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Sea Level Rise Impacts on the City of Cape Coral, Southwest Florida from 2020 to 2050

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SEA LEVEL RISE IMPACTS ON THE CITY OF CAPE CORAL, SOUTHWEST FLORIDA FROM 2020 TO 2050

BY

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THESIS ACCEPTANCE PAGE

Jawata Afnan Saba

This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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I dedicate this thesis to my mother.

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ABBREVIATIONS

CoVI	Coastal Vulnerability Indices
FDOT	Florida Department of Transport
IPCC	Intergovernmental Panel for Climate Change
SFWMD	South Florida Water Management District
NOAA	National Oceanic and Atmospheric Administration
SoVI	Social Vulnerability Indices
PCA	Principal Component Analysis
USACE	United States Army Corps of Engineers
FEMA	Federal Emergency Management Agency
DEM	Digital Elevation Model
NTDE	National Tidal Datum Epoch
MEOW	Maximum Envelop of High Water
MoM	Maximum of MEOW

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ABSTRACT

SEA LEVEL RISE IMPACTS ON THE CITY OF CAPE CORAL, SOUTHWEST FLORIDA FROM 2020 TO 2050

JAWATA AFNAN SABA

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Sea level rise, a consequence of global climate change, has been affecting the U.S. coasts with flooding and exacerbated storm surges. Florida is highly vulnerable because it has low-lying topography and coastlines on both the Atlantic Ocean and the Gulf of Mexico. The City of Cape Coral, Southwest Florida, is known as a 'waterfront wonderland' with 400 miles of canals that provide waterfront property to the residents. Most of the canals are navigable, and many have access to the Gulf of Mexico. The city is vulnerable to sea level rise because of its canals, site between the Matlacha Pass and the Caloosahatchee River, and much development in hazardous areas. In this research, I estimated the inundated area with Sea Level Rise Calculator tool, for three postulated sea level rise scenarios, by the U.S. Army Corps of Engineers (USACE), on the City of Cape Coral from 2020 to 2050 and created a Coastal Vulnerability Index (CoVI) using Principal Component Analysis (PCA). PCA reduced 25 variables to six factors that explained 78% of the variance in the data. The study revealed that the whole city has a medium to high vulnerability to sea level rise induced coastal flooding. Projected flooding showed the vulnerable areas for future flooding, whereas CoVI identified the vulnerable populations and their locations in the city. One important finding is that the wealthy people in Cape Coral are more vulnerable than the poor people. My research has significant implications in disaster preparedness, response, and recovery. It can act as a

guideline for the city for disaster management and can be updated with the most recent data.

Keywords: Sea Level Rise, City of Cape Coral, Principal Component Analysis, Coastal Vulnerability Index, Sea Level Rise Calculator tool

CHAPTER 1: INTRODUCTION

1.1.Introduction

Globally 800 million people living in the coastal areas are at risk from rising seas and associated problems (Parker 2015). Sea level is projected to continue rising because of global climate change, and the rate of rise has been faster than predicted. Since 1950, global sea level is projected to rise by up to 2 m by the end of the century (Oppenheimer et al. 2019). In the 2000s, the global assets exposed to coastal hazards were worth US$ 3 trillion. While Asia has the highest population living in the coastal flood plain, which accounts for 65% of the total exposed population to sea level rise globally, North America has the largest economic value of properties and infrastructure exposed to sea-level rise (Hanson et al. 2010). Globally, by 2100, the population exposure could increase threefold whereas, the assets' exposure could increase ten times with the projected rate of sea level rise (Hanson et al. 2010).

The ocean has been warming because of global warming since 1970 (Pierre-Lious 2018), and this warming is disturbing the ice-water ratio on the Earth's surface. Half of the global warming has been stored in the ocean since the 20th century (Goodell 2017). If people slow greenhouse gas emissions today, the ocean will keep warming for years (Dasgupta et al. 2009). Continental ice sheets melting from the polar regions because of global warming are adding more water to oceans. Ice sheets melting in both Greenland (Aschwanden et al. 2019) and Antarctica is accelerating.

Global warming will have serious impacts on oceans and their coasts by increasing the frequency and intensity of coastal hazards. Warmer ocean temperatures and higher sea levels are expected to intensify the impacts of hurricanes and storm surges (*Hurricanes and Climate Change* 2021). Many of these impacts will be in coastal areas around the world that have been becoming increasingly vulnerable to sea level rise and associated hazards such as higher storm surges and tidal floods, saltwater intrusion, and so on. In 2020 the costs of climate disasters in the U.S. increased to $95 billion from $91 billion in 2018, causing 22 separate billion dollars events, among them 13 were severe storms and seven were hurricanes. The year 2020 broke the previous annual record of 16 climate extreme events, which occurred in 2011 and 2017 (NOAA 2020; Smith 2021). Coastal communities around the world are particularly vulnerable to hazards that are associated with oceans such as hurricanes, floods, tsunamis, and sea-level rise. Within coastal communities, though marginalized populations are at risk (Cutter, Boruff, and Shirley 2003), wealthy and privileged populations are not immune to the hazards. Coastal communities also have been becoming more vulnerable to coastal hazards because of the decisions people make to develop coasts (Gaul 2019). The risk of coastal communities to hazards lead to a greater focus in both research and policy on coastal vulnerabilities and resilience.

1.2.Geography themes

Among the four traditions of geography, my research falls under the man-land tradition because it investigates the impacts of sea level rise on coastal people (Pattison 1963). Broadly, my research focuses on the human transformation of the Earth and the global climate. Global climate change includes global warming driven by human emissions of greenhouse gases and the resulting changes in both local and regional climate. Starting in the 20th century, the increased anthropogenic activities led to global warming and resulted in an accelerated ice sheet melting and a rapid rise in global sea level (Shum, Kuo, and Guo 2008).

My research focuses upon human impacts of sea level rise by measuring and mapping the physical footprint of sea level rise and analyzing the vulnerability of community residents. My research uses theories and methods of inundation to understand the future inundation in Cape Coral from sea level rise. I used the bathtub model and hydroconnectivity (hydrological connectivity) model to estimate the inundated areas in Cape Coral (Poulter and Halpin 2008).

In this study, I used the theories and methods of vulnerability to understand and analyze the vulnerability of the coastal people to sea level rise. Vulnerability is the inability of people to respond to, cope with, and recover from a natural disaster (Cutter and Finch 2008). There are different types of vulnerability such as: biophysical vulnerability, place vulnerability, and social vulnerability (Cutter, Boruff, and Shirley 2003). A vulnerability index identifies the vulnerable population (Cutter and Finch 2008). For an example, in this study, I created a Coastal Vulnerability Index (CoVI) that identifies a sensitive population in a coastal area and the factors that underlie the vulnerabilities.

1.3. Focusing on the problem

Anthropogenic activities have been transforming the Earth. Perhaps the most important consequence of this transformation has been global climate change. Sea level rise is recognized as a consequence of anthropogenic climate change (Shum, Kuo, and Guo 2008). Sea level rise will have substantial social and economic impacts on the Earth as many people live within 100 km of the coast (Shum, Kuo, and Guo 2008).

Sea level rise is spatially uneven, temporarily unstable, and highly unpredictable (Ezer 2013). Scientists identified the mid-Atlantic region along the East Coast of the United States as one of the hot spots for accelerated sea level rise (Ezer 2013), yet the cities situated in the Atlantic Coast have different rate of sea level rise (figure 1). For example, considering the historical data from 1880 to 2000, the lowest SLR rate was found at Wilmington, North Carolina (2.01 mm/yr), and the highest SLR rate was at Norfolk, Virginia (4.66 mm/yr) (Ezer 2013). The Intergovernmental Panel for Climate Change (IPCC) projected that New York City might experience a 2.5m (8 ft) sea level rise from 1950 to 2100 (Oppenheimer et al. 2019). The United States Army Core of Engineers (USACE) high scenario projection showed that sea-level rise near Cape Coral and Fort Myers, Florida might be 5 ft from 2000 to 2100 , (*Sea-Level Change Curve Calculator (Version 2019.21)* 2019).

Florida is highly susceptible to sea level rise for several reasons (Noss 2011; Oppenheimer et al. 2019). First, Florida has a low average elevation and plain topography. Ten percent of Florida's land area is less than 1 m above the mean sea level (Noss 2011). Second, the state experiences both Atlantic Ocean and the Gulf of Mexico hurricanes. Third, many cities in Florida have canal networks and canal-based subdivision designed to drain the wetlands. Fourth, the population growth rate has been very high in Florida compared to the national average. Florida had a population of over

21 million and a population growth rate of 17%, which was higher than the national growth rate (10%) during 2000-2010 (Decennial Census of Population and Housing 2010; Noss 2011). People may become vulnerable to hazards when they move to vulnerable areas such as flood plains and low-lying coastal areas. Finally, the development system of Florida is complex and highly manipulated, but it lacks a sound planning and management tool to guide state responses to complex environmental changes such as sea level rise (Noss 2011).

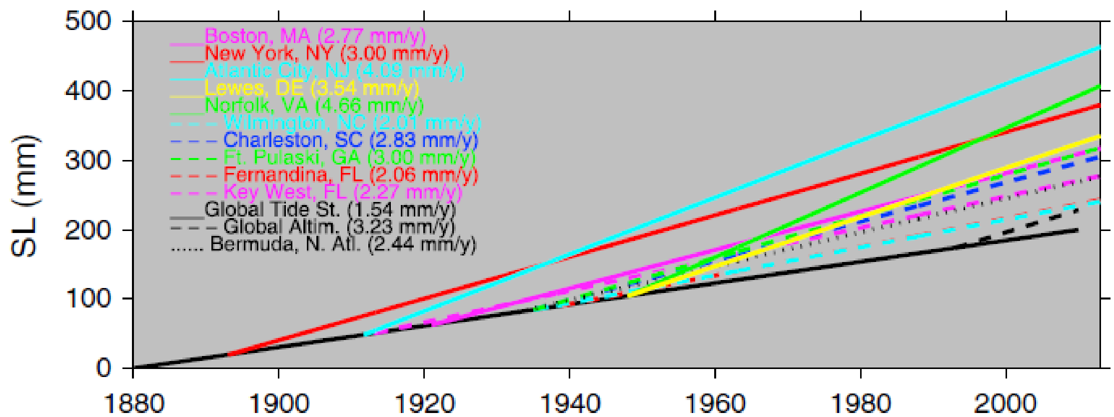

Figure 1: Sea level rise measurement in different areas in the Atlantic Coast of the U.S., source (Ezer 2013).

The City of Cape Coral, Florida has a peninsular location, surrounded by the Caloosahatchee River and the Gulf of Mexico (figure 2) and has a plain topography and low elevation (Beever III, Walker, and Kammerer 2017a). It is called the ‘waterfront wonderland’ because it has 400 miles of canals that provide residents with waterfront properties. Fifty-eight percent of the canals are saltwater and have access to the Gulf of Mexico (Beever III, Walker, and Kammerer 2017a). Cape Coral has more than 16 waterfront communities with thousands of waterfront houses. Many of them are in gated communities and are only minutes away from the Gulf of Mexico by boats (such as Cape

Harbor, Gulf Access). There are also several gated condominiums, for example, Paradise Point and Parkside at Rivers that have waterfront access (*Greater Fort Myers Real Estate* 2021).

A slight increase in sea level can severely impact Cape Coral because of its plain topography, low elevation, and complex infrastructure. The canal network was built to improve drainage by removing wetlands (Beever III, Walker, and Kammerer 2017a), provide overland flood protection (requires low water level), and reduce saltwater intrusion (requires high water level), which are conflicting goals (Noss 2011). Canals provided a waterfront real estate business, which is one of the primary economic activities of the city. Canal construction and canal-based subdivisions not only removed or degraded the city's natural landscape but stimulated rapid population growth and commercial growth. Coupled with natural and man-made features the lucrative real estate business and recreational facilities have made the city vulnerable to sea level rise and associated disasters such as storm surges, high tidal surges, and coastal flooding, which leads to the problem of my research: more than 180,000 residents of the city are vulnerable to sea level rise.

1.4. Thesis statement and objectives

I will investigate the impacts of sea level rise on people and property in the City of Cape Coral, Southwest Florida, from 2020 to 2050, because I want to examine people's vulnerability based on postulated sea level rise. I also want to determine the impact of a given sea level rise on the city's artificial canals.

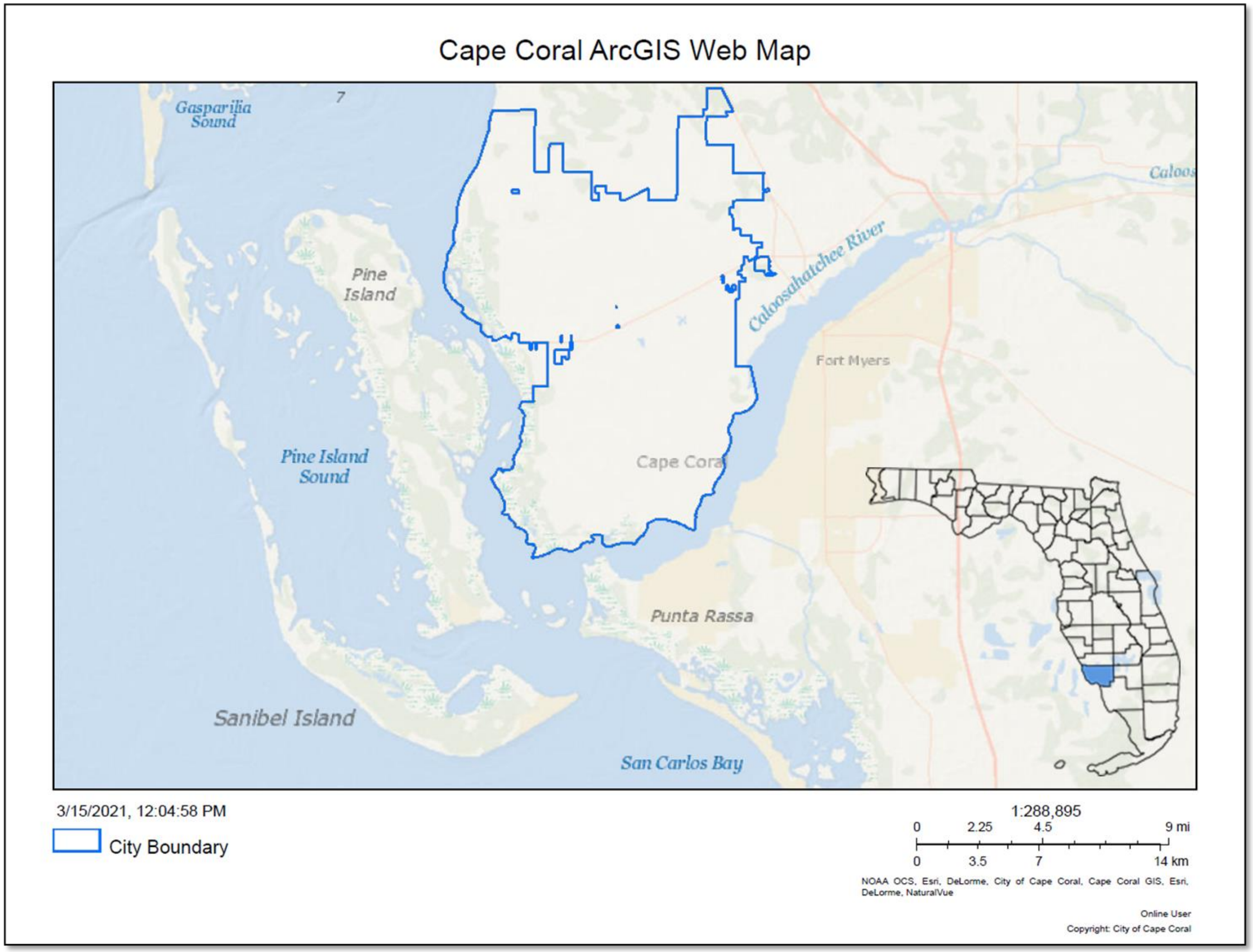

Figure 2: Cape Coral location.

1.4.1. Research objectives

The primary objectives of my research are as follows:

1. Estimate the flooded areas in Cape Coral for three projected sea level rise scenarios (low, medium, and high), by the United States Army Corps of Engineers (USACE), from 2020 to 2050 and

2. Build a Coastal Vulnerability Index (CoVI) for the City of Cape Coral.

1.4.2. Research questions

My research asks several research questions. They are as follows:

1. How much area will become inundated because of sea level rise, in the City of Cape Coral?

2. What factor(s) make the people of Cape Coral vulnerable or resilient to sea level rise?

3. What factor(s) contribute most to the vulnerability index?

4. Which area(s) of the city will be more vulnerable?

5. Who will be more vulnerable?

1.4.3. Hypothesis

The hypothesis of my research is that the wealthy residents of Cape Coral are more vulnerable to sea level rise than others.

1.5. Conclusion

Sea level rise will increase the risk of damage from hurricanes, storm surges, tidal surges, and excessive rainfalls because higher sea levels permit storm surges to travel farther from the coastline in low lying areas (Goodell 2017). The United States is highly susceptible to sea level rise because the U.S. has shorelines on the Atlantic Ocean, the

Pacific Ocean, and the Gulf of Mexico. Coastal areas comprise 17% of the United States' land area, 53% of the nation's population (Noss 2011), and account for 46% of the nation's GDP (Socioeconomic Data Summary 2017). The East Coast of the United States, which has many cities, is considered as a hot spot of sea level rise (Ezer 2013). Florida's long coastline, low elevation from mean sea level, plain topography, and rapid development in floodplain areas make the area highly vulnerable to sea level rise (Beever III, Walker, and Kammerer 2017a). The cities in coastal Florida need to be resilient to sea level rise since sea level rise cannot be prevented (Goodell 2017).

My thesis's outputs will be inundation maps of Cape Coral from projected low, medium, and high sea level rise from 2020 to 2050 and a Coastal vulnerability index that identifies vulnerable people and their location on the maps. In the following chapters of my thesis, I will discuss the causes of sea level rise, its impact on coastal Florida, vulnerability and resilience literature, the study area (Cape Coral), methods, results and interpretations, limitations, conclusions, and implications of my research, respectively.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

The scientific evidence for sea level rise is overwhelming (Dasgupta et al. 2009; Cazenave and Llovel 2010; Cazenave, Lombard, and Llovel 2008; Williams 2013). Sea level rise is a complex phenomenon that is difficult to determine because it interacts with all components of climate system, such as oceans, ice sheets, glaciers, atmosphere, and fresh water reservoirs (Cazenave and Llovel 2010). Immediate adaptation strategies are necessary because they are easier than future expensive retrofits (Dasgupta et al. 2009).

2.2. Causes of sea level rise

The causes for sea level rise include ice sheets melting in Greenland and Antarctica, glaciers melting, thermal expansion, and land subsidence (figure 3). This section will take a closer look at each of the causes and explain how they contribute to sea level rise. Thermal expansion and mass loss in glaciers and ice sheets are considered the primary causes of sea level rise. Thermal expansion in response to ocean warming contributes 30-50% to sea level rise, whereas mass loss in mountain glaciers and ice sheets contributes 55% of the increase (Cazenave and Llovel 2010; Cazenave, Lombard, and Llovel 2008).

2.2.1. Ice sheets melting in Greenland and Antarctica

Global warming raises sea level rise through ice sheet melting and thermal expansion (Rahmstorf 2010). Ice sheet melting in Greenland is one of the important causes of sea level rise (figure 4 (a)). Greenland could raise sea level by 7 m if melted completely (Cazenave and Llovel 2010; Alley et al. 2005; Dowdeswell 2006). At present, Greenland is the single largest contributor to sea level rise in terms of meltwater runoff from icesheets (Alley et al. 2005) . Greenland could contribute 5 to 33 cm to sea level rise by 2100 (Aschwanden et al. 2019).

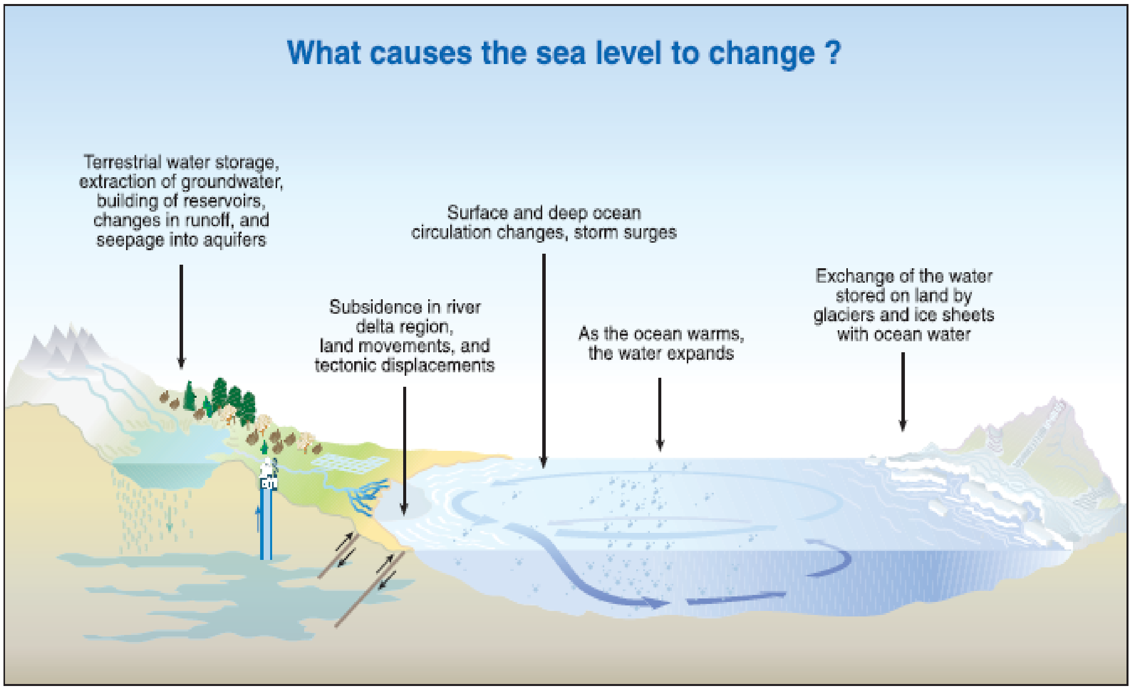

Figure 3: Processes that contribute to sea level rise, source: (Williams 2013; Rekacewicz and Digout 2005).

Antarctica is also on track to rise sea level substantially (figure 4 (b)) by the end of the 21st century. West Antarctica can contribute to 3-5 m to sea level rise, if melted completely (Alley et al. 2005; Cazenave and Llovel 2010)

Ice sheet melting in both Greenland and Antarctica is accelerating. While Antarctica will contribute the most in sea level rise over the long term, Greenland is contributing more today. Between the years 2000 and 2100, scientists project that global sea level may rise of 0.5~.8 to –1.2~1.5 m under high emission scenario (Kopp et al. 2014; Kopp et al. 2017).

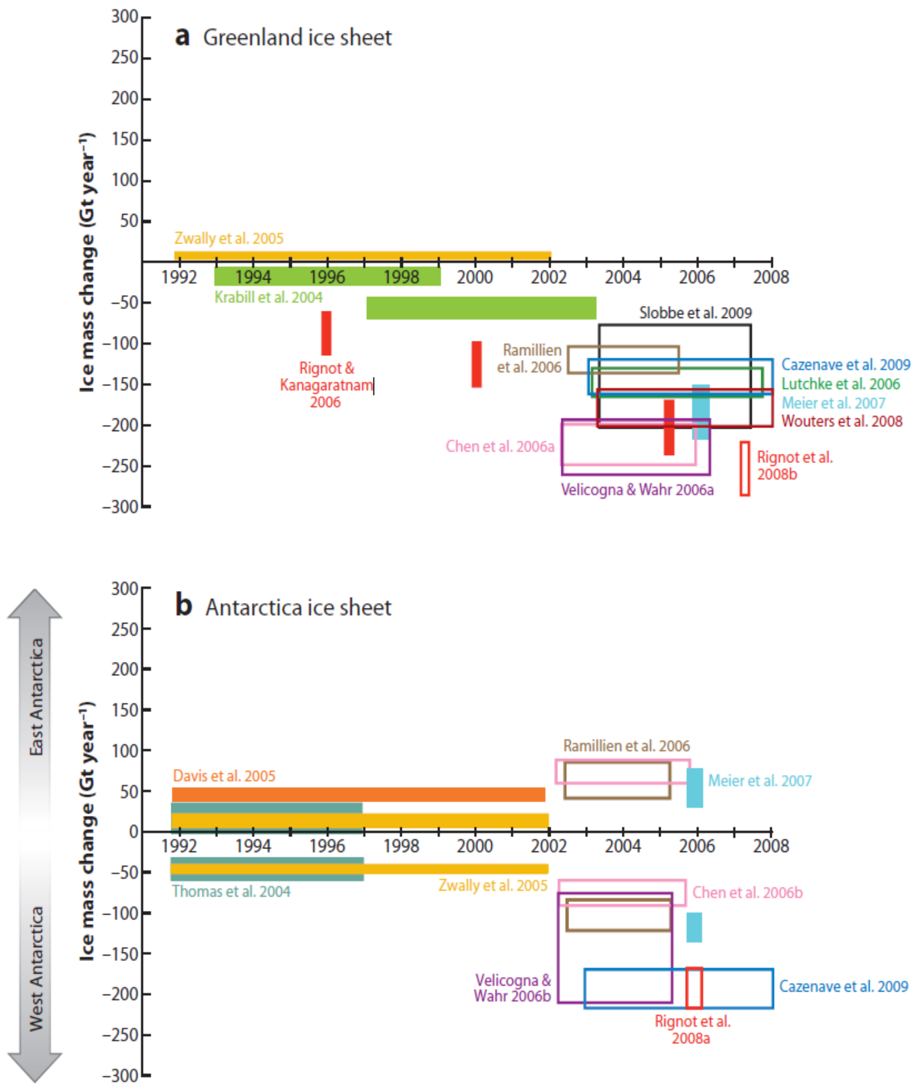

Figure 4: (a) Compilation of Greenland ice sheet mass loss based on remote-sensing observations between 1992 and 2008. (b) Same as (a) but for the Antarctica ice sheet, source: (Cazenave and Llovel 2010).

2.2.2. Glaciers melting

Glaciers have been retreating with an accelerated rate since the 1990s (Cazenave and Llovel 2010). Glaciers are very sensitive to global warming. Glaciers could add 35 cm to sea level if melted completely. Glacial contribution to sea level rise was 0.77 ± 0.22 mm/year throughout 1993–2003 (Cazenave and Llovel 2010)

2.2.3. Thermal expansion

If people stabilize greenhouse gas emissions in the near future thermal expansion and polar ice sheets retreating will continue to contribute to sea level rise for many years (Dasgupta et al. 2009; Meehl et al. 2005). Global temperature rise in oceans is certain (Dasgupta et al. 2010). Sea level is projected to raise because of thermal expansion by 23 cm by the 2090s (Rahmstorf 2010). Sea level rise from thermal expansion refers to the expansion of the volume of water when it is heated. The extra energy makes the water molecules move around causing them to take up more space. The ocean soaked up more than 90% of the extra heat generated by humans since 1950, and the rate of heating by anthropogenic activities has accelerated over the past decades (Pierre-Lious 2018). Even if the greenhouse gas concentration had been stabilized by 2000, the oceans would continue to warm and increase sea level by thermal expansion by the end of the 21st century (Meehl et al. 2005). If people could stabilize greenhouse gas concentration at some level, the thermal inertia of the climate system would contribute to an oceanic temperature increase that results in further sea level rise (Meehl et al. 2005). Geographic pattern of global warming shows that more warming occurs at high northern latitudes and land areas. (Meehl et al. 2005). For instance, The Parallel Climate Model (PCM) and Community Climate System Model version 3 (CCSM3) projected that North America would likely warm by one half degree after stabilizing the greenhouse gas concentration in the atmosphere (Meehl et al. 2005).

2.2.4. Subsidence

Land subsidence plays a vital role in changing the sea level in some areas (Al Mukaimi, Dellapenna, and Williams 2018). Groundwater and fossil fuel mining cause land subsidence in some coastal cities (Cazenave and Llovel 2010). For example, Tokyo subsided by 5 m, Shangai by 3 m, and Bangkok by 2 m during the 20th century (Cazenave and Llovel 2010). Fossil fuel mining in many locations in the Gulf of Mexico causes subsidence around the Gulf coast at a rate of 5-10 mm/year (Cazenave and Llovel 2010). Some areas experience the combined effect of land subsidence and sea level rise which lead to a higher rate of relative sea level rise.

2.3. Impacts of sea level rise (global)

The primary impacts of sea level rise include inundation and recurrent flooding in association with storm surges, wetland loss, shoreline erosion, saltwater intrusion in surface water bodies and aquifers, and rising water tables (Cazenave and Llovel 2010; Parkinson, Hronszky, and Nelson 2009). As long term impacts, sea level rise may reshape the coasts by greatly increasing the expected number of ‘1-in-10’ and ‘1-in-100’ year events (Kopp et al. 2014). Higher sea levels will cause higher coastal floods (Strauss et al. 2014). South and Southeast Asia’s heavily populated coasts, particularly those in Bangladesh, China, and Vietnam, could be inundated (Dasgupta et al. 2009; Parker 2015).

The intensity and frequency of coastal disasters have increased because of ocean temperature rise (Dasgupta et al. 2010). For example, three devastating cyclones, Sidr in Bangladesh 2007), Nargis in Myanmar (2008), Ayla in India, and Bangladesh (2009), caused huge landfalls in South Asia in three consecutive years. The storm surge created by these cyclones killed people and damaged livelihoods in South Asia. For example, the government of Bangladesh reported that 3,000 people died, and 7 million people lost their livelihoods in Sidr (Summary of Cyclone Situation 2007). During Cyclone Nargis, 100,000 people died, and 1.5 million people lost their livelihoods (Dasgupta et al. 2010).

Cyclone Amphan in 2020 had a storm surge of more than 15 feet that damaged crops, cattle, and fisheries in coastal South Asia.

2.4. Impacts of sea level rise on the United States

The trend of sea level rise along the U.S. Atlantic coast and the Gulf coast is clearly upward. The U.S. Atlantic coast is considered one of the hotspots of sea level rise (Ezer 2013). The country will face multi-faceted issues because of sea level rise.

The economic costs of infrastructure damage because of rising seas may become unaffordable for the U.S. In the U.S., trillion-dollar coastal property and public infrastructure are at risk of flooding because of sea level rise (Fleming et al. 2018). Many urban systems such as transportation and utility networks can break down. Around 60,000 miles of U.S. roads and bridges in coastal floodplains are vulnerable to extreme storms and hurricanes that cost billions of dollar in repairs (Fleming et al. 2018). Andreucci and Aktas (2017) estimated the economic cost for only seven coastal municipalities in Connecticut, stretching along 94 km of coastline, would be $1.3 billion and $2.2 billion, for 1 and 2 m sea level rise, respectively, by the end of 21st century, for residential property only (Andreucci and Aktas 2017). The City of Fort Lauderdale, Florida, spent millions of dollars fixing roads and drains because of tidal floods (Gillis 2016).

Floods from coastal storms will be more frequent because of sea level rise. Low-lying coastal areas might flood up to 20 times more frequently because of coastal storms (Cooper, Beevers, and Oppenheimer 2008). Tybee Island, Georgia, becomes disconnected from the mainland because the only connecting road goes beneath the sea several times a year because of the tidal flood (Gillis 2016).

The Atlantic coast and the Gulf coast areas of the U.S. will face serious flooding issues. Scientists projected that approximately 1-3 percent of the land area of New Jersey will be permanently inundated by the end of 21^{st} century (Cooper, Beevers, and Oppenheimer 2008). If the sea rises by 0.6 m by 2100, it will inundate 70% of the total land surface and 12% of real estate property in the Florida Keys (Zhang et al. 2011). The impact might be devastating if the sea level rise is more than 1 meter (Zhang et al. 2011). Scientists projected that a 1.5 m sea level rise would inundate a total of 90% of the Florida Key's land area and affect 71% and 68% of the population and property, respectively (Zhang et al. 2011).

Florida is highly vulnerable to sea level rise because of its long coastline, low topography, and exposure to both the Atlantic Ocean and the Gulf of Mexico. St Petersburg, Tampa, Miami, Miami Beach, and Panama City in Florida are in the list of top 20 cities that will suffer most because of sea level rise (Bergman 2019). A study in 2016 showed that one in eight homes in Florida would be flooded by 2100, incurring a loss of $413 billion in the property (Bergman 2019). About 2.4 million people in the southeastern counties of Florida, such as Monroe, Miami-Dade, Broward, and Palm Beach, live less than four feet above the high-tide line. The streets of Fort Lauderdale, Hollywood, and Miami Beach often flood during the occasional king tides, which are much higher than normal high tides (Parker 2015). A two-foot rise of water would be enough to strand the Miami-Dade County sewage-treatment plant on Virginia Key and the nuclear power plant at Turkey Point, both on Biscayne Bay (Parker 2015).

2.5. Estimate of the impacts of sea level rise (theories and methods)

Scientists have been continuing to estimate the probable damages of future sea level rise. Andreucci and Aktas (2017), analyzed seven coastal municipalities in Connecticut together with land inundation, economic impacts, and societal impacts. They calculated economic costs of $1.3 billion and $2.2 billion for 1 and 2 m sea level rise respectively for those seven coastal municipalities stretching along 94 km of coastline (Andreucci and Aktas 2017). In this study, the geographic data were integrated with economic and social data at a parcel level resolution through GIS (Andreucci and Aktas 2017). The model applies to any coastal areas with necessary changes in variables (Andreucci and Aktas 2017).

Another group of scientists assessed the potential impacts of sea level rise on the coastal region of New Jersey, USA (Cooper, Beevers, and Oppenheimer 2008). They used episodic flood events to project future inundation and Federal Emergency Management Agency (FEMA) tidal surge frequency and floodwater levels' data for Atlantic City, New. They divided the land into several categories: wetlands, forest, beach, residence, industry, and agriculture to assess the vulnerability of the land to three given sea level rise scenarios: 0.61, 1.22, and 2.90 m sea level (Cooper, Beevers, and Oppenheimer 2008). They suggested that approximately 1-3 percent of the land area of New Jersey would be permanently inundated over the next century (Cooper, Beevers, and Oppenheimer 2008).

Coastal Florida is susceptible to saltwater intrusion. A group of scientists assessed the stress of salinity that resulted from the increased tidal flooding (Desantis et al. 2007). Increased salinity degraded the rich diversity of coastal forests in Waccasassa

Bay, Florida, USA. The scientists chose 400 m^2 coastal forest stands having an elevation gradient of 0.58–1.1m, frequently affected by tidal flooding and rising sea levels in Waccasassa Bay, Florida, USA. They analyzed the data from 1992 to 2005 and found that the diversity of native tree species declined significantly (Desantis et al. 2007). On the other hand, salt-tolerant species regenerated substantially. Thus, the diversity in the species in the forests decreased with the increased tidal flooding frequency and saltwater intrusion towards land (Desantis et al. 2007).

Sea level rise will cause higher storm surges in coastal areas across the U.S. (Shepard et al. 2012). A group of scientists quantified potential changes in storm surge risk because of sea level rise on Long Island, New York, using a GIS-based approach. They found that an increase of 0.5 m in sea level by the 2080s would increase the number of affected people and properties by 47% and 73%, respectively, in New York (Shepard et al. 2012)

2.6. Coastal growth and sea level rise impact

Historically, many rich civilizations were built near the coast. People have been attracted to coastal zones because of their climates, resources, and means of trade and transport. The coastward net in-migration has increased despite prevalent coastal hazards in the late 20th and 21st centuries (Crossett et al. 2004), and the trend of migration will likely continue. People are putting themselves at risk by moving towards coastal hazards areas.

Generally, the coast is referred to as the interface of land and ocean. Many organizations have defined coastal areas based on their purpose. For example, in the U.S., for research and reporting purposes National Oceanic and Atmospheric

Administration (NOAA) defines a county as coastal if a) at least 15 percent of a county's land area lies within a coastal watershed or b) a portion of or an entire county accounts for at least 15 percent of coast cataloging unit (Crossett et al. 2004). It also divides the United States into five coastal zones: the Northeast coast, the Southeast coast, the Gulf coast, the Pacific coast, and the Great lakes coast.

2.6.1. Global coastward migration (global)

A combination of economic and geographic opportunities drives coastward migration (Crossett et al. 2004). Most of the world's megacities are located on the coasts (Pelling and Blackburn 2013). The growth rate and urbanization rate in coastal areas outstrip the inland. Many nations in Asia are experiencing higher growth rates in coastal zones than inland. For example, in Bangladesh, the population growth rate in coastal areas is twice the national growth rate (Neumann et al. 2015). In China, the urbanization rate in coastal zones is three times higher than the inland (Neumann et al. 2015).

2.6.2. Coastal growth in the U.S.

Coasts are the economic machine in the U.S. (Fleming et al. 2018). Twenty-three of the twenty-five most densely populated U.S. counties were coastal in 2000 (Crossett et al. 2004). As of 2013, coastal counties comprised of 133 million people (42% of the population) (Fleming et al. 2018), which was an increase of 33 million people since 1995 (Crossett et al. 2004). The Southeast coast and the Gulf coast, especially Georgia, North Carolina, and Florida experienced the highest migration between 1995 and 2000 (Crossett et al. 2004). The Gulf coast has six coastal states and 144 coastal counties, and it comprised of 13 percent of the nation's population (Crossett et al. 2004).

2.6.3. Coastal Florida growth

Florida has been one of the most rapidly growing states in the U.S. since 1980 and is expected to continue growing rapidly in the future (Smith 2005). It showed the greatest percentage of population increase in the nation from 1980 to 2003 (Crossett et al. 2004). Florida had the largest number of seasonal housing units (24 percent) in 2000. Warm temperature, active marine recreation, family-oriented recreation, and senior-oriented features made Florida the desired location for both vacation and retirement homes (Crossett et al. 2004). Population growth rate at coastal areas will exacerbate the sea level rise impacts. With the massive influx of people, huge assets and wealth have been concentrating in the coastal areas; that make more people vulnerable to the sea level rise, and effects of sea level rise more expensive.

2.7. Taxes, subsidies, and coastal development

Subsidies and insurance programs starting from the National Flood Insurance Program (NFIP) to homeowner tax breaks encourage development in coastal areas that are susceptible to disasters (Bagstad, Stapleton, and D'Agostino 2007). For example, the subsidized cost of fossil fuel extraction led to inefficient overuse of fossil energies, which resulted in an irrecoverable impact on the Earth (Neumann et al. 2015). Unfortunately, the insurance programs do not take sea level rise into their consideration for insurance coverages and prices (Reality, Risk, & Rising Seas 2017).

Barnegat Bay, Beach Haven, and Long Beach Township, New Jersey, are representatives of many coastal areas where subsidized coastal development was inappropriate (Gaul 2019). In the 1950s, a few foresighted developers bought lands in those areas and developed small beach houses, small bungalows, and eventually large modern bungalows (Gaul 2019). Undoubtedly, people were attracted to those beach houses because they needed a way to escape the crowd of the city and enjoy vacations close to nature. Though many Atlantic hurricanes devasted those beach houses, the rebuilding process never stopped because of many subsidized insurances and disaster relief programs.

Taxes, subsidies, and certain insurance structures have been enhancing coastal development over the last sixty years in the Gulf Coast of the United States (Neumann et al. 2015). Subsidized insurance allows developers to build in areas that otherwise are considered risky for construction (Neumann et al. 2015). For example, areas prone to storm surges, higher tidal floods (coastal areas), earthquakes, landslides, and wildfire. When a hurricane or flood strikes an area, developers buy large parcels of impacted area at a discounted price, rebuild and sell the property at a rate that does not reflect the site's potential for flooding (Reality, Risk, & Rising seas, 2017). This rebuilding process turns natural disasters into human tragedies (Gaul 2019) and costs the National Flood Insurance Program (NFIP) millions of dollars each year (Bagstad, Stapleton, and D'Agostino 2007). NFIP, in fact, encourages this rebuilding process by paying claims multiple times for the same property without increase rates (Bagstad, Stapleton, and D'Agostino 2007).

Several tax breaks encourage coastal residential developments (Bagstad, Stapleton, and D'Agostino 2007). Interest and property tax reductions for second homes, along with the accelerated depreciation for seasonal rental properties, provide a direct incentive for coastal development (Bagstad, Stapleton, and D'Agostino 2007). Many wealthy people are encouraged to own second homes, seasonal homes, and rental properties in coastal areas because of this policy. New coastal development comprises these types of properties.

Beaches are always susceptible to hazards such as erosion, hurricanes, and flooding (Gaul 2019). People are making it problematic by putting infrastructure there (Gaul 2019). Policies and pro-development attitudes of people make natural disasters expensive. Subsidized coastal development has turned into a tragedy of commons (Gaul 2019).

2.8. Vulnerability

Vulnerability is an important term when we discuss hazards and disasters. A disaster is a sudden event that causes great damage to lives and properties. A hazard is any source of potential damage, harm or adverse effects on something or someone. Basically, a hazard is a potential for harm or an adverse effect (for example, to people as health effects, to organizations as property or equipment losses). Where a hazard is a source for potential loss, vulnerability is the potential loss for people who live in the hazard area.

There are many definitions for vulnerability. Susan Cutter defined social vulnerability as the identification of, “sensitive populations that may be less likely to respond to, cope with, and recover from a natural disaster” (Cutter 1996). The Social Vulnerability Index (SoVI), in the context of natural hazards, determines the places that need specialized attention and immediate response, and long-term recovery after a natural hazard event, given the sensitivity of the populations who live there and their lowered capacity to respond (Cutter and Finch 2008).

Vulnerability can be an output of exposure and response to an event. Exposure is a condition of being subject to the effect of an event (for instance, a natural disaster) (Leichenko and O'Brien 2008). Response is the action taken by the individuals, households, groups, or institutions either in anticipation of or following the event (Leichenko and O'Brien 2008). Responses can be decision, policies, or behaviors (Leichenko and O'Brien 2008). The responses also refer to the strategies, adjustments, or adaptations which can help to minimize the output (Leichenko and O'Brien 2008).

Vulnerability can be the product of unequal access to a community's social, economic, and natural resources (Cutter and Emrich 2006). Vulnerability can arise from the geographic context such as: location, elevation, and proximity (Cutter, Boruff, and Shirley 2003). All these factors act together in assessing risk. Vulnerability can be of different types, such as biophysical vulnerability, place vulnerability, and social vulnerability (Cutter, Boruff, and Shirley 2003).

2.8.1. Factors of Vulnerability

There are several factors that can define vulnerability. Vulnerability is a function of both the demographic characteristics of the population (age, gender, wealth, and so forth) and complex social structures (such as health care provision, social capital, and access to life-saving services) (Cutter and Emrich 2006). Some of the many factors that influence social vulnerability include socio-economic status (in terms of income, political power, and prestige), gender, race and ethnicity, age, commercial and industrial development, loss of employment, rural or urban, residential property, infrastructure and lifelines, renters, occupation, family structures, education, population growth, medical services, social dependence, and special needs populations (Cutter, Boruff, and Shirley 2003).

Presence or absence, intensity, and different aspects of these factors define whether a particular sub-group of the overall population is vulnerable. For example, women sometimes are more vulnerable than men, because the society may put certain restrictions and responsibilities (such as making families and raising children) on them (Cutter, Boruff, and Shirley 2003). Tribal communities might be vulnerable as they may have less access to facilities and resources. They can also be vulnerable because of different languages and cultures (Cutter, Boruff, and Shirley 2003). Children and older people are also susceptible to risk because they may have less mobility and more dependence on others (Cutter, Boruff, and Shirley 2003). People who live on natural resources such as farming, fishing, and so forth are more vulnerable to natural disasters than those who do managerial work (Cutter, Boruff, and Shirley 2003). Families with a high number of dependent members are vulnerable to natural disasters because more people depend on fewer income (Cutter, Boruff, and Shirley 2003). Educated people are less susceptible to extreme events because they can predict the uncertainties to some extent based on their knowledge and take measures accordingly (Cutter, Boruff, and Shirley 2003). Access to adequate health services (medicine, physicians, hospitals, and so forth) help people become more resilient to natural disasters or extreme events (Cutter, Boruff, and Shirley 2003). People with high social dependence (subsidized people) are also vulnerable to shocks and stresses (Cutter, Boruff, and Shirley 2003).

Vulnerability can be complex, and dynamic based on the situation. Though rich people are usually less vulnerable to an event as they have wealth to recover, they can also be vulnerable to an event (Cutter, Boruff, and Shirley 2003). The owners of expensive residential properties are vulnerable to natural hazards because they have invested much of their wealth in a house and cannot escape the house as easily as renters can (Cutter, Boruff, and Shirley 2003).

2.8.2. Assess vulnerabilities (theories and methods)

People can assess vulnerability. Assessment of vulnerability is important because people can reduce the vulnerability by several mitigation strategies. Many researchers consider variables (that cause vulnerability) to measure vulnerability.

Professor Susan Cutter from the University of South Carolina has made a profound contribution in the field of hazards and vulnerability. She and her research team introduced the Social Vulnerability Index (SoVI) to measure the nationwide vulnerability of people to environmental hazards. The research used 42 variables from City and County Data Books for 1994 and 1998, U.S. Census, to develop social vulnerability for all 3,141 U.S. counties (Cutter, Boruff, and Shirley 2003). Examples of some the variables from Cutter, Boruff, and Shirley (2003) are as follows (table 1):

Table 1: Important Variables.

Variables	**Why they are important**
Age	Some age groups such as older and children are vulnerable to natural disaster.
Language	Sometimes speaking more than one language reduce vulnerability. It also helps people to gain social capital soon.
Per capita income (in dollars)	Usually rich or employed people are less vulnerable to disaster because they can move easily.
Median dollar value of owner-occupied housing	If the price of house is more the loss will be more.
Median rent (in dollars) for renter-occupied housing units	Renters can easily shift elsewhere.
Number of physicians per 100,000 population	Access to health care reduce the vulnerability.
Percent of population under five years old	Children are more susceptible to disasters.
Percent of population over 65 years	Older people usually have less mobility because of age and disability.
Percent of households earning more than $75,000	Rich people have more mobility and alternative resources.
Percent living in poverty	Poor people are already vulnerable.
Children living with both parent	Children living with both parents are less vulnerable than single parent children.
Percent people working in service industry	People working in service industry (restaurants, shops) might be poor but have greater mobility because they can use their skills in different places.
Percent people working in extractive industry	Working in extractive industry poses health risk. This specialized skill might not be applicable in other places.

Table remade from (Cutter, Boruff, and Shirley 2003)

2.9. Resilience

Like vulnerability, multiple definitions of resilience exist in the literature (Cutter et al. 2008; Leichenko and O'Brien 2008; Leichenko 2011). The relationship between vulnerability, resilience, and adaptation is complex and not very well understood (Cutter et al. 2008). When vulnerability refers to inability, resilience refers to the ability of a city, system, or group of population to withstand a wide array of shocks and stresses (Leichenko 2011). Some key features of resilient cities, populations, neighborhoods, and systems include diversity, flexibility, adaptive governance, and capacity for learning and innovation (Leichenko 2011).

The idea of climate resilient or resilient city emphasizes that the cities, areas, systems, or constitutes are able to bounce back from climate related shocks and stresses (Leichenko 2011). Resilience refers to the ability of a(n) city, area, or system to withstand a wide array of shocks and stresses. Resilience is typically understood as the ability of a system to withstand a major shock and maintain or quickly return to normal function (Leichenko 2011).

Four types of resilience have been mentioned in the resilience literature (Leichenko 2011): a) Ecological resilience, b) Hazards and disaster risk reduction, c) Economic resilience, and d) Resilience of governance and institution. Ecological resilience refers to the ability of an ecosystem to withstand any kind of uncertainties and nonlinearities and the self-organizing capacity against any system changes (Leichenko 2011). In hazards and disaster risk reduction literature, resilience is referred to the enhancing capacities of a system so that it can quickly recover from any natural or man-made hazards (Leichenko 2011). Economic resilience refers to the ability of an economy to quickly recover any losses in advance (Leichenko 2011). The resilience of governance refers to how robust a governance system is to quickly respond to the shocks and take actions to recover from these shocks (Leichenko 2011).

Climate hazards are receiving growing importance in the resilience literature. Climate resilient or resilient cities are common terms in resilience literature. Climate change is one of many types of shocks and stresses that cities face, and climate change-related shocks typically occur in combination with other environmental, economic, and political stresses (Leichenko 2011). The long-term resilience for climate hazards requires both adaptation and mitigation strategies combined with policies and plans. Resilience can be an integral part of the adaptive strategy (Cutter et al. 2008).

2.10. Adapting strategies

Since people do not have any permanent solution to prevent sea level rise, adaptation might be one of the best solutions for this problem (Goodell 2017). Fortunately, people of some parts of the coastal area have started adapting. Miami Beach is leading the way. Miami has already been spending $500 million on new pumps, systems, raising street level, and buildings to adapt to higher tidal floods (Reality, Risk, & Rising Seas 2017; Ki-Moon and Francis 2019).

Southeast Florida adopted deep planning for future infrastructure design using the Unified Sea Level Rise Projection (Strauss et al. 2014). Water, wastewater, and storm utilities might be severely impacted because of sea level rise and saltwater intrusion. Bloestscher, Heimlich, and Meeroff, (2011), developed an adaptation toolbox for water, wastewater, and storm utilities to cope with sea level rise for Southeast Florida. All these tools can be used in local conditions (Bloestscher, Heimlich, and Meeroff

2011). While some of the tools apply to each utility throughout the year, others are limited to seasonal use (Bloestscher, Heimlich, and Meeroff 2011). Though the tools were made for Southeast Florida, they can be used in other regions of the world having the same type of climatic conditions and seasonal variability (Bloestscher, Heimlich, and Meeroff 2011).

2.11. Conclusion

A significant proportion of Americans live in coastal areas. More than 150 million Americans (53 percent of the then nation's population) (Crossett et al. 2004) live on the coastal counties. The number of people living on coast increased from 28 percent in 1980 to 53 percent in 2003 (Cutter and Emrich 2006). Most importantly, many people live in hurricane prone areas along the Atlantic Ocean and the Gulf of Mexico (Cutter and Emrich 2006).

Several characteristics of a place make the people of that place either resilient or vulnerable to extreme natural events (Cutter and Emrich 2006). Coastal counties have been getting many year-round residents because many people choose these coastal cities as the destinations for the rest of their lives. In addition, diversified race and ethnic people have also been fueling the population growth of the coastal counties because of the availability of low wage-earning jobs (Cutter and Emrich 2006). With the significant increase in the number of people, the characteristics of coastal residents have changed. The rich live right along the shore, and the income gradient decreases with distance away from the water's edge, showing a wealth gap in the coastal areas (Cutter and Emrich 2006).

From tourism to transportation, Florida is highly dependent on its coasts (Reality, Risk, & Rising Seas 2017; Hine 2013). Beaches, estuaries, and keys are very important in Florida's landscape, coastal development, and economy (Hine 2013). The next chapter will discuss the study area, the City of Cape Coral, Florida.

CHAPTER 3: STUDY AREA

3.1. Introduction

Geologically, Florida was born from the ocean (Hine 2013). It sits on the Florida platform. The surface of the state only covers 50% of Florida platform, and rest of it lies beneath the ocean. The present coastline of Florida has been shaped by changing and static sea levels (Hine 2013). Florida is located in the southeastern United States and is a peninsula surrounded by the Atlantic Ocean and the Gulf of Mexico on three sides (east, west, and south), and Alabama and Georgia in the north (figure 5). Every economic activity of the state is based on its geologic and geographic features (Hine 2013).

3.2. Geographic Location of Cape Coral

The City of Cape Coral is situated in Lee County, Southwest Florida. The city is surrounded by the Caloosahatchee River to the South and East and Matlacha pass (the Gulf of Mexico) to the West. The city is called 'Waterfront Wonderland' because of its 400 miles of canals (figure 5), considered the largest urban canal network in the world (Toor and Rainey 2009). Most of the canals are navigable, and a significant portion of them have access to the Gulf of Mexico. The city has an area of 120 square miles (311 km^2), of which 110 square miles (285 km^2) are land, and 10 square miles (26 km^2) (9%) are water. The topography is flat and poorly drained (Beever III, Walker, and Kammerer 2017a). The average elevation of the city is 5ft (2 m).

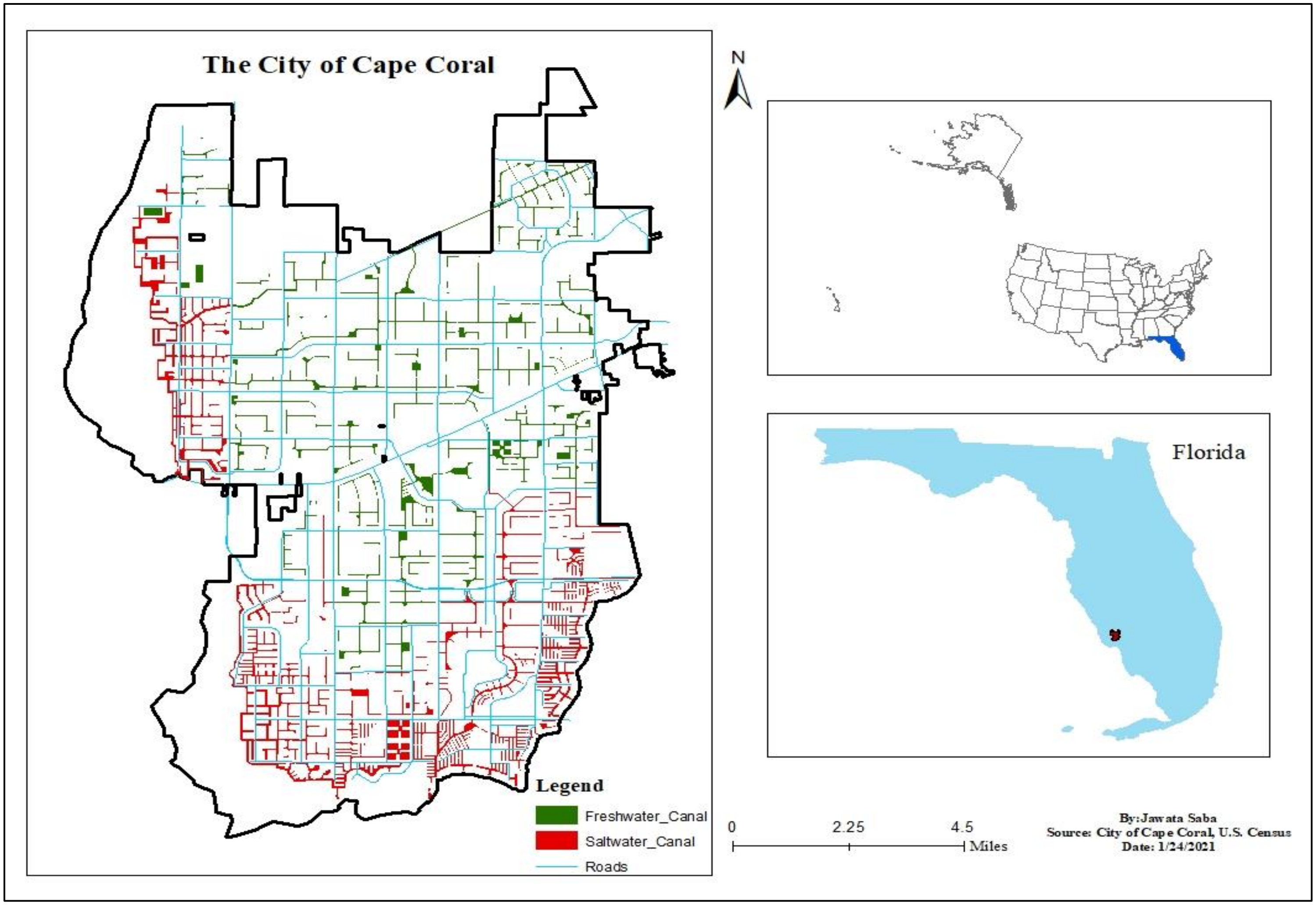

Figure 5: The location of the City of Cape Coral in Florida.

3.2. Emergence and growth of Cape Coral

3.2.1. History and development of the city

The population of Florida has been growing rapidly since the mid-twentieth century. Florida once was home to only a few hundred homesteaders, ranchers, fishermen, and wildlife hunters scattered over its vast swamplands (Davis 2017). It has been becoming a destination for vacation and retirees because of its beautiful shoreline, temperate climate, and many canal-based residential subdivisions. In 1950 Florida had 2.7 million people and ranked 20th among the states in population, but by 1970, it had grown to 6.7 million people and ranked 9th (Stroud 1991). In 2020, the state's population increased to 21.5 million (*United States Census Bureau* 2020). The huge influx of people and a pro-development attitude among the local officials stimulated the state's real estate business and overall growth (Stroud 1995).

The history of Cape Coral is relatively new. The city was founded in 1957 (Beever III, Walker, and Kammerer 2017a). In 1958, two real estate developers Leonard Rosen and Jack Rosen (two brothers), formed Gulf Guaranty Land and Title Company and started a real estate business in Cape Coral (Stroud 1995). They purchased a 103-square-mile (270 km^2) tract known as Redfish Point for $678,000 (Beever III, Walker, and Kammerer 2017a) and began to make one of the largest subdivisions the City of Cape of Coral in Florida (Stroud 1995). The Gulf American Land Corporation (GALC) was formed to oversee the development of the area (Beever III, Walker, and Kammerer 2017a; Stroud 1991). Celebrities such as Bob Hope, Anita Bryant, Jayne Mansfield, and Hugh Downs were hired to promote the city, and the film Fat Spy (1966) and the TV show Route 66, used Cape Coral for location shots (Beever III, Walker, and Kammerer 2017a). In the 1960s, Cape Coral had only 200 people, and by 2016 it had more than

180,000 people (Grunwald 2017). The 1970 U.S. Census recognized and counted Cape Coral as a city. According to Forbes magazine 2016, the City of Cape of Coral ranked ninth of the Top 25 Cities To Retire in the United States (Beever III, Walker, and Kammerer 2017a).

The City of Cape Coral was a poor choice for development because of its sensitive and fragile ecosystem and location between the Caloosahatchee River and the Gulf of Mexico (Stroud 1991). Development was concentrated in a natural area with a low tolerance for anthropogenic disruption. Cape Coral was a vast wetland before the development of the city. The city had 9,752 acres of wetlands, including 1,297 acres of native freshwater wetlands and 8,454 acres of native saltwater wetlands. Native saltwater wetlands included 7,628 acres of mangroves and 826 acres of salt marsh (table 2) (Beever III, Walker, and Kammerer 2017a). Dredging and filling to create canals, roads, and subdivisions destroyed much of the natural wetlands. The development of the city removed approximately seventy-eight percent of the natural ecosystem, including the hydrology, soils, and vegetation (Beever III, Walker, and Kammerer 2017a), and reduced the city's Pine tree coverage to less than 15 percent from more than 50 percent. Houses were built in the 100-year flood plain (Stroud 1995). Construction of an extensive canal system degraded surface water quality as an adequate buffer zone was not provided between the lands and canals (Stroud 1991).

Most of the areas in Cape Coral are developed (figure 6 and 7). Substantial development already occurred in hazard prone areas (figure 7) (*City of Cape Coral: Open Data Portal* 2016). The Comprehensive Plan of the City of Cape Coral (CCCC) projected that 70% of Cape Coral's land area would be built up together with commercial, industrial, and residential development by 2030 (Beever III, Walker, and Kammerer 2017a). Though natural preserves and water resources will not be permitted to be developed under this plan, the city hardly has its original landscape. Inappropriate development can endanger ecologically fragile areas. Development in a hazardous area is one of the many reasons that make the city highly vulnerable to coastal hazards.

Table 2: Land use in Cape Coral in 2016.

Land Use	**Areas in Acre**	**Percentage**
Developed	47,256.44	64.54
Agriculture	178.72	0.24
Rangeland	3,801.98	5.19
Upland Forests	3,237.75	4.42
Waters	7,907.44	10.80
Wetlands	9,769.39	13.34
Barren Land	351.15	0.48
Transportation, Communications, and Utilities	713.58	0.97

Source: modified from (Beever III, Walker, and Kammerer 2017b)

3.2.2. Demography of the city

The population growth of Cape Coral has been rapid and more than many cities in Florida. The average annual population increase of Cape Coral was approximately 5.5% from 1990 to 2015 (Beever III, Walker, and Kammerer 2017a). The city had a population of 181,000 in 2016, and the number increased to 194,000 in 2019 (*United States Census Bureau* 2021). In 2018 the city ranked eighth in terms of population in Florida and was considered one of the ten fastest-growing cities in the United States in 2019 (McCann 2020). The University of Florida’s Bureau of Economic and Business Research projected that by 2030, considering medium growth, Cape Coral’s population would be 314,000 (Beever III, Walker, and Kammerer 2017a). By 2050, the city's population might grow more than ever and that can lead to more development in hazard prone areas.

The important demographic facts of the city are summarized in this chapter (table 3). Chapter 5 will explain the relation and contribution of these demographic facts to the vulnerability of the city.

Table 3: Demographic facts of Cape Coral.

The City of Cape Coral	
Variables	**Estimate**
Percent Asian American People	3
Percent African American People	6
Percent Hispanic People	21
Percent Native American People	0.5
Percent Population 65 and over	23
Percent Households/families Receiving Social Security Benefits	40
Percent Poverty	11
Percent Households Earning over $200,000 annually	5
Per Capita Income	29,970
Percent Speaking English as a Second Language with Limited English Proficiency	9
Percent of population without health insurance	13
Percent with Less than 12th Grade Education	6
Percent Renters	26
Percent Mobile Homes	1
Percent of Housing Units with No Car	3
Percent Unoccupied/Vacant Housing Units	22
Percent Owner occupied	75

Source: (*United States Census Bureau* 2021)

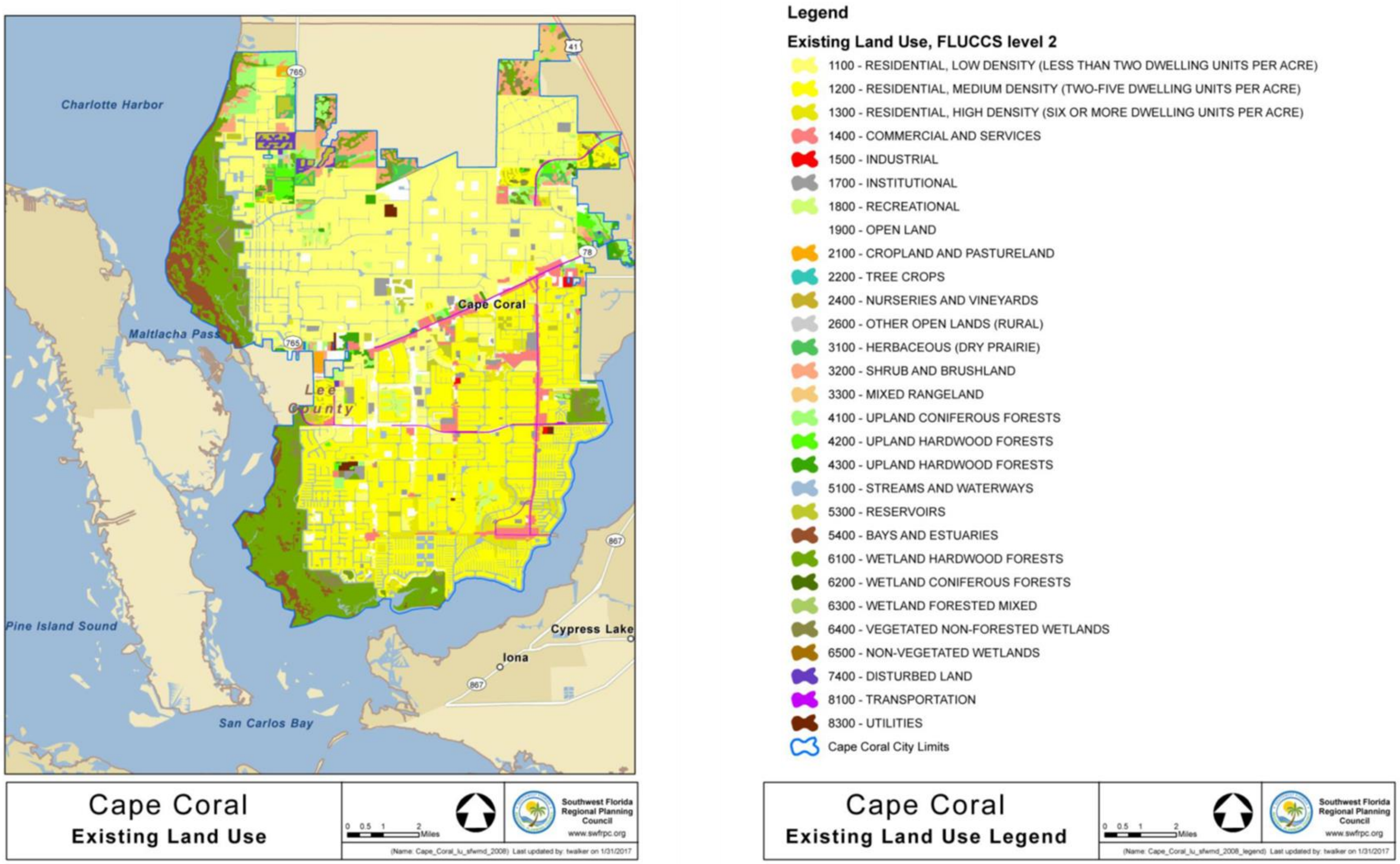

Figure 6: Existing Land Use in Cape Coral in 2016, source: (Beever III, Walker, and Kammerer 2017a).

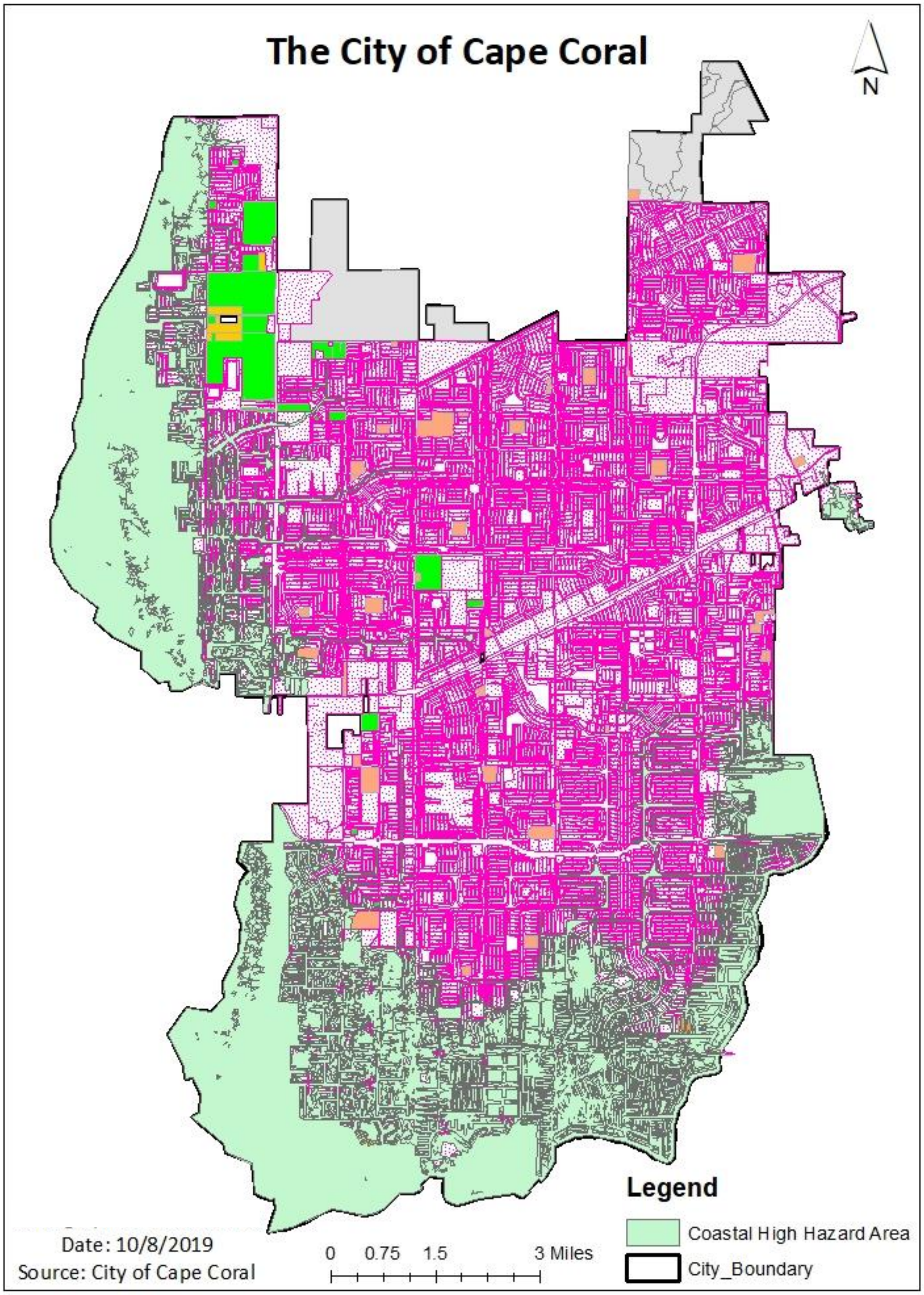

Figure 7: Development occurred in a high hazard area; Source: (City of Cape Coral: Open Data Portal 2016).

3.2.3. Recreational facilities

The recreational facilities of Cape Coral play an important role in attracting residents, seasonal migrants, and tourists. The Waterfront Wonderland has an advantage for water based recreational activities because of its geographic location. The city has a 14 acre Sun Splash Water Park (the largest in southwest Florida), a sandy beach, a fishing pier on the Caloosahatchee River, a yacht basin and club, and a cruise club (Beever III, Walker, and Kammerer 2017a). It also has several night clubs, bars, and so on. People also can enjoy beaches in nearby Sanibel Island, Pine Island, and Fort Myers. Cape Coral has more than 30 recreational parks that provide playgrounds, open fields, walking and running trails, fishing, and so on (Beever III, Walker, and Kammerer 2017a). The city has seven golf courses. It has three senior centers, several museums, and an art studio. The city also has several bird watching centers in its parks.

3.3. Physical Geography of Cape Coral

3.3.1. Geology

Florida sits on the Floridan Platform that extends up to a 50-fathom line (approximately 100 m) (Hine 2013). The Florida Platform is a very stable, flat geologic platform, that provides a tectonically quiet foundation for the Florida peninsula (Obeysekera et al. 1999). Florida has a very high rate of carbonate sediment formation because of the humid subtropical climate, both by inorganic (precipitation of calcium carbonate in solution in seawater) and organic processes (production of coral and algal reefs). Florida’s bedrock consists primarily of limestone, a sedimentary rock, resting upon a much older basement of igneous, metamorphic, and some sedimentary rocks such as sandstone and shale (Hine 2013). The geologic formation underneath Cape Coral, Florida, is the Anastasia formation (figure 8), which consists of quartz sands resulting from marine deposition (Obeysekera et al. 1999).

3.3.2. Hydrology

Water Management Districts in Florida manage the hydrology and water supply systems of the state. Flood control and water supply are the two major purposes of Water Management Districts. During the wet season, the primary mode of water management is flood control, while in the dry season, it is primarily to satisfy various water demands (Abtew et al. 2010). The South Florida Water Management District (SFWMD) has divided south Florida into the five following hydrologic regions or basins: Upper and Lower Kissimmee Basins, Lake Okeechobee, the Everglades Agricultural Area, Lower East Coast, and the Lower West Coast.

I will discuss the Lower West Coast's hydrology because Cape Coral falls into the Lower West Coast. The Upper and Lower Kissimmee basins drain into Lake Okeechobee through the Kissimmee River (C-38 canal). Lake Istokpoga and the Lake Istokpoga water management basins drain into Lake Okeechobee through three major canals. Lake Okeechobee discharge and local runoff flow into the Gulf of Mexico to the west through the Caloosahatchee River (C-43 canal) and to the St. Lucie Estuary to the east through the St. Lucie River (C-44 canal) (figure 10) (Abtew et al. 2010). The Caloosahatchee River (C-43 canal) is a major canal in the Lower West Coast. As the river carries a large volume of runoff from the Lower West Coast and releases into the Gulf of Mexico, the cities situated on the river are vulnerable. When the runoff exceeds the capacity of the C-43 canal the cities on its two sides flood. Since Cape Coral is situated at the Caloosahatchee estuary it is especially vulnerable to sea level rise. A slight increase in the sea level can impact the runoff carrying capacity of the river and cause flooding along its banks and adjacent areas.

Generally, South Florida has low topographic relief, meaning that ground surface elevation differences from site to site are relatively small. From Lake Tohopekaliga in the Upper Kissimmee Basin to Florida Bay in the south, the elevation drops gradually 54 ft over 250 miles. Most of the drop occurs in the basin north of Lake Okeechobee (Abtew et al. 2010). The elevation drop from Lake Tohopekaliga to Lake Okeechobee is 44 ft in about 81 miles. On average, the water level drop from Lake Okeechobee to the Caloosahatchee Estuary (71 miles to the west) and the St. Lucie Estuary (35 miles to the east) is 14 ft. Since low-relief features dominate the hydrology in south Florida, a slight increase in sea level and tide level can cause severe consequences in the Caloosahatchee estuary and Cape Coral (Abtew et al. 2010).

The central water management canal in the Lower West Coast is the Caloosahatchee River (C-43 canal) (figure 10) (Abtew et al. 2010), which runs from Lake Okeechobee to the Caloosahatchee Estuary. Inflows to the Caloosahatchee River are runoff from the basin watershed and releases from Lake Okeechobee by operation of the S-77 structure according to regulation procedures of USACE in 2008 (figure 10). Downstream of S-77 is S-78, a gated spillway that also receives inflows from its local watershed to the east. The outflow from the Caloosahatchee River (downstream of S-78) discharges into the estuary via S-79, a gated spillway and lock operated by the USACE. S-79 is the last structure on the Caloosahatchee River that controls discharges into its estuary. The operations of S-79 include managing stormwater runoff from the west Caloosahatchee and east Caloosahatchee watersheds (Abtew et al. 2010).

Cape Coral is highly susceptible to floods in unusually wet years because of its hydrology and precipitation pattern. For example, in 2009, the Caloosahatchee River received 375,722 acre-feet and the Caloosahatchee Estuary received 1,016,333 acre-feet runoff, which was 71% and 81% higher than the historical average and the water management structures operated by both SFWMD and USACE that time were unable to control the overflow (Abtew et al. 2010). Acre-feet (ac-ft) is the quantity of water required to cover 1 acre to a depth of 1 foot. Acre-feet is the unit of volume most convenient for expressing the storage in reservoirs.

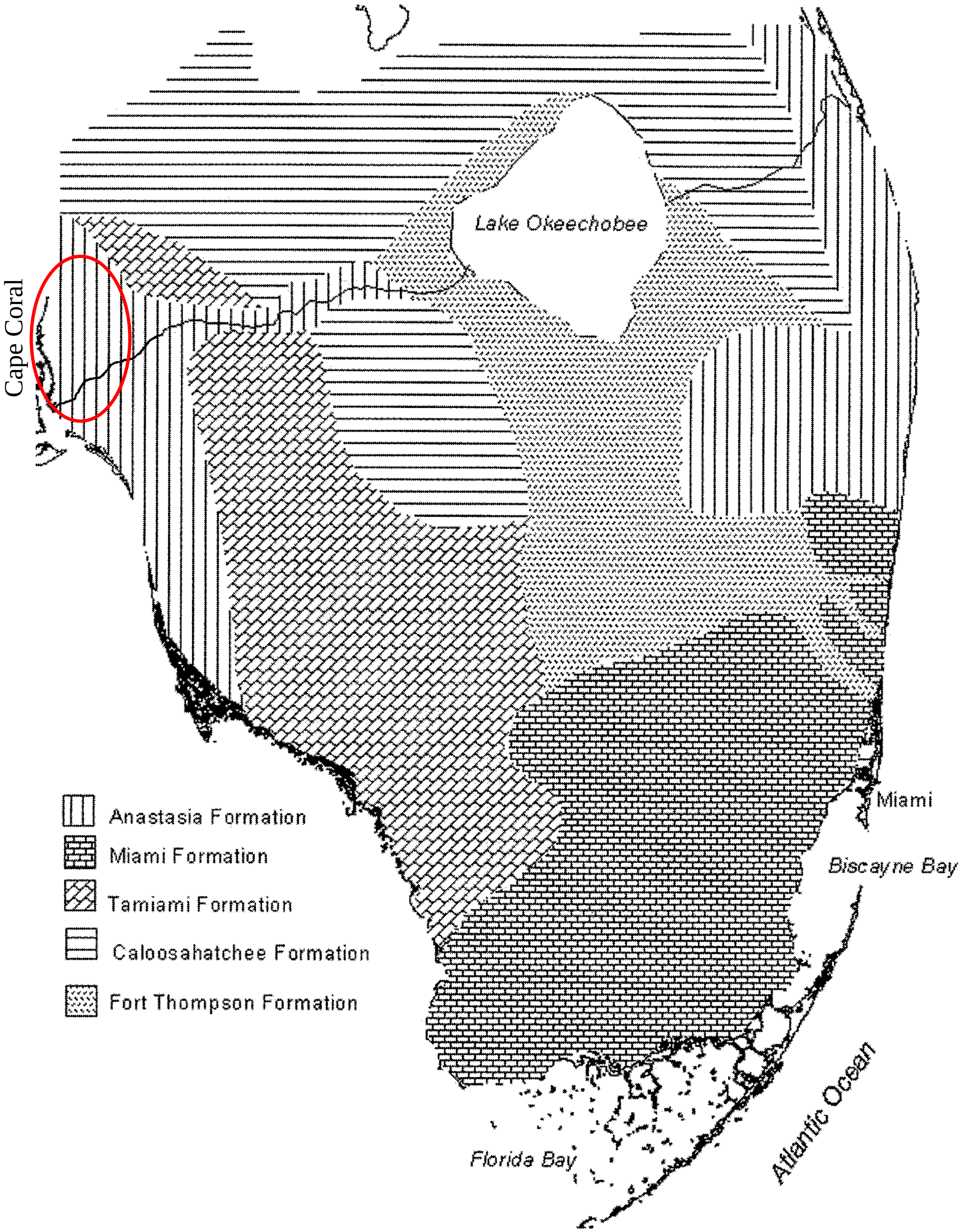

Figure 8: The geology of South Florida shows the surface distributions of the main geologic formations, source: (Obeysekera et al. 1999).

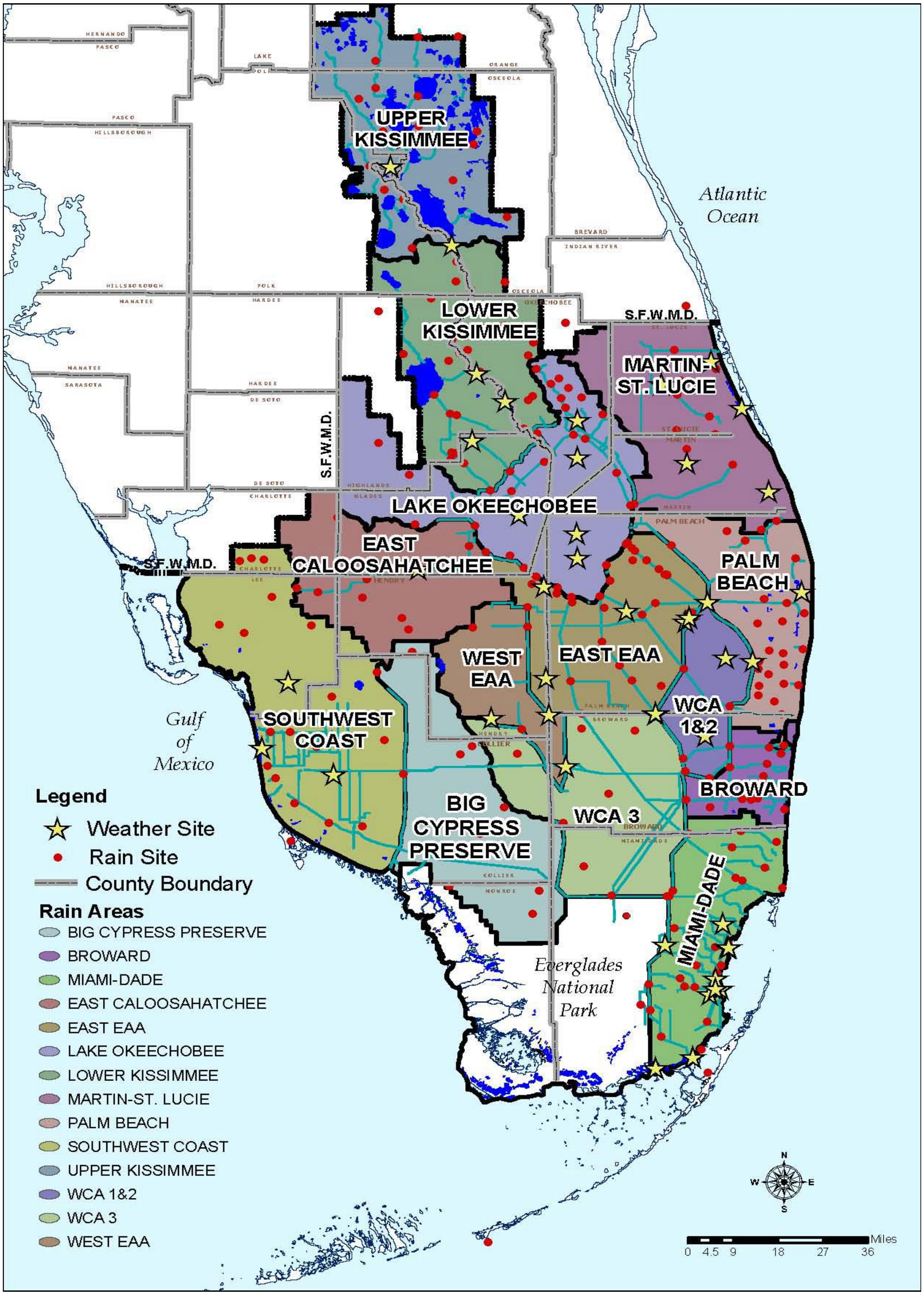

Figure 9: Hydrologic Components and Rainfall Areas in South Florida Water Management District; source: (Abtew et al. 2010).

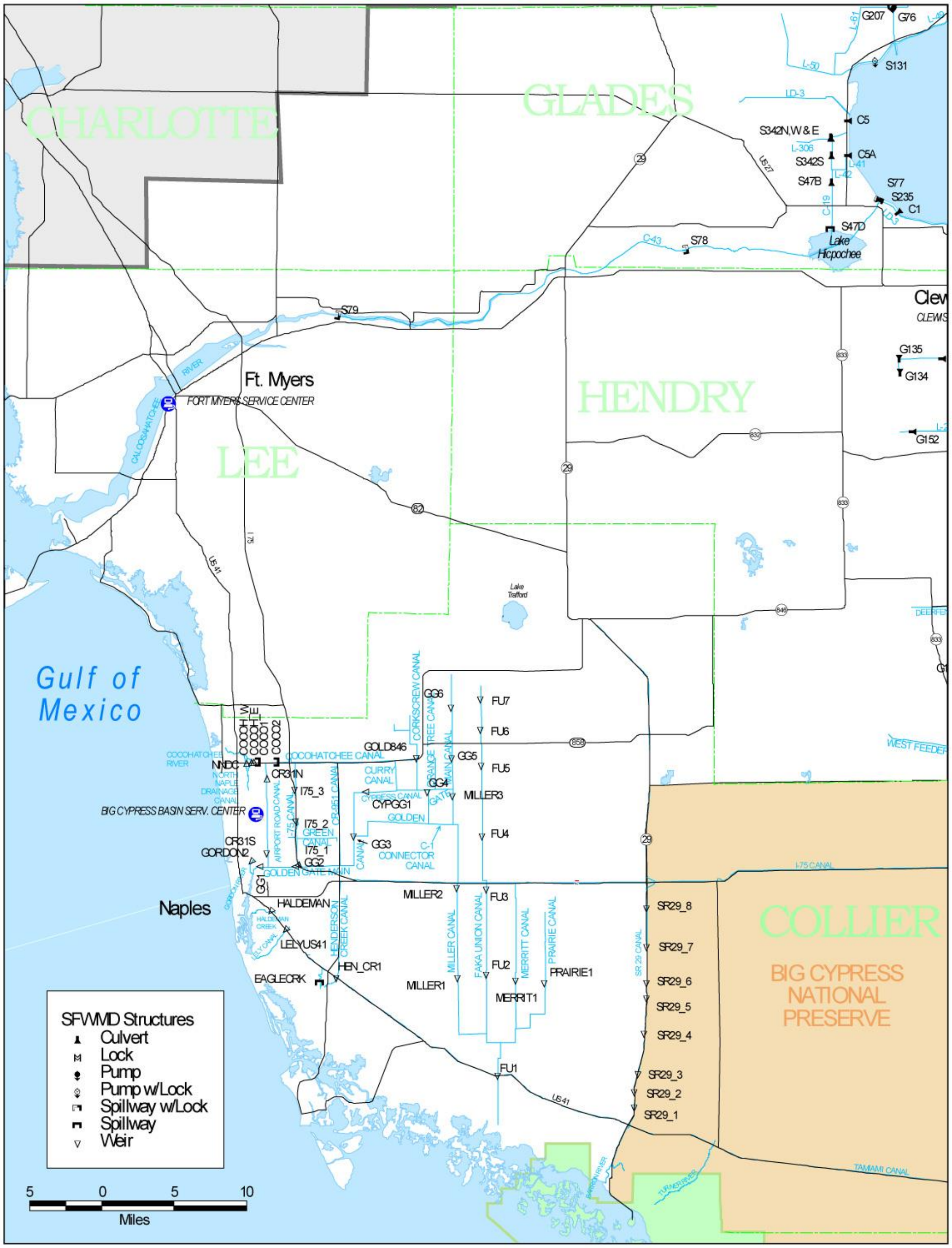

Figure 10: Lower West Hydrological structure and water management; Source:(Abtew et al. 2010).

3.3.3. Groundwater

Florida has an extensive groundwater resource, the Florida Aquifer, a layer of water bearing permeable carbonate rock from which groundwater can be extracted (Hine 2013). This extensive regional aquifer is comprised of a series of thickly bedded permeable marine limestones separated by relatively thin clays, dolomites, cherts or evaporite beds (Stroud 1991). This aquifer was formed from rocks that are approximately ten times more permeable than those below and above it (Hine 2013). The aquifer is an essential water source for southeastern United States' coastal plain areas, although it may be referred to by different names outside of Florida (Stroud 1991). It extends beneath nearly all of Florida. This aquifer provides water for industrial, residential, agricultural and agricultural uses in Florida, Alabama, Georgia, and South Carolina. It is recharged by surface runoff and rainfall. Its thickest section is 1,040 m, which occurs in southwest Florida (Hine 2013).

Florida permits groundwater mining (Hine 2013), which is the exploitation of aquifers beyond their flow and recharge capacities. Groundwater is a crucial resource in Florida, because it is surrounded by saltwater on three sides. Groundwater mining causes an additional problem when the aquifer is near the ocean or sea where fresh groundwater and saline seawater converge (Christopherson and Brikeland 2017). The freshwater flows on top of the saline water, because it is less dense than saltwater. Excessive pumping of groundwater can bring saltwater closer to the surface and eventually within reach of groundwater pumps which will pull it into the freshwater system (Christopherson and Brikeland 2017).

The Cape Coral region is underlain by four aquifers: the water table aquifer, the Mid-Hawthorn Aquifer, the Lower Hawthorn Aquifer, and the Florida Aquifer System (Stroud 1991). The Hawthorn Aquifer System is a regional aquifer system underlying all of southwest Florida (Hine 2013). Beneath Cape Coral the water-table aquifer is unconfined and occurs from the top of the water table near the land surface to depths ranging from 20 ft in the central and northeastern part of Cape Coral to 40 ft towards the southeast.

Cape Coral has two aquifers: the Mid Hawthorn and the Lower Hawthorn Aquifers (Stroud 1991). The Mid-Hawthorn Aquifer in Cape Coral occurs in a series of limestone, marl, and dolomite rock beds. The Lower Hawthorn Aquifer consists of interbedded phosphatic limestones, dolomites, dolosilts, and various mixed carbonate lithologies. The top of this aquifer is approximately 500 ft below the surface in the Cape Coral area. Water quality in the Lower Hawthorn Aquifer is slightly saline, with dissolved chloride concentrations less than 1000 mg/l (Hine 2013).

In south Florida, the aquifers, for the most part, contain saltwater that needs desalination treatment for potable uses. The Suwannee Aquifer is one of them. It includes permeable sediments of the lower part of the Hawthorn Group, the Suwannee Limestone, the Ocala Group, the Avon Park Limestone, and the Lake City Limestone (Hine 2013; Stroud 1991). Beneath Cape Coral, the top of the Suwannee Limestone generally occurs between 700 ft below land surface and extends to a depth of between 1000 and 1300 ft. Although the Suwannee Aquifer or deeper wells have not been drilled in Cape Coral, the water quality is similar to the quality of water in the deeper portions of the Lower Hawthorn Aquifer. The Suwannee Aquifer is not heavily used except where adequate shallower sources are not available.

Cape Coral's groundwater supply is limited. The massive excavation for roads and canals, and pollution from septic tanks severely damaged Cape Coral's water-table aquifer (Stroud 1995; Stroud 1991). The Mid-Hawthorn formation had already experienced severe problems with drawdown produced by excessive pumping. The next most accessible aquifer is the Lower Hawthorn. Since the aquifer above the Lower Hawthorn was already over exploited, the city was forced to dig deeper (Stroud 1991). The levels below the Lower Hawthorn are too saline for potable uses. As the Lower Hawthorn aquifer has many positive elements, other users might be looking to tap it soon. Neighboring cities might look to the Lower Hawthorn Aquifer as their next water source since increasing populations and strict regulations prevent the potential water supply from shallower sources (Stroud 1991).

3.3.4. Cape Coral water supply system

Before the 1970s, a centralized pipe water supply did not exist in Cape Coral. When Cape Coral constructed a public water distribution system, the city chose to take water from the Lower Howthorn aquifer (Stroud 1991). The Lower Hawthorn Aquifer has been the sole source for the Cape Coral municipal water system (Stroud 1991; *Utilities Water Production Common Questions* 2021). The wells supplying water to the water supply system were initially 600-700 ft deep (Stroud 1991) and are now 700 to 800 ft deep (*Utilities Water Production Common Questions* 2021). This water from the Lower Hawthorn Aquifer is slightly saline because of the high level of chloride (between 50 and 1100 parts per million (ppm), which exceeds the Department of Environmental

Regulation standard of no more than 250 ppm in public drinking water (Stroud 1991). As a result, the city built a reverse osmosis water treatment plant to desalinate brackish water. Reverse Osmosis is a process designed to substantially reduce chlorides (salts) and remove debris and impurities in the water (Christopherson and Brikeland 2017). The Cape Coral reverse osmosis water production facility was completed in 1977 (Stroud 1991) and has been expanded several times to support the city's growth. It is one of the largest in the world (*Utilities Water Production Common Questions* 2021).

3.3.5 Weather and Climate

Cape Coral features both humid subtropical and tropical savanna climates because it falls in the transition between these two climate zones. Most of Florida falls in a humid subtropical climate, where a portion of south Florida falls under the tropical savanna climate under the Köppen climate classification. Though it is debatable, many climatologists think that Cape Coral falls under a humid subtropical climate (Hela 1952; Beever III, Walker, and Kammerer 2017a). Humid subtropical climates have hot summers and are moist all year (Christopherson and Brikeland 2017). This type of climate usually occurs on the eastern coasts of continents (the United States, China, Japan), usually in the 20s and 30s latitudes. Humid subtropical climates have a warm and wet flow from the tropics that creates warm and moist conditions in the summer months. Summer is often the wettest season in this climate. Since the city falls in the transition of two climate zones, precipitation always does not occur as projected. Therefore, the city must be prepared for unexpected floods and droughts.

Cape Coral has two primary seasons: summer and winter. Seasonal variation is virtually absent in the city since humid subtropic and tropical savanna climates do not offer much seasonal variety. The summers are hot, humid, and rainy, and the winters are relatively dry with comfortable temperatures (Beever III, Walker, and Kammerer 2017a). The average winter temperature is 65^0 Fahrenheit, while the summer's average is 82^0 Fahrenheit (Bradley 1972). Cape Coral receives many tourists and seasonal migrants because of its mild winter.

Rain is common from June to September (Riebsame, Woodley, and Davis 1974). The area experiences 355 days of sunshine and 145 days of precipitation in an average per year (Bradley 1972). The annual average rainfall is 54 inches (Bradley 1972). The area attracts people because it has sunny days throughout the year.

3.3.6. History of disaster

Like other cities in Florida, Cape Coral is vulnerable to tropical storms, hurricanes, and storm surges (figure 11, 12 and 13, and table 4, 5, and 6). Tropical storms cause most of the disasters in Florida (Dean and Malakar 1999). Tropical storms occur when a warm-core, low-pressure system with organized circulation reaches a wind speed of 35 miles per hour (mile/h) and hurricanes begin at 75 mile/h (Abtew et al. 2010).

Hurricanes are common and frequent in Southwest Florida. The area experiences both Atlantic and Gulf of Mexico hurricanes (Drew and Schomer 1984). Though hurricane season occurs from June to November (Drew and Schomer 1984; Jordan 1973), most thunderstorms occur during the summer (Duever et al. 1979). The impacts of hurricanes in Cape Coral are high wind, storm surge, and heavy rainfall (Beever III, Walker, and Kammerer 2017b). Eighty-two percent of tropical storms and hurricanes occur in hurricane season (Drew and Schomer 1984; Jordan 1973). A total of 114 hurricanes and tropical storms affected the Florida peninsula between 1871 and 1996

(Abtew et al. 2010). More than a hundred hurricanes and tropical storms occurred in the Atlantic Ocean from 1995 to 2019. Among them, the following hurricanes made landfall in southwest Florida and Cape Coral (table 4) (*National Oceanic and Atmospheric Administration* 2020).

Table 4: List of Atlantic Hurricanes that made landfall in southwest Florida and Cape Coral from 1995 to 2019.

Name	**Wind (kt) (1 nautical mile per hour)**	**Type**	**Total damage (Billion)**	**Date**
Allison	65	Hurricane		June 3-6, 1995
Erin	80	Hurricane		Jul 31- Aug 6, 1995
Jerry	35	Tropical Storm		Aug 22- 28, 1995
Josephine	60	Tropical Storm		Oct 4-8, 1996
Danny	70	Hurricane		July 16-26,1997
Earl	85	Hurricane		Aug 31- Sept 3, 1998
Georges	135	Major Hurricane		Sept 15 – Oct 1, 1998
Harvey	50	Tropical Storm		Sep 19- 22, 1999
Irene	95	Hurricane		Oct 12-19, 1999
Gordon	70	Hurricane		Sep 14-18, 2000
Helene	60	Tropical Storm		Sep 15-25, 2000
Leslie	40	Tropical Storm		Oct 4-7, 2000

Allison	50	Tropical Storm	12.1	Jun 5-17, 2001
Barry	60	Tropical Storm		Aug 2-7, 2001
Gabrielle	70	Hurricane		Sep 11-19, 2001
Edouard	55	Tropical Storm		Sep 1- 6, 2002
Hanna	50	Tropical Storm		Sep 12-15, 2002
Henri	50	Tropical Storm		Sep 3-8, 2003
Bonnie	55	Tropical Storm		Aug3-14, 2004
Charley	125	Major Hurricane	21.4	Aug 9-14, 2004
Frances	125	Major Hurricane	13.1	Aug 25-Sep 8, 2004
Ivan	145	Major Hurricane	27.3	Sep 2-24, 2004
Jeanne	105	Major Hurricane	10.3	Sep 13-28, 2004
Rita	N/A	Hurricane	24.2	
Arlene	60	Tropical Storm		Jun 8-13, 2005
Dennis	130	Major Hurricane	3.3	Jul 4-13, 2005
Katrina	150	Major Hurricane	163.8	Aug 23-30, 2005
Tammy	45	Tropical Storm		Oct 5-6, 2005

Wilma	160	Major Hurricane	24.9	Oct 15-25, 2005 (Total 28 hurricane, tropical storm and subtropical storm occurred this year)
Alberto	60	Tropical Storm		Jun 10-14, 2006
Ernesto	65	Hurricane		Aug 24- Sep 1, 2006
Barry	50	Tropical Storm		Jun 1-2, 2007
Fay	50	Tropical Storm		Aug 15-26, 2008
Claudette	50	Tropical Storm		Aug 16-17, 2009
Ida	90	Hurricane		Nov 4-10, 2009
Bonnie	40	Tropical Storm		Jul 22-24, 2010
Beryl	60	Tropical Storm		May 26-30, 2012
Debby	55	Tropical Storm		Jun 23-27, 2012
Andrea	N/A	Tropical Storm		Jun 5-7, 2013
Colin	45	Tropical Storm		Jun 5-7, 2016
Hermine	70	Hurricane		Aug 28-Sep 3, 2016
Julia	45	Tropical Storm		Sep 13-18, 2016

Matthew	145	Major Hurricane	10.5	Sep 28-Oct 9, 2016
Emily	50	Tropical Storm		Jul 30 – Aug 1, 2017
Harvey	116	Major Hurricane	126.3	Aug 17-Sep 1, 2017
Irma	64	Hurricane	50.5	Aug 30 – Sep 12, 2017
Maria	135	Major Hurricane	90.9	Sep 16- 30, 2017
Alberto	39	Tropical Storm		May 25-31, 2018
Florence	64	Major Hurricane	22	Aug 31- Sep 17, 2018
Gordon	N/A	Tropical Storm		Sep 3-6, 2018
Michael	140	Major Hurricane		Oct 7-11, 2018
Barry	70	Hurricane		Jul 11-15, 2019
Chantal	53	Tropical Storm		Aug 20-23, 2019
Dorian	160	Major Hurricane		Aug 27-Sep 7, 2019
Nestor	N/A	Tropical Storm		Oct 18-19, 2019

Source: Modified from (Gaul 2019; *National Oceanic and Atmospheric Administration* 2020)

3.4. Sea level rise and Cape Coral

Cape Coral is highly susceptible to hurricanes and storm surges (Tables 4 and 5). The ocean temperature will continue to rise because of global warming. Higher ocean temperatures will create frequent and intense hurricanes that can damage the coast and further inland (Beever III, Walker, and Kammerer 2017a). A total of 16 percent of the city will flood if the sea level rises as high as 3 ft on the Gulf coast (table 6).

The City of Cape Coral used the maximum of Maximum Envelope of Water (MEOW) to identify hurricane affected areas and develop evacuation zones (figure 11 and table 7) (Beever III, Walker, and Kammerer 2017a). The maximum of MEOW (MoM) is widely used to identify hurricane affected areas. Maximum Envelope of Water (MEOW) is used to find the worst case basin snapshot for a particular storm category (*National Oceanic and Atmospheric Administration* 2020). It considers forward speed, trajectory, and initial tide to forecast a landfall location (*National Oceanic and Atmospheric Administration* 2020). In this model, the whole city falls under evacuation zones (*City of Cape Coral: Open Data Portal* 2016) (figure 11).

The most recent measurement (2016) showed that sea level rise near Cape Coral was 2.85 mm per year (Beever III, Walker, and Kammerer 2017a). In 2007, IPCC projected three different probabilities of sea level rise from the year 2020 to 2050 in the Atlantic Ocean near Florida (Beever III, Walker, and Kammerer 2017b). They were: least case (13 cm) (90% probability), moderate case (23 cm) (50% probability), and worst case (41 cm) (5% probability) (Beever III, Walker, and Kammerer 2017b). The projection was higher in the latest IPCC draft Assessment Report (AR) in 2019

(Oppenheimer et al. 2019). The final Assessment Report 6 will publish the new projection of sea level rise (Oppenheimer et al. 2019).

In this study, I considered the USACE projection because it focuses on regional scales, mainly in the United States, whereas IPCC covers global scales. USACE projected that sea level rise could be as high as 1.5 ft in Fort Myers by 2050 (figure 13), which is only 9 miles away from Cape Coral and on other side of the Caloosahatchee River (*Sea-Level Change Curve Calculator (Version 2019.21)* 2019).

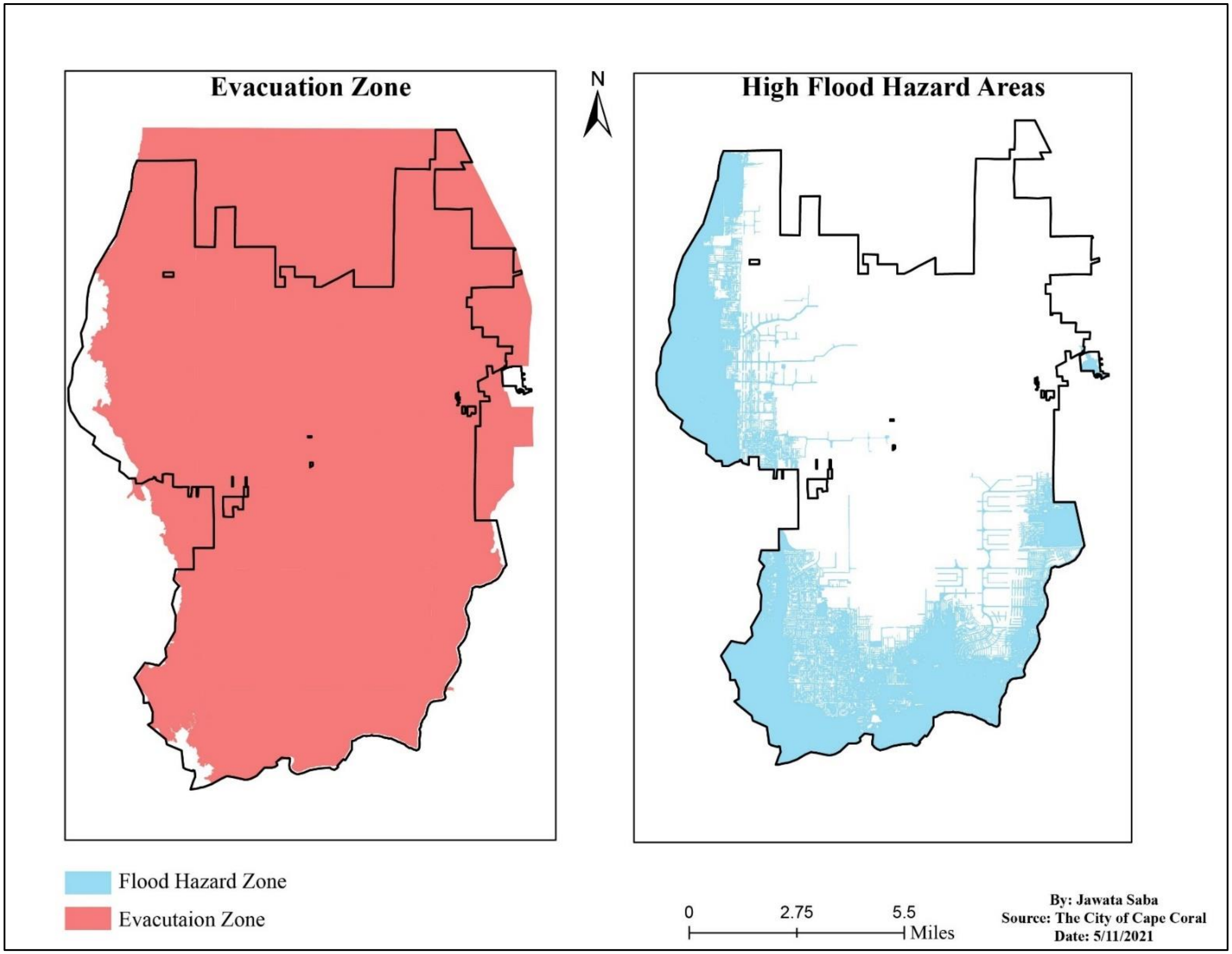

Figure 11: Evacuation zones and high hazards areas in Cape Coral.

Table 5: Areas projected to be affected by different categories of storm surge.

North/Northwest Storm Surge		East/Northeast Storm Surge		North/Northeast Storm Surge		West/Southwest Storm Surge	
Storm Surge Category	% of the city affected	Storm Surge Category	% of the city affected	Storm Surge Category	% of the city affected	Storm Surge Category	% of the city affected
1	30.63	1	33.27	1	33.38	1	17.66
2	83.63	2	86.64	2	87.28	2	23.73
3	99.93	3	99.82	3	99.97	3	46.64
4	99.99	4	100	4	100	4	77.54
5	99.996	5	100	5	100	5	88.63
Not in surge zone	0.004	Not in surge zone	N/A	Not in surge zone	N/A	Not in surge zone	19.54

Source: modified from (Beever III, Walker, and Kammerer 2017a)

Table 6: Acres of land at and below different sea level rise elevations in the city of Cape Coral.

Area Affected by Different Levels of Sea Level Rise			
Increase in Sea Level (in feet)	Acres of the City of Cape Coral Affected	Cumulative Acres Affected	Percentage of the City
1	7,053.70	7,053.70	10.01%
2	2,297.58	9,351.28	13.27%
3	1,578.96	10,930.25	15.51%

Source: modified from (Beever III, Walker, and Kammerer 2017a)

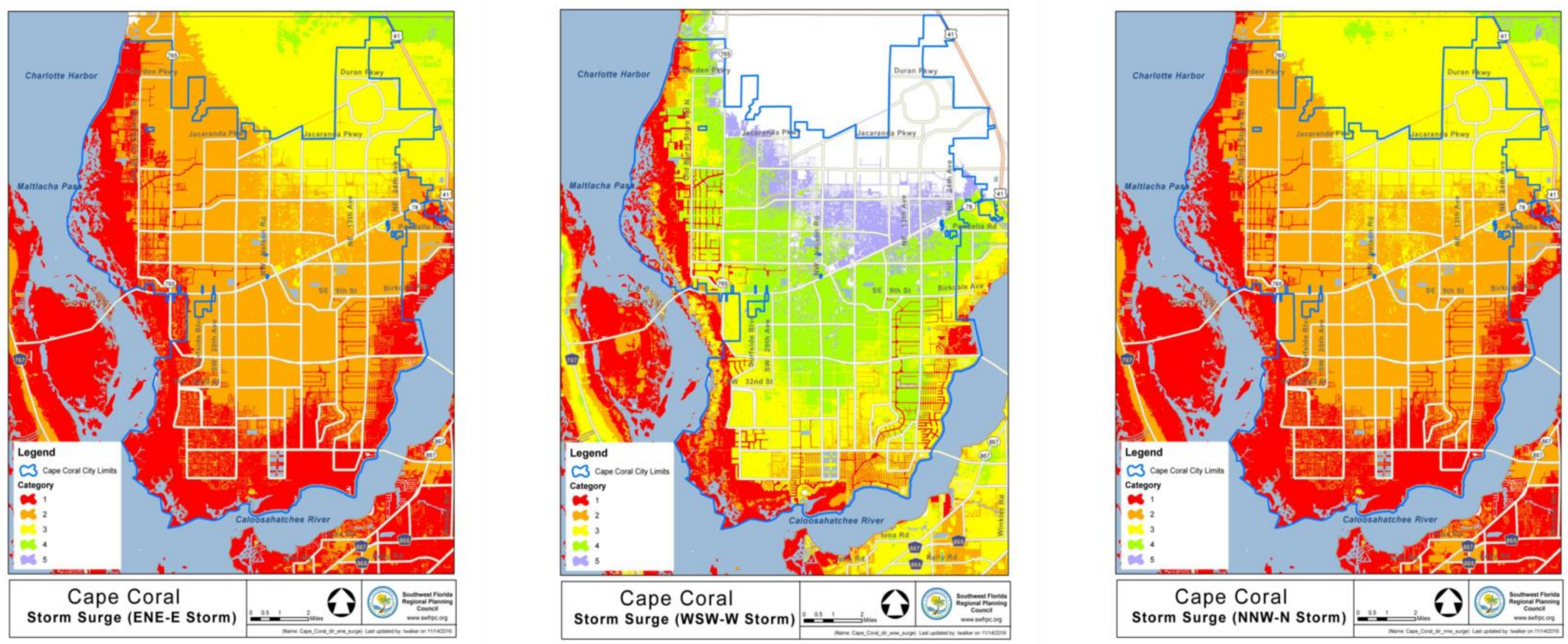

Figure 12: Affected Area for different storm surges; source: (Beever III, Walker, and Kammerer 2017a).

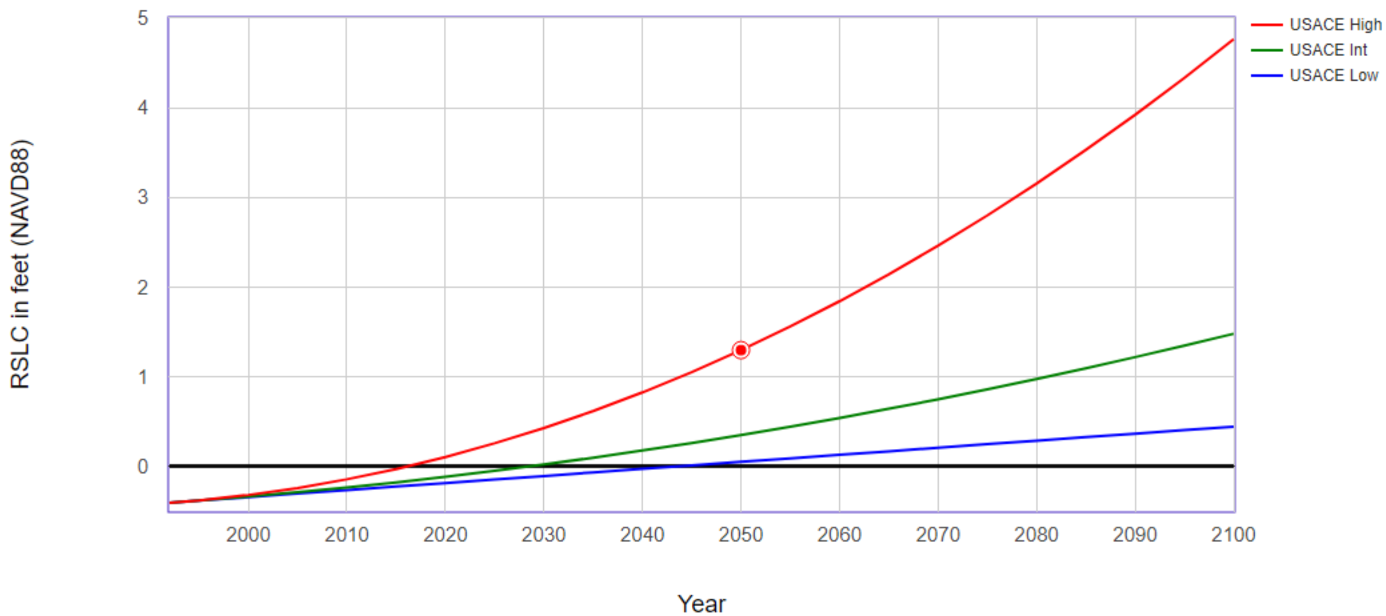

Figure 13: Estimated Relative Sea Level Change Projections, Fort Myers, Florida, source (Sea-Level Change Curve Calculator (Version 2019.21) 2019).

Table 7:Storm surge affected area in Cape Coral based on Maximum of MEOW (MoM).

Storm Surge Category	Cumulative Areas in Cape Coral affected (in Acres)	Cumulative Percentage
Tropical Storm	16,901	22
Hurricane Category 1	24,524	33
Hurricane Category 2	66,257	87
Hurricane Category 3	76,151	99
Hurricane Category 4	76,232	99
Hurricane Category 5	76,234	100

Source: modified from (Beever III, Walker, and Kammerer 2017a)

3.5. Conclusion

Cape Coral is growing in terms of population, real estate, number of businesses, and tourism. Like most other coastal cities of Florida, the economy of Cape Coral is based on real estate, tourism, and water-based recreation. Damage from coastal disasters has brought significant financial loss to the city. Real estate and tourism businesses do not want to incur losses that result from sea level rise on the properties they sell. When people have to pay more to own the risks, the decision of where and how they live will undoubtedly change (Goodell 2017).

Rapid growth can cause harm to naturally sensitive areas. Initially, the City of Cape Coral had 140,000 lots (Stroud 1991), and the number is increasing. In 2016, the city had 268,000 lots, and a future land use plan showed that the city would add 5,000 more lots (*City of Cape Coral: Open Data Portal* 2016). Cape Coral is sensitive in many aspects because of its geographic location, physical geography, ecology, landscape, weather and climate, and demographic conditions. While these factors individually play a crucial role in the vulnerability to coastal disasters, together, they can cause severe damage to the city. In the next chapter, I will estimate inundation areas and create a Coastal Vulnerability Index (CoVI) for Cape Coral.

CHAPTER 4: METHODS

4.1. Introduction

I used mixed methods (two different methods) to achieve the two objectives of my research. As noted in chapter 1, this study has two parts 1) estimating and mapping inundated area from future sea level rise (2020-2050) and 2) building a Coastal Vulnerability Index (CoVI) for the City of Cape Coral. I used the Sea Level Rise Calculator add-in tool to achieve the first objective and Principal Component Analysis (PCA) to attain the second objective. Here I will discuss the methods used to accomplish these two tasks.

4.2. Estimation and mapping of inundated area

4.2.1. Sea level rise Scenario Sketch Planning Tool

4.2.1.1. Introduction

I used the Sea Level Rise Scenario Sketch Planning Tool to estimate the future inundated area in Cape Coral. Since my research objective was not to make an inundation model, I used an existing suitable model. A group of researchers from the GeoPlan Center, at the University of Florida developed the Sea Level Rise Scenario Sketch Planning Tool in collaboration with the Florida Department of Transportation (FDOT), the National Oceanic and Atmospheric Administrative (NOAA), and the U.S. Army Corps of Engineers (USACE) (Thomas et al. 2013). The sketch planning tool consists of a set of three tools: 1) A map viewer, 2) The output modeled data layers (inundation surfaces and affected infrastructure), and 3) Sea Level Change Inundation Surface Calculator for creating custom inundation surfaces. Users can use these tools independently or together in assessing the potentially flooded area (Thomas et al. 2013).

I used the third tool (Sea Level Change Inundation Surface Calculator) for creating custom inundation surfaces.

Sea Level Change Inundation Surface Calculator (also known as the SLR calculator) is an ArcGIS 10.4 add-in toolbar for creating custom inundation surfaces for sea level rise. It allows users to choose one of the three USACE projected sea level rise curves (low, intermediate, and high), a time period (as a decade between 2020-2100), a single tide station (in Florida), and a Digital Elevation Model (DEM) layer (Thomas et al. 2013). The outputs include (1) a bathtub inundation surface, (2) a refined inundation surface with hydrologic connectivity filter run (optional), and (3) a depth of inundation surface (Thomas et al. 2013). Inundation surfaces can be output as rasters (grids) or shapefiles (Thomas et al. 2013). The SLR calculator tool requires ArcGIS software, advanced technical skill, and GIS expertise (Thomas et al. 2013). With this tool, users can create a more refined inundation surface using a DEM with a higher horizontal resolution (Thomas et al. 2013). The tool has been designed for higher capacity planning organizations that have a high level of technical expertise and desire to create their inundation surfaces and run analyses of vulnerable infrastructure using their local data (Thomas et al. 2013).

4.2.1.2. Function

The SLR Calculator tool is an interactive framework of GIS-based components. It incorporates standardized spatial data input layers including, but not limited to, scale-appropriate topographic data, USACE sea level change projections, NOAA tide station data, tidal datums, FDOT-derived data from the Roadway Characteristics Inventory (RCI), Strategic Intermodal System (SIS), and the Unified Basemap Repository (UBR)

(Thomas et al. 2013). Tidal datums include Mean Lower Low Water (MLLW), Mean Low Water (MLW), Mean Sea Level (MSL), Mean High Water (MHW), and Mean Higher High Water (MHHW). These input layers are the foundation for creating an inundation scenario for future sea level rise. The output map layer shows the portion (square miles or area) of the map that would potentially inundate in the future for sea level change.

MHHW is the average of the higher high water heights of each tidal day observed over the National Tidal Datum Epoch (NTDE), and MHW is the average of all the high water heights observed over the NTDE (*Tide & Currents, NOAA* 2021). "NTDE is a 19-year time period established by the National Ocean Service for collecting observations on water levels and calculating tidal datum values (e.g. mean sea level, mean lower low water)" (*National Tidal Datum Epoch, NOAA* 2021). MSL is the arithmetic mean of hourly heights observed over the NTDE (*Tide & Currents, NOAA* 2021). MLW is the average of all the low water heights observed over the NTDE, and MLLW is the mean of the lower low water height of each tidal day observed over the NTDE (*Tide & Currents, NOAA* 2021).

The University of Florida GeoPlan Center compiled sea level rise projection values from 1992 to 2100 using the USACE projection curve calculator that has been built on the specific formula of USACE engineer curricula and the National Research Council (NRC) publication - Responding to Changes in Sea Level: Engineering Implications (1987) (Thomas et al. 2013). Sea level rise projection rates were calculated based on the rate of sea level change such as historic, intermediate (curve II), and high (curve III) (Thomas et al. 2013). The historic projection is a linear rate of change assuming a continuation of rates of sea level change reported by NOAA (Thomas et al. 2013). Intermediate and high projected rates were derived from scenarios originally developed by the NRC and modified by the USACE to account for the most recent Intergovernmental Panel on Climate Change (IPCC) projections and the local rate of vertical land movement (i.e. relative sea level rise) (Thomas et al. 2013). The rate for the USACE Intermediate Curve was computed from the modified NRC Curve II considering both the most recent IPCC projections and modified NRC projections with the local rate of vertical land movement (Thomas et al. 2013). The rate for the USACE High Curve has been computed from the modified NRC Curve III considering both the most recent IPCC projections and modified NRC projections with the local rate of vertical land movement (Thomas et al. 2013).

The GeoPlan center obtained sea level rise trend data from NOAA tide gauges data (Thomas et al. 2013). Fourteen tide gauge locations (table 8) were used that met the 40-year minimum data record as per the guidance of the USACE. The 40-year period covers two tidal epochs (NTDE) that minimize error in calculating mean sea level trends (Thomas et al. 2013). A 19-year time period is considered the official time range over which tide observations and mean values for datums has been calculated. Using NOAA tidal station data, future sea levels can be adjusted based on revised sea level change projections and tidal datums (Thomas et al. 2013).

4.2.1.3. Hydro-connectivity

The SLR calculator tool uses two connectivity approaches 1) the bathtub model and 2) the hydro-connectivity model. In the bathtub approach, to calculate the inundation, land elevation is subtracted from water elevation, with the difference indicating the presence or absence of inundation (Thomas et al. 2013; Poulter and Halpin 2008). In this model, a grid cell floods if its elevation is less than the water level and neighboring cells irrespective of the connection to the neighboring cells (Poulter and Halpin 2008). It is also called the zero side rule or static model as hydrological connectivity to neighboring cells is not considered in this approach (Poulter and Halpin 2008).

Hydro-connectivity considers hydrological connections in a terrain. The hydro-connectivity model includes rivers, canals, estuaries, bays, and other water bodies that directly connect to open water (Thomas et al. 2013). The hydro-connectivity model is based on two rules, such as the four-sided rule and the eight-sided rule. In each approach, a grid cell floods if its elevation is less than the water level, and it is connected to the neighboring cells either by its four sides or eight sides (Poulter and Halpin 2008).

4.2.2. Estimation of Flooded area in Cape Coral

I collected the required data to estimate the inundated areas from different sources. I used the DEM of Cape Coral from NOAA (*Data Access Viewer*) (table 9 and 10). I collected the required shapefiles (table 9) of the City of Cape Coral form an open data website of Cape Coral (*City of Cape Coral: Open Data Portal* 2016).

Table 8: Florida tidal stations details, the tidal data of these stations have been used in SLR calculator formation (I used the tidal data of Fort Myers since it is closest to Cape Coral).

Station	**Station ID**	**Year established**	**Mean SLC trend (mm/yr)**
Apalachicola	8728690	1967	1.38
Cedar key	8727520	1914	1.8
Clearwater Beach	8726724	1973	2.43
Daytona Beach Shores	8721120	1925	2.32
Fernandina Beach	8720030	1897	2.02
Fort Myers	8725520	1965	2.4
Key West	8724580	1913	2.24
Mayport	8720218	1928	2.29
Miami Beach	8723170	1931	2.39
Naples	8725110	1965	2.02
Panama City	8729108	1973	0.75
Pensacola	8729840	1923	2.1
St. Petersburg	8726520	1947	2.36
Vaca Key	8723970	1971	2.78
Virginia Key	8723214	1994	2.39

Source: modified from (Thomas et al. 2013)

I used ArcGIS 10.4 because the latest SLR Calculator was designed as an add-in tool for 10.4, and it is crucial to use the same version. Though the SLR model itself has a

DEM of Florida, I used the higher resolution DEM from NOAA. I used the Fort Myers tidal station (table 8) since it was the closest station for Cape Coral. I then used one of the three USACE projected curves (low, intermediate, or high), a time period (such as a decade between 2020-2100), a single tide station (Fort Myers), tide gauge data (MHHW, MHW, MSL, MLLW, or MLW), and a DEM (table 9 and 10) layer to generate an output inundation surfaces.

4.3. Creating a Coastal Vulnerability Index (CoVI)

In this research, I created a CoVI for the City of Cape Coral. The CoVI is a modified version of the Social Vulnerability Index (SoVI) developed by Cutter, Boruff, and Shirley (2003). Primarily, I built CoVI by following the method of SoVI (Cutter, Boruff, and Shirley 2003). Many scientists have modified the original SoVI and applied it in many places and contexts (Cutter and Finch 2008; Aksha et al. 2018; Aksha et al. 2020). I named the vulnerability index a Coastal Vulnerability Index (CoVI), because I used coastal features (such as elevation and hazard prone areas) of Cape Coral to explain socio-economic vulnerability and future vulnerability of people. There are other Coastal Vulnerability Index exist, but they are different from my study.

SoVI measures vulnerability to environmental hazards. I am taking the idea to the next level by developing a vulnerability index specific to a coastal city. CoVI is more suitable for coastal cities than the SoVI for several reasons. First, since CoVI is an index for a coastal city it considers specific variables that are important and prevalent only in coastal cities. Second, CoVI aims to measure vulnerability for a specific disaster, that is inundation from sea level rise. Finally, the projected inundation from sea level rise is embedded within CoVI to see the future vulnerability of the place.

Table 9: Sources of data and their description.

Data	Source	Raster/Vector	Projection
DEM	National Oceanic and Atmospheric Administration	Raster	NAD_1983_StatePlane_Florida_West_FIPS_0902_Feet
City Boundary Shapefile	City of Cape Coral: Open Data Portal	Vector	NAD_1983_StatePlane_Florida_West_FIPS_0902_Feet
Canal Network Shapefile	City of Cape Coral: Open Data Portal	Vector	NAD_1983_StatePlane_Florida_West_FIPS_0902_Feet
Costal High Hazard area	City of Cape Coral: Open Data Portal	Vector	NAD_1983_StatePlane_Florida_West_FIPS_0902_Feet
Zoning shapefile	City of Cape Coral: Open Data Portal	Vector	NAD_1983_StatePlane_Florida_West_FIPS_0902_Feet
Major Streets	City of Cape Coral: Open Data Portal	Vector	NAD_1983_StatePlane_Florida_West_FIPS_0902_Feet
Lots	City of Cape Coral: Open Data Portal	Vector	NAD_1983_StatePlane_Florida_West_FIPS_0902_Feet

Future Land Use plan	City of Cape Coral: Open Data Portal	Vector	NAD_1983_StatePlane_Florida_West_FIPS_0902_Feet
Evacuation zones	City of Cape Coral: Open Data Portal	Vector	NAD_1983_StatePlane_Florida_West_FIPS_0902_Feet
Building permits	City of Cape Coral: Open Data Portal	Vector	NAD_1983_StatePlane_Florida_West_FIPS_0902_Feet

Table 10: Description of DEM.

Parameters	**Information**
Source	National Oceanic and Atmospheric Administration (NOAA)/ Florida Geographic Data Library
Cell size (x, y)	5 m, 5 m
Pixel type	Signed integer
Pixel depth	16 bit
Datum	D_North_American_1983_HARN
Spatial Reference	Albers Conical Equal Area
Projection	NAD_1983_StatePlane_Florida_West_FIPS_0902_Feet

4.3.1. Method of Constructing the CoVI

This section discusses how I built the CoVI. First, I selected 25 variables for Cape Coral. Second, I collected data for the variables at the tract level from the American Community Survey. Third, I conducted a factor analysis with PCA in SPSS software to reduce the 25 variables to six factors. Fourth, I fixed cardinality for factors. Fifth, I put the scores of factors in an additive model to generate CoVI. Finally, I mapped the CoVI in ArcGIS based on the standard deviation from the mean.

4.3.1.1. Variables

I considered a set of 25 variables, which included relevant social, economic and housing variables for Cape Coral, to create CoVI (table 11). Though I started with the list of variables from Cutter and Colleagues (Cutter, Boruff, and Shirley 2003) I introduced new variables important for Cape Coral. For example, I introduced a new variable, 'percent vacant house', because Cape Coral had a higher percentage of vacant housing units than the national average. A vacant house can be intended for sale, rent, or occasional use. It can be temporarily occupied by persons with a usual residence elsewhere (Understanding and Using American Community Survey Data: What All Data Users Need to Know 2020). Many of the vacant houses were intended for temporary use in Cape Coral as Florida has been receiving a large influx of seasonal migrants every year (Crossett et al. 2004). I did not include the percent of Native Americans (which was included in the study of (Cutter, Boruff, and Shirley 2003)) because the percentage of Native Americans was zero in most of the tracts. The same applies to the percentage of people who work in the extractive industry. I have used other variables such as total population, population growth rates, future land use, canal networks to analyze and interpret the results. I did not include these variables in the factor analysis.

4.3.1.2. Data Collection

I collected the socio-economic and demographic data from the American Community Survey (ACS) 5-year estimates (*United States Census Bureau* 2021) (table 11). There are three types of ACS estimates, a 1-year estimate, 3-year estimate, and 5-year estimate. The ACS 3-year estimate was discontinued after 2013 (Understanding and Using American Community Survey Data: What All Data Users Need to Know 2020). I decided to use the 5-year estimate for several reasons. First, the 5-year estimate is preferred when a detailed investigation of the area or population is required because it uses a larger sample size (Understanding and Using American Community Survey Data: What All Data Users Need to Know 2020). Second, the sample size of the data is the largest (Understanding and Using American Community Survey Data: What All Data Users Need to Know 2020). Third, the reliability of the data is high compared to the 1-year estimate (Understanding and Using American Community Survey Data: What All Data Users Need to Know 2020). On the other hand, the 1-year estimate is more current but less reliable than the five year estimates (Understanding and Using American Community Survey Data: What All Data Users Need to Know 2020). The recent ACS 5-year estimate was collected over 2015-2019, so the data were up to date. I did not use the decennial census because the data were not up to date. Since my study investigated the vulnerability of people from 2020 to 2050, the data collected over the period from 2015-2019, served the purpose of my research very well.

I considered the census tract as the smallest geographic unit for analysis. The City of Cape Coral has 34 census tracts. "Census tracts are the small and relatively permanent statistical subdivision of counties, delineated by a local committee of census data users for presenting data. They nest within counties, and their boundaries usually follow visible features. They ideally contain 4,000 people and 1,600 housing units, and may also follow legal geographic boundaries and other nonvisible features" (Understanding and Using American Community Survey Data: What All Data Users Need to Know 2020).

4.3.1.3. Factor Analysis and Principal Component Analysis (PCA)

Factor analysis refers to statistical techniques whose common objective is to represent a set of variables in terms of a smaller number of hypothetical variables, known as factors. Factors must be smaller than the number of observed variables, and they are responsible for the covariation among the observed variables. The analysis involves an examination of the inter-relationship among the variables (Kim and Muller 1978).

Principal Component analysis (PCA) is one kind of factor analysis. PCA is a multivariate technique that analyzes a dataset in which observations can be explained by several inter-correlated quantitative dependent variables. Its primary purpose is to extract the important information from the dataset, represent it as a set of new variables called principal components, and display the pattern of similarity or correlations of the observations and the variables in maps (Abdi and Williams 2010). PCA is an appropriate tool for this research for several reasons. First, this is a factor reduction technique that allows reduction of a large number of variables into a smaller set of hypothetical variables (Kim and Muller 1978). For example, in this research, PCA reduced 25 variables to six factors. Second, it allows users to see the correlation among the variables, which is very important in my research. It shows how variables are correlated to other variables (positively or negatively) and contribute to vulnerability (Abdi and

Williams 2010). Third, it creates a robust set of variables that can be monitored and updated with the up-to-date data to assess the vulnerability over time (Cutter, Boruff, and Shirley 2003). Finally, it allows a user to display the correlation of factors and variables in a map (Abdi and Williams 2010).

First, I placed the data for each tract into an Excel spreadsheet I then prepared the data for analysis by normalizing (percentages, per capita values, and density functions), if the original data were not in standard format (Cutter, Boruff, and Shirley 2003). It is important to avoid missing values because statistical analyses do not run properly with missing values. Missing values can be replaced with a mean (Bloomberg 2009; Cutter, Boruff, and Shirley 2003). I did not have any missing values as I was able to collect data for all the variables for each tract.

I conducted a factor analysis with PCA to analyze the Cape Coral's social, economic, and housing conditions. I used IBM SPSS 26 software to perform PCA. The data in the Excel spreadsheet were uploaded in SPSS in the data view. The variable view of SPSS was loaded with variables, their types, and descriptions. A factor analysis with PCA and a varimax rotation (100 iterations) was performed (Cutter, Boruff, and Shirley 2003; Aksha et al. 2018). This procedure reduces a large number of variables to a much smaller and more manageable number of independent factors that explain the most variance among the data (Kim and Muller 1978).

Table 11: List of Variables.

Serial No	Variable type	Variable name	Variable description	Source	Variable increases/decreases vulnerability (+/-)
1	Demographic	QASIAN	Percent Asian	ACS 5-year estimate Table ID: DP05	-
2	Demographic	QBLACK	Percent African American	ACS 5-year estimate Table ID: DP05	+
3	Demographic	QHISP	Percent Hispanic	ACS 5-year estimate Table ID: DP05	+
4	Demographic	QCHILD	Percent Population under 5 years	ACS 5-year estimate Table ID: DP05	+
5	Demographic	QAGEDEP	Percent Population 65 and over	ACS 5-year estimate	+
6	Demographic	QFAM	Percent Children Living in 2-parent families	ACS 5-year estimate Table ID: B23008	-
7	Demographic	MEDAGE	Median Age	ACS 5-year estimate Table ID: DP05	

8	Economic	QSSBEN	Percent Households/families Receiving Social Security Benefits	ACS 5-year estimate Table ID: S1902	-
9	Economic	QPOVTY	Percent Poverty	ACS 5-year estimate Table ID: S1701	+
10	Economic	QRICH	Percent Households Earning over $200,000 annually	ACS 5-year estimate Table ID: S1901	-
11	Social	PERCAP	Per Capita Income	ACS 5-year estimate Table ID: B19301	-/+
12	Demographic	QESL	Percent Speaking English as a Second Language with Limited English Proficiency	ACS 5-year estimate Table ID: S1601	+
13	Social	QFEMALE	Percent Female	ACS 5-year estimate Table ID: DP05	-
14	Social	QFHH	Percent Female Headed Households	ACS 5-year estimate Table ID: S2302	+
15	Social	QNOHLTH	Percent of population without health insurance	ACS 5-year estimate Table ID: S2701	+
16	Economic	QED12LES	Percent with Less than 12th Grade Education	ACS 5-year estimate Table ID: S2301	+

17	Economic	QCVLUN	Percent Civilian Unemployment	ACS 5-year estimate Table ID: DP03	+
18	Housing	QRENTER	Percent Renters	ACS 5-year estimate Table ID: DP04	+
19	Housing	MDHSEVAL	Median Housing Value	ACS 5-year estimate Table ID: B25077	-
20	Housing	MDGRENT	Median Gross Rent	ACS 5-year estimate Table ID: DP04	+
21	Housing	QMOHO	Percent Mobile Homes	ACS 5-year estimate Table ID: DP04	+
22	Economic	QSERV	Percent Employment in Service Industry	ACS 5-year estimate Table ID: DP03	-/+
23	Economic	QFEMLBR	Percent Female Participation in Labor Force	ACS 5-year estimate Table ID: S2401	-
24	Housing	QNOAUTO	Percent of Housing Units with No Car	ACS 5-year estimate Table ID: DP04	+
25	Housing	QVAC	Percent Vacant Housing Units	ACS 5-year estimate Table ID: DP04	-/+

The rule for deciding how many factors should be kept after the PCA is debatable. Three rules are commonly used: the Kaiser rule or the eigenvalue criterion, scree plot, and the proportion of variance explained. The common and most acceptable rule is the Kaiser rule or the eigenvalue criterion (Kim and Muller 1978). The eigenvalue criterion encourages the researcher to keep all the factors whose eigenvalues are greater than 1. Scree plot is another way to extract factors. Users can examine the scree plot for significant drops in the eigenvalue as the number of components included in the analysis increases. While some disjoint in the scree is anticipated (such as those that occur between the first few components), subsequent decreases in eigenvalue indicate appropriate thresholds for factor extraction (Cutter, Boruff, and Shirley 2003). In another way, users can keep the factors that appear before the elbow. For example, the number is three for this study (figure 15). In the proportion of variance explained method, users can keep the number of factors that describe at least two-thirds variance of the data. In this research, I checked all three rules for the data and decided to use the eigenvalue rule for factor extraction. The scree plot (figure 15) suggested only three factors that explained only 61% variance of the data. According to the Kaiser rule or the eigenvalue criterion, I kept six factors that had an eigenvalue greater than 1 (table 12 and figure 15); these six factors explained 78 % of the variance (table 12) in the data.

A Varimax rotation was employed in the PCA to make the data simpler and make the results more interpretable. Rotated factor solutions explain exactly as much covariation in the data as the initial solution (Kim and Muller 1978). They simplify the solution by removing the stipulations that the first factor has to account for as much variance as possible; the second factor must account for as much of the residual variance left unexplained by the first factor, and so on (Kim and Muller 1978).

The next task was assigning names for factors. Factors were named according to the variables with significant factor loadings (or correlation coefficients) (table 12) (Cutter, Boruff, and Shirley 2003). Factor loading is the correlation coefficient for the variable and factor. Factor loading shows the variance explained by the variable on that particular factor. Usually, loading values greater than .700 or less than -.700 are considered significant, but in some cases, Cutter and colleagues (2003) examined factor loading from greater than .500 and less than-.500.

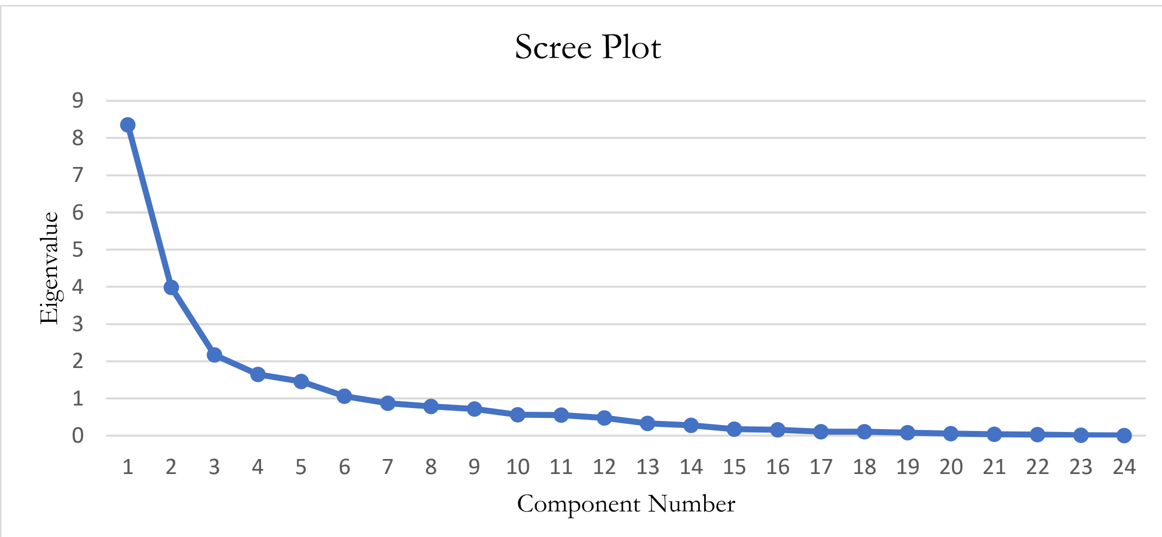

Figure 14: Scree Plot; first six factors having eigenvalue greater than 1remained.

4.3.1.4. Adjusting cardinality

Next, a directional adjustment (or cardinality) was applied to all the factors to ensure that the signs of the subsequent defining variables were appropriately describing the tendency of the phenomena to increase or decrease vulnerability (Cutter, Boruff, and Shirley 2003). For example, Factor 1 was named Age because it was heavily loaded on age variables (table 13). Factor 1 is positively correlated with older adults (increases vulnerability), median age, percent receiving social security income (decreases vulnerability), and percent vacant housing (increases/decreases vulnerability). To fix the cardinality in this case, I considered that factor 1 would increase overall vulnerability because the elderly population in Cape Coral has been vulnerable to coastal hazards in many ways. First, older people have less mobility, and many require intensive health care. Specific and intensive health care may become inaccessible during a disaster event. Second, older people may have some disability or physical dependency which may hinder a quick evacuation during an emergency evacuation. Though sea level rise is a long term, slowly increasing (chronic) condition, acute events (hurricane storm surge) can be exacerbated by sea level rise. Third, they receive social security income, and they are not currently in the labor force, which has been indicated by a negative correlation with the employment factor. Many older people own expensive houses in Cape Coral. Though wealth is considered to decrease vulnerability it can also increase vulnerability. For example, owners of expensive residential properties cannot easily escape as renters do (Cutter, Boruff, and Shirley 2003). Finally, flooding can lower the value of their house, which may cause financial loss to them. I, therefore, assigned a positive cardinality (meaning that it increases vulnerability) to factor 1 as it would overall increase the vulnerability. When the sign of the loading value (whether positive or negative correlation) creates confusion, it is recommended to look into the values only (Cutter, Boruff, and Shirley 2003).

Factor 2 was named Race because it was positively correlated with the Hispanic population, African American population, and people who speak English with limited proficiency, which increase vulnerability. It correlated negatively with wealth variables such as median housing value, households earning over $ 200,000 annually, and per capita income, so the factor scores on this dimension should be positive, meaning that factor 2 would increase overall vulnerability. Factor 2 was multiplied by +1 to represent the factor's tendency to increase social vulnerability (Cutter, Boruff, and Shirley 2003). The cardinality of factors 3, 4, and 5 was assigned positive likewise as these factors increased vulnerability (table 13).

Factor 6 was labeled Ethnicity because it was heavily loaded (positively correlated) with Asians and the Asian American population. Though ethnicity can increase vulnerability (noted in chapter 2), I have assigned a negative cardinality because the census data shows that Asian people in Cape Coral work in the skilled labor force, and many earned over $200,000 annually. Therefore, this factor has been reducing vulnerability. The factor score's dimension, in this case, must be negative (table 13). Factor 6 was multiplied by -1 to represent the factor's tendency to decrease social vulnerability (Cutter, Boruff, and Shirley 2003).

4.3.1.5. CoVI scores and mapping

The new component scores were saved in a separate file. I calculated a new variable named CoVI by placing all the components with their directional adjustments into an additive model to generate the overall CoVI score. An additive and equal weighting approach (Cutter, Boruff, and Shirley 2003; Aksha et al. 2018) has been used to generate CoVI because of the absence of empirical and justifiable evidence for weighting components (Aksha et al. 2018).

CoVI score = Factor 1+ Factor 2+ Factor 3+ Factor 4+ Factor 5- Factor 6 (Cutter, Boruff, and Shirley 2003)

I then mapped CoVI scores using ArcGIS 10.4.1, an objective classification (such as quantiles and standard deviations) with 3 to 6 divergent classes to illustrate areas of high, medium, and low vulnerability (Cutter, Boruff, and Shirley 2003). Usually, 1.5-2 standard deviations from the mean were used (Cutter, Boruff, and Shirley 2003).

Table 12: The Eigenvalue and the proportion of variance explained.

Component	**Initial Eigenvalues**			**Extraction Sums of Squared Loadings**		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	8.358	34.825	34.825	8.358	34.825	34.825
2	3.985	16.604	51.429	3.985	16.604	51.429
3	2.175	9.061	60.490	2.175	9.061	60.490
4	1.644	6.850	67.340	1.644	6.850	67.340
5	1.454	6.060	73.400	1.454	6.060	73.400
6	1.062	4.425	77.825	1.062	4.425	77.825
7	0.870	3.625	81.450			
8	0.790	3.291	84.741			
9	0.715	2.981	87.722			
10	0.566	2.358	90.080			
11	0.550	2.293	92.373			
12	0.475	1.979	94.353			

Table 13: Principal Component and Cardinality.

Principal Component	**Cardinality**	**Name the Factor**	**% Variance Explained**	**Dominant Variables**	**Variables**	**Component Loading**
1	Plus (+)	Age	35	Median Age	Median Age	0.883
					Percent Population below 5 and 65 and over	0.869
					Percent Households Receiving Social Security Benefits	0.79
					Percent Vacant Housing Units	0.74
					Percent Employment in Service Industry	-0.53
2	Plus (+)	Race	17	Percent Hispanic	Percent Hispanic	0.761
					Median Housing Value	-0.76
					Percent Households Earning over $200,000 annually	-0.752
					Per Capita Income	-0.72
					Percent African American	0.64
					Percent Speaking English as a Second Language with Limited English Proficiency	0.579

3	Plus (+)	Health	9	Percent of population without health insurance	Percent of population without health insurance	0.772
					Percent Renters	0.762
					Percent Children Living in 2-parent families	-0.703
					Percent Poverty	0.68
					Percent Female Headed Households	0.59
4	Plus (+)	Mobile Homes	7	Percent Mobile Homes	Percent Mobile Homes	0.939
					Percent with Less than 12th Grade Education	0.866
					Percent Civilian Unemployment	0.566
5	Plus (+)	Gender	6	Percent Female	Percent Female	0.937
					Percent Female Participation in Labor Force	0.689
6	Minus (-)	Ethnicity	4	Percent Asian	Percent Asian	0.753
					Median Gross Rent	-0.724
			Total 78 % variance explained			

4.3.1.6. Suitability of data for PCA

The sample size of my study is small, because the City of Cape Coral has only 34 census tracts. It is beneficial to have a large sample size to conduct a PCA analysis. I used PCA though I have a small sample size, because PCA has been a widely used technique to analyze socio-economic and demographic data. Cutter, Boruff, and Shirley (2003) used PCA to create the SoVI by using more than 3,000 U.S. counties. Others used the same methodology (Aksha et al. 2018; Aksha et al. 2020; Bloomberg 2009), usually with a large sample size and none of them discussed minimum sample sizes.

Many scientists who conducted vulnerability analysis at the local level used different methods. They did not look at the social and demographic status of people. For example, Conyers and colleagues (2019) created a vulnerability index for Miami Beach, Florida. They considered vulnerability a city's readiness and exposure to Sea Level Rise (Conyers, Grant, and Roy 2019) based upon physical attributes of the city. Some of the attributes of readiness to adapt to sea level rise include seawalls, green buildings, artificial reefs, mangrove forest, stormwater drainage, dune restoration locations, monument locations, and seagrass bed as readiness to sea level rise, and elevation, distance from the coastline, and used Federal Emergency Management Agency (FEMA) flood zone maps to determine the city's exposure to sea level rise.

I wanted to examine the socio-economic condition of the people, so I followed the SoVI method developed by Cutter, Boruff, and Shirley (2003) that created a vulnerability index from socio-economic factors. I examined the socio-economic condition of the people because vulnerability is a function of both the demographic characteristics of the population (age, gender, race, ethnicity, income, employment, and so forth) and complex social structures (such as political power, social prestige, health care provision, social capital, access to life-saving services, and so on) (discussed in chapter 2) (Cutter and Emrich 2006; Cutter, Boruff, and Shirley 2003). Therefore, it is essential to understand the social and demographic conditions of populations to measure their vulnerability to an extreme natural event. The SoVI method is a solid and accepted method to measure vulnerability. The method can be applied to other countries by adjusting the variables. For example, the SoVI method has been applied to Nepal to measure the country's social vulnerability (Aksha et al. 2018) and vulnerability to natural hazards (Aksha et al. 2020).

There is a debate about the minimum sample size needed to conduct a valid PCA analysis. The sample size is a crucial factor to do a PCA. Early PCA research focused upon the benefits of using a large sample, and minimum sample sizes appeared in the literature (Gorsuch 1983). Later research found that samples could be as small as 50 or fewer and still produce good results (Comery and Lee 1992; de Winter, Dodou, and Wieringa 2009) . Though a large sample size is always beneficial for PCA, research opportunities should not be ignored because of the small sample size (de Winter, Dodou, and Wieringa 2009).

As PCA became more widely used, statisticians and scientists considered different ways to decide the minimum number of observations and how to best extract useful information when the sample size is small. These factors include the factor loadings (f), principal component or factor, number of variables, and ratio of sample size to the number of variables (n:p, where n is the number of observations and p is the number of variables). For example, some say that if the loading is as high as 0.9, it should not be a problem if the sample size is even below 30 (de Winter, Dodou, and

Wieringa 2009). Others say that users should consider one or two principal components when sample size is small. Three or more principal components are acceptable when the model has at least 24 variable (Comery and Lee 1992). Many scientists think that the number of observations should be larger than the number of variables or three times larger than the variable (de Winter, Dodou, and Wieringa 2009).

In this study, I checked the mentioned criteria for the data for the suitability of the PCA. The data for this study satisfied several criteria. The data should meet the requirements for the suitability of the PCA, but the literature does not say that the data should meet all the requirements. Instead, scientists should choose the criterion based upon on their data. In this study, I found high factor loading values for many variables (table 13). Since I have considered more than three factors, the data met the criterion of having minimum variables of 24 (table 11). The number of observations is also larger than the number of variables in this study.

Additionally, I have tested the data with the Kaiser-Meyer-Olkin (KMO) and Bartletts sampling adequacy test. Usually, if the result is 0.8, the data is considered suitable for PCA, but if the test result is close to 0.6 the data are also acceptable for PCA (Glen 2016). Some statisticians consider at least 0.5 as acceptable (Glen 2016). The test result of my data using the Kaiser-Meyer-Olkin (KMO) sampling adequacy test is 0.6. Recently, many scholarly publications have suggested that there should not be any absolute minimum for sample size (de Winter, Dodou, and Wieringa 2009). A smaller sample size can do PCA depending on the purpose of the research and other factors (de Winter, Dodou, and Wieringa 2009).

4.4. Spatial Autocorrelation

I tested the spatial autocorrelation of the vulnerability among the tracts. Spatial autocorrelation is the correlation among values of a single variable strictly attributable to their relatively close locational positions on a two-dimensional surface, introducing a deviation from the independent observations assumption of classical statistics (Griffith 1987). In other words, for a given variable, spatial autocorrelation entails the assessment of that variable in reference to the spatial location of the observational units. It measures the level, nature, and strength of interdependencies among the data points (or observational units) within the variable both in terms of space and the attribute under consideration (Plant 2019). I performed Global and Local Moran's I to test whether the CoVI was clustered or random across the city.

The global Moran's I test determines whether the result (vulnerability) exhibits a spatial pattern (Hatfield 2017; Aksha et al. 2018). Moran's I values close to +1 indicate strong positive spatial autocorrelation (Hatfield 2017) (clustering of either high or low values of coastal vulnerability), while values close to - 1 indicate strong negative spatial autocorrelation (Hatfield 2017) (alternation of high and low values for adjacent observations). Values near zero indicate the absence of spatial patterns or randomness (Hatfield 2017).

Local Moran's I shows any spatial association (Hatfield 2017) in the vulnerability pattern (Aksha et al. 2018). The Moran's I value is categorized into four categories (Hatfield 2017). The categories are as follows: 1)the High– High (HH) indicates a census tract with a high CoVI score surrounded by tracts with high CoVI scores; (2) Low–Low (LL) indicates tracts with a low CoVI score surrounded by tracts with low CoVI scores;

(3) High-Low (HL) indicates a tract with a high CoVI score surrounded by tracts with low CoVI scores; and (4) Low–High (LH) identifies tracts with a low CoVI score surrounded by tracts with high CoVI scores (Hatfield 2017; Aksha et al. 2018).

4.5. Conclusion

I initially planned to visit the City of Cape Coral to get a firsthand idea of the city's residents, visitors, and common lifestyles. I also planned to interview people to learn what they think about sea level rise. Unfortunately, I was unable to conduct that fieldwork because of the COVID-19 pandemic. I completed this research with available secondary data. In Chapter 5, I will discuss the results from the SLR calculator tool and CoVI and their interpretation.

CHAPTER 5: RESULTS AND INTERPRETATIONS

5.1. Introduction

My research has two parts (noted in chapter 1): 1) estimating inundated area from Sea Level Rise in Cape Coral and 2) and creating a Coastal Vulnerability Index (CoVI). In this chapter, I will discuss the results of these two parts and interpret them. This chapter is divided into two parts. In the first part, I discuss the results from the SLR calculator and interpret them. The second portion of the chapter is focused on interpreting the results from the principal component analysis.

5.2. Estimation of flooded areas in Cape Coral

I used the Sea Level Rise calculator (SLR calculator) tool to estimate flooded areas in Cape Coral for three sea level rise scenarios: low, medium, and high projected by USACE. The study shows flooding scenarios under five tidal datums: Mean Lower Low Water (MLLW), Mean Low Water (MLW), Mean Sea Level (MSL), Mean High Water (MHW), and Mean Higher High Water (MHHW). I considered the bathtub and hydro-connectivity approaches to estimate flooded areas.

The bathtub model projected that Cape Coral will flood during the 2020s. In this model, cells are flooded if their elevations are lower than the projected sea level. This model projected flooding for medium and high sea level rise. In each case, the flooding only occurred in MHHW and MHW tide levels, and no flooding was projected for other tide levels. In both cases, the flooded area was 3.53 sq km (1.36 sq mi). The hydro-connectivity model did not project any inundation under any tidal scenarios for the 2020s (Table 14).

The inundation scenario of the 2030s was almost identical to that of the 2020s. The bathtub model projected that the Cape Coral will flood under three projection scenarios (low, medium, and high). In this decade, flooding will occur in two tidal scenarios MHHW and MHW (figure 15). In each case, the flooded area remains the same (3.53 sq km) as in 2020 (figure 15). The hydro-connectivity model did not project any inundation for the 2030s (Table 14).

The inundation projection for the 2040s was similar to the 2030s. In the 2040s, inundation will occur in each sea level rise scenario MHHW and MHW tide levels, and the amount of inundated area remains the same as 2020 and 2030 (3.53 sq km) (Table 14) for each tidal level. The hydro-connectivity model did not project any flooding for the 2040s (Table 14).

The SLR calculator tool projected that in the 2050s, parts of the city will become inundated under both models. The bathtub model projected that more area would become inundated than the hydro-connectivity model projected (Table 14). The bathtub model usually projects more flooding than the hydro-connectivity model (Poulter and Halpin 2008). The hydro-connectivity model results in lower inundation estimates than the bathtub model because connections must actually exist in the hydro-connectivity model. Consequently the hydro-connectivity model has fewer connections between flooded cells, which decreased the area of the landscape that was flooded (Poulter and Halpin 2008). Hydrological connectivity allows water to pass around rather than flood low-elevation cells in front of and behind the obstructions, which the bathtub model permits (Poulter and Halpin 2008). The bathtub model projected inundation for low to high sea levels under two tide levels MHHW and MHW. The inundated area for the bathtub approach will be 5.2 sq km (2 sq mi). The hydro-connectivity model showed flooding for only high sea level and two tidal scenarios, the MHHW and MHW. In the hydro-connectivity model, no inundation was projected in other tide levels because areas below MHHW and MHW tidal datums are already subject to periodic inundation due to the normal action of tides. Both tidal scenarios projected the same amount of inundation, an area of 4.66 sq km (1.8 sq mi) (Table 14). The reason for the same inundation in both tidal levels may be because of using a DEM with only integer meter elevations.

Table 14: Estimation of flooded area in Cape Coral by SLR calculator in different tide levels.

Years	Flooded area (sq km)			
	Bathtub Model		Hydroconnectivity Model	
	MHHW, MHW	MSL, MLW, MLLW	MHHW, MHW	MSL, MLW, MLLW
2020	3.53	N/A	No inundation	N/A
2030	3.53	N/A	No inundation	N/A
2040	3.53	N/A	No inundation	N/A
2050	5.2	N/A	4.66	N/A

The reason for similar flooding scenarios for three consecutive decades (2020, 2030, and 2040) can be explained from the Cape Coral canal network. The canal system extends into 25 sq km (10 sq miles) of the city. The saltwater and freshwater canals are deliberately separated. Since the canals are not connected, the SLR tool does not project inundation for low sea levels rise. Eventually, the sea level rises over the years, and the model projects flooding. Since the flooding occurs in the coastal areas and follows the canals into the city (figure 16), the breaks between saltwater and freshwater canals prevent flooding in the hydro-connectivity model in 2030, and 2040. The canals in Cape

Coral were built to drain the wetlands and protect the city from overland flooding. The areas are not projected to flood until the water level reaches a certain threshold. The USACE projected that for the high scenario, in 2030 and 2040, the sea level would rise 1.38 cm (0.0451 ft) and 24.68 cm (0.81 ft), respectively, in the Fort Myers region, (Figure 13, chapter 3) (*Sea-Level Change Curve Calculator (Version 2019.21)* 2019). Fort Myers is the closest tide gauge station to Cape Coral and is located only 15 km (9 miles) from the city. In 2050 and 2060, the sea level is projected to rise by 39 cm (1.279 ft) and 56 cm (1.822 ft) respectively in that area (*Sea-Level Change Curve Calculator (Version 2019.21)* 2019), and Cape Coral starts to inundate more than in earlier past decades when the sea level will rise above 30 cm (1 ft). The SLR tool projected inundation in both the bathtub and hydro-connectivity models during the 2050 to 2100 period.

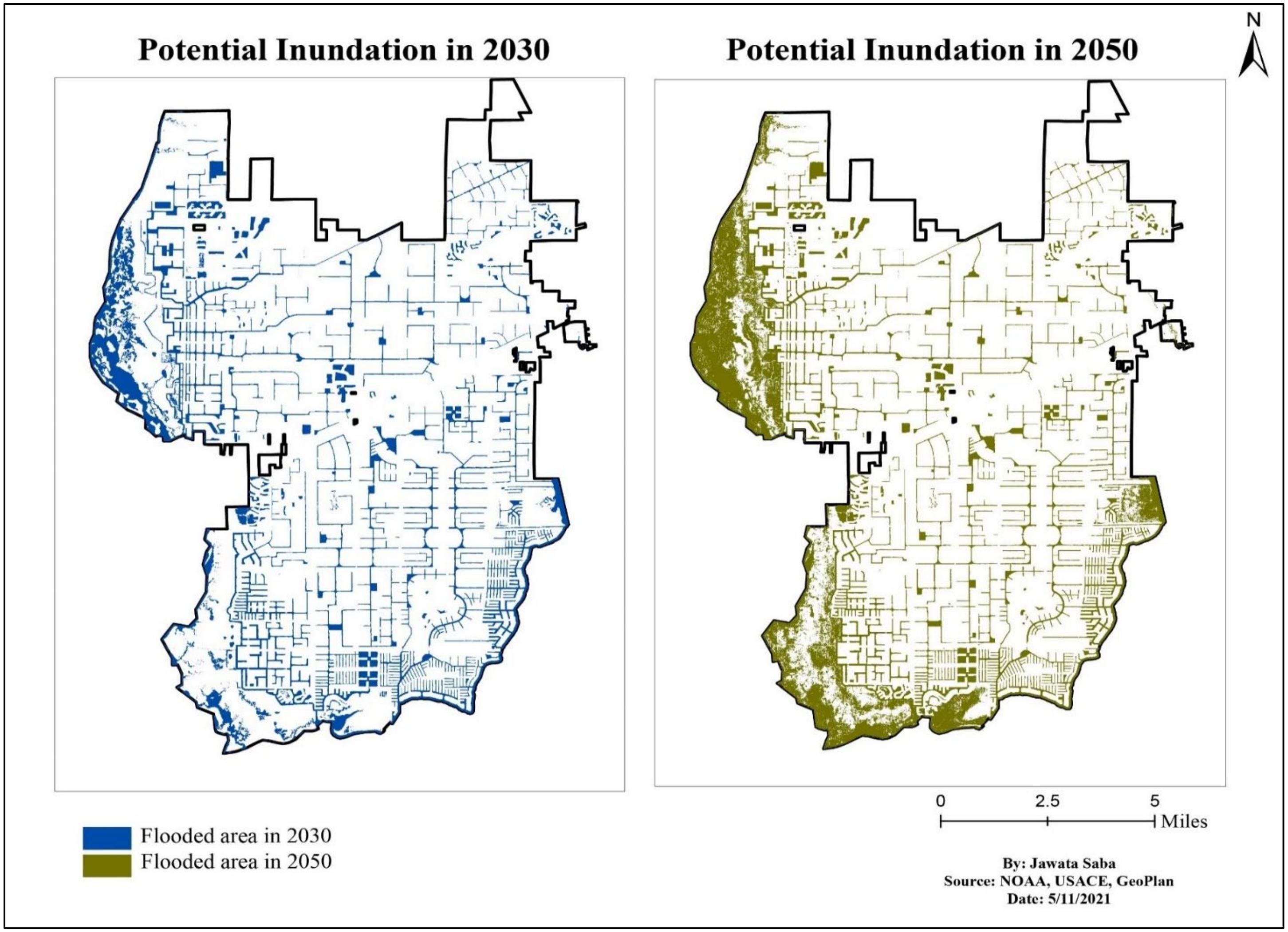

Figure 15: Inundation in 2030 and 2050 from bathtub model in MHHW and MHW tidal levels for both high and medium sea level rise projections.

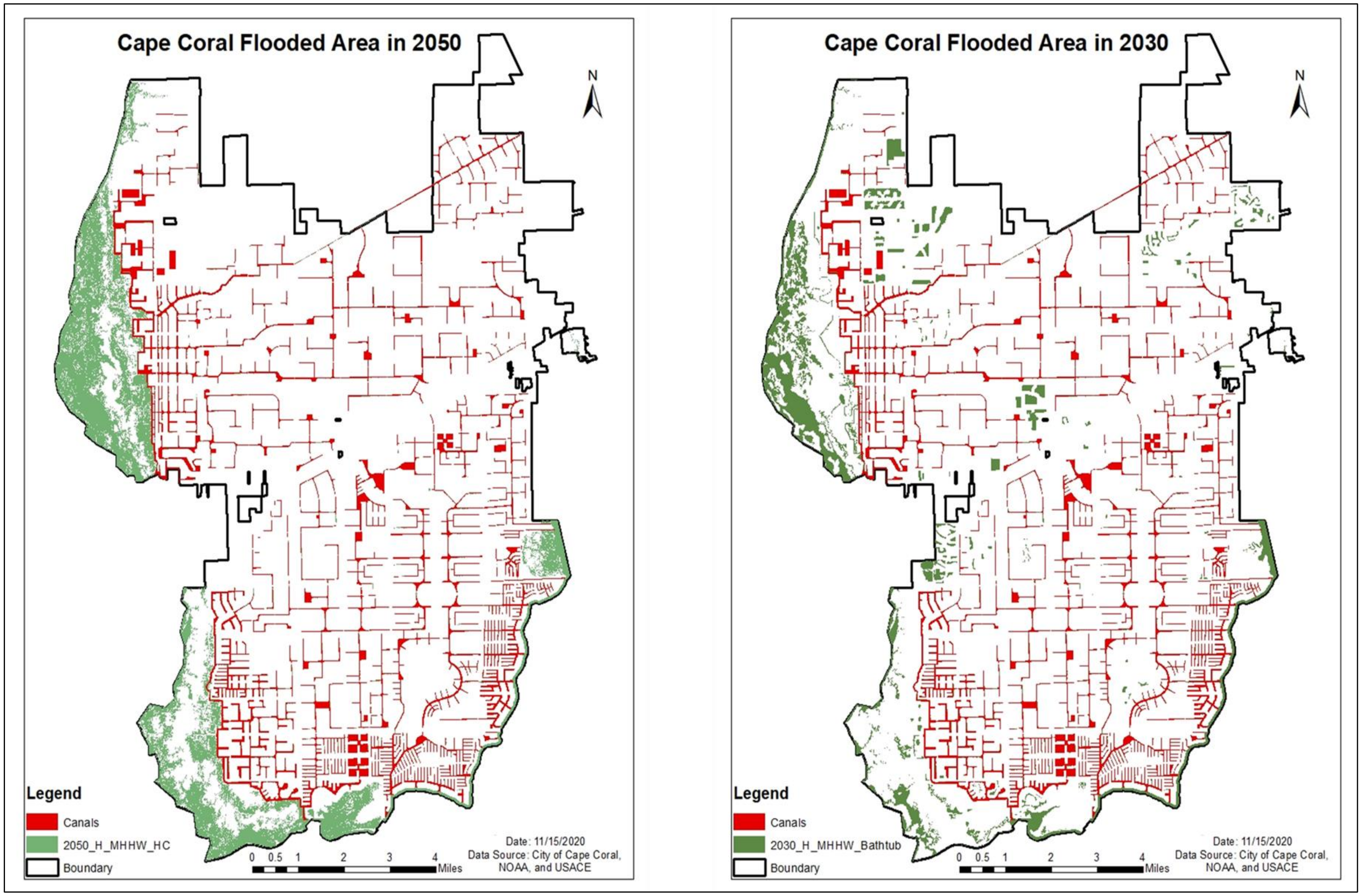

Figure 16: Inundation in 2050 from hydroconnectivity model in MHHW for high sea level rise projections with canals; and Inundation in 2030 from bathtub model in MHHW for high sea level rise projections with canals.

5.3. Creating CoVI scores

5.3.1. PCA results

A Principal Component Analysis (PCA) of the socioeconomic data of Cape Coral reduced 25 variables into six factors or principal components. These accounted for 78 percent variance within the data (discussed in chapter 4). This section takes a closer look into each principal component, their correlation with the variables and contribution to vulnerability, and future vulnerability.

5.3.1.1. Factor 1: Age

The dominant variable in the first principal component is age (Chapter 4, table 13). The first component or factor explained 35 percent of the variance. Variables such as median age, population less than five years and 65 years and over, percent receiving social security income, and vacant housing units were heavily loaded (significantly correlated) on factor 1. Census data showed that the percentage of the population less than five years of age is very low, while the population 65 years and older is high compared to other groups of people in Cape Coral (*United States Census Bureau* 2021). The variables such as percent employed in the service industry were negatively correlated with this factor. A negative correlation with employment in the service industry suggests that this population is not currently in the workforce, and a positive correlation with social security income indicates these people are retired.

Factor 1 explained a particular population group in Cape Coral that was older and wealthy. Census data shows that people of 65 years and over in Cape Coral are retired, earned social security income, and own waterfront property (*United States Census Bureau* 2021), which indicate economic stability. Children and older adults are vulnerable to disasters because they have less mobility and dependency on others. The older population contributes to vulnerability because a higher proportion of this demographic group has restricted mobility, underlying health conditions, age-related disabilities, and some members of this group require access to health care facilities (Cutter, Boruff, and Shirley 2003). It might be difficult for them to access medical facilities after a disaster, move quickly to a new residence, and cope with, and recover from the extreme natural events exacerbated by sea level rise.

5.3.1.2. Factor 2: Race

The dominant variable in the second principal component is race, which explained 17 percent of the variance within the data. This component is positively loaded with Hispanic and African American populations, and people who speak English with limited proficiency, which increased vulnerability. Component 2 is negatively correlated with wealth variables such as median housing value, households earning over $200,000 annually, and per capita income, which indicates that the Hispanic and African American populations are not rich. Many do not own a house. Earning less than $200,000 annually does not necessarily mean they are poor but considering the negative correlation with other wealth variables and reviewing census data, I considered them comparatively poor. Race is considered to increase vulnerability because some people from certain races (such as African American, Hispanic, and so on) lack access to resources and facilities because of cultural differences, or social, economic, and political marginalization (Cutter and Emrich 2006; Cutter, Boruff, and Shirley 2003) (as noted in chapter 2). For example, in an English-speaking country, limited fluency in English can lead to reduced access to education, job, and business. Component 2 contributes to the vulnerability of Cape Coral because it represents a high percentage of the Hispanic population with limited proficiency in English and African American people with low per capita income.

5.3.1.3. Factor 3: Health

The third principal component is the population without health insurance. Component 3 explained 9 percent of the data variance. This component was named after the dominant variable, the percent of the population without health insurance (discussed in chapter 4). Factor 3 is positively correlated with populations without health insurance, percent renters, percent poverty, and female-headed households, which increase the vulnerability of an area. On the other hand, variables such as children living with two-parent families, which reduces vulnerability, is negatively correlated with this component. Factor 3 included populations without health insurance, renters, people living under poverty, female-headed households, and single parents, primarily single mothers. Each of these variables contributes to vulnerability. Though the percentage of people living under poverty in Cape Coral (10%) (*United States Census Bureau* 2021) is slightly lower than the national average (11%) (Semega et al. 2020), that group of people in Cape Coral is positively correlated with this factor. This population group is economically vulnerable. An economically vulnerable group is highly susceptible to natural disasters since they may not have enough resources to cope with and recover from the event, so this marginalized group in Cape Coral is already vulnerable and will be highly vulnerable to natural disasters.

5.3.1.4. Factor 4: Mobile Homes

The dominant variable for the fourth principal component is mobile homes. Component 4 explained 7 percent of the variance of the data. It was heavily loaded on the variable of percent of the population that lives in mobile homes. This factor was positively correlated with percent of the population that has less than a 12^{th} grade education and percent civilian unemployment. It explains that many people who did not graduate from high school are unemployed, and do not have enough money to recover after disasters. The unemployed and mobile home dwellers are less likely to receive financial aid in the disaster recovery phase (Cutter, Boruff, and Shirley 2003) because it is easier to receive financial aid through institution.

5.3.1.5. Factor 5: Gender

Gender is the dominant variable for the fifth principal component. Component 5 explained 6 percent of the variance within the data. It is positively loaded on variables such as percent female and female participation in the labor force. Though female participation in the labor force can contribute to economic growth, women are generally considered more vulnerable to natural disasters than men. Women can find difficulty recovering from disasters and adapting to post- disasters situations, often because of sector specific employment, lower wages, family care, and child raising responsibilities (Cutter, Boruff, and Shirley 2003).

5.3.1.6. Factor 6: Ethnicity

The dominant variable for the last component is ethnicity, which explained 4 percent variance of the data. The last principal component is positively correlated with the Asian population and negatively correlated with median gross rent, meaning that Asians in Cape Coral do not pay rents and live in their own houses. Though vulnerability literature considers that members of any race except white population in the U.S. can be vulnerable because of lack of accesses to facilities and resources (Cutter, Boruff, and

Shirley 2003), the Asian population in Cape Coral is different. The U.S. Census, ACS (American Community Survey) data shows that the Asian population in Cape Coral is highly educated, and skilled in technical sectors such as engineering, medicine, and different branches of sciences. Many Asian households earn over $200,000 annually. This group of people is less vulnerable to natural disasters because they can anticipate disasters with their knowledge and education, recover quickly, and get new jobs in new places with their skills.

5.3.2. Coastal Vulnerability Index (CoVI) in Cape Coral

5.3.2.1. Vulnerability and Socio-economic factors

The Cape Coral census tracts map shows that the smaller tracts are located on the southeastern portion of the city. The larger tracts are located in the north, west, and southwestern parts of the city. The city boundary cut out a few unincorporated enclaves inside of the city; the white areas inside the boundary of the city are not the parts of the city.

Though the Coastal Vulnerability Index was generated from socio-economic variables, it is named CoVI because the vulnerability of Cape Coral has been explained by several coastal features such as elevation, canal network (both saltwater and freshwater), coastal high hazard area, and evacuation zones. The negative standard deviation shows low vulnerability in the vulnerability map, represented by green, whereas the positive standard deviation shows higher vulnerability, represented by red color (figure 17).

The age factor vulnerability is different from the composite vulnerability because it solely looks at the distribution of the age factor. Age factor vulnerability is the high to medium near the south and northwest portion of the city (figure 17). As the age factor is loaded on older people, the map indicates that older people live near the south and northwest side of the city. The older people in Cape Coral are more likely to live in the sparsely populated area (figure 26). For example, tracts such as 104.6, 108.1, 101.05, and 101.02 have low population and housing density, and these tracts are medium to highly vulnerable for age factors (figure 17).

The vulnerability of the age factor is higher in the high hazard area, indicating that older people live in a hazard-prone area (figure 18). This leads to further concern that an already vulnerable population will be vulnerable during coastal disasters such as hurricanes, tidal surges, and storm surges because they live in a risky area. Age vulnerability is also higher where canal network is dense (figure 18), which indicates that most of the older people have waterfront property. Three tracts such as 101.03, 102.01, 102.03 are least vulnerable for age factor. The canal network is also sparse in these tracts. When the saltwater canal map is overlaid on the age vulnerability map, it shows that saltwater canals are spread over the higher vulnerable tracts and high hazard areas. There is a high possibility of saltwater intrusion in these tracts with tidal surge and storm surge. A group of socially vulnerable people lives in places that are susceptible to natural disasters because of the places' geographic location (high hazard area) and infrastructure (canal network, especially saltwater canal). When a socially vulnerable area is complemented with physical vulnerabilities, the vulnerability of the area certainly increases.

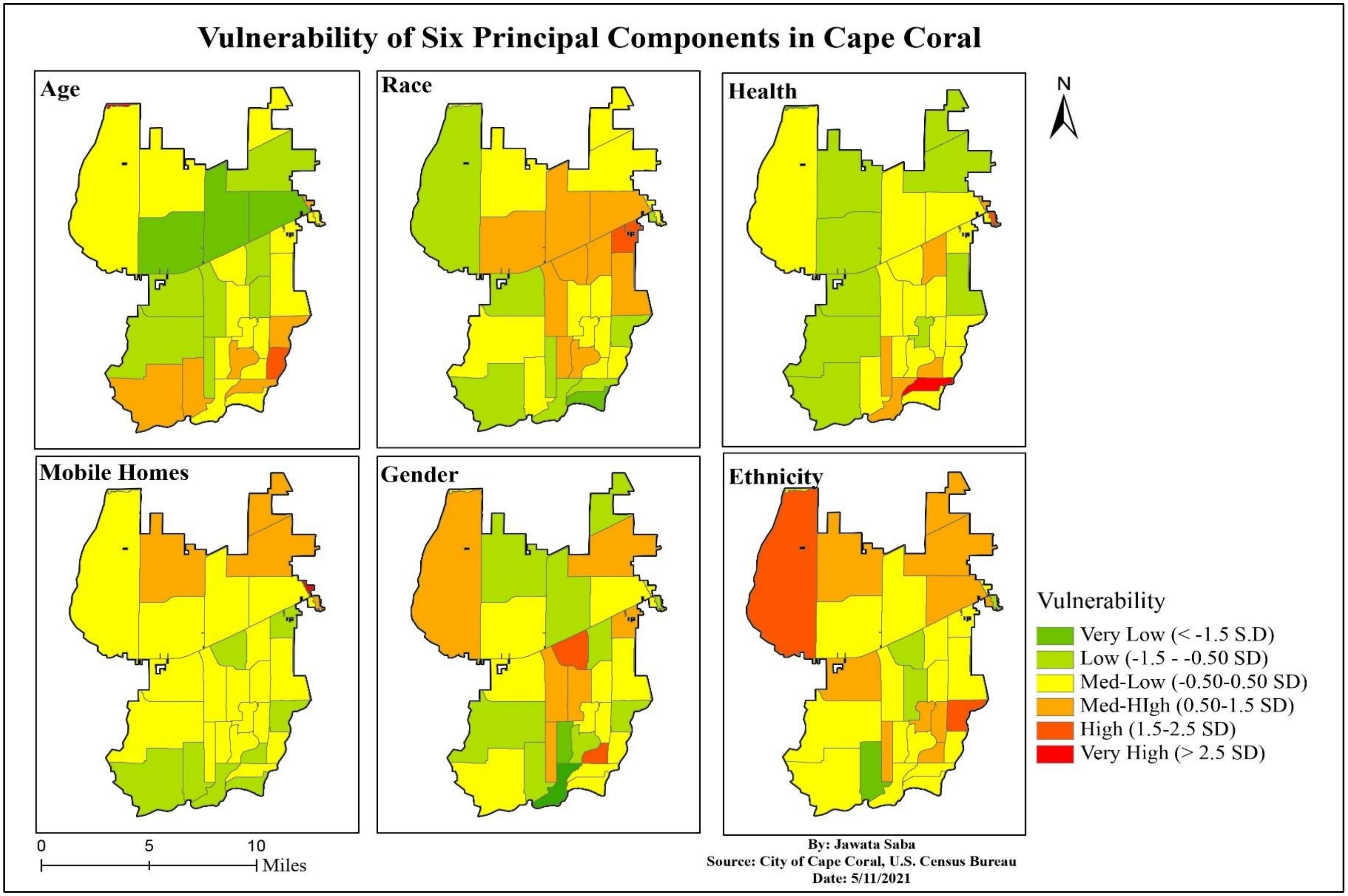

Figure 17: Vulnerability of each component in Cape Coral in 2020.

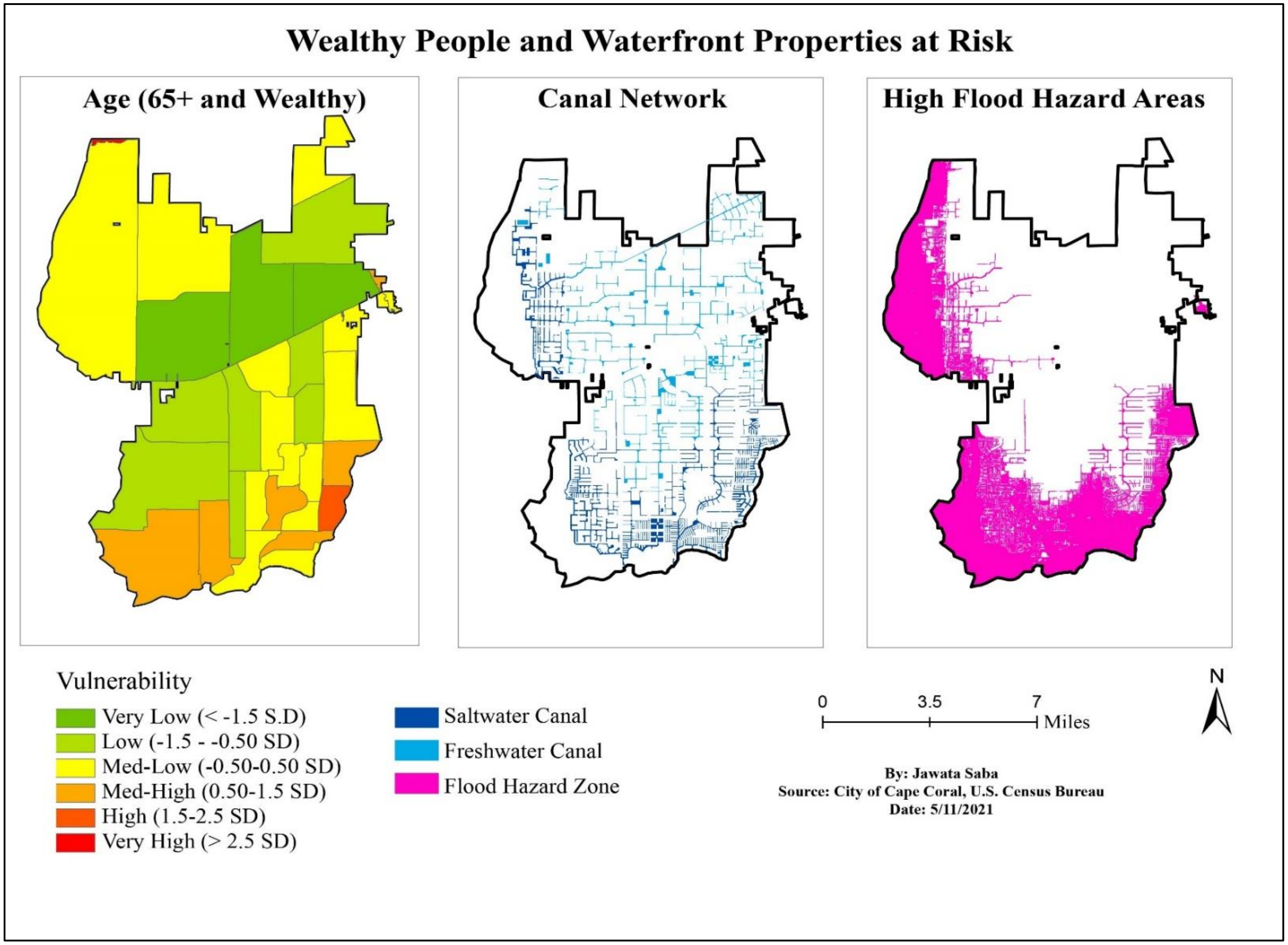

Figure 18: Wealthy people live at high hazard areas and saltwater canals.

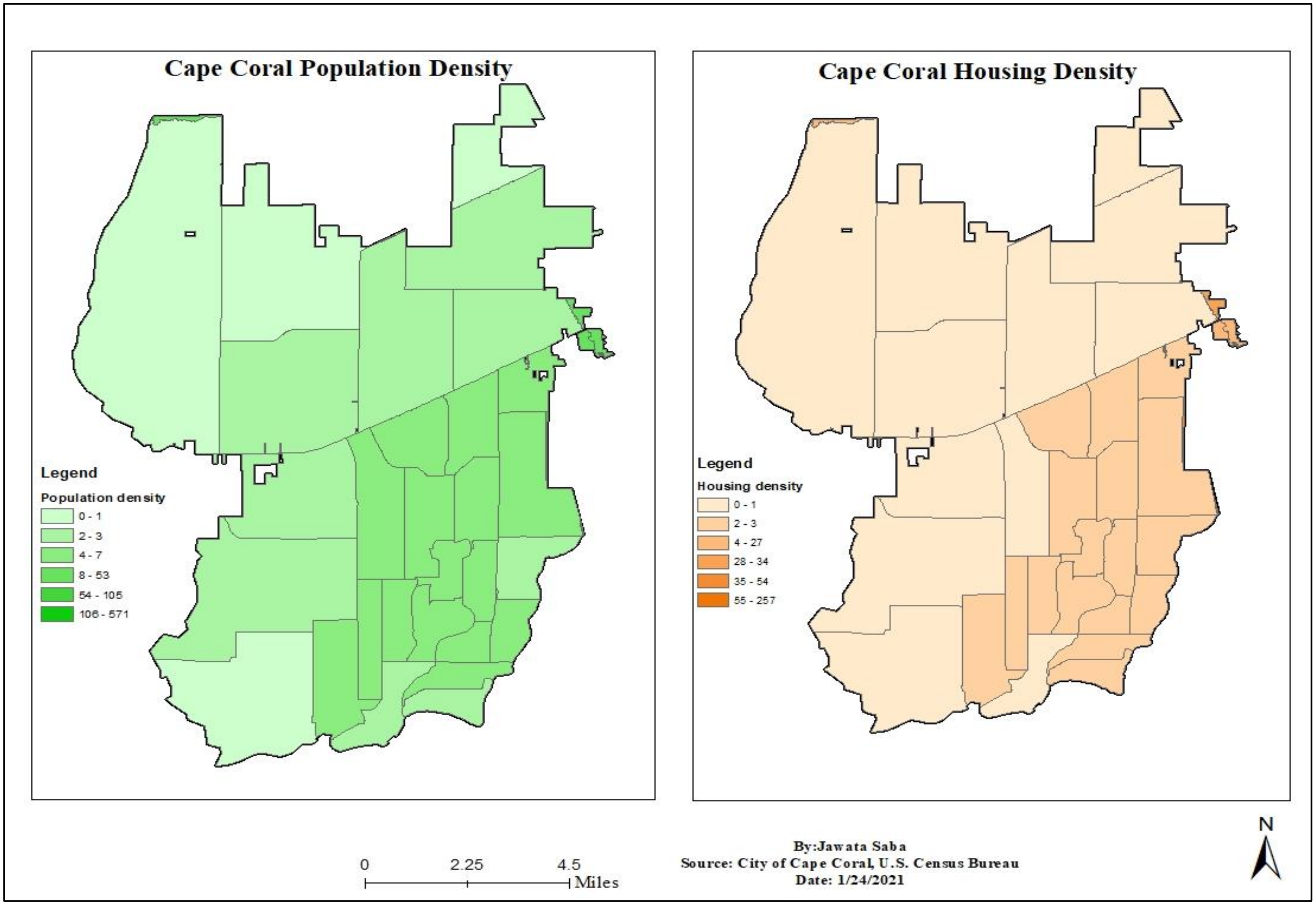

Figure 19: Population density (people/hectare) (left), housing density (houses/hectare) (right); Densities measured as the number of housing or people in an hectare of each tract.

The race factor is positively loaded on the Hispanic and African American populations, and people speaking English with limited proficiency. A vulnerability map of the race factor (figure 17) indicates that the Hispanic and African American populations are widely spread across the city. Tracts that are less vulnerable to the age factor are highly vulnerable to the race factor (figure 17). Factor 1 represents a group of older people, who are mostly retired, not currently working, have health insurance, and earn social security income. The age vulnerability map shows the location of this group in the city. On the other hand, the race vulnerability map represents a Hispanic population with limited proficiency in English, and African American population earning low per capita income who live in an entirely different part of the city (table 15, figure 17). The race vulnerability map shows tracts such as 101.03, 102.01, 102.03, 104.04, 103.06, 103.07, 103.04 are highly vulnerable, whereas these tracts are less vulnerable for the age factor (table 15). African American and Hispanic people primarily live in the area where the canal network is comparatively less, indicating that many people living in these tracts (such as 101.03, 102.01, 102.03) do not have waterfront property. Though the map (figure 17) indicates segregation in the City of Cape Coral, either based on race or wealth I have not applied any quantitative segregation measure to quantify the level of segregation.

The health factor vulnerability map (figure 17) shows that there is not much vulnerability in Cape Coral, which means that the number of people without health insurance is not significant. This map also shows that some tracts that are highly vulnerable on the age factor are less susceptible to health factors. There is a correlation. Health factors are loaded on the population without health insurance, percent renters, percent poverty, and female-headed household. The age factor variables are opposite to them. It suggests that the older people who live in these tracts have health insurance, are not renters, and do not live in poverty.

The mobile home factor is positively loaded on mobile homes, people who did not graduate from high school, and percent of the population that is unemployed. The mobile home factor (figure 17) shows that the whole city has a low vulnerability for this factor. This is not a significant variable for Cape Coral that increases vulnerability. This factor suggests that the city has a small number of uneducated and unemployed people, resulting in very low vulnerability for mobile home factors (figure 17). Only two tracts, 101.02 and 208, show higher vulnerability for mobile homes. Census data also shows that very few tracts have mobile homes.

The gender vulnerability map (figure 17) does not resemble any significant correlation to other factors. Census data shows that the female population lives all over the city. The data reveals that a substantial portion of the female population is in the labor force.

Ethnicity is highly loaded on the Asian population. The ethnicity component (figure 17) reveals higher vulnerability throughout the city meaning that the percentage of Asian people is small in the city (*United States Census Bureau* 2021). Since ethnicity factor reduces the vulnerability of the city a high vulnerability for this factor indicates small number of Asian people in the city. If the city has higher percentage of Asian people, it could reduce the vulnerability for the ethnicity factor in the city. The ethnicity vulnerability map shows low vulnerability on four tracts 103.06, 104.05, 104.07, and 206, indicating that most Asian and Asian American people in the city live in these tracts (figure17).

Though African American and Hispanic people do not live in high hazard areas, they are still vulnerable to natural disasters and sea level rise. Wealthy people live closer to water, and poor people live away from water since they cannot afford waterfront property. The wealthy are vulnerable because of their investments in waterfront real estate ,and the poor are vulnerable because they do not have the social and financial stability to cope with a disaster. Wealthy people have social and economic stability, but they simply live in hazardous areas. The city authority calls this area hazardous because it inundates during hurricane and storm surges from category 1 to 5. The financial loss of wealthy people in one hurricane might prevent them from coping with other extreme events. Therefore, the whole city is vulnerable in one way or another.

The ethnicity factor (figure 17) map shows that tracts such as 104.04, 104.05, 103.06, 103.03, 104.07, and 101.03 are less vulnerable for the ethnicity factor since these tracts have high density of Asian population. Other tracts have high vulnerability for this factor because they have a low density of Asian population.

5.3.2.2. Vulnerability and Canals

Now, I will discuss whether the canals can make the city vulnerable to sea level rise. The city has two networks of canals that together are 400 miles in length. One network is the saltwater system that is located closer to Gulf of Mexico water in both distance and elevation. The vulnerability and canal network maps show that more vulnerable tracts have an intricate saltwater canal network (figure 20 and 21). Though social-economic variables have generated the CoVI, it is clear these tracts would be more vulnerable in the event of high tidal flooding or storm surges. The most vulnerable tracts are already located in the high hazard area (figure 21). When high tidal surges or storm surges occur, they likely to follow and be channeled by the canals (figure 16). Since there is no buffer zone between canals and waterfront property, houses will flood if the storm surges are higher than the canal rim. If the canals start to flood in high tides and storm surges, people living nearby will be in trouble. Irrespective of social and economic stability, people can find difficulty to recover again and again from multiple flood events.

Flooding from saltwater has long-term consequences. When the water level goes down, salt molecules remain trapped in the soil. Salt poisoned soil cannot grow crops, vegetables, or ornamental trees and damages houses, lawns, boats, and infrastructures such as roads, water and power supplies. The freshwater canals are located outside the hazard-prone area where the overall vulnerability is low to medium (figure 21). They are located outside the hazard-prone area of the city. When flooding occurs from tidal surges, storm surges, or hurricanes, these areas might flood, but there is less possibility of saltwater intrusion in these areas.

The elevation map (Figure 22) shows that most of the city has low elevation except the northeast part of the city. In this study, I considered the saltwater canals areas low elevation because the topography and elevation of the area allowed them to connect the canals to the Gulf of Mexico. If the elevation and composite vulnerability maps are compared, it is clear that the higher vulnerable areas are located on low elevation areas (figure 22). Vulnerability maps were first generated from socioeconomic data.

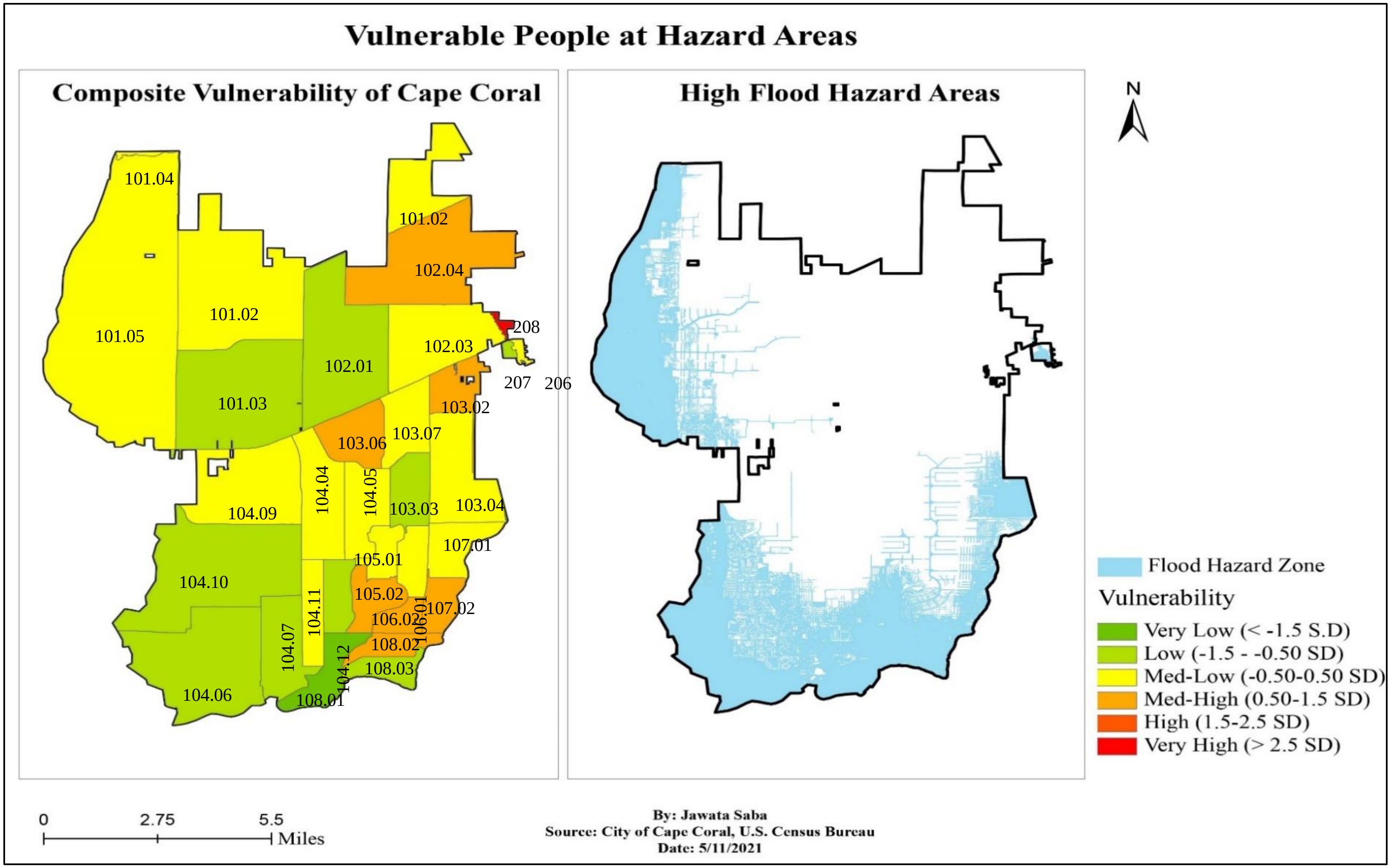

Figure 20: Vulnerability of Cape Coral (right), numbers of the map denote tract number; High hazard areas defined by the City of Cape Coral susceptible to all categories of hurricanes and storm surge (left).

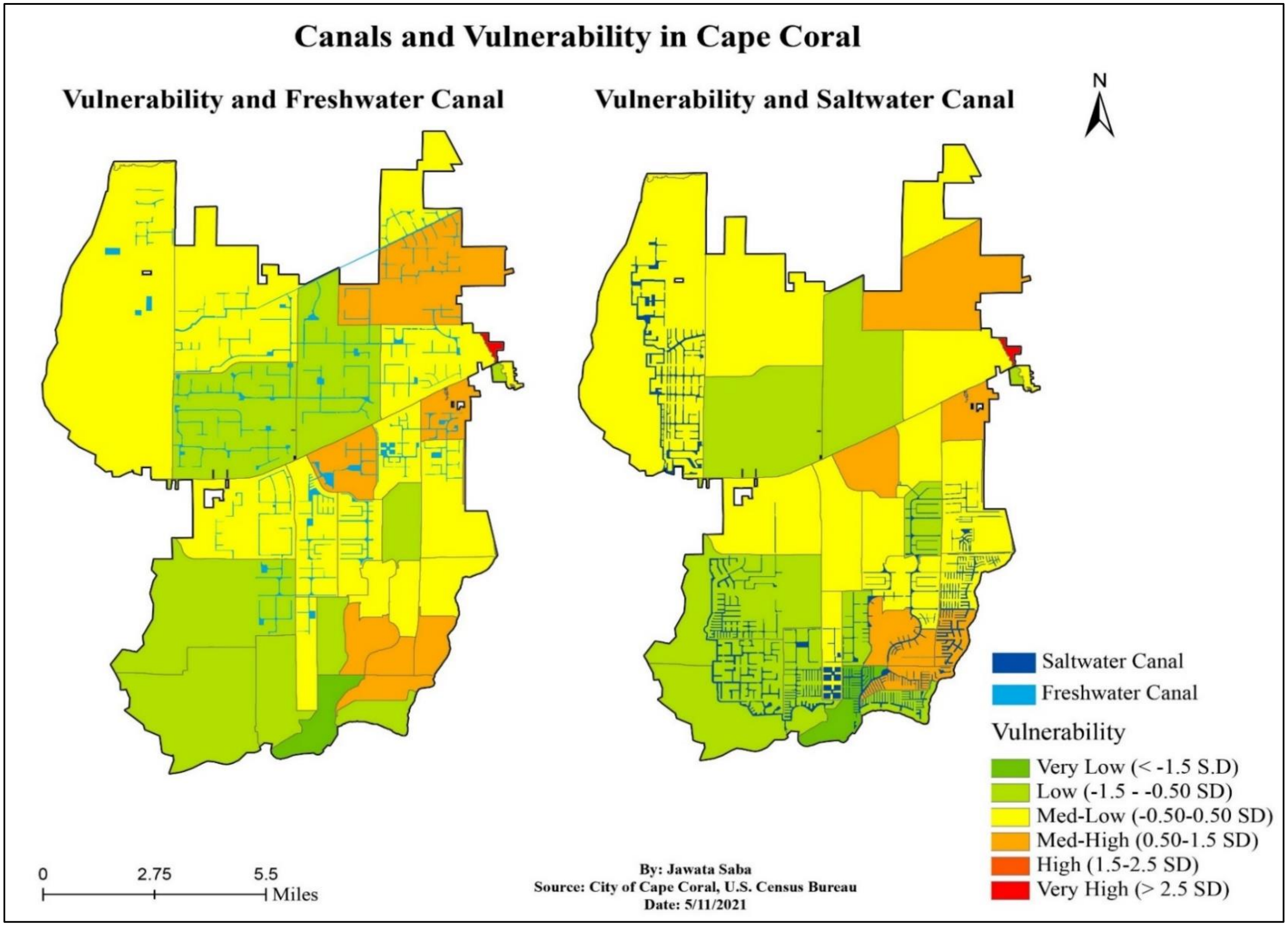

Figure 21: Vulnerability and canal network of Cape Coral; freshwater canal (left) and saltwater canal (right)

When the two maps are compared and overlaid, I found highly vulnerable tracts are located on low elevation areas that are usually vulnerable to inundation disasters. Irrespective of the vulnerability, the whole city falls under the evacuation zone (discussed in chapter 3) for any coastal disasters (figure 11), which means the whole city must be evacuated in any hurricanes from category 1 to 5.

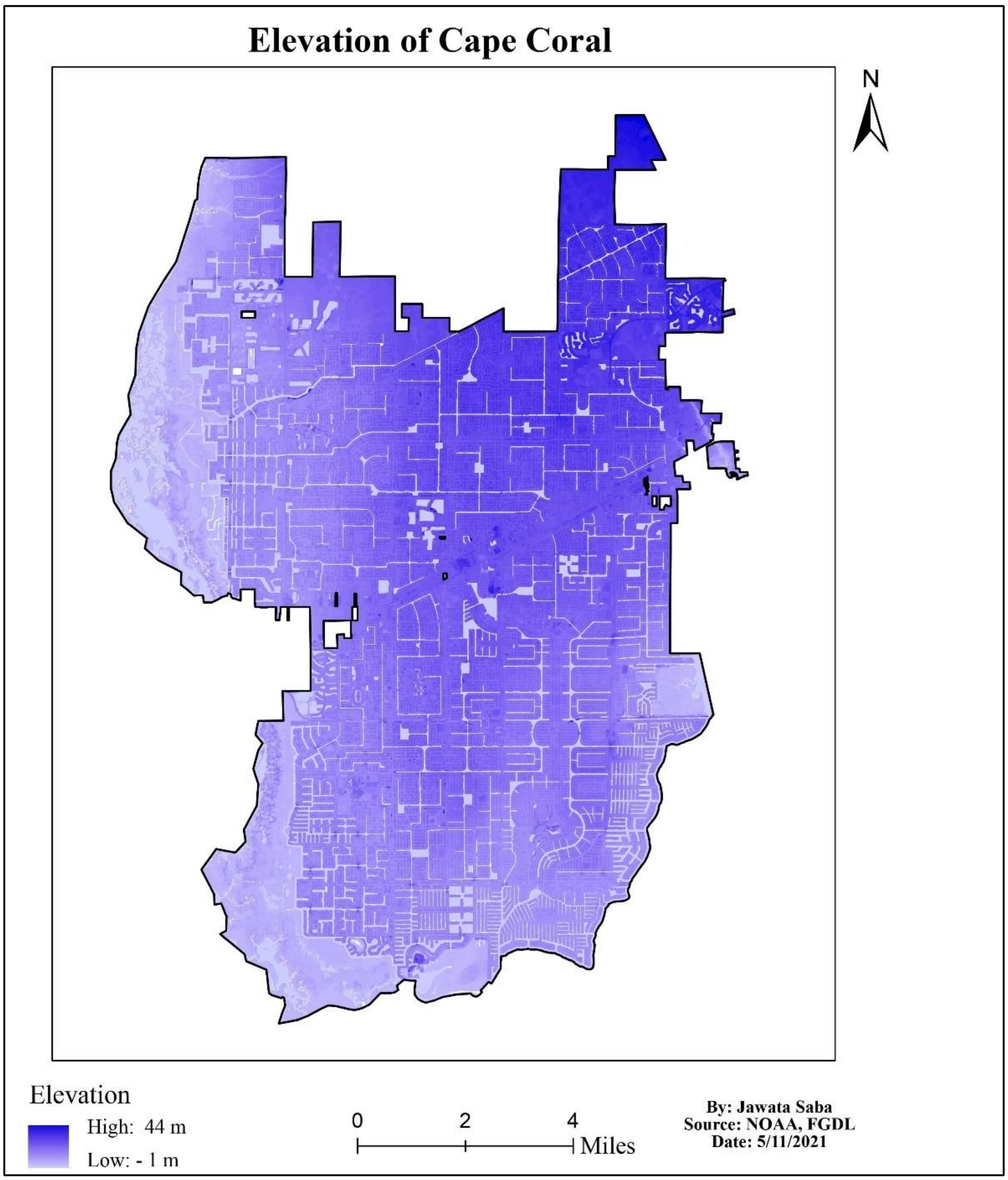

Figure 22: Elevation of Cape Coral.

Table 15: Overall Vulnerability in canal and hazard-prone areas.

Tracts no	Age	Race	Overall CoVI	Canal Salt/freshwater	High Hazard Area
101.02	Medium	Medium	Medium	freshwater	Yes
101.03	Low	High	Low	freshwater	Yes
102.01	Low	High	Low	freshwater	No
102.03	Low	High	Medium	freshwater	No
102.04	Medium	Medium	High	freshwater	No
103.02	Medium	High	High	freshwater	No
103.03	Medium	Medium	Low	Fresh/Saltwater	Yes
103.06	Medium	High	High	freshwater	No
103.07	Medium	High	Medium	freshwater	No
104.04	Medium	High	Medium	freshwater	No
104.06	High	Medium	Low	Saltwater	Yes
104.07	High	High	Medium	Saltwater	Yes
104.10	Medium	High	Low	Freshwater	Yes
104.12	Medium	High	Low	Saltwater	Yes
105.02	High	High	High	Saltwater	Yes
106.02	Medium	Medium	High	Saltwater	Yes
107.02	High	Medium	High	Saltwater	Yes
108.01	Medium	Medium	Low	Saltwater	Yes
108.02	High	Medium	High	Saltwater	Yes
208	High	Medium	High	No canal	No

The composite vulnerability map shows that tracts in southeastern side of Cape Coral have a higher vulnerability than tracts in the northern part of the city (figure 20). These tracts have high population and housing densities. A comparison between the age vulnerability and population and housing density shows that the age factor vulnerability is medium to high in low to medium dense areas (figure 17 and 19). Race factor vulnerability is medium to high in high density areas. Though older people all over the city they are concentrated in some sparsely populated tracts of the city. The southeastern portion of the city, which has relatively smaller tracts (105.02, 107.02, 108.02, 108.01, 108.03, and 106.02) (in context of area), shows higher population and housing densities. These tracts show a combination of all factors (age, race, health, and gender) and have medium to high overall vulnerability.

5.3.3. Spatial Autocorrelation

In this research, I tested Moran's I statistics on CoVI scores. The test results (figure 23, table 16) show spatial randomness, which indicates that the vulnerability of Cape Coral is not spatially correlated. Given the z-score of 0.167, the pattern does not appear to be significantly different than random.

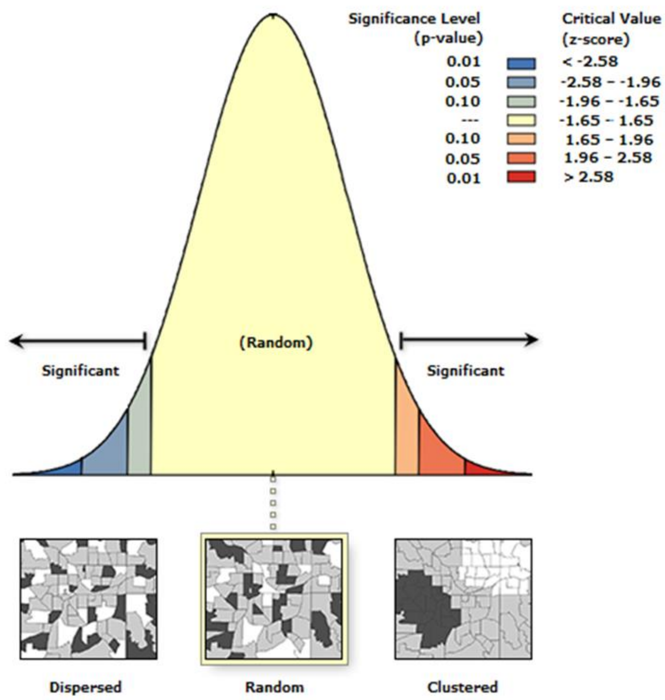

Figure 23: Moran's I test result.

Table 16: Moran's I test statistics.

Statistical variables	**Values**
Moran's Index	-0.019593
Expected Index	-0.030303
Variance	0.004100
z-score	0.167265
p-value	0.867162

5.3.4. Vulnerability in 2050

When the flooding scenario in the 2050 map was overlaid on the vulnerability map, the new map shows that the highly vulnerable area will flood (figure 24). The canal network and inundation projections showed that flooding will occur following the canal network (figure 16). Highly vulnerable tracts are situated on the saltwater canal (figure 24). In the near future, if these canals flood as projected, the city will face consequences from saltwater intrusion.

The comprehensive plan of the city shows that the city is plans to add more than 5,000 lots by 2030 (*City of Cape Coral: Open Data Portal* 2016; Future Land Use Element 2019). The sea level rise scenarios from the SLR calculator shows significant flooding in the high hazard area. This study has suggested that the highly vulnerable places will become more vulnerable in the future, because these areas are located in the projected flooding areas and high hazard areas (figure 24). The warning is that the city still considers developing new lots. If the city imposes restrictions for future development in the high hazard and projected inundated areas, the areas will become less vulnerable. Though the land use plan indicates future development, the present land use map (chapter 3, figure 6) does not show large undeveloped areas in the city.

When future land use is overlaid on the projected flooding map in 2050, many lots are projected to flood. Sea level rise and coastal flooding will not always follow the mathematical or software projection. It can flood more or less than the projection. The city is already susceptible to hurricanes and storm surges. If the city floods equal to or more than the projected flooding, the residents will be in trouble. The south and western parts of the city are in high hazard areas, have saltwater canals, and are projected to flood in the future. When the sea level rises, it will raise the water table and level of canal water. The soil of these areas may be attacked with salt from the canal flooding.

Results of the study revealed that a small portion of the population lives in the southwest and northwest sides of the city, which fall under the high hazard areas (figure

19). The housing and population density is higher in the southeast parts of the city (figure 19). Since the southwest and northwest of the city have less density, they might be developed in future (figure 19). The comprehensive plan of the city plans future development in these areas (Future Land Use Element 2019). The southeast side of the city has a high density of population and housing and falls in hazard-prone areas, meaning that a high proportion of population is susceptible to disasters.

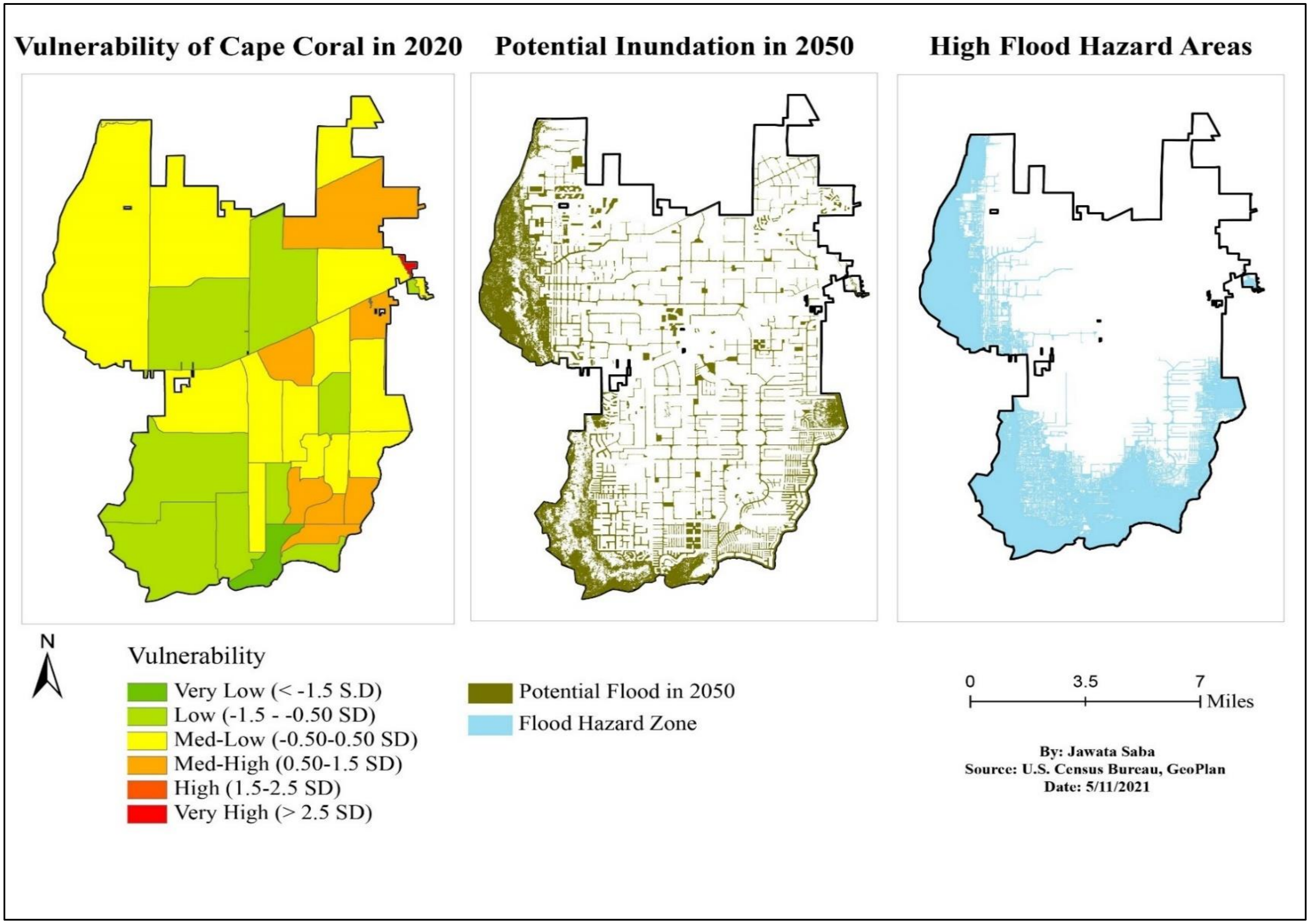

Figure 24: Cape Coral' present vulnerability (left), Inundation scenario in 2050 (middle), high hazard areas (right); Inundation is projected to occur in coastal high hazard areas and both high and low vulnerable tracts.

5.4. Conclusion:

From this study, I found that the city has both socially and economically vulnerable and stable groups of people. The whole city is vulnerable to sea level rise and associated hazardous events, such as hurricanes and storm surges. In Cape Coral the economically stable groups are vulnerable to disasters because they live in hazardous areas. Usually rich and wealthy people are considered less vulnerable to natural disasters, but in Cape Coral wealthy people are vulnerable to disasters because they live in high hazard areas, and they have valuable properties in the high hazard areas.

The next chapter is the conclusion of my thesis where I will discuss the overall conclusion of the research. I will also discuss the implications and limitations of the research. The chapter ends with the future possibility of this research.

CHAPTER 6: CONCLUSION

6.1. Introduction

In this study, I investigated the spatial pattern of the City of Cape Coral's coastal vulnerability based on socio-economic and demographic data, canal networks, and projected flooding. Cape Coral was established in the 1950s in a coastal hazard-prone area (discussed in chapter 3). Since the 1970s the population of the city has grown fast. The city was primarily developed for real estate businesses to attract people who would love to have waterfront property and enjoy water-based recreation and secondarily for tourism. This research shows the original purpose of the city's development as a cause of vulnerability to coastal disasters.

6.2. The research questions and findings

The inundation projection maps for Cape Coral show that the city will moderately flood from sea level rise in the 2020s, 2030s, and 2040s, but after 2050s the water levels will increase substantially. These maps are based upon the USACE sea level rise projection and tidal levels and did not consider any extreme events such as hurricanes. Historically, southwest Florida has been highly susceptible to Atlantic Ocean and the Gulf of Mexico hurricanes. Higher sea levels will result in storm surges from hurricanes, which will make Cape Coral more susceptible to flooding than this study projects.

Though the canals were built to prevent flood and saltwater intrusion, it is unclear how the canals will respond to sea level rise. The inundation projection in this study shows that flooding from sea level rise will follow the saltwater canals, which are located in the high hazard area. Hurricanes, tidal surges, and storm surges will inundate these canals frequently with increased sea levels, if the city does not take mitigation steps.

Frequent flooding and saltwater intrusion may severely impact the city's real estate business.

I found the whole city to be vulnerable in one way or another. Vulnerability analysis revealed that there are two prominent groups of people in the city. One group of people is economically stable. They are retired, earn social security income, and live in waterfront properties. Another group is people who have less economic stability and work in the service industry.

The older group of people mostly own waterfront property and live in the high hazard area, which is highly susceptible to flooding and any coastal disasters. The older population in the city that owns waterfront property and earns social security income contributes to the city's vulnerability in several ways instead of reducing it. First, they live in a hazard-prone area, which is susceptible to flooding and requires frequent evacuation. Second, frequent flooding can lower their houses' value, which might cause financial loss for these people. Real estate businesses in the city may incur loss because of the frequent flooding of their properties. Finally, frequent evacuation might be troublesome since some older people have health issues.

Another group of vulnerable people work in the service sector, are primarily Hispanic or African American, and earn a low income. These individuals either live in hazard-prone areas or the middle of the city. They are already marginalized and do not have enough economic stability to recover and relocate multiple times. Many people may become unemployed during and after disaster events, which makes their personal and family recovery difficult.

Poverty, illiteracy, unemployment can act as the factors that increase vulnerability (Cutter, Boruff, and Shirley 2003). In my thesis, I found that wealth can also increase vulnerability. In Cape Coral, wealth, waterfront property, living in the high hazard location are the primary factors that make people vulnerable to coastal inundation and hazards.

6.3. Limitations of the research

This study has several limitations. First, the study did not consider people's perspectives about vulnerability and sea level rise. Second, it did not validate the CoVI index. Third, though the CoVI index explained vulnerability by physical variables, it did not include physical variables in the PCA. Fourth, the sample size for the PCA analysis was small. Finally, all factors were given equal weight to generate the vulnerability index.

The study did not analyze people's perspectives about sea level rise and its impact on waterfront property. It is essential to consider whether people know that their valuable properties are in hazardous areas. Initially, I planned to visit the study area and interview people in Cape Coral. I received the America View Mini-grant to do the field visit, but I could not visit the study area because of the COVID-19 pandemic.

I did not empirically validate the CoVI index. Though the index was generated from a widely recognized method, I did not justify the model. I assumed that all factors would contribute equally to the vulnerability because of the absence of empirical and justifiable evidence for weighing components. Though the CoVI index for Cape Coral has been explained by several coastal variables such as canals, elevation, evacuation zones, and hazardous areas, these were not included as PCA variables. Future research could address this issue and justify whether these variables increase vulnerability, as stated in this study.

The small sample size limited the number of available variables, because most Census products do not provide data at the Census Tract level. A larger study area would permit using counties as the basic geographic unit and increase the number of available variables. Using Census Tracts, however, had the advantage of focusing on one city and the local spatial patterns of physical and socio-economic vulnerability within it. A local vulnerability study coupled with fieldwork might contribute a new idea about the socio-economic vulnerability issues that coastal communities face and provide guidance about developing long-term adaptation plans.

6.4. The contribution of the research

This study can act as a guideline to the City of Cape Coral for disaster planning. The inundation maps show the future inundation in the city, and the vulnerability maps give a clear idea of socio-economically vulnerable people and their location. This study will help the city authority identify the vulnerable populations and their locations for disaster planning and preparedness. The study identified the factors that increase or decrease vulnerability, which the city authority can use to reduce the future exposure of vulnerable populations.

The study can act as a robust guideline for the city authority. As the study is based on the census data, sea level rise projections, and tidal data, the results can be revised and updated every ten years as the data will change. Thus, the city will get a comprehensive picture of vulnerability and can see the shift of vulnerability over time. The study can be an integral part of the adaptive strategy and resiliency plan of the city.

6.5. Future research

Vulnerability studies published so far focused on larger geographic scales. Scarcity of research exits at the county or municipal scales. When I selected a city as a study area, I realized a gap of understanding of vulnerability in smaller geographic scales. Since sea level rise is a complex phenomenon and spatially and temporally variable it is challenging to analyze vulnerability from sea level rise in smaller geographic scales.

This research attempted to incorporate sea level rise with social vulnerability. Future research is needed to model municipal or county scale vulnerability because sea level rise and associated vulnerability vary in each small geographic unit. Though cities in a region have similarities, they are different as well. It is important to consider all related factors of a city to analyze its impact of sea level rise. These analyses will help coastal city authorities to take better decisions in disaster preparedness and mitigation phases. In my doctoral study, I plan to devise a model that can analyze vulnerability to sea level rise at municipal scales.

During the literature review, I found that southwest Florida, especially the Cape Coral area has been little researched. Though I tried to minimize that gap with research, it is not enough. This area needs further research. I had to depend on several vulnerability reports made by the city in cooperation with South Florida Water Management District (SFWMD) and NOAA because there were few refereed journal articles about Cape Coral.

6.5. Future Adaptation Strategy

Cape Coral currently does not have any resilient feature to sea level rise; however, the land use plan shows that the city is planning to raise buildings' height and building a seawall. The city mandated several adaptation policies for the city. For example, elevation for future critical facilities, should be 15 ft above ground elevation. New construction of essential facilities should be prohibited in the hurricane high hazard zone. When existing critical facilities reach the end of their useful life, all rebuilds should have at least a 1-3 ft increase in base floor elevation (Beever III, Walker, and Kammerer 2017b). The city could also use berms to reduce flooding from canals.

A seawall will not be the ultimate solution to sea level rise since Florida sits on porous limestone. Increased sea levels can flood the city beneath the soil. Sea level rise along with groundwater mining can cause salt intrusion in the freshwater canals. Though many cities are trying to adapt to sea level rise (such as Miami) and land subsidence (such as Louisiana), adaptation strategies are expensive. The city and its population people will need to decide whether they want to bear the expenses of a resilient city or relocate.

6.6. Conclusion

The wealthy people in the City of Cape Coral are more vulnerable to sea level rise than the others. While many factors are responsible for the city's vulnerability, wealth is the most important. The vulnerability of the city is high because substantial wealth is concentrated in a high hazard area. People will not be vulnerable if they do not live in the high hazard area. More than 80 percent of the residents have assets in the flood zone (Beever III, Walker, and Kammerer 2017b). The future land use plan shows that the city still plans to support development in the high hazard area. The city does not have any concrete plan for managed retreat. Managed retreat and building restrictions in developing the hazard-prone area might be cheaper for the city. If the city keeps investing in risky areas in the future, it might face a great financial loss.

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