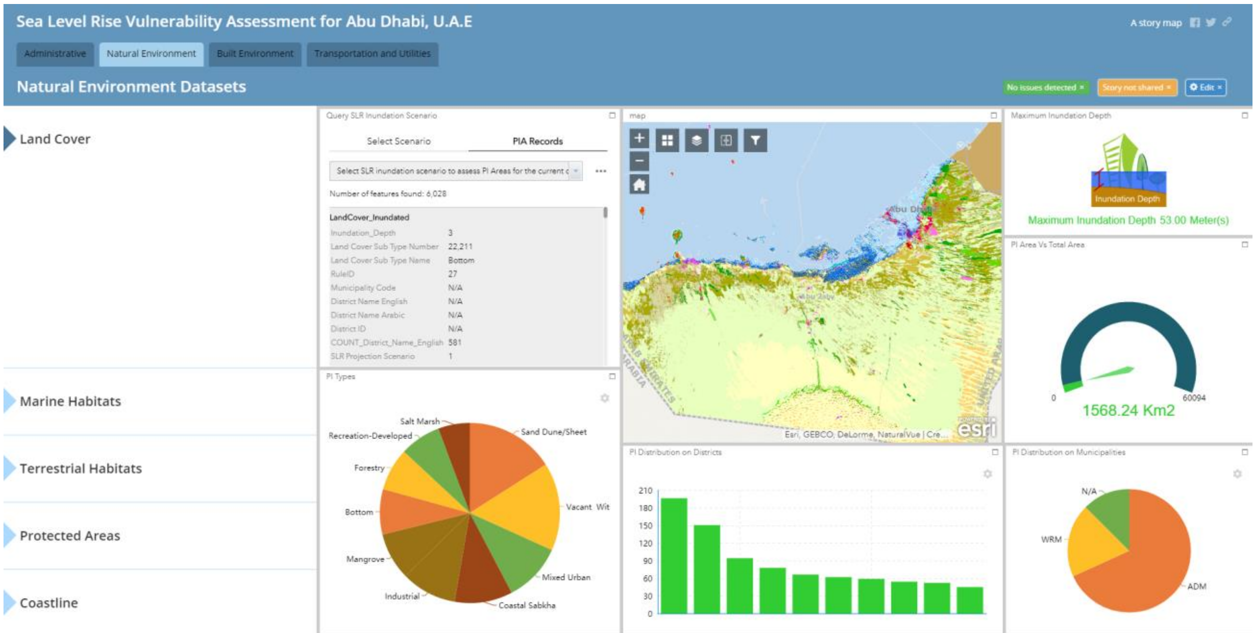

Figure 4-9: Land Cover Vulnerability Dashboard showing – on map, charts and graphs- anticipated 1 meter SLR impact on Abu Dhabi Governorate Land-cover types. (Graphs showing distribution of potentially inundated land-cover areas by; type, district, municipality; as well as size of potentially impacted land-cover areas versus total land-cover area; and maximum inundation depth for land-cover areas. Map showing hydrologically connected PIAs with metric inundation depth value, where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth)

– *Marine Habitat*

Table 4-6: Potentially Inundated Marine Habitat Areas Summary & Statistics

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
Top PIA by Type	1. Deep Subtidal Seabed 2. Unconsolidated bottom 3. Sea grass bed 4. Hard bottom 5. Coral reef	1. Deep Subtidal Seabed 2. Unconsolidated bottom 3. Sea grass bed 4. Hard bottom 5. Coral reef	1. Deep Subtidal Seabed 2. Unconsolidated bottom 3. Sea grass bed 4. Hard bottom 5. Coral reef
Top PIA by District(s)	1. Al Ruwais 2. Abu Dubayyah 3. Zarkuh 4. Nad Al Shebba 5. Bayah Al Sila	1. Al Ruwais 2. Abu Dubayyah 3. Zarkuh 4. Nad Al Shebba 5. Bayah Al Sila	1. Al Ruwais 2. Abu Dubayyah 3. Zarkuh 4. Nad Al Shebba 5. Bayah Al Sila
Top PIA by Municipality	ADRM	ADRM	ADRM

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
Total area of PI Marine Habitat areas	26, 722 km^2	26, 734 km^2	26, 741 km^2
PIA Maximum Inundation Depth	33 meters	34 meters	35 meters

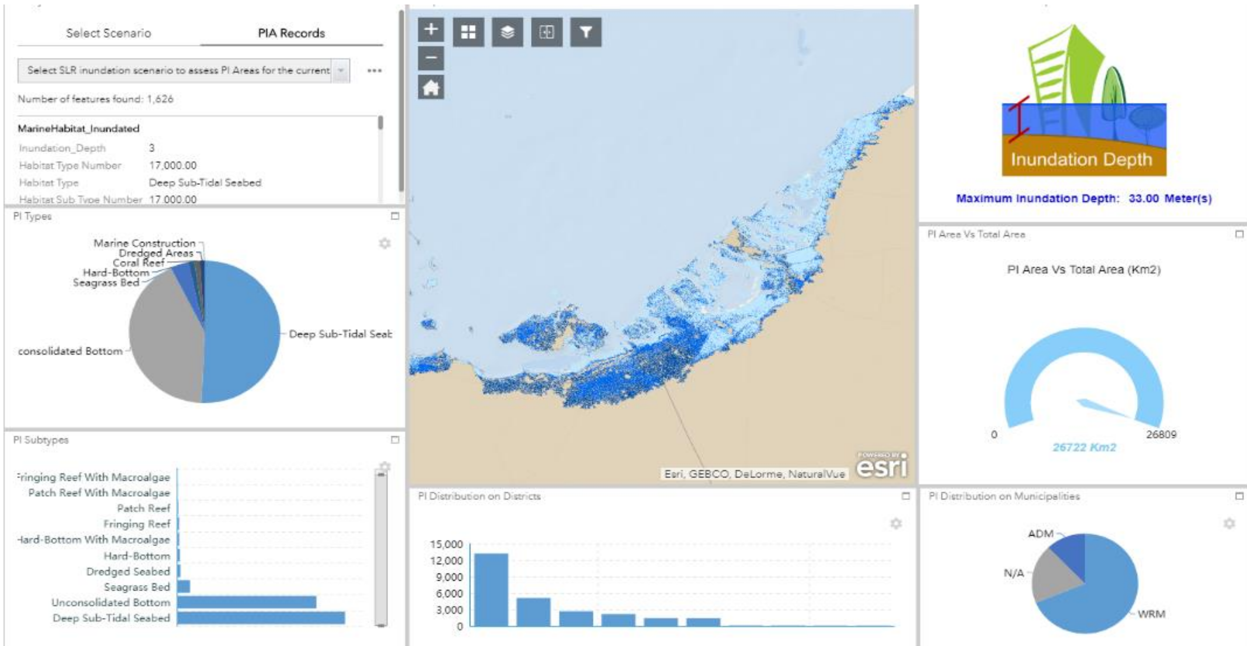

Figure 4-10: Marine Habitat Vulnerability Dashboard showing – on map, charts and graphs- anticipated 1 meter SLR impact on Abu Dhabi Governorate Marine Habitat (Graphs showing distribution of PIA by marine habitat type, by sub type, by district; by municipality; as well as potentially impacted marine habitat areas versus total marine habitat area and maximum inundation depth for marine habitat areas. Map showing hydrologically connected PIAs with metric inundation depth value, where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth)

– ***Terrestrial Habitat***

Table 4-7: Potentially Inundated Terrestrial Habitat Areas Summary & Statistics

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
Top PIA by Habitat Type	1. Intertidal habitats 2. Coastal Plains, sand sheets and low dune 3. Urban, industrial and commercial habitat types 4. Coastal sabkha including sabkha matti 5. Oasis, Farmland and forestry	1. Coastal Plains, sand sheets and low dune 2. Coastal sabkha including sabkha matti 3. Intertidal habitats 4. Urban, industrial and commercial habitat types 5. Sand sheets and dunes	1. Coastal Plains, sand sheets and low dune 2. Coastal sabkha including sabkha matti 3. Intertidal habitats 4. Urban, industrial and commercial habitat types 5. Sand sheets and dunes
Top PIA by Habitat Sub Type	1. Coastal plains on well drained sandy ground 2. Mudflats and sands exposed at low tide 3. Coastal sabkha including sabkha matti 4. Disturbed ground 5. Mangroves	1. Coastal plains on well drained 2. Coastal sabkha including sabkha matti 3. Mudflats and sands exposed at low tide 4. Disturbed ground 5. Mangroves	1. Coastal sabkha including sabkha matti 2. Coastal plains on well drained sandy ground 3. Mudflats and sands exposed at low tide 4. Disturbed ground 5. Sand sheets and dunes with perennial herbs and graminoids
Top PIA by District(s) location	1. AD Dubayyah 2. Al Ruwais 3. Al Selmiyyah 4. Abu Al Abyad Island 5. Ghanadhah	1. AD Dubayyah 2. Al Ruwais 3. Western Region 4. Abu Al Abyad Island 5. Garaiwah	1. Western Region 2. AD Dubayyah 3. Al Ruwais 4. Abu Al Abyad Island 5. Garaiwah
Top PIA by Municipality	ADM	ADM	ADM
Total area of PI Terrestrial Habitat Areas	1568 km^2	2223 km^2	3045 km^2

PIA Maximum Inundation Depth	12 meters	12 meters	13 meters

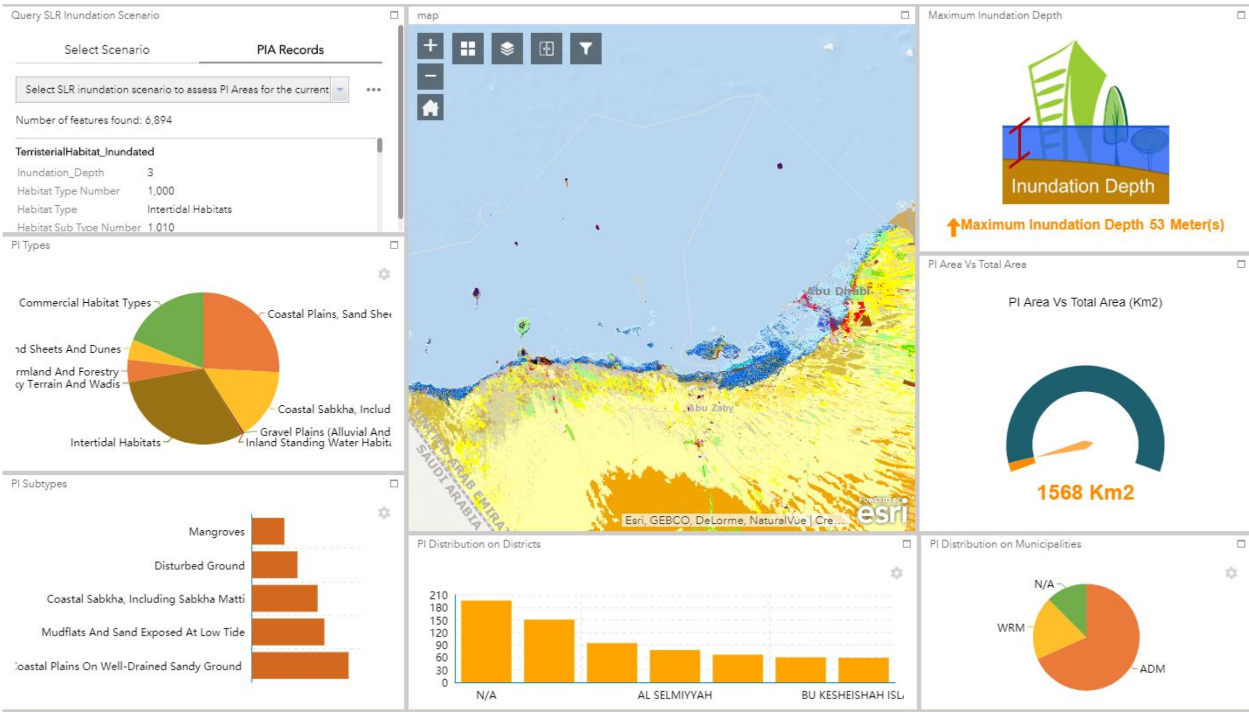

Figure 4-11: Terrestrial Habitat Vulnerability Dashboard showing – on map, charts and graphs- anticipated 1 meter SLR impact on Abu Dhabi Governorate Terrestrial Habitat. (Graphs showing distribution of PIA by terrestrial habitat; type, sub type, district, municipality; as well as size of potentially impacted terrestrial habitat areas versus total terrestrial habitat area and maximum inundation depth for terrestrial habitat areas. Map showing hydrologically connected PIAs with metric inundation depth value, where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth)

– *Protected Areas*

Table 4-8: Potentially Inundated Protected Areas Summary & Statistics

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
Top PIA by Type	1. Established Protected Areas	1. Established Protected Areas	1. Established Protected Areas
Top PIA by Class	1. Marine Class	1. Marine Class	1. Marine Class
Top PIA by District(s)	1. Al Ruwais 2. Bayah Al Sila 3. Al Silmiyah 4. Sadiyat Island 5. Ghanadhah	1. Al Ruwais 2. Bayah Al Sila 3. Al Silmiyah 4. Sadiyat Island 1. Ghanadhah	1. Al Ruwais 2. Bayah Al Sila 3. Al Silmiyah 4. Sadiyat Island 5. Ghanadhah
Top PIA by Municipality	ADRM	ADRM	ADRM
Total area of PI Protected Areas	6,215 km^2	6,305 km^2	6,382 km^2
PIA Maximum Inundation Depth	22 meters	23 meters	24 meters

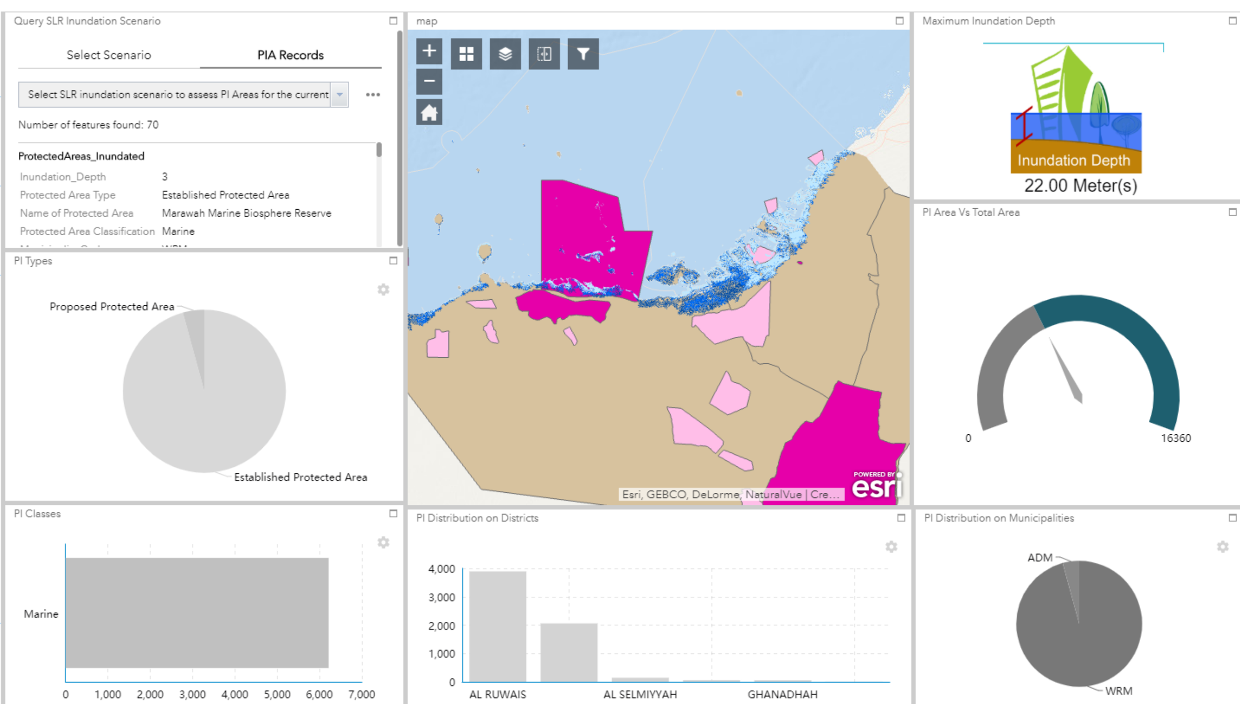

Figure 4-12: Protected Areas Vulnerability Dashboard showing – on map, charts and graphs- anticipated 1 meter SLR impact on Abu Dhabi Governorate protected areas. (Graphs showing distribution of PIA by protected areas; type, class, district, municipality; as well as size of potentially impacted protected areas versus total protected areas and maximum inundation depth for protected

areas. Map showing hydrologically connected PIAs with metric inundation depth value, where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth)

– ***Coast-line***

Table 4-9: Potentially Inundated Coast Line Summary & Statistics

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
Total Length of PI Coastline	3,637 Km of 4446 Km	3,905 Km of 4446 Km	4,097 Km of 4446 Km
PI Coastline Maximum Inundation Depth	33 meters	34 meters	35 meters

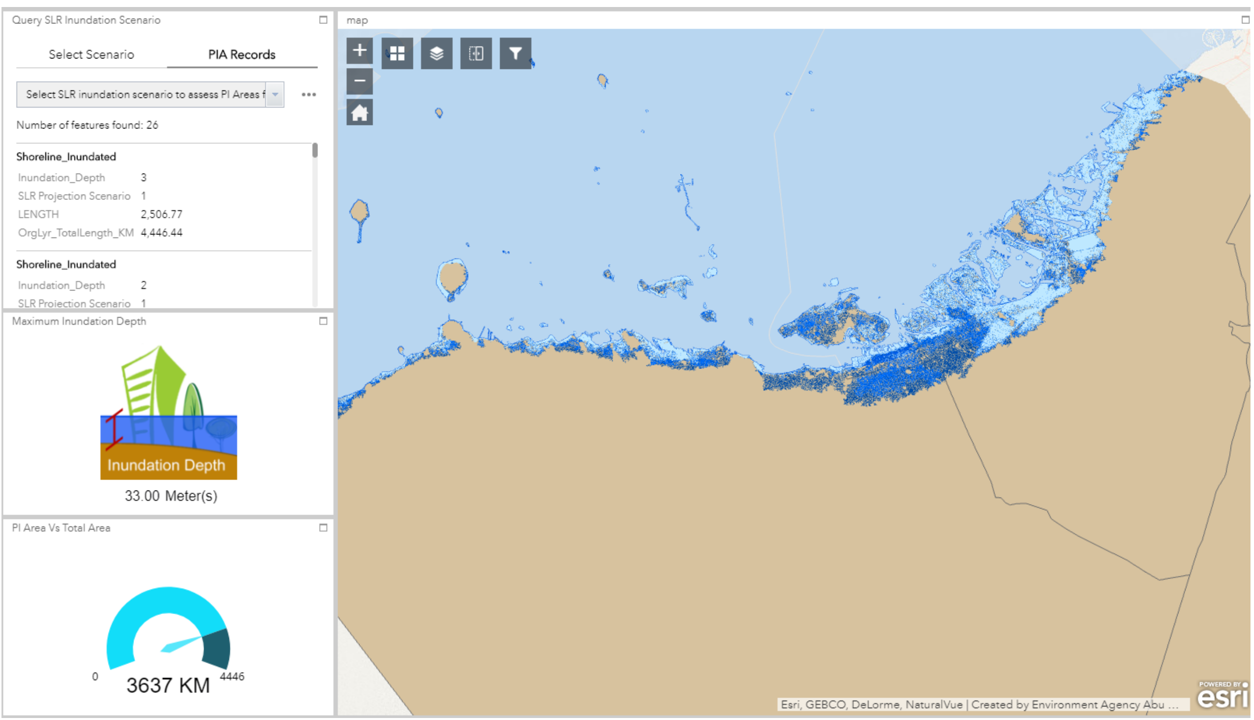

Figure 4-13: Coastline Vulnerability Dashboard showing – on map, charts and graphs- anticipated 1 meter SLR impact on Abu Dhabi Governorate Coastline. (Graphs showing maximum inundation depth for coastline and length of potentially inundated coastline versus total coastline length. Map showing hydrologically connected PIAs with metric inundation depth value, where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth)

C. *Built Environment*

– *Land-use*

Table 4-10: Potentially Inundated Land-use Areas Summary & Statistics

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
Top PIA by Type	1. Vacant 2. Private 3. Governmental 4. Residential 5. Industrial	1. Vacant 2. Private 3. Governmental 4. Residential 5. Industrial	1. Vacant 2. Private 3. Residential 4. Governmental 5. Industrial
Top PIA by Sub Type	1. Military Facility 2. Island 3. Palace 4. Vacant with improvements 5. Private Land	1. Military Facility 2. Island 3. Palace 4. Vacant with improvements 5. Private Land	1. Military Facility 2. Island 3. Palace 4. Vacant with improvements 5. Private Land
PIA by Tenancy Contract Presence	1. No Tenancy Contract 44.38% 2. Has tenancy contract 0.38%	1. No Tenancy 37.62% 2. Has tenancy contract 0.28%	1. No Tenancy Contract 31.05% 2. Has tenancy contract 0.18%
PIA by Ownership Types	1. Permanent 2. Allocated 3. Allocated Federal Government 4. Temporary 5. Allocated local Government	1. Permanent 2. Allocated 3. Allocated Federal Government 4. Temporary 5. Allocated local Government	1. Undefined 2. Permanent 3. Allocated 4. Allocated Federal Government 5. Temporary 6. Allocated local Government
PIA by Construction Status	1. Constructed 2. Not constructed 3. Under Construction	1. Not constructed 2. Constructed 3. Under Construction	1. Not constructed 2. Constructed 3. Under Construction
Top PIA by District(s) location	1. Al Ruwais 2. Western Region 3. Al Hamra 4. Unknow islands 5. Abu Al Abyad Island	1. Western Region 2. Al Ruwais 3. Abu Al Abyad Island 4. Al Hamra 5. Unknow islands	1. Western Region 2. Al Ruwais 3. Abu Al Abyad Island 4. Nadd Al Shebba 5. Unknow islands

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
PIA by Municipality	1. ADM 56.47% 2. ADM 43.53%	1. ADM 51.33% 2. ADRM 48.67%	1. ADM 56.62% 2. ADRM 43.38%
Total area of PI Land-Use Areas	1.894 km^2	2,550 km^2	3,374 km^2
PIA Maximum Inundation Depth	53 meters	54 meters	55 meters

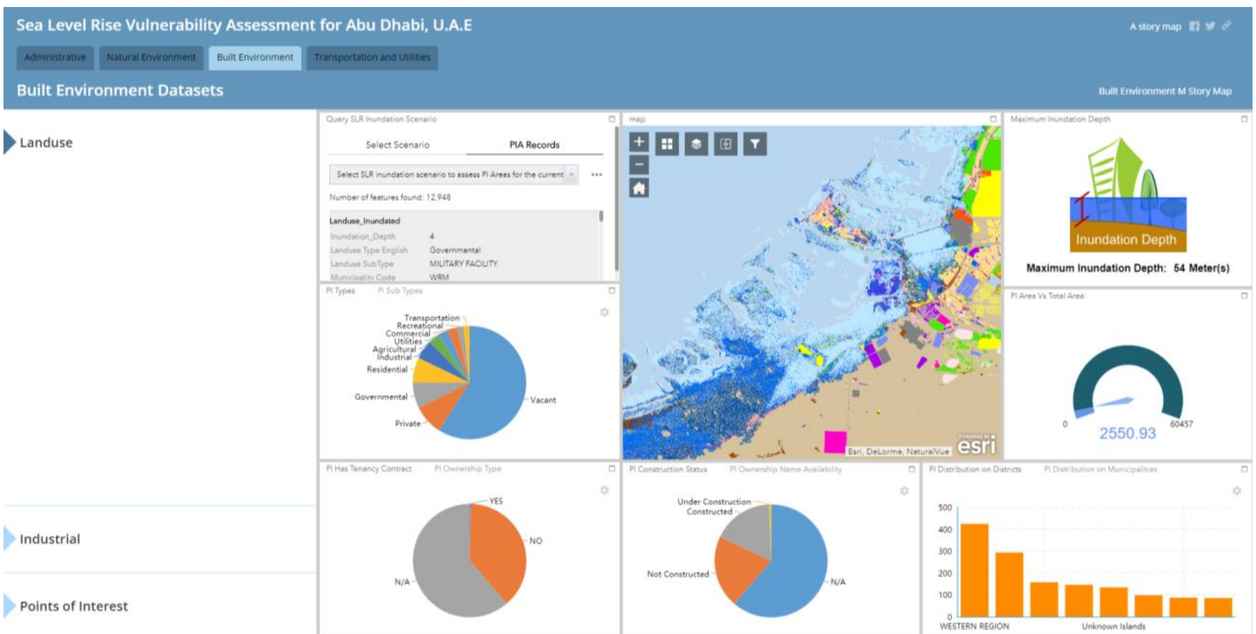

Figure 4-14: Land-use Vulnerability Dashboard showing – on map, charts and graphs- anticipated 2 meters SLR impact on Abu Dhabi Governorate Land-use area. (Graphs showing distribution of PIA by land-use; tenancy contract, construction status, district; as well as size of potentially impacted land-use areas versus total land-use areas and maximum inundation depth for land-use areas. Map showing hydrologically connected PIAs with metric inundation depth value, where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth)

– ***Industrial***

Table 4-11: Potentially Inundated Industrial Areas Summary & Statistics

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
Top PIA by Types	1. Factory 2. Industrial Land 3. Other 4. General Industry 5. Temporary Industrial Land	1. Factory 2. Industrial Land 3. Other 4. General Industry 5. Temporary Industrial Land	1. Factory 2. Industrial Land 3. Other 4. General Industry 5. Temporary Industrial Land
Top PIA by District(s)	1. Musaffah South 2. Khalifah Industrial City A 3. Barakah 4. Musaffah 5. Al Taweelah	1. Musaffah South 2. Khalifah Industrial City A 3. Musaffah 4. Barakah 5. Al Taweelah	1. Musaffah South 2. Khalifah Industrial City A 3. Musaffah 4. Barakah 5. Al Ruwais
Top PIA by Municipality	1. ADM 82% 2. ADRM 18%	1. ADM 79% 2. ADRM 21%	1. ADM 77% 2. ADRM 23%
Total area of PI Industrial Areas	107 km^2	134 km^2	152 km^2
PIA Maximum Inundation Depth	53 meters	54 meters	55 meters

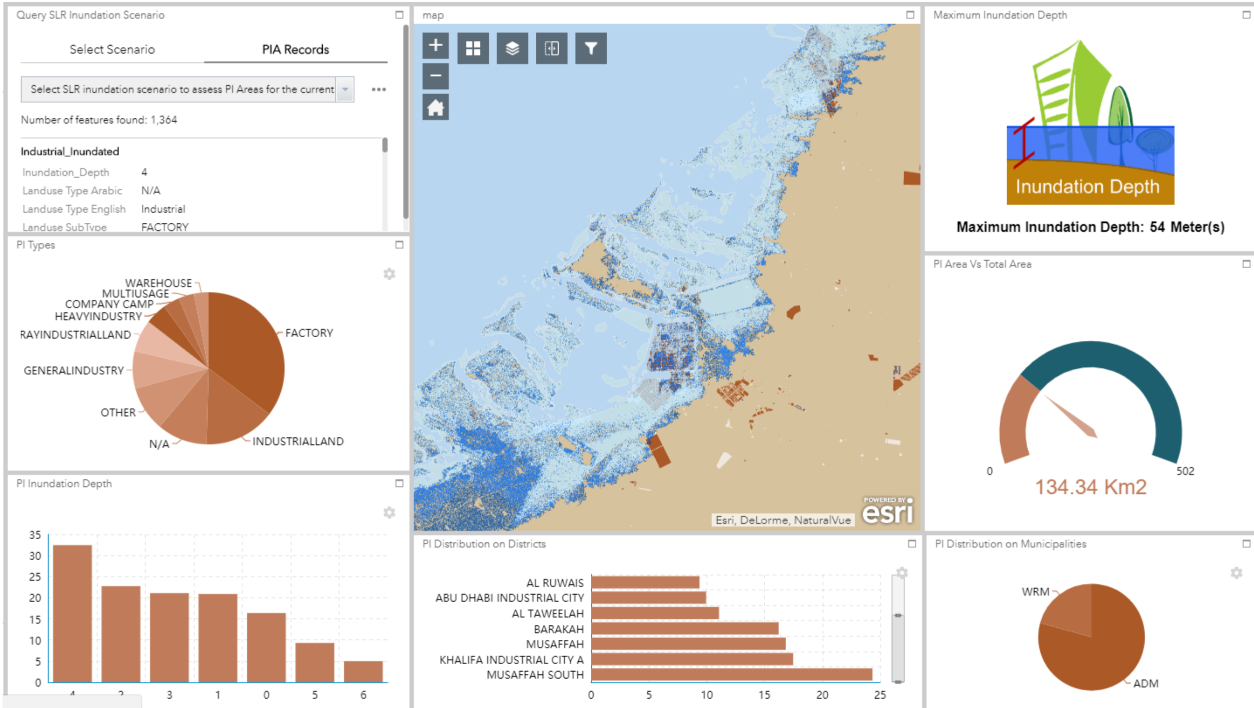

Figure 4-15: Industrial Vulnerability Dashboard showing – on map, charts and graphs- anticipated 2 meters SLR impact on Abu Dhabi Governorate industrial Areas. (Graphs showing distribution of PIA by industrial areas; type, inundation depth, district, municipality; as well as size of potentially impacted industrial areas versus total industrial area and maximum inundation depth for industrial areas. Map showing hydrologically connected PIAs with metric inundation depth value, where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth)

– *Points of Interests*

Table 4-12: Potentially Inundated Points of Interests Areas Summary & Statistics

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
Top PIA by Types	1. Government and public services 2. Automotive 3. Eating and drinking 4. Leisure 5. Lodging	1. Government and public services 2. Automotive 3. Eating and drinking 4. Leisure 5. Lodging	1. Government and public services 2. Automotive 3. Eating and drinking 4. Leisure 6. Lodging
Top PIA by District(s)	1. Musaffah south 2. Al Taweelah 3. Abu Dhabi Island 4. AD Dubayyah 5. Khalifa City	1. Musaffah south 2. Al Taweelah 3. Abu Dhabi Island 4. AD Dubayyah 1. Jabel Al Dhannah	1. Musaffah south 2. Al Taweelah 3. Abu Dhabi Island 4. Jabel Al Dhannah 5. AD Dubayyah

Top PIA by Municipality	1. Abu Dhabi Municipality 89% 2. Al Dhafra Region Municipality 3%	1. Abu Dhabi Municipality 80% 2. Al Dhafra Region Municipality 14%	1. Abu Dhabi Municipality 71% 2. Al Dhafra Region Municipality 25%
Total Count of PI POIs	491 POIs	679 POIs	898 POIs
PI POIs Maximum Inundation Depth	14 meters	16 meters	17 meters

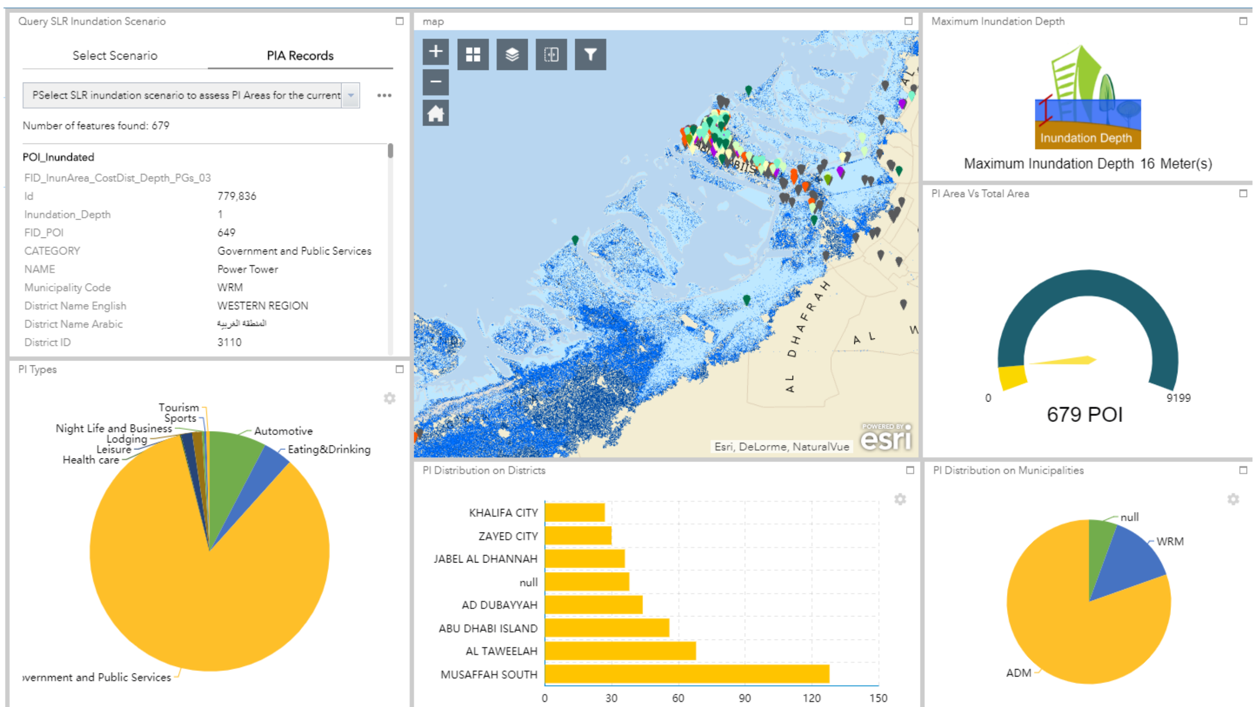

Figure 4-16: Points of Interests Vulnerability Dashboard showing – on map, charts and graphs- anticipated 2 meters SLR impact on Abu Dhabi Governorate points of interest. (Graphs showing distribution of PIA by POI; type, district, municipality; as well as count of potentially impacted POIs versus total POIs and maximum inundation depth for POIs. Map showing hydrologically connected PIAs with metric inundation depth value, where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth

D. *Transportation & Utilities*

– *Roads*

Table 4-13: Potentially Inundated Roads Areas Summary & Statistics

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
Most PIA by Type	1. Unclassified 2. Secondary 3. Tertiary 4. Residential 5. Motorway	1. Unclassified 2. Secondary 3. Tertiary 4. Motorway 5. Residential	1. Unclassified 2. Motorway 3. Secondary 4. Tertiary 5. Residential
Most PIA by Lane Count	1. 5 Lanes 2. 3 Lanes 3. 4 Lanes 4. 2 Lanes	1. 5 Lanes 2. 3 Lanes 3. 4 Lanes 4. 2 Lanes	1. 5 Lanes 2. 3 Lanes 3. 4 Lanes 4. 2 Lanes
Most PIA by One-way or Two-way	1. One-way 2. Two-way	1. One-way 2. Two-way	1. One-way 2. Two-way
Most PIA by District(s)	1. Khalifa City 2. Abu Dhabi Island 3. Al Sader 4. AD Dubayyah 5. Mussafah	1. Khalifa City 2. AD Dubayyah 3. Abu Dhabi Island 4. Al Sader 5. Al Ruwais	1. Khalifa City 2. AD Dubayyah 3. Al Ruwais 4. Abu Dhabi Island 5. Al Sader
Most PIA by Municipality	1. ADM 97% 2. ADRM 2.9%	1. ADM 96% 2. ADRM 3%	1. ADM 87% 2. ADRM 12%
Total area of PI Roads Length	1478 Km	2048 Km	2648 Km
PIA Maximum Inundation Depth	50 meters	51 meters	52 meters

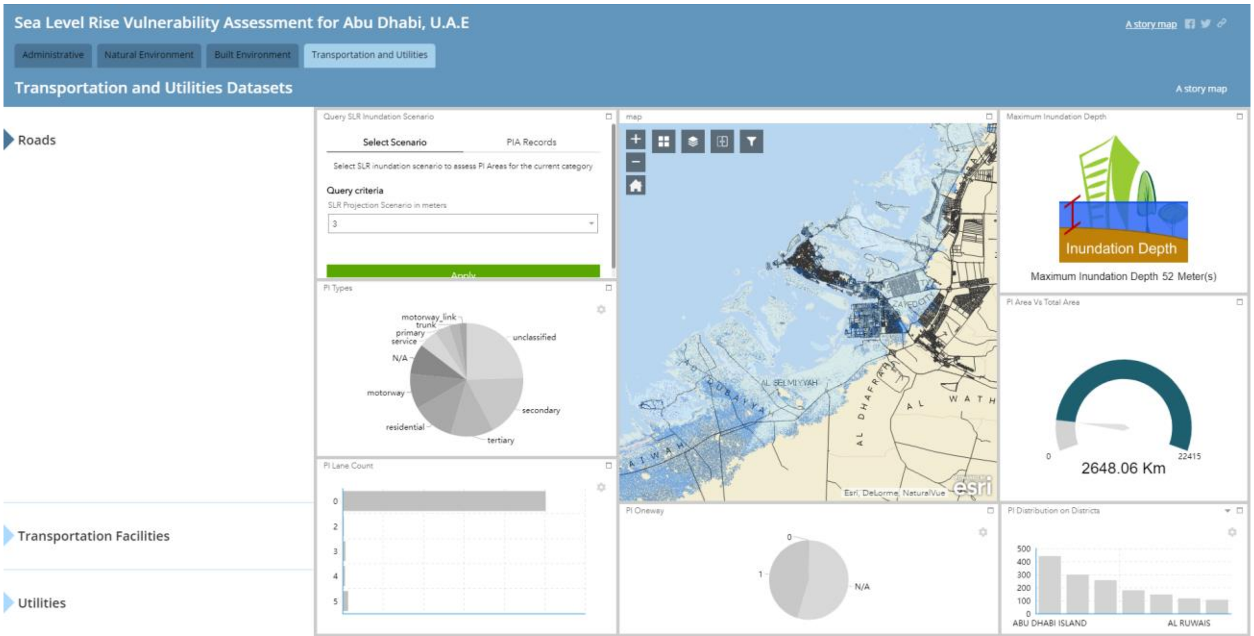

Figure 4-17: Roads Vulnerability Dashboard showing – on map, charts and graphs- anticipated 3 meters SLR impact on Abu Dhabi Governorate roads. (Graphs showing distribution of potentially inundated roads by; type, lane count, one-way, district; as well as length of potentially impacted roads versus total roads network length and maximum inundation depth for roads. Map showing hydrologically connected PIAs with metric inundation depth value, where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth

– ***Transportation Facilities***

Table 4-14: Potentially Inundated Transportation Facilities Areas Summary & Statistics

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
Most PI by Facilities Type	1. Harbor	1. Harbor 2. Railway 3. Airport	1. Harbor 2. Railway 3. Airport
Most PI by Facilities Construction Status	1. Constructed 56 % 2. Not constructed 3%	1. Constructed 16% 2. Not constructed 44%	1. Constructed 33% 2. Not constructed 28%
Most PI by Facilities Service Status	1. Available 58%	2. Available 43% 3. Not Available 16%	4. Available 33% 5. Not Available 26%

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
Most PI Facilities by District(s)	1. Al Taweelah 2. Nad Al Sheba 3. Abu Dhabi Island 4. Al Sader	1. Al Taweelah 2. Nad Al Sheba 3. Western Region 4. Abu Dhabi Island 5. Madinet Zayed	1. Nad Al Sheba 2. Al Taweelah 3. Western Region 4. Madinet Zayed 5. Abu Dhabi Island
Most PI Facilities by Municipality	1. ADM 63.5% 2. ADRM 36.46%	1. ADM 50% 2. ADRM 50%	1. ADRM 60.5 % 2. ADM 39.5%
Total area of PI Transportation Facilities	31 km^2	43 km^2	57 km^2
PIA Maximum Inundation Depth	50 meters	51 meters	52 meters

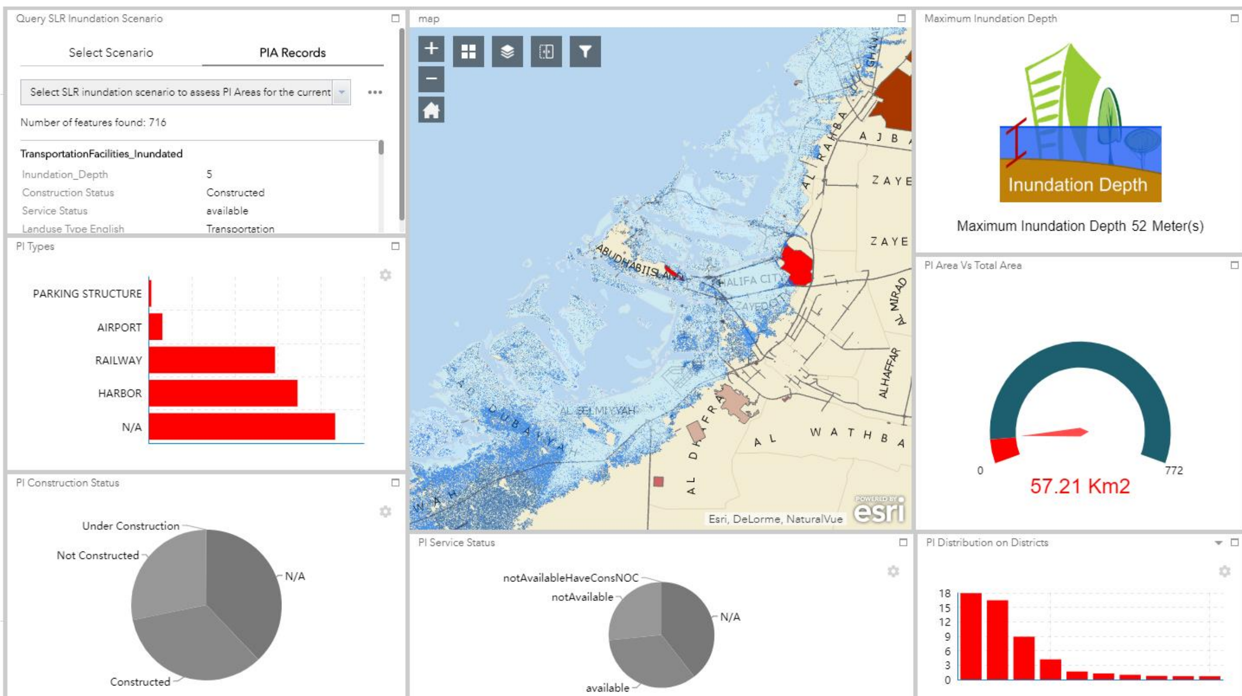

Figure 4-18: Transportation Facilities Vulnerability Dashboard showing – on map, charts and graphs-anticipated 3 meters SLR impact on Abu Dhabi Governorate transportation facilities. (Graphs showing distribution of potentially inundated transportation facilities by; type, construction status, service status, district; as well as size of potentially impacted transportation facilities versus total transportation facilities areas and maximum inundation depth for transportation facilities areas. Map showing hydrologically connected PIAs with metric inundation depth value, where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth

– ***Utilities***

Table 4-15: Potentially Inundated Utilities Areas Summary & Statistics

Statistical Indicator	Scenario 1 (1 meter SLR)	Scenario 2 (2 meters SLR)	Scenario 3 (3 meters SLR)
Most PIA by Type	1. Power Stations 2. Desalination Plants 3. Oil Refinery Plants	1. Power Stations 2. Desalination Plants 3. Oil Refinery Plants, Gas Plant Refinery, Petrol Stations	1. Power Stations 2. Desalination Plants 3. Oil Refinery Plants, Gas Plant Refinery 4. Petrol Stations, primary station
Most PIA by Construction Status	1. Not Constructed 77% 2. Constructed 15%	1. Not Constructed 69% 2. Constructed 18%	1. Not Constructed 61% 2. Constructed 19%
Most PIA by Service Status	1. Available 83 % 2. Not Available 8%	1. Available 76% 2. Not Available 11%	1. Available 67% 2. Not Available 13%
Most PIA by District(s)	1. Barakah 2. Al Taweelah 3. Jebel Al Dhannah 4. Mussafah South 5. Bayah Al Sila	1. Barakah 2. Al Taweelah 3. Western Region 4. Jebel Al Dhannah 5. Al Ruwais	1. Barakah 2. Western Region 3. Al Taweelah 4. Al Ruwais 5. Al Marfaa
Most PIA by Municipality	1. ADRM 80% 2. ADM 20%	1. ADRM 80% 2. ADM 20%	1. ADRM 82% 2. ADM 18%
Total area of PI areas	60 km^2	71 km^2	84 km^2
PIA Maximum Inundation Depth	27 meters	28 meters	meters

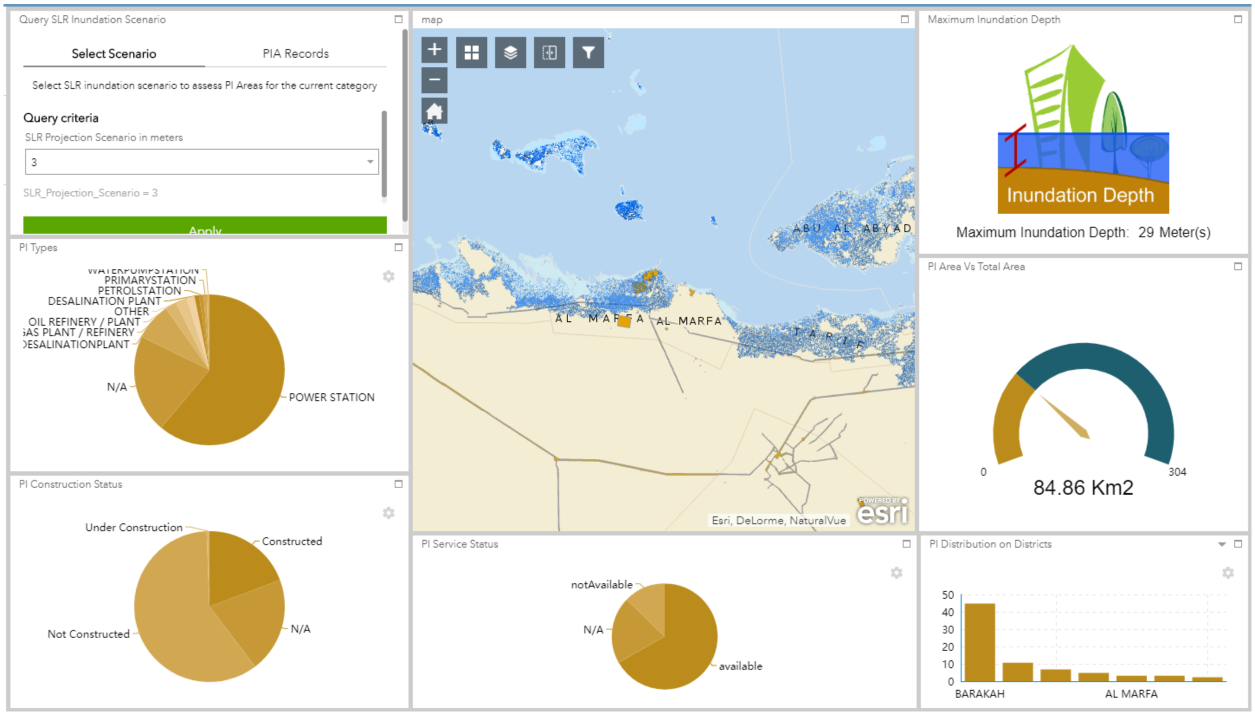

Figure 4-19: Utilities Vulnerability Dashboard showing – on map, charts and graphs- anticipated 3 meters SLR impact on Abu Dhabi Governorate utilities. (Graphs showing distribution of potentially inundated utilities by; type, construction status, service status, district; as well as size of potentially impacted utilities versus total utilities areas and maximum inundation depth for utilities areas. Map showing hydrologically connected PIAs with metric inundation depth value, where lightest blue areas are inundated with 0-1 meter and darker blue areas have greater inundation depth (3 meters scenario)

5 Discussion

5.1 Data Limitations

5.1.1 Digital Elevation Model DEM resolution and impact on analysis results

The vertical accuracy of SRTM - 1arc second (30 m) version 3 – dataset used within this study is of 16-meter absolute vertical error and 10-meter relative vertical error (Cushing, 2013), despite some accuracy assessments accomplished by the USGS, National Imagery and Mapping Agency (NIMA), and the SRTM project team had shown that the absolute vertical error is much smaller, with the most reliable estimates of approximately 5-meter absolute vertical error (Santillana et al., 2016).

While the vertical accuracy is the major factor for specifying the quality of elevation data as it represents the closeness of data value to real value, it will be affecting the output accuracy. Moreover, it has put a limitation on the inundation scenarios where modelling fractional sea level rise scenarios – less than 1 meter- is not possible with the SRTM dataset. On the other hand, its 30-meter horizontal accuracy poses generalization on site-specific features like roads and small sized land-use plots.

Despite the fact that flood models generated from SRTM data may underestimate the inundation extent (Yunus et al, 2016), the SRTM - 1arc second (30 m) version 3 DEM is the best free dataset currently available for Abu Dhabi, so more accurate results may be generated using the same methodology if a higher resolution DEM – for example LIDAR data- would become available. On the other hand, the latest study conducted by EAD (EAD, 2010) used the SRTM 60 meter data product, so this research may give more precise results if we consider the effect of improved DEM resolution.

5.1.2 Built-up Environment, Transportation and Utilities Data

The built-up environment datasets were collected from Abu Dhabi Department of Municipal Affairs (DMA). However, the data production within the department was still under development during the project data acquisition phase so, the data acquired does not include the complete representation of built up environment although it is more comprehensive in Abu Dhabi municipality than Al Ain municipality and Al Dhafra Region Municipality.

For that reason, the vulnerability results related to: Land-use dataset, Industrial dataset, POI dataset, Utilities and Transportation datasets – does not completely reflect the current case and may be more optimistic than reality.

5.1.3 Ground Water Data

The ground water data could not be acquired from governmental authorities; consequently this research could not assess the impact of sea level rise on local ground water.

5.2 Potentially Inundated Areas Extraction Methods

5.2.1 Bathtub Inundation Model

The reliability of sea level rise vulnerability studies is dependent on topographic data accuracy and the modelling approach. The bathtub inundation model is a popular sea level rise mapping methodology. A typical bathtub model utilizes only DEM to consider any area, with any elevation value that is less than the projected flood value being a potentially inundated area. For example, if studying a sea level rise scenario of meter rise, then all areas with a DEM value less than 1 are assumed to be flooded areas. The main disadvantage of this model is that it would include in the results low lying areas that are not connected to the water surfaces, in other words, some low-lying areas may be isolated from the flood by high rise areas (isolated sinks), so in such cases those low-lying areas are not subject to flooding. The flow of floodwater among cells is conditioned by the cell elevation value to be within flood height and its connectivity to the flood source without obstacles. So, if we add the hydrological connectivity evaluation to the bathtub model, it will enhance the results' accuracy by excluding isolated sinks from the results.

5.2.2 Hydrological Connectivity using Region Group and Zonal Statistics Versus Cost Distance

To examine the potentially inundated areas hydrological connectivity to flood surface, two technical methods were adapted to validate and compare the results. The methods were applied on the output of the simple bathtub model results, which had extracted low-lying areas with DEM value =< sea level rise scenario into a new raster dataset.

Table 5-1: Hydrological Connectivity using Region Group and Zonal Statistics Versus Cost Distance.

	Method 1	**Method 2**
Tools	- Generalization method >Region Group - Zonal method > Zonal Statistics - Extraction Method > Extract by attribute	- Raster Distance analysis method > Cost Distance
Input(s)	- Bathtub results (low lying areas within flood height) - Flood Source or Land raster dataset with an assigned value of 1for gulf water and creeks boundaries and value of 0 to Land	- Bathtub results (low lying areas within flood height) - Flood Source raster dataset with an assigned value of 1for gulf water and creeks boundaries

Objective	- Identify low lying connected regions that overlay with flood source.	- Identify low-lying cells connected to flood source.
Description	- "Region Group" grouped connected cells in the bathtub inundation boundary layer into regions and omitted disconnected cells using 8 cells neighborhood. - "Zonal statistics" functioned on Region Group output and Flood Source raster (valued 1) to retrieve the maximum value each region overlaps with, i.e. regions that overlaps with the gulf water pixels will be returned with value 1, while those which overlaps with land will return with value 0. - "Extract by Attribute" extracted the regions that overlap with the Gulf water layer (with value =1) resulting from the Zonal statistics leaving those regions that did not intersect with flood surface.	- "Cost Distance" extracted cells from bathtub inundation boundary layer that are connected to the flood source layer.
Results	The total area of potentially inundated areas for 1 m SLR using this methodology was: 28,322.08 km^2	The total area of potentially inundated areas for 1 m SLR using this methodology was: 28,322.08 km^2

By comparing the results of the 2 methods for 1-meter sea level rise scenario, the Cost Distance approach returned a slightly bigger area with only 0.01 km^2 (precisely 13,000 m^2) more than the Region Group *approach (*Figure 5-1*).* The fact that it returned bigger areas, besides its being a single step method, caused it to be selected to run for the rest of the sea level rise scenarios.

In the NOAA study "Detailed Methodology for Mapping Sea Level Rise Inundation" (NOAA, 2012), the potentially inundated area was extracted by identifying the biggest region(s) from region group analysis output (included in method #1). Then this one region was considered as the PIA without overlaying the flood surface. While the University of Florida study entitled "Development of a Geographic Information System (GIS) Tool for the Preliminary Assessment of the Effects of Predicted Sea Level and Tidal Change on Transportation Infrastructure" (Thomas and Watkins, 2013) introduced a further step of checking all regions' connectivity using the next zonal statistics step, where all regions that overlap with water pixels be returned with value of 1, while those which overlap with land will return with value of 0. A third study "The development of a salt marsh migration tool and its application in long island sound" (Hoover et al., 2010) developed by The Nature Conservancy introduced the cost distance analysis to evaluate connected areas to the sea water and extract potentially inundated areas accordingly. With respect to experimenting with those approaches in this project, the region group analysis combined with zonal statistics returned more cells that are overlapping with the sea cells (which means they are connected to sea water).

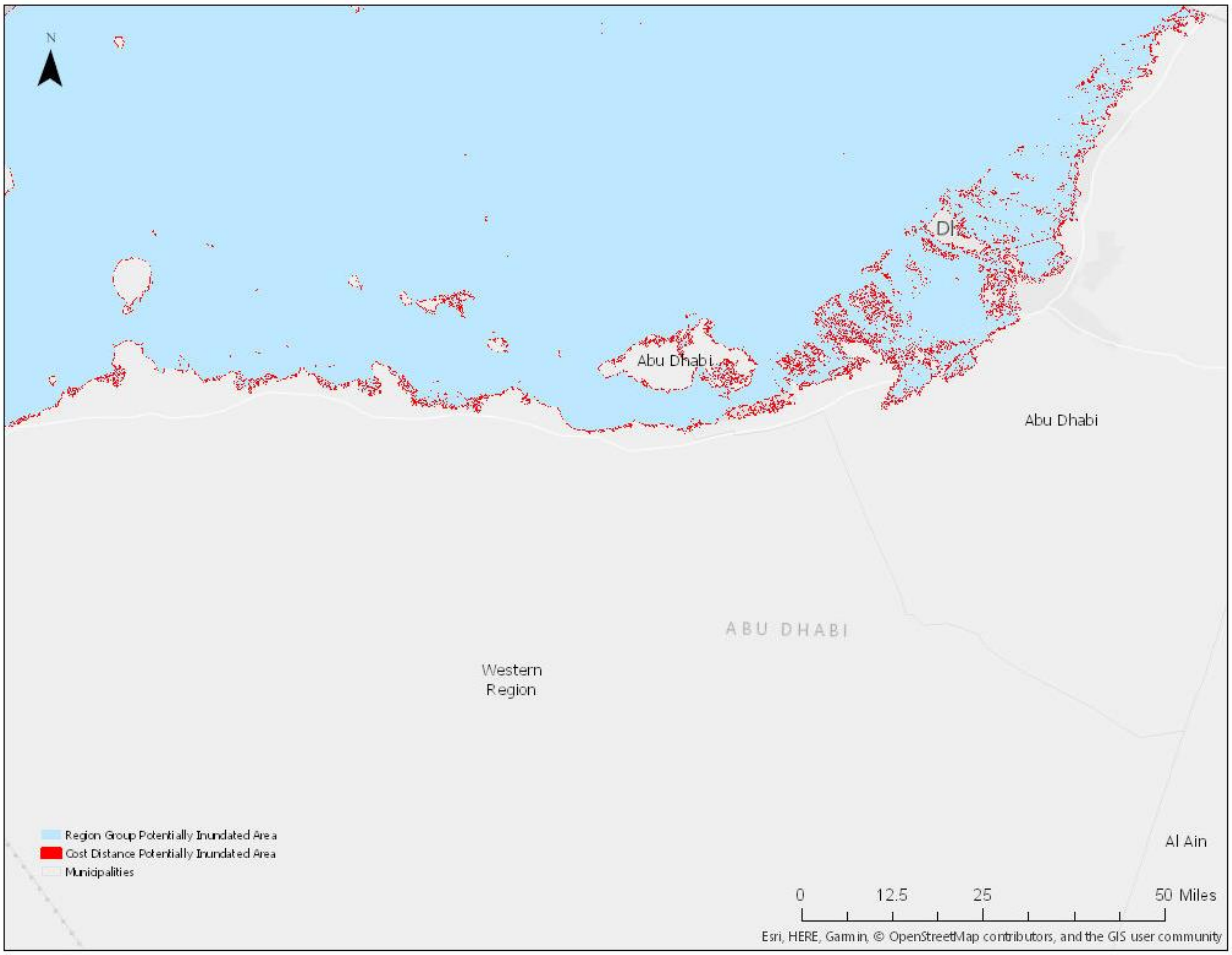

Figure 5-1: Difference between both approaches, where the Cost Distance Approach returned a slightly bigger area with only 0.01 km2 (precisely 13,000 m2) more than the Region Group approach highlighted as red cells

5.3 Identifying Top Vulnerable Classes

Upon extracting the hydrologically connected potentially inundated areas and overlaying with natural and built-up environmental layers, the summary of impact for each environmental or administrative category could be easily extracted identifying the answers of research questions related to sea level rise impact. The below part aims to summarize the most vulnerable classes which were recognized according to size of potentially exposed area to SLR within each class.

5.3.1 Administrative

- ***Governorate***

The anticipated total governorate area subject to inundation ranges from 2.61% (1,568 km2) of total governorate area with a 1 meter SLR scenario, 3.7% (2,223 km2) of total governorate area for 2 meters SLR scenario till represents 5.07% (3,045 km2) of total governorate area for the 3 meters SLR scenario. However – with reference to above Urban concentration section- the built-up environment and population density are mostly on the coastal areas where the PIA mainly lies.

- ***Municipalities***

The research had identified only 2 municipalities would be impacted- Abu Dhabi Municipality and Al Dhafrah Region municipality (earlier Western Region municipality) while Al Ain municipality will not be impacted as it does not have access to coastline and high elevation so its land was not included in the PIA boundary.

A 1 meter SLR scenario was found to potentially inundate 1,215 km2 from Abu Dhabi Municipality (presenting 77.5% of total PIA) and 353 km2 in Al Dhafra Region Municipality (presenting 22.5% of total PIA), the 2 meters SLR scenario was found to potentially inundate 1,588 km2 from Abu Dhabi Municipality (presenting 71.4% of total PIA) and 635 km2 in Al Dhafra Region Municipality (presenting 28.6% of total PIA). While 3 meters SLR scenario could inundate 1,951 km2 from Abu Dhabi Municipality (presenting 54% of total PIA) and 1,094 km2 in Al Dhafra Region Municipality (presenting 22.5% of total PIA),

- ***Districts***

Districts found subject to inundation were mainly concentrated in Abu Dhabi Municipality. The top 5 districts exposed to inundation- according to their PIA size- in the 1 meter SLR scenario were AD Dubayyah, Musaffah south, Al Ruwais, Al Selmiyyah, and Garaiwah. while for the 2 meters SLR scenario: AD Dubayyah, Al Ruwais, Abu Al Abyad Island and Garaiwah and for the 3 meters SLR scenarios Western Region district is the top impacted then Abu Al Abyad Island, Garaiwah, AD Dubayyah and Al Ruwais.

- ***Population***

With respect to population, the total impacted population for 1 meter SLR was found to represent 16% of total governorate population (298,306 Capita in Abu Dhabi Municipality and 8,280 Capita Al Dhafrah Region Municipality), and for 2 meters SLR, 23 % of total Abu Dhabi governorate population will be impacted (417,679 Capita in Abu Dhabi Municipality and 14,931 Capita in Western Region Municipality), while in 3 meters SLR the percentage goes up to 30 % of total governorate population (527,480 Capita in Abu Dhabi Municipality and 22,680 Capita in Western Region Municipality).

The geographical distribution for the potentially impacted population distinguished the districts subject to inundated was ranked by potentially impacted population which differs from the above district section that evaluates according to size of district area found with PIA boundary. For instance the top district with most population impacted for the 3 SLR scenarios is Abu Dhabi Island which is the T-shaped main island in Abu Dhabi with the highest population occupancy.

5.3.2 Natural Environment

- ***Land Cover, marine habitat and terrestrial habitat***

The top 5 land cover classes identified for all 3 SLR scenarios where sand dunes, vacant, coastal sabkhas, mangroves then mixed urban. The maximum inundation depth for land cover classes varied from 13 meters in 1 meter SLR scenario, 14 meters in 2 meters SLR scenario, till 15 meters in 3 meters SLR scenario.

While the marine habitat classes subject to SLR impact are deep subtidal seabed, unconsolidated bottom, sea grass bed, hard bottom and coral reefs. They will be submerged with more water varying from 33 meters for 1 meter SLR, 34 meters for 2 meters SLR, and 35 meters for 3 meters SLR.

Across the 3 studied sea level rise scenarios, the terrestrial habitat classes subject to inundation included: intertidal habitats, coastal plains, sand sheets and low dune, urban, industrial and commercial habitat types, coastal sabkha including sabkha matti, oasis/farmland/forestry, and sand sheets / dunes. The inundation depth will vary from 12-13 meters across the 3 sea level rise scenarios.

- ***Protected Areas***

The top 5 vulnerable protected areas are classified as marine protected areas and lies in Al Dhafrah Region municipality. Namely they are: Al Ruwais, Bayah Al Sila, Al Silmiyah, Sadiyat Island and Ghanadhah. They could be submerged with 22 meters, 23 meters till 24 meters across the 3 SLR scenarios while their PIA range from 6,215 km2 to 6,382 km2.

- ***Coast-line***

Abu Dhabi governorate is a low lying land, DEM value for the governorate area ranges from - 61 meters to 1147 meters. A total length of 3,905 Km representing 82 % till 4,097 Km representing 92 % of total coastline of coastline will be subject to inundation for 1 meter and 3 meters successively with maximum inundation depth ranging from 33 meters to 35 meters.

5.3.3 Built Environment

The research identifies the top impacted 5 land-use classes across the 3 sea level rise scenarios as: Vacant land, Private owned land, Governmental, Residential and industrial. The identified land plots tenancy contract status were mostly lacking tenancy contract while ownership types ranged from permanently owned land plots, temporary owned, allocated to federal government, or allocated to local Government.

The potentially inundated industrial areas size ranged to 107 km2 for 1 meter SLR scenario (82% in Abu Dhabi Municipality and 18% in Al Dhafrah Region Municipality), 134 km2 for 2 meters SLR scenario (79% in Abu Dhabi Municipality, 21% in Al Dhafrah Region Municipality) to152 km2 for 3 meters SLR scenario (77% in Abu Dhabi Municipality, 23% in Al Dhafrah Region Municipality). The top industrial classes identified across the 3 SLR scenarios were factory, industrial land, general industry and temporary industrial land.

The summary of potentially inundated points of interest showed that a total POIs of 491 POIs for 1 meter SLR scenario, 679 POIs for 2 meters SLR scenario to 898 POIs for 3 meters SLR scenario. The top categories of POIs identified across the 3 SLR scenarios were government and public services, automotive, eating/drinking, and leisure/lodging.

5.3.4 Transportation & Utilities

The potentially inundated total length of roads network was anticipated to be 1478 Km for 1 meter SLR scenario, 2048 Km for 2 meters SLR scenario and 2648 Km for 3 meters SLR scenario. The potentially inundated roads are either one-way or two-ways, with lanes ranging from two to five lanes distributed among Abu Dhabi Municipality and Al Dhafrah Region Municipality.
While the transportation facilities impacted would be mostly harbors, railway then airports with a total area starting from 31 km2 for 1 meter SLR scenario, 43 km2 for 2 meters SLR scenario and 57 km2.
Finally the utilities subject to inundation includes power stations, desalination plants, oil refinery Plants, gas plant refinery, and petrol Stations. Having such urban features subject to inundation could cause greater negative impacts on the environment and economy.

5.4 Publishing Results

5.4.1 Publishing Abu Dhabi Sea Level Rise Vulnerability Dashboard

The Global Mean Sea level (GMSL) has been rising at an accelerated rate due to the two factors induced by global climate change; (1) thermal expansion of oceans water, and (2) melting glaciers, ice caps and ice sheets. International organizations have led global initiatives to engage governments in the fight against global climate change. On the other hand, many countries have founded dedicated local councils or authorities that aim to conduct studies and lead scientific research in fields related to global climate change. The study of climate change in terms of impact assessment, risk mitigation and adaption had become an imperative for all developed countries.

In compliance with the above, blending Government Information Sharing trend and the current technology trends led to a conclusion that the results of Abu Dhabi sea level rise vulnerability assessment, shall be shared across governments to enable the establishment of a one-government response to SLR risk. In other words, the need of publishing and sharing the results emerges from the fact that Abu Dhabi sea level rise vulnerability assessment is a Disaster Risk Reduction (DRR) exercise. To fulfill its goal, it shall be shared with all concerned governmental authorities. Those authorities should take protective actions to save its resources with the highlights of vulnerable assets found in the vulnerability assessment results. Taking protective actions prior to the disaster would help prevent or decrease the impact of sea level rise thus mitigating the disaster risk.

The best practice for Abu Dhabi sea level rise vulnerability assessment, would be that the main concerned authority (mostly the Environment Agency of Abu Dhabi or of Ministry of Climate Change and Environment, UAE) conducts the disaster risk reduction exercise then share its results with other governmental authorities - like Urban Planning Council, Abu Dhabi

Municipalities, Department of Transport - enabling them to develop mitigation plans. Conducting mitigation plans would reduce disaster impact on natural and built environments. Also, this transparent approach may help authorities initiate new laws or regulations to mitigate sea level rise possible impacts. For example, in sea level rise case, building rules may prohibit building in certain areas, or mandate building on high piles, etc.

6 Conclusions

The study area was Abu Dhabi Emirate/Governorate wide, so it had included the 3 municipalities of Abu Dhabi Governorate; Abu Dhabi Municipality, Al Dhafra Region Municipality and Al Ain Municipality. The output of the project included (1) A geoprocessing model: Potentially Inundated Areas (PIAs) Extraction Model, (2) A web-based application on ArcGIS online platform: Abu Dhabi Sea Level Rise Vulnerability Dashboard, and (3) Data layers: Natural/Built up environment Vulnerability Results and Statistics. The outputs can be utilized independently or combined to assess the vulnerability of a certain area or city to sea level rise.

The PIAs Extraction Model was designed to consider hydrological connectivity of PIAs to seawater and thus enhance the accuracy of regular bathtub inundation model. The sea level rise scenario was one of the model parameters, and in this research three scenarios were assessed (1 meter, 2 meters and 3 meters). However, the low-resolution elevation data used produced coarse results with low accuracy. This comes with a future recommendation to apply the same methodology on higher resolution DEM – for example LIDAR data- to improve the assessment accuracy. On the other hand the small size low resolution imagery was in the benefit of processing huge governorate wide area using a personal computer.

The vulnerability assessment was conducted on multiple datasets that included: Administrative dataset, Built-up environment dataset, Natural Environment dataset, Population dataset, Utility and Transportation datasets. The outputs of the analysis were multiple layers containing potentially inundated geometries extracted from the examined features, which had complex geometries and huge disk size. To carry on the statistics and charting part, the outputs were (1) exported to standalone tables to speed up querying for statistical use on the web app dashboard, (2) published as map tile services to view on the web app dashboard upon user selection. If the study area was not huge, then it might have been possible to query feature services for statistics rather than exporting the data to standalone tables.

The aims of the web-based application dashboard were (1) to give stakeholders a quick insight on the most vulnerable classes/areas to potential sea level rise for each sub domain, and (2) to fulfill the Government Information Sharing trend by providing a shared online view on the vulnerability assessment results to all concerned governmental authorities through networked government infrastructure. The ArcGIS online platform is a cloud-based mapping platform that can be accessible by different subscribing organizations. It made the implementation quite easy and feasible for most GIS professionals, as it does not require programming or web development skills, yet it is easy, customizable and configurable.

Moreover, engaging different authorities in the vulnerability assessment exercise can help in getting higher quality and more updated data into the exercise. And thus, the results would be more accurate and help in providing a credible view on the potential impacts of sea level rise and, visualize critical vulnerabilities. Eventually this project represents an example of sea level rise disaster preparedness practices that aims to reduce the risk impacts by increasing the resilience of potentially impacted elements prior to the disaster occurrence.

Further work on the dashboard can provide more flexibility for participating authorities by:

(1) Upon the availability of higher resolution DEM dataset, the project analysis methodology can be re-applied using different and fractional sea level rise scenarios to increase results credibility and accuracy.

(2) Adding a simplified version of the Inundation Areas Extraction Model to the web-based application dashboard as a geo-processing service, where participating authorities can run it using updated data on smaller areas with different sea level rise scenarios to assess its vulnerability to potential sea level rise.

(3) Participating authorities can have the privilege of editing the web-based application dashboard views to customize it based on their subject matter key elements and designated priorities. This will produce an application view with high relevance and usability for each domain.

(4) Upon the availability of ground water dataset, further analysis may be conducted to deduce possible salt-water intrusion.

(5) The practice introduced by this project research is a disaster preparedness one, a next step can be on developing a disaster response practice which purpose can be on summarizing disaster impact, conducting detailed damage assessment, planning evacuation routes based on the updated network status, etc.

(6) Adaption planning applications may also be developed with a goal of developing and manipulating our natural and built environment to increase its resilience to the risk of sea level rise. The solutions may include actions like developing natural buffer area, building sea walls or barriers between sea front buildings. The Adaption planning applications should evaluate the Protective solutions before introducing to our social-ecological systems then plan their distribution upon proving their effectiveness.

(7) In the phase of preparedness, providing an insight to the public, private sectors and development parties about a potential risk may help increase the society resilience to a disaster. So, it may be feasible to give them an access to certain views on the vulnerability dashboard.

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8 Appendices

Appendix A – Datasets Details

I. Elevation Data

- *Digital Elevation Model Dataset (Ellipsoidal Model vertical datum)*

A digital elevation model (DEM) is a basic data requirement to derive sea level rise inundation surfaces. The inundation analysis results are highly dependent on the DEM accuracy as well as modelling approach. On the other hand, while most DEM vertical resolutions range from 1.5 to 10 to 100 meters, these resolutions cannot accurately simulate < 1 m sea level rise scenarios.

The National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission (SRTM) developed global elevation data at 30-meter (1 arc second) resolution which is considered to be the best publicly available DEM data in many locations.

Within this research, the NASA Version 3 SRTM Global 1 arc second dataset is used for the inundation analysis. The Version 3.0 was issued with the objective of eliminating gaps and voids in SRTM DEM that were present in previous versions. (LP DAAC, 2015)

Dataset details:

- **Source data:** SRTM V1.0 Digital Elevation Model Data; ASTER GDEM2 (Global Digital Elevation Model Version 2); National Elevation Dataset (NED); USGS GMTED2010
- **Dataset Resolution:** 30 meters
- **Vertical error:** absolute 16m; relative 10m
- **Horizontal error (CE90):** absolute 20m; relative 15m

II. Satellite image

Global satellite imagery data is available online through several sources. One of the best free online sources is Landsat 8 OLI-TIRS, where the spatial resolution is 30 meters in most bands, while the panchromatic band is provided at15 meters resolution.

In this research case, ArcGIS online service will be used instead for visualization purposes, since the resolution starts from 15 meters then goes as high as 15cm with a sub-meter resolution in the Middle East area.

Dataset details:

- **Service name:** World_Imagery (MapServer)
- **Update date:** November 2016
- **Description:** World Imagery provides one meter or better satellite and aerial imagery in many parts of the world and lower resolution satellite imagery worldwide. The map includes

15m TerraColor imagery at small and medium scales (591M down to 72k) and 2.5m SPOT Imagery (288k to 72k) for the world, and USGS 15m Landsat imagery for Antarctica. The map features 0.3m resolution imagery in the continental United States and 0.6m resolution imagery in parts of Western Europe from Digital Globe. Recent 1m USDA NAIP imagery is available in select states of the US. In other parts of the world, 1 meter resolution imagery is available from GeoEye IKONOS, AeroGRID, and IGN Spain. (Metadata source: EAD , Service URL: http://services.arcgisonline.com/arcgis/rest/services/World_Imagery/MapServer)

III. Administrative Dataset

- *Country Borders (polygon):*

UAE country border was downloaded from GADM, which is a website developed by GADM (Global administrative areas. University of Berkeley, Museum of Vertebrate Zoology and the International Rice Research Institute), and the country borders around Abu Dhabi governorate were updated using data received from the Environment Agency – Abu Dhabi (EAD).

- *Abu Dhabi Governorate (polygon):*

Abu Dhabi governorate borders were extracted from the EAD dataset.

- *Abu Dhabi Governorate municipalities (polygon)*

Abu Dhabi Governorate includes 3 municipalities; Abu Dhabi Municipality, Al Ain municipality, and Al Dhafra Region Municipality. The municipalities' layer was derived from Abu Dhabi Department of Municipal Affairs (DMA) dataset.

- *Abu Dhabi Municipalities Districts*

Main districts layer was received from DMA, which represent main districts in the 3 municipalities.

IV. Built-up Environmental Dataset

- *Land-use*

Two different layers were collected from DMA and EAD. The DMA land-use layer is on the plot level and covers the main urban areas within the 3 municipalities. While EAD layer is a lower scale one representing land blocks and covering the whole governorate. The layers include information about land plots/ blocks indicating the use of each whether industrial, agricultural, transportation, utilities, residential, institutional or etc. However, EAD land use data is satellite derived mapping of Land Use categories, where the imagery used is the same as the one specified in the on page 77Eco System datasets section.

The 2 layers were merged to cover the data deficiency in DMA plots land-use.

- *Points of interests*

The point of Interests dataset (POIs) was downloaded from Mapcruzing.com (MapCruzing.com is an independent firm specializing in the publication of educational and research resources). The point layer contained +9000 POI features distributed in AD governorate. Categories of POIs ranged from leisure, tourism, governmental services, health care, sports, etc.

- ***Industrial***

Industrial Plots were extracted from DMA land-use plots layer and EAD land-use layer.

V. Transportation Network Dataset

- ***Roads***

Two datasets were available, the first one was downloaded from Mapcruzing.com with +17000 street feature for Abu Dhabi governorate. The second one was provided by EAD and includes +1000 road features.

EAD layer metadata states that the dataset depicts the location and basic classification for road centerlines covering the whole UAE. This information was compiled by German Technical Cooperation Agency (GTZ) as a general map reference to support the comprehensive water resource assessment project.

Both layers were merged after removing common streets from the EAD dataset.

- ***Transportation facilities***

Transportation facilities features were extracted from DMA land-use plots layer and EAD land-use layer.

VI. Environmental Dataset

- ***Sea shoreline layer, creeks & islands***

Abu Dhabi land morphology is composed of plenty of islands, generating a long shoreline with many creeks in-between.

The data with the highest morphological accuracy was the EAD dataset, thus the shoreline was extracted from EAD land-use dataset.

- ***Protected areas***

The Protected Areas (PA) layer was received from EAD. The layer covers the whole governorate area and contains feature for 19 protected areas.

Layer metadata states that the dataset represents national protected areas, national parks, biosphere reserves across the Emirate of Abu Dhabi. The boundaries of marine and terrestrial protected areas in Abu Dhabi are depicted in this layer. These areas are either established or proposed protected areas beginning from 1998. The protected area type is along with the status type and purpose of each PA. There are other protected areas in the emirate of Abu Dhabi managed by other authorities such as Private Departments, Emirates Heritage Club, etc. and these are not included in this layer.

- *Eco System datasets*

The eco system database was provided by EAD. It has been created by EAD as part of the Abu Dhabi Baseline Habitat Mapping project. It contains three datasets, Land cover, terrestrial habitats, and marine habitats.

The three datasets are Satellite derived habitat mapping of land cover categories, terrestrial areas and marine areas successively. Input satellite imagery used was Digital Globe WorldView-2, 8-band, 2 meters multi-spectral, 0.5 meter panchromatic. The imagery was acquired between 07/10/2011 and 20/05/2014. Automated and semi-automated image processing techniques were used, along with cartographic generalization principles and local ground truthing and ecological knowledge. (Metadata source: EAD)

- *Land cover layer*

The layer represents 27 land cover categories. The Land Cover classification was based on Land-Use Landcover Scheme for Abu Dhabi Emirate created by EAD in 2009. (Reference Metadata)

- *Terrestrial Habitat layer*

41 terrestrial habitats are mapped on this layer. The terrestrial habitat classification was based on the Major Terrestrial Natural and Semi-Natural Habitat Types of Abu Dhabi Emirate, Brown and Boer (2004). (Metadata source: EAD)

- *Marine Habitat layer*

The layer delineates 13 marine habitats. The marine habitat classification was based on the Coastal Marine Resources and Ecosystem Classification System (CMRECS) Manual (2009). (Reference Metadata

VII. Demographic Dataset

- *Population dataset*

Demographic data was provided by DMA. The data includes the total population of each district and the total number of males and females as well.

Appendix B – Analysis steps

I. Generate the Potentially Inundated Areas (PIAs)

- *Initial Inundated boundary layer*

- **Aim**: Produce an initial inundation layer representing inundated area boundary for each sea level rise projection scenario using the bathtub approach, where all cells in DEM less than or equal the SLR values will be extracted to a new raster grid.
- **Method applied**:

Tool used : Spatial Analyst > Raster Calculator

PIA_Initial1 = Con("Mstr_SRTM_DTED_PRJ40N" <= SLRpx,1)

Where SLRpx represent the metric value of sea level rise projection (3, 4, ..etc).

- **Output description:** within the ourput raster grid all cells less than or equal to SLRv value will be extracted from the DEM and assigned a value of 1.

- *Inundation depth layer*

- **Aim:** Produce an initial inundation layer representing inundation depth in meters for each sea level rise projection scenario using the bathtub approach, where all cells in DEM less than or equal the SLR values will be extracted to a new raster grid .
- **Method applied**:

Tool used : Spatial Analyst > Raster Calculator

- Map Algebra expression PIA_InitialDepth1 = Con("Mstr_SRTM_DTED_PRJ40N" <= SLRpx, SLRpx -"Mstr_SRTM_DTED_PRJ40N")

Where SLRpx represent the metric value of sea level rise projection (3, 4, ..etc).

- **Output description:** within the ourput raster grid all cells less than or equal to SLRv value will be extracted from the DEM and given a value that represent the depth of inundation as follows:
  - Inundation depth value = SLRv – DEM value
  - Where SLRv = SLRp scenarion (1m, 2m or 3m) + Tidal range value (2m)

II. Evaluate Inundation Areas Hydrological Connectivity to Gulf/Creeks water

- *First approach to Evaluate Inundation Areas Hydrological Connectivity to Gulf/Creeks water*

Group Connected cells into regions

- **Aim:** Group cells in the inundated boundary layer to connected regions.
- **Method applied**:

Tool used : Spatial Analyst >Generalization> Region Group

- The number of neighboring cells to use in evaluating connectivity between cells was defined to be "**8 neighborhoods"**. (includes to the right, left, above, or diagonal to each other.
- The Zone grouping method selected was "**Within"** which ensures that cells grouped to 1 region are connected (based on **8 neighborhoods**) and have the same value.

- **Output description:** The output raster grid will contain grouped cells that lies in the same connected region with the same value (in this case all inundated values has value of "1") and thus disconnected cells with height below sea level rise projection will be excluded from the analysis.

Create Sea and Land Raster Grid

- **Aim:** In order to evaluate regions connectivity to water surface, a layer representing sea and land shall be created to be used later in testing hydrological connectivity.
- **Method applied**:

- Create new polygon feature class called "Land0_ Water1"
- Load Data to the new layer from Abu Dhabi Municipalities and Water fetaure Layers.
- Add new field to indicate value 0 for land and 1 for Water (Arabian Gulf) in the new feature layer
- Calculate field values.
- Merge municipalities to one feature.

***Tool used**: Conversion Tools >To Raster> Polygon to Raster*

- **Output description:** "*Land0_ Water1*" raster layer represents UAE extent where the Arabian Gulf was given a value of 1 (representing water surface)) while all municipalities land including islands were assigned the value 0.

Identify hydrologically connected regions to Gulf water and isolated regions

- **Aim:** Region(s) that overlaps with the gulf water shall be extracted to represent the potentially inundated areas, while regions that are not connected to water surface, shall be excluded from the analysis.
- **Method applied**:

Tool used: Spatial Analyst >Zonal> Zonal Statistics

- Region Group output was defined as the Zone, where Value field is the Zone field , "Land0_ Water1" raster layer is the value raster layer and the Maximum is the Statistics Type selected.

Tool used: Spatial Analyst >Extraction> Extract by Attributes

- The input raster is the ourput of zonal statistics function, where the extraction will run to extract cells which value = 1. Thus the output from extract by Attribute will represent regions with height less than or equal SLRp and connected to the gulf water.

- **Output description:** Upon performing Zonal Statistics method on the connected regions as Zones, *"Land0_ Water1" layer as Value layer,* and Maximum as statistics type, the tool will assign the connected regions the maximum value found in *"Land0_ Water1" layer* cells intersecting with each region. In other words, if a region is overlapping with land (valued 0) and water (value 1), the output region will be assigned the water value (1) which means that this region intersects with water.

The next output generated from Extract by Attribute method will contain only the regions with value 1 (overlapping with water cells) and exclude other isolated regions that are not connected to Gulf water.

- ***Second approach to Evaluate Inundation Areas Hydrological Connectivity to Gulf/Creeks water***

Extracting hydrologically connected regions to Gulf water and isolated regions

- **Aim:** Extract from Inundation Boundary layer, cells that are hydrologically connected to the Gulf water and exclude disconnected cells.

- **Method applied**:

> *Tool used: Spatial Analyst >Extraction> Extract by Attributes*
>
> - The input raster is the *Land0_ Water1* layer, where the extraction will run to extract cells which value = 1. Thus the output will represent Gulf/Creeks water only.
>
> *Spatial Analyst >Distance Analysis> Cost Distance*
>
> - Source layer : Gulf/Creeks Water Layer
> - Cost Layer: Initial Inundation layer

- **Output description:** the first output is a layer containing only the Gulf water which was extracted layer from *Land0_ Water1* layer to be used in the Cost Distance tool.

Then using the Raster Distance analysis – Cost Distance method, where the Gulf water layer set as the source layer and the cost layer was the innundation boundary layer, generated an output representing the connected cells to the water with height less than or equal SLR value.

Then it was assigned as the souce layer to Cost Distance analysis tool while the cost layer was the initial innundated layer. The aim of this step was to evaluate initial innundated layer cells connectivity to Guld/Creeks water layer, where the output will contain only the connected cells to the source layer.

III. Update Hydrologically Connected Inundation Areas with Inundation Depth

- **Aim:** Add the inundation depth information to the hydrologically connected areas layers generated from the 2 approaches above (Evaluate Inundation Areas Hydrological Connectivity to Gulf/Creeks water
- First approach to Evaluate Inundation Areas Hydrological Connectivity to Gulf/Creeks water and Second approach to Evaluate Inundation Areas Hydrological Connectivity to Gulf/Creeks water).

- **Method applied**:

Tool used: *Spatial Analyst >Extraction>Extract by Mask*

- *The input raster is the inundation depth layer, while the mask layer is the output of the 2 approaches* (Evaluate Inundation Areas Hydrological Connectivity to Gulf/Creeks water
- First approach to Evaluate Inundation Areas Hydrological Connectivity to Gulf/Creeks water and Second approach to Evaluate Inundation Areas Hydrological Connectivity to Gulf/Creeks water*) which represents the inundated area boundary after updating with hydrological connectivity evaluation.*

- **Output description :** The inundation depth layer boundary (created in the first step Generate the Potentially Inundated Areas (PIAs)) will be updated with the two approaches outputs so that the final outputs will represent the hydrologically connected PIAs with inundation depth incorporated in the cell value.

IV. Convert Final Inundation Depth Raster Layer to Polygon Layer

- **Aim:** As a last step in modelling the PIAs, the final Inundation Depth raster Layer was converted to polygon feature class then dissolve all polygons with the same inundation depth into 1 polygon in order to speed up the map display and facilitate the overlaying processes in the next impacts assessments methods.
- **Method applied**:

Tool used: Conversion Tools >From Raster>Raster to Polygon

- The input raster is the hydrologically connected PIAs with Depth layer
- Simplify Polygon was not used to maintain areas shapes.

Tool used: Data Management Tools >Generalization>Dissolve

- The result of convert raster to polygon is used to generate 1 polygon for all hydrologically connected PIA.

- **Output description:** The result of convert raster to polygon contains split polygons representing connected areas of inundation associated with the inundated depth value.

While the Dissolve output will merge all feature with the same inundation depth value to 1 feature to decrease the count of feature in the inundation depth polygon feature class.

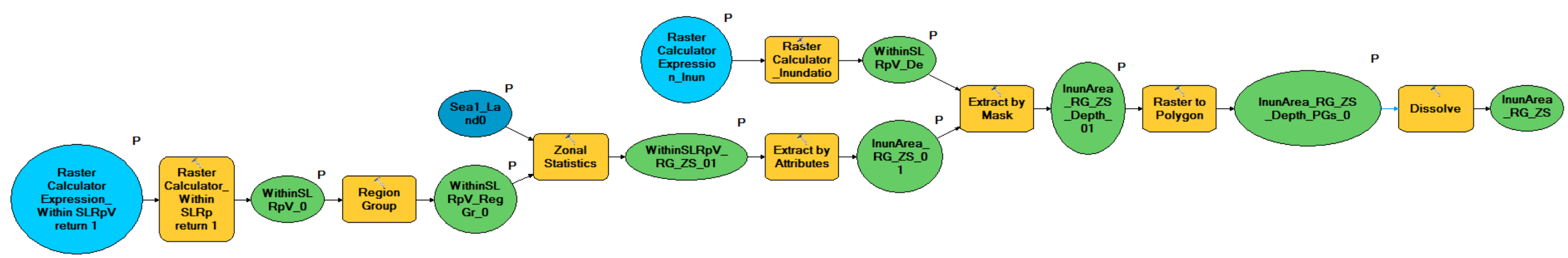

Figure 8-1: The First Approach Model used to generate Potentially Inundated Areas for different Sea Level Rise Projections- Design Mode

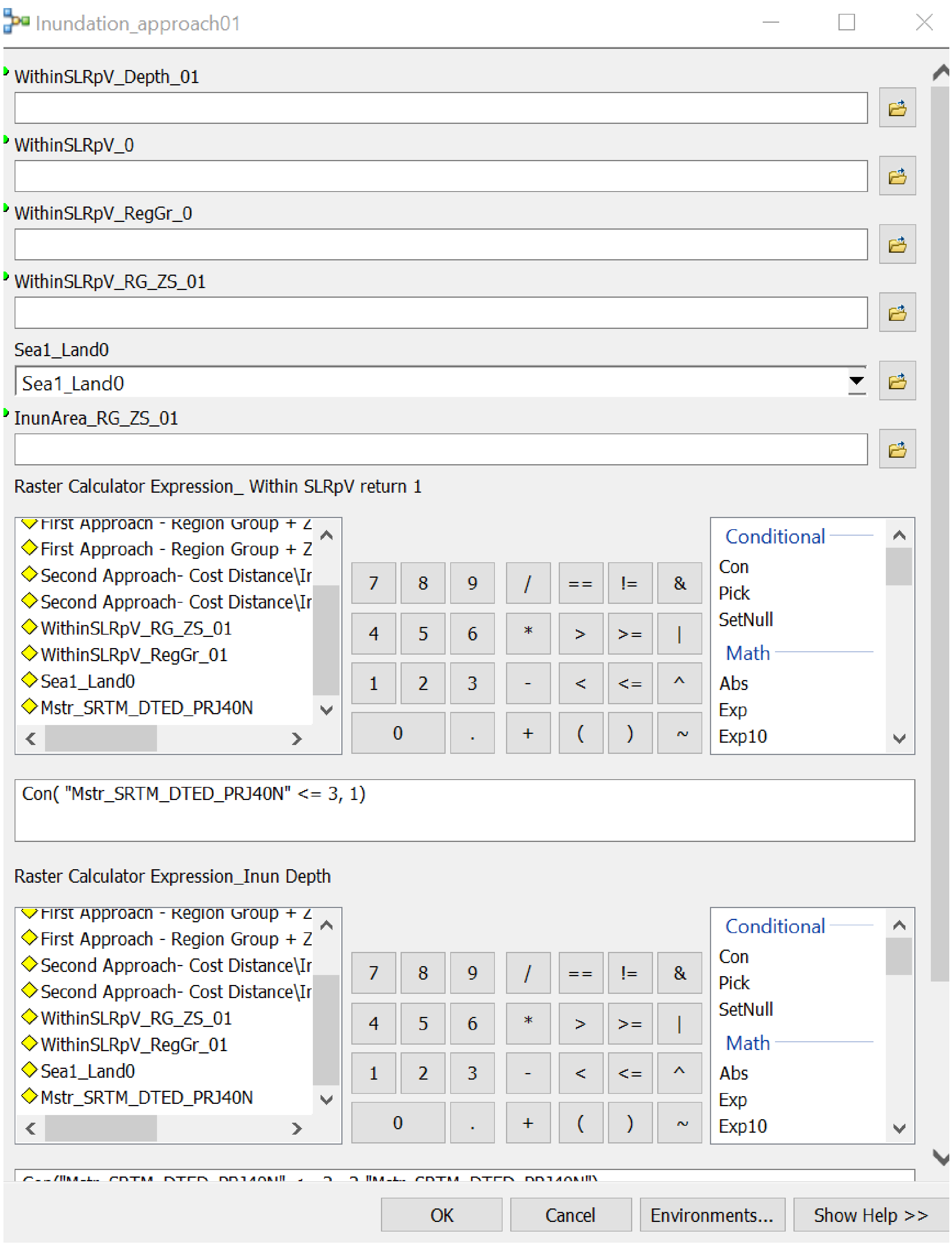

Figure 8-2: The Region Group (first approach) Model used to generate Potentially Inundated Areas for different Sea Level Rise Projections- Runtime Mode

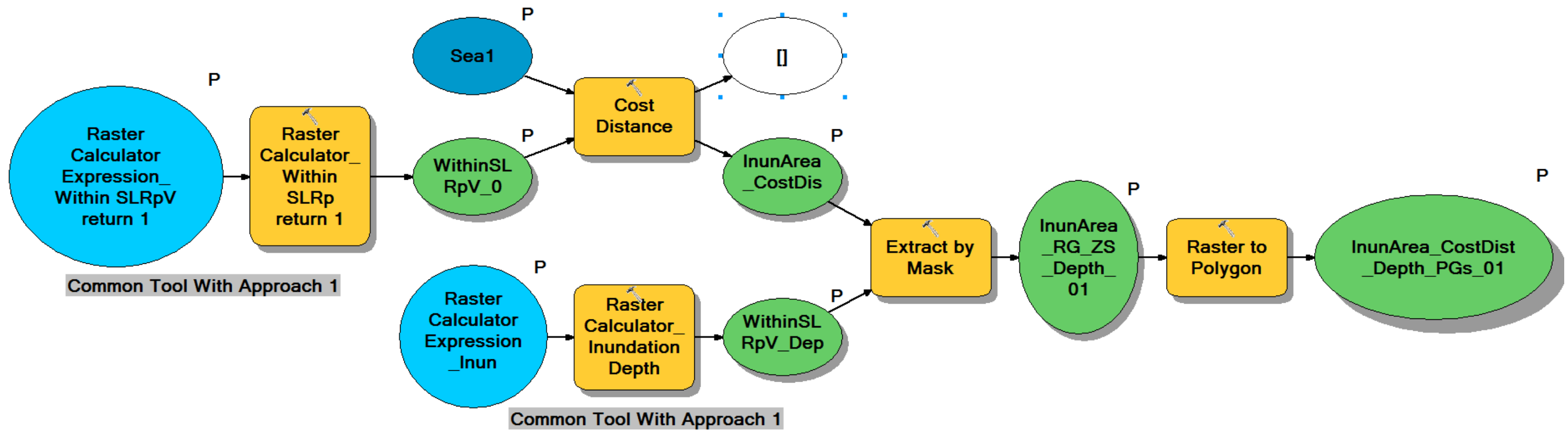

Figure 8-3: The Second Approach Model used to generate Potentially Inundated Areas for different Sea Level Rise Projections- Design Mode

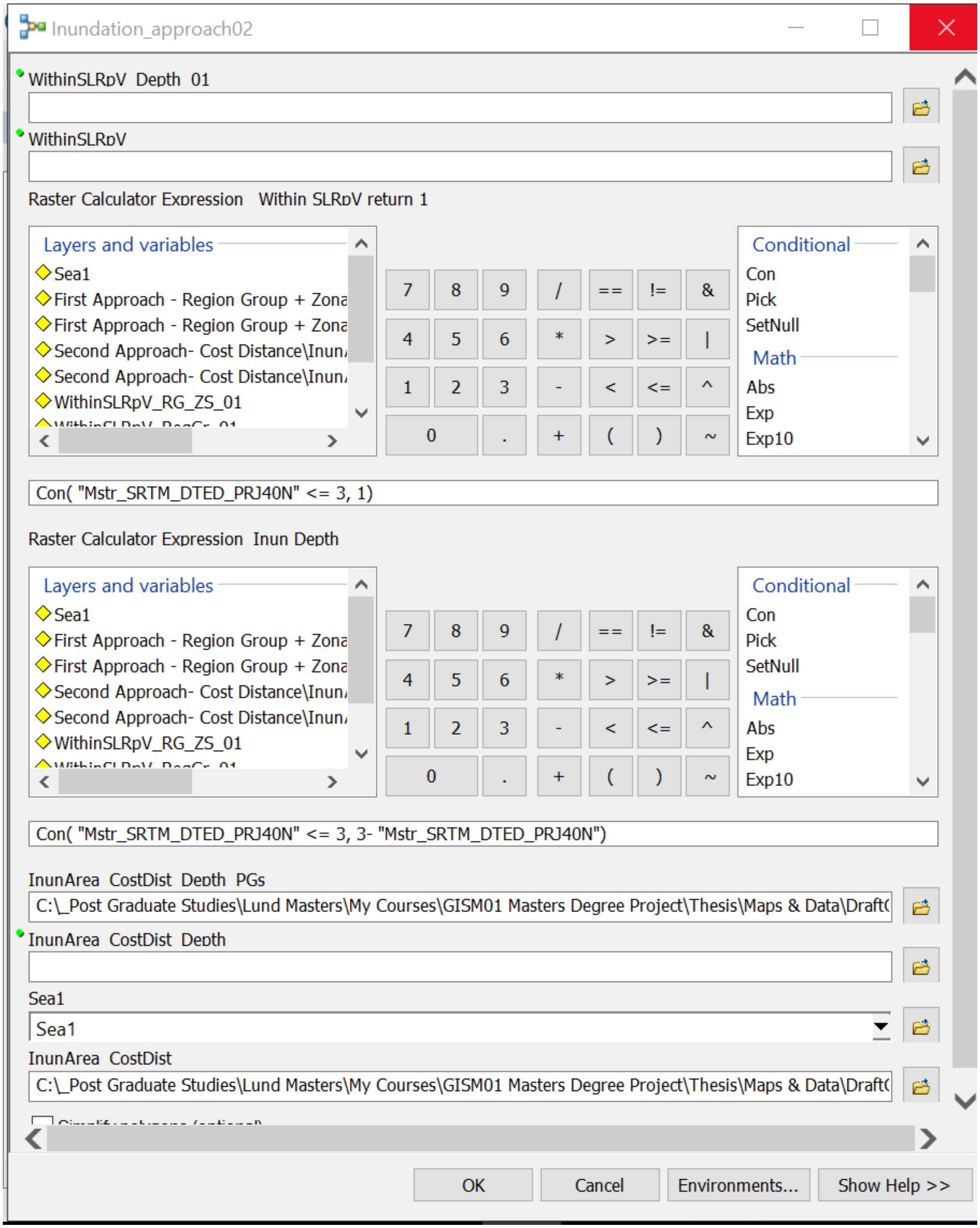

Figure 8-4: Cost Distance (second approach) Model used to generate Potentially Inundated Areas for different Sea Level Rise Projections- Runtime Mode

V. Assess Inundation Impact on Natural and Built Environment, and Population

- ***Overlay inundation layers with natural and built environments datasets.***

- **Aim:** Identify features from natural and built environment overlapping with the final inundation depth layer.
- **Method applied**:

Tool used: Analysis tools >Overlay >Intersect

- The input feature layers are the inundation polygons depth and the natural/built environment layers where features will snap according to the XY tolerance.
- For the join attribute, all the attributes was chosen be transferred to the output feature class.
- XY_tolerance was set to be 60 meters which is double the resolution(cell size) used.

Tool used: Data Management tools >Generalization >Dissolve

- The feature layer to be aggregated is the Intersect output
- The Dissolve_fields on which the features will be aggregated are the built/natural environment feature identifier and inundation depth value.
- Multi_part feature is allowed.

- **Output description:** The intersect output feature class will contain split features representing each built/natural environment feature after being overlaid with inundation depth polygon, where each feature represents the inundation depth it was exposed to (in other words one feature from natural/built environment may be split into multi features if it was intersection with different inundation depth values from inundation depth layer)

Then the dissolve methods will combine intersect layer features according to inundation depth as well as natural/built environment feature subtype(s).

- ***Summarize population subject to inundation***

- **Aim:** The districts layer contains statistics on the population, so the aim is to extract the rational number of impacted population according to the percentage of district area subject to inundation.

- **Method applied**:

> *Tool used: Analysis tools >Overlay > statistics>tabulate intersection*
>
> - Input Zone Features: Inundation Depth
> - Zone Fields: Inundation Depth
> - Input Class Features: Districts
> - Class Fields: District Name

- **Output description:** The tabulate intersection tool will calculate the areas from Districts Layer intersecting with inundation depth layer and cross tabulate the percentage of impacted population according to the ratio of intersection part of district to its whole area.

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