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GEOSPATIAL ANALYSIS BASED ON HURRICANE STORM SURGE SCENARIOS ON COASTAL SOUTH TEXAS AND NORTH MEXICO

A Thesis

by

LAYDA BELIA SPOR LEAL

Submitted in Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

Major Subject: Civil Engineering

The University of Texas Rio Grande Valley

May 2023

GEOSPATIAL ANALYSIS BASED ON HURRICANE STORM SURGE

SCENARIOS ON COASTAL SOUTH TEXAS

AND NORTH MEXICO

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May 2023

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ABSTRACT

Spor Leal, Layda B., Geospatial analysis based on hurricane storm surge scenarios on coastal south Texas and north Mexico. Master of Science (MS) , May 2023, 72 pp., 10 tables, 34 figures, References, 36 titles.

The coastal area of the Lower Rio Grande Valley, Texas, and Northern Tamaulipas, Mexico, has historically faced a variety of natural disasters involving flooding hazards, such as hurricanes and tropical storms. These scenarios not only represent imminent danger for the population in the area but can lead to long term effects on the infrastructure located in the impact zone. As such, it is imperative to conduct analysis on not only the specific areas that will be affected, but the severity of flooding that can result after a catastrophic event. Modelling work that simulates the storm surge in case of various scenarios have lately been implemented in hydrological fields to attempt to address this issue. However, these simulations often fail to address the effects of flooding outside the country of focus. In areas like the South Texas, where culture, transportation and economy are heavily entangled with Mexico, it is imperative to address the effects on both countries to effectively analyze the extent of risks. As such, this Thesis will investigate the effects of flooding on a binational level, utilizing and further developing existing hurricane storm surge models to obtain accurate results in a variety of scenarios. This information will be processed and further investigated with the use of available geographic information data and systems in order to detail flooding extension, severity, and

supplementary information that may provide insight towards urban development and infrastructure management.

DEDICATION

I dedicate my work to my family who have supported me through everything and to my mentors at URGV that have continued to motivate my work despite all the hardships.

ACKNOWLEDGMENT

I would like to thank the Texas General Land Office Coastal Management Program and the Dwight David Eisenhower Transportation Fellowship Program for Engagement in Transportation Related Academic Research funded by the Federal Highway Administration (FHWA) for their sponsor of the hurricane storm surge flood map project.

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CHAPTER I

INTRODUCTION

The Lower Rio Grande Valley Area (LRGV) is located in the Southmost area of Texas, sharing a frontier with the North Tamaulipas, Mexico, area. Both states face the Gulf of Mexico eastward and present a variety of important water bodies such as the Laguna Madre, lake “El Barril,” and the shared boundary river of the Rio Grande, also known as Rio Bravo. The area has faced a surge of economic development stemming from an increase in the development of individual projects (such as SpaceX, located in the Boca Chica area) and binational treaties supporting the trade between countries. Despite the area’s increased infrastructural and economic development, there is a prevalent issue regarding flooding, as tropical storms and hurricanes have historically occurred frequently and heavily impacted the lives of thousands. The flooding itself leads to a variety of issues, which are not limited to housing and personal damages, but long-term infrastructural ones, as roads face prevalent flooding and consequent damage to the asphalt and concrete composition. These long-term effects can lead to further consequences that affect sectors of the America-Mexican economy and subsequently decrease the quality of living of those affected.

Due to the prevalent flooding hazard, the naturally extensive swamp environment in the region, and the constant traffic flow due to the intermingled economy between the US and Mexico, it has become increasingly necessary to analyze the risks and better the infrastructural planning. Storm surge urge modelling through ocean modelling has previously been used to analyze the severity of rainfall can result in case of tropical storms or hurricanes. Models, such as ADvanced CIRCulation (ADCIRC) (Lysaniuk, et al., 2021), simulate the ocean circulation in case of the determined scenario and present results in the shape of storm surge estimation. This simulation, however, only results in numerical data that requires further processing in order to denote the actual extents and impact according to the geographical area that is affected. The use of Geographic Information Systems (GIS), coupled with the numerical results obtained from modelling work can illustrate both the severity and extension of risks for future urban development and evacuation routing planning (Zerger, 2002; Hong Zhang, 2021). The use of GIS analysis can also further denote features that pose a higher threat to the population by highlighting the evacuation routes that may be affected, the extension of urban areas and shelters that will be rendered inaccessible, or account for the international routing that may suffer due to these scenarios. Analyzing and understanding the repercussions of flooding scenarios in a geographical area such as coastal South Texas and North Tamaulipas could help prevent future peril and aid in the development of efficient risk management plans.

Problem Statement

Geographic Information Systems allow for the thorough analysis of affected areas in a variety of situations. By coupling the information obtained from hurricane storm surge simulations alongside accurate geographic data of a location, an in-depth analysis can be conducted. This can highlight not only the extension and severity of flooding, but the potential areas of importance, such as international access points, evacuation routes, and urban areas affected. It is through this research that I propose utilizing these geographical and flooding models, to conduct an analysis on the effects of a variety of hurricane storm surge scenarios in coastal South Texas and North Tamaulipas. Geographical data for the region has noted constant updates by the United States Geological Survey (USGS) and the National Institute of Statistics and Geography (INEGI), presenting more accurate and up to date information of the features located in both the United States and Mexico. Weather variables required for modelling are available through the National Oceanic and Atmospheric Administration (NOAA), allowing for accurate inputs in the existing hurricane storm surge model which was previously developed by researchers at UTRGV.

The research conducted for this thesis seeks to obtain answers for the following:

1. What is the extension and severity of flooding that will affect South Texas and North Tamaulipas in case of a variety of hurricanes?
2. How does the flooding severity defer based on hurricane category impacting the area of focus?
3. What important features can be affected due to flooding based on GIS analysis, and what consequences can lead as a result?
4. What is the extension of evacuation routes affected in case of different hurricane scenarios?
5. How much of the population in the study area will be affected based on urban surface affected?
6. How efficient and accurate can GIS analysis be as a result of utilizing the most recently available data in flooding forecasting scenarios?

Objectives

The purpose of this research is to conduct a thorough analysis of the effects of hurricane storm surge caused by a variety of scenarios, which are simulated through the use of existing models used in previous studies. The area of focus includes a binational extension, focusing on both North Tamaulipas, Mexico and South Texas, USA, allowing for a more complex analysis of the effects of flooding while utilizing currently available data. Through the use of GIS, a variety of maps, graphs and tabulated data can be extracted to present both graphical and numerical results that can be used for a variety of audiences in future research. The data analyzed will be sourced from a validated ADCIRC model, which presents accurate numerical information of the impact in the coastal area but has previously been limited to an analysis of South Texas only. Finally, the analysis conducted will be summarized in a categorized report denoting all the findings of affected areas in the area of research.

CHAPTER II

REVIEW OF LITERATURE

Area of Study

The South Texas and North Tamaulipas area has historically been affected by hurricanes and tropical cyclones, leading to lasting issues that affect the communities populating the area. On September 20th, 2013, three inches of rain lead to an overflow that impacted the U.S. Highway 83 in Starr County, and on November 6th of the same year, a thunderstorm flooded West Brownsville with over 4 inches of rain (U.S. Department of Commerce, 2020). Scenarios like this are common in the study area, and with current developments due to climate change, it has become increasingly necessary to analyze potential threats and plan accordingly for the future. The hydrological and geographical characteristics of South Texas – North Mexico could be considered one of the major reasons behind the frequency and severity of flooding affecting the area. The close proximity to the Gulf of Mexico eastward, the variety of water channels and resacas across the region, coupled with the relative flat elevation across the entire region present issues when dealing with heavy rainfall and its resulting water runoff (Texas Parks and Wildlife, n.d.). Consequently, a variety of agencies across Mexico and the U.S. dedicate their resources to not only monitor the status of the hydrological characteristics of the area, but also provide data for further research and studies.

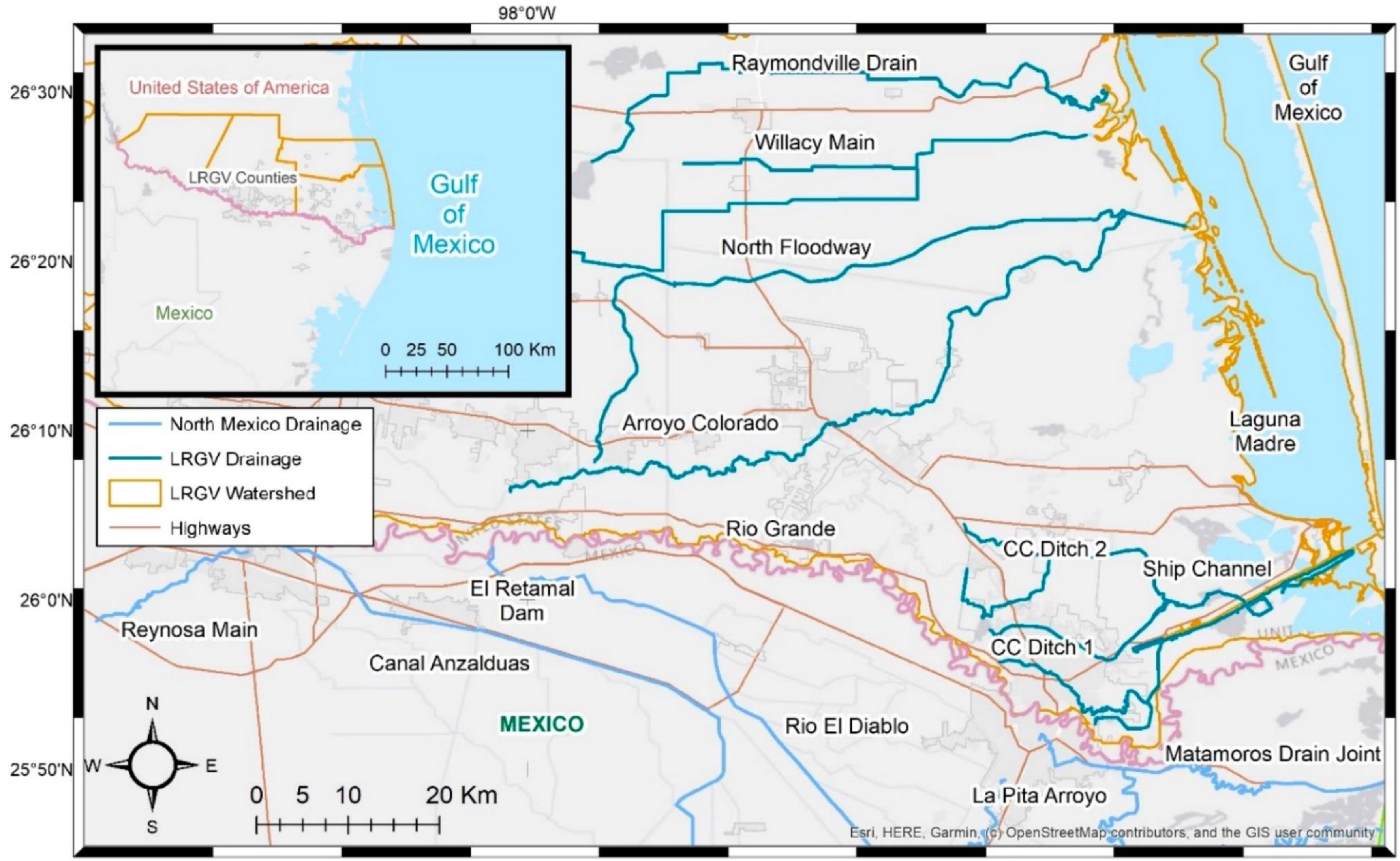

Figure 1: Map of the Study Area and its Hydrological Characteristics.

Binational Emergency Management

Through analysis of governmental information provided by a variety of sources, active and past policies can be analyzed to estimate the probable evacuation routing, international port course of action and dispatch of emergency services. Agencies, such as the U.S. Environmental Protection Agency (EPA), and the Secretaria de Relaciones Exteriores of Mexico have delineated procedures in case of hydrological emergencies affecting the border, which can be used as a basis for emergency planning. The Secretaria de Relaciones Exteriores of Mexico denote the existing border crossing points and its influence on both transportation and economy for both the United States and Mexico, highlighting the constant development of newer entry points, such as “Los Tomates -Veterans”, which started operating in 2014 with an extended development for further traffic inflow (Secretaria de Relaciones Exteriores, 2014). Figure 2 highlights the existing border crossing points in the study area that can potentially be affected in case of flooding scenarios. The study area in the South Texas border denotes a “Sister City Agreement”, in which four of the urban locations with border crossing accessibility agree in mutual cooperation in case of hydrological contamination and evacuation efforts, listing the different agencies that may come into action to help in border management and evacuation arrangements (Environmental Protection Agency, 2015).

However, despite the existing plans for environmental emergencies, emergency scenarios due to flooding do not have an existing emergency plan. The FEMA agreement between countries ensures mutual cooperation in case of emergency scenarios and continues to develop emergency management courses to prepare the existing personnel in case of binational emergencies. Despite these current efforts, the Texas Department of Transportation denote that most of these efforts focus on the management of chemical emergencies only and has a wide room of growth to better their emergency response (Texas Department of Transportation, 2020).

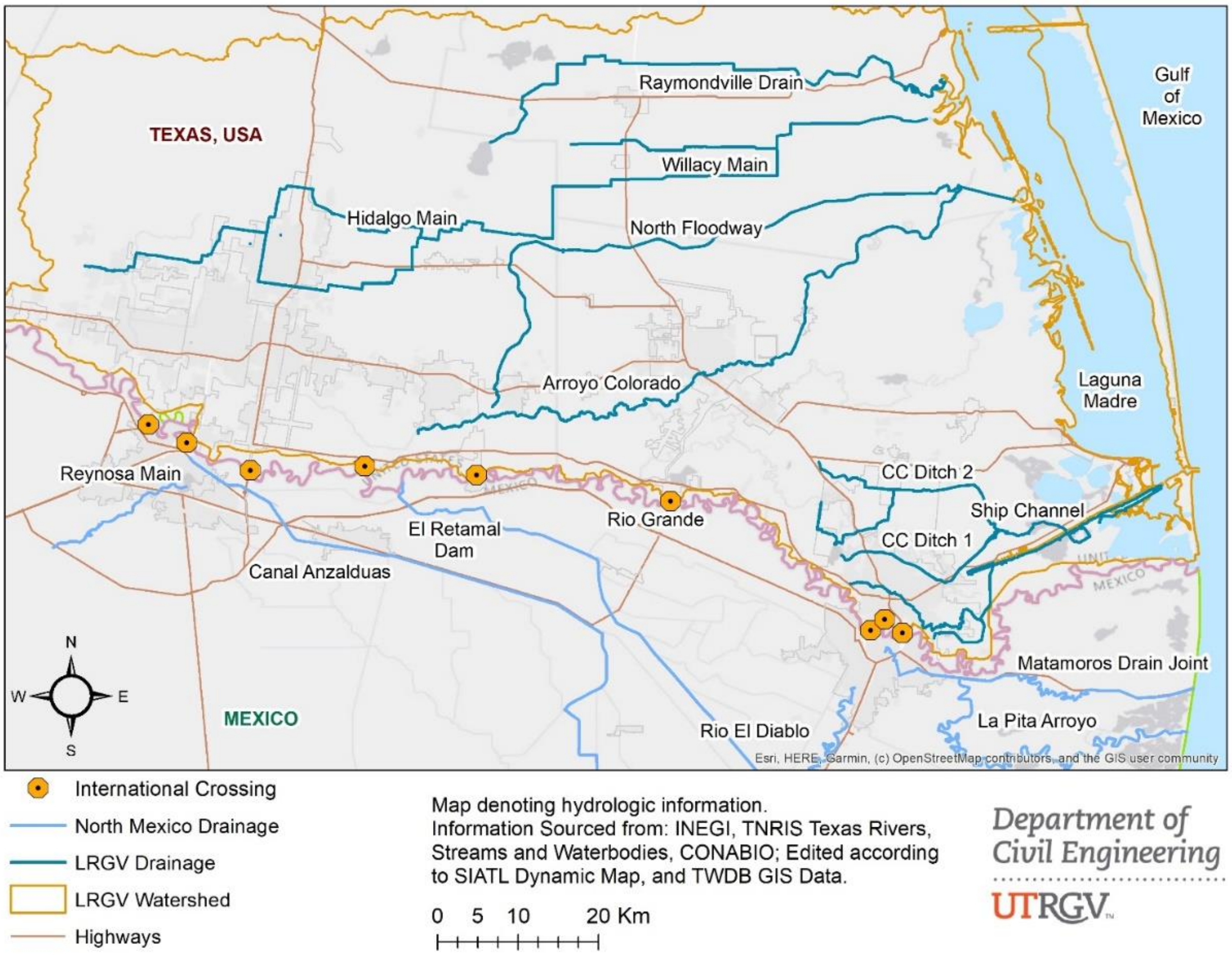

Figure 2: Map denoting existing International crossing points in the study area.

Related Work

Previously, researchers have utilized GIS alongside natural hazard simulations to obtain potential results to develop urban planning and evacuation routes (Zhang, Zhang, Zhang, & Hou, 2021). Regarding the methodology used to conduct this analysis through the use of GIS, the procedure can vary depending on the subject to be analyzed. Population studies correlate population to surface area, attempting to adjust for locations in which population density is higher, but data availability can affect the accuracy of the results (Lysaniuk, et al., 2021). Furthermore, the analysis of flooding impacts with the use of GIS can help us denote other notable issues. For example, in the case of evacuation routes affected, it can be noted that most roads are made of asphalt. Studies have shown that asphalt mixtures are more sensitive to moisture, leading to long term damage that may need to be addressed after flooding events (Hu, Wang, Zheng, Li, & Shi, 2021). The use of GIS has also been highlighted in a variety of analyses which focused on binational watersheds of U.S. – Mexico with the purpose of denoting possible ecological concerns (Brown, Czerniak, & Buscaglia). The use of GIS in emergency management has ultimately been critical as a useful tool for comprehensive emergency management, as it can be part of the mitigation step, mapping risks and expanding research.

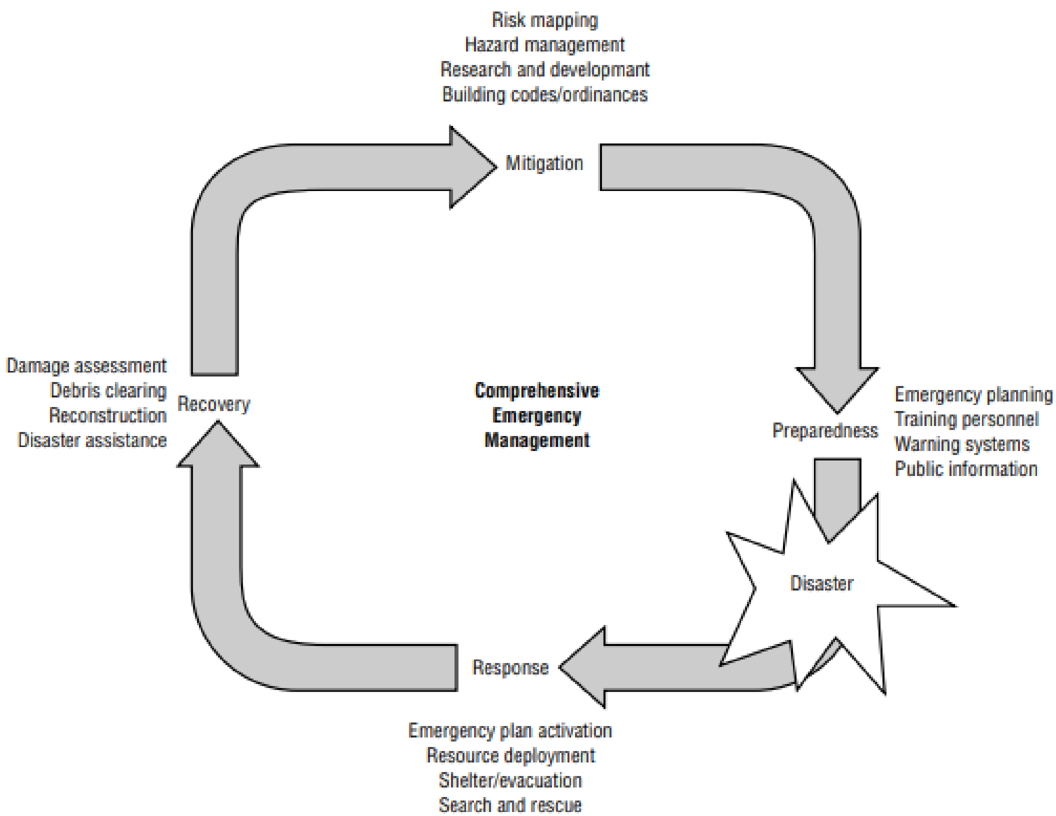

Figure 3: Comprehensive Emergency Management steps.

More specific studies have utilized flooding modeling to analyze the geographic impact, denoting the population affected and proposing that this methodology can aid in risk management; furthermore, past flooding case studies have developed analysis for situations in which geographical data may be limited (Shao, et al., 2021). The coupling of GIS software alongside the usage of hydrological modelling is a consistent methodology found across a variety of studies, as the addition of geographical analysis can emphasize the impact of flooding (Ozcelik, Gorokhovich, & Doocy, 2012). Data limitations are imperative to consider when developing a binational study incorporating a country such as Mexico, which does not have as much data readily available (Center for International Earth Science Infromation Network, 2017). Furthermore, the data available between two different countries presents a variety of formatting and resolution issues that have to be addressed. The usage of various resolutions requires further processing which, when done effectively, can lead to the development of successful models that expand the scope of analysis for a more effecting forecast (Elston & Buckland, 1993). Despite limitations, past studies have achieved binational hydrological analysis in a variety of situations, including the discussion of flood risk management and vulnerability due to shared water bodies similar to the Rio Grande (Freimund, Garfin, Norman, Fisher, & Buizer, 2022). These analyses have included greater water bodies that meet a variety of countries to be affected in case of flooding (de Vries, et al., 2013) or have been used to create vulnerability assessments for policy making (Rosa, 2020)

ADCIRC has been utilized for multiple coastal forecasting scenarios, including some located in Texas (Sebastian, et al., 2014). The existing model developed by researchers at UTRGV to be utilized in this study has been thoroughly analyzed by students and faculty alike in the past, denoting the model calibration and its use for determination of impact on other water bodies in the South Texas region, and even coupled with other models to develop a more thorough scenario and analysis (Davila Hernandez, Davila, Flores, Ho, & Kim, 2022). The use of this flooding forecast has allowed for the analysis of highways affected across the coastal zone (Davila, Garza, & Ho, 2018), the impact of flooding on existing resacas across the study area (Reyna, 2022), and further coupled with other models to analyze the flooding effects with a higher accuracy (Ho, Kim, & Oubeidillah, 2021).

Due to the international nature of this analysis, it is imperative to analyze the political aspects regarding emergency management and its difference between countries. Both the United States and Mexico have a variety of agencies in charge of emergency relief and management, ranging from municipal to federal level. Consequently, each country and agency may have a different course of action determined in case of flooding. Previous studies have analyzed the perceptions of citizens located at border towns when facing flooding risk and their perception of risk towards international travel in case of a binational emergency (Freimund, Garfin, Norman, Fisher, & Buizer, 2022). Analyzing international borders and its traffic will only continue to grow as a point of concern, as climate change will continue to create further emergency situations that will extend farther than the reach of a single nation. This pressing issue has been denoted in different borders around the world, emphasizing the urgency of creating adaptable plans to face emergencies in border regions (Murphy, 2017).

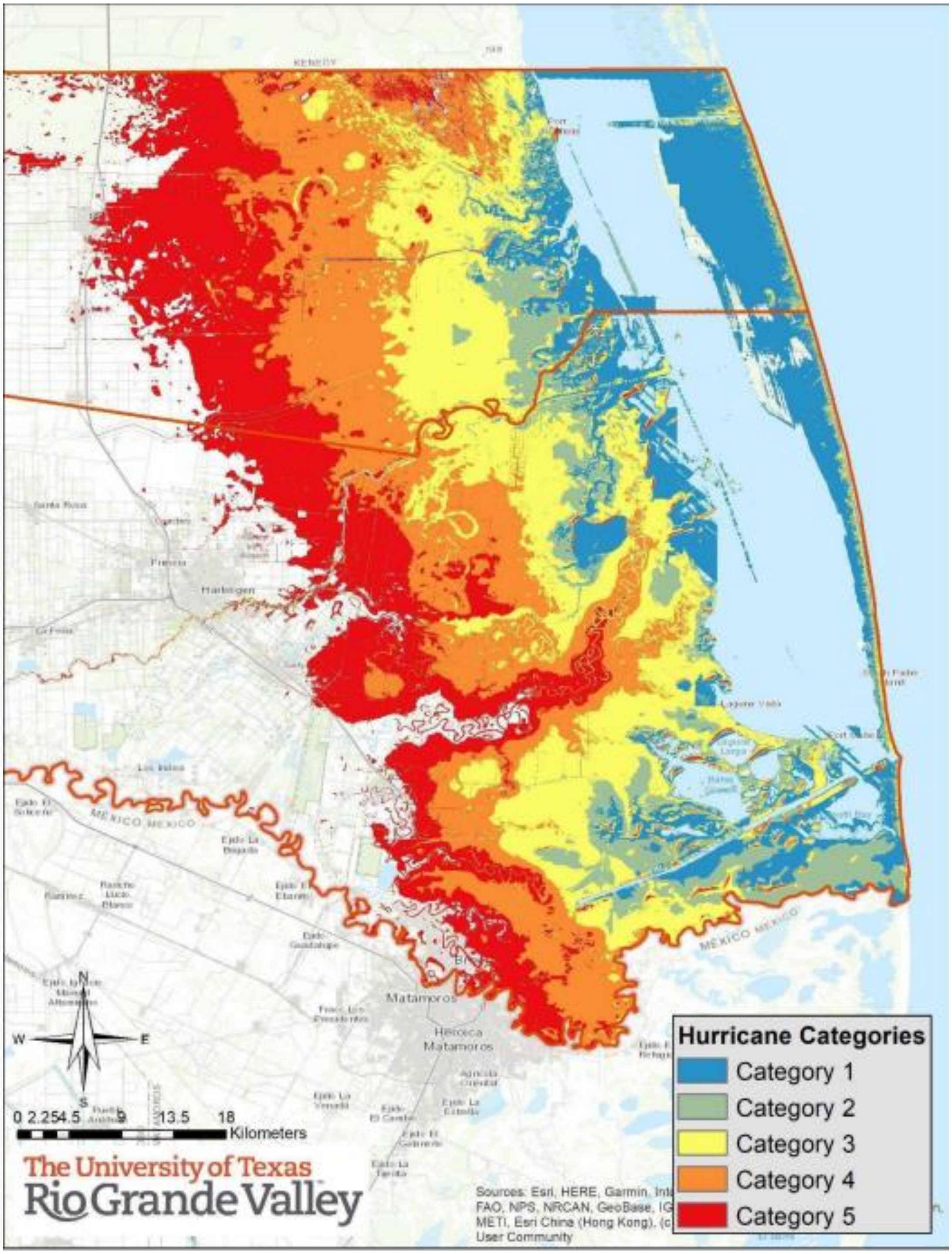

Figure 4: Developed Map of Flooding Based on Hurricane Impact (Ho, 2021).

CHAPTER III

METHODOLOGY

The research conducted for the purpose of this thesis involved data retrieval for geographic analysis, alongside the use of existing hurricane storm surge model for simulation and verification of data. The following sections detail the methodology taken for the final results of this work.

Literature review

The review focused on obtaining information on previous work relating to the usage of water modeling simulations and GIS analysis relating to the usage of hydrological features. An emphasis on binational study was remarked due to the binational aim of this research as described throughout chapter II. This information was used to denote features that can be analyzed in the study area and accurately present the results of the research, as well as obtain previous methodology in regard to the analysis of mixed resolutions of geographical data. The availability of data allowed for the establishment of the study area, delimiting the extensions that can be analyzed near the U.S. – Mexico border. Different agencies from both countries were reviewed in order to determine the existing analyses and what extensions could be conducted with this work. Hydrological networks denoted by available maps and previous studies were taken as reference for modelling notes and helped denote the extension of the work conducted through geospatial software.

Data gathering

Data used was sourced from a variety of open sources available online, including government sources from both the United States and Mexico. INEGI and the USGS have compiled an in-depth data source denoting multiple geographical features that allowed for the development of the study. Further sources included to denote substantial features such as water bodies and evacuation routing information were included to extend the geospatial analysis scope as shown in table 1.

Table 1 - Agencies and data sourced according to the country of origin.

Country	**List of Sources**	**Data Available**
U.S.A.	United Stated Geological Survey – USGS (https://www.usgs.gov/products/maps/gis-data)	National Elevation Dataset South Texas Lidar Texas Rivers, Streams, and Water Bodies
	International Boundary and Water Commission – IBWC (https://www.ibwc.gov/GIS_Maps/GIS_Program.html)	Rio Grande Bathymetry
	Texas Water Development Board (https://www.twdb.texas.gov/mapping/gisdata.asp)	Precipitation Data

Table 1 - Agencies and data sourced according to the country of origin (cont.)

Country	List of Sources	Data Available
México	Comisión Nacional para el Conocimiento y Uso de la Biodiversidad – CONABIO (http://www.conabio.gob.mx/informacion/gis/)	Major Basins
	Instituto Nacional de Estadística, Geografía, e informática – INEGI (https://www.inegi.org.mx/app/geo2/elevacionesmex/)	Hydrographic Network Bathymetric Data Road Network Elevation Dataset

Model Simulation

The existing model simulating hurricane scenario in the South Texas area was utilized to determine peak flood values and apply them for the geographic analysis of this thesis. The model used to simulate utilizes Surface Water Modelling Systems (SMS) and ADCIRC. Due to ADCIRC's efficiency at simulating ocean movement as a consequence of wind, storm surge, and resulting tide patterns across the United States coasts, it was adopted for this coastal study (Sebastian, et al., 2014). In order to execute a simulation through the use of ADCIRC, SMS must be used to specify and edit the parameters required. These parameters include bathymetric data, nodal strings, wind forcing data, a finite mesh generated with the software, and the required control variables for each simulation. ADCIRC requires a combination of nodes and bathymetry to generate a boundary condition. The rest of the parameters are used as hydrodynamic inputs to construct the model.

Model Domain

The domain extension of this model encompasses the focus area of the Laguna Madre and the Gulf of Mexico. This model mesh was developed by modifying existing Bathymetric information provided by the National NOAA databases and including a 1/3 arc-second raster dataset to account for the Laguna Madre with the use of SMS software (National Oceanic and Atmospheric Administration, n.d.). Figure 5 shows the model finite element mesh for the Lower Laguna Madre and the Gulf of Mexico. The nodes developed based on the bathymetric data are used to triangulate the resulting geometry, which incorporates the interpolated elevation and coordinates of the specified area. This model utilizes 64,271 nodes to cover the entire grid. An attempted extension procedure of the model domain can be found in Appendix A.

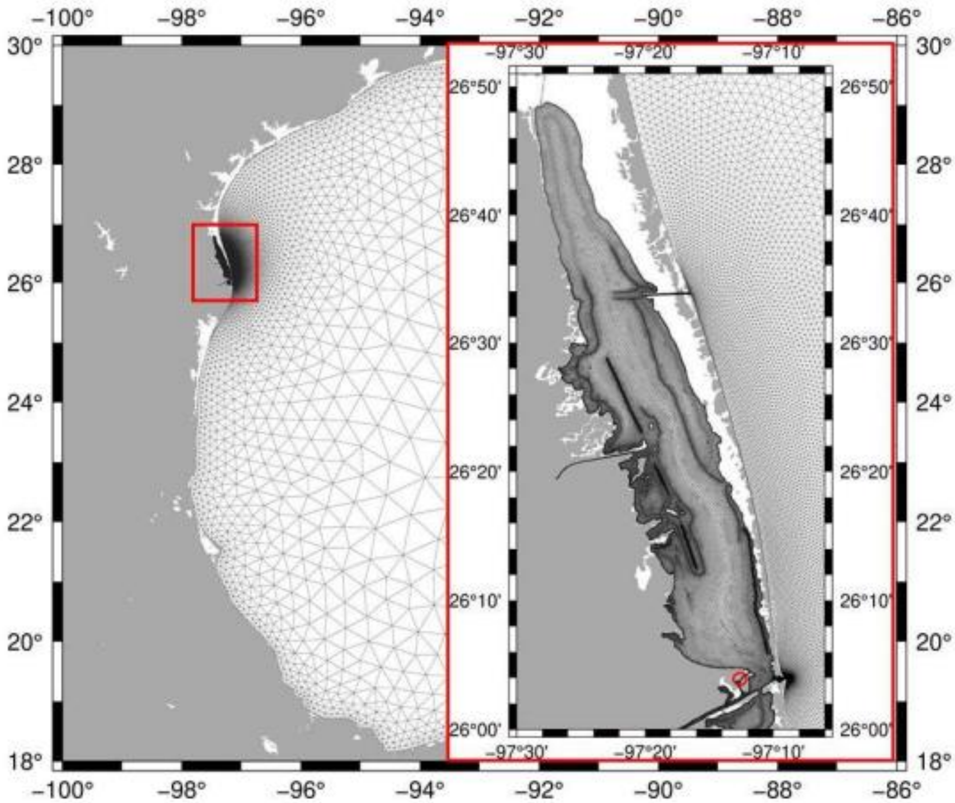

Figure 5: Finite Element Mesh (Davila, Garza, & Ho, 2018).

Storms Simulation

Four different historical hurricanes were used as data for simulations, aiding with the analysis of the results given that they could be compared with observed water surface elevations. The storms used to simulate were Hurricane Bret, Hurricane Emily, Hurricane Dolly, and Hurricane Alex (National Weather Service, n.d.; National Oceanic and Atmospheric Administration, n.d.). These storms were used to create the base patterns to simulate the storm patterns and corroborate the accuracy of the developed model. Based on NOAA's "Best Track" hurricane data files, the specific paths and wind velocities for each storm scenario were used as input in SMS. This data included the duration of each storm, the max sustained wind velocity, and the minimum central pressure.

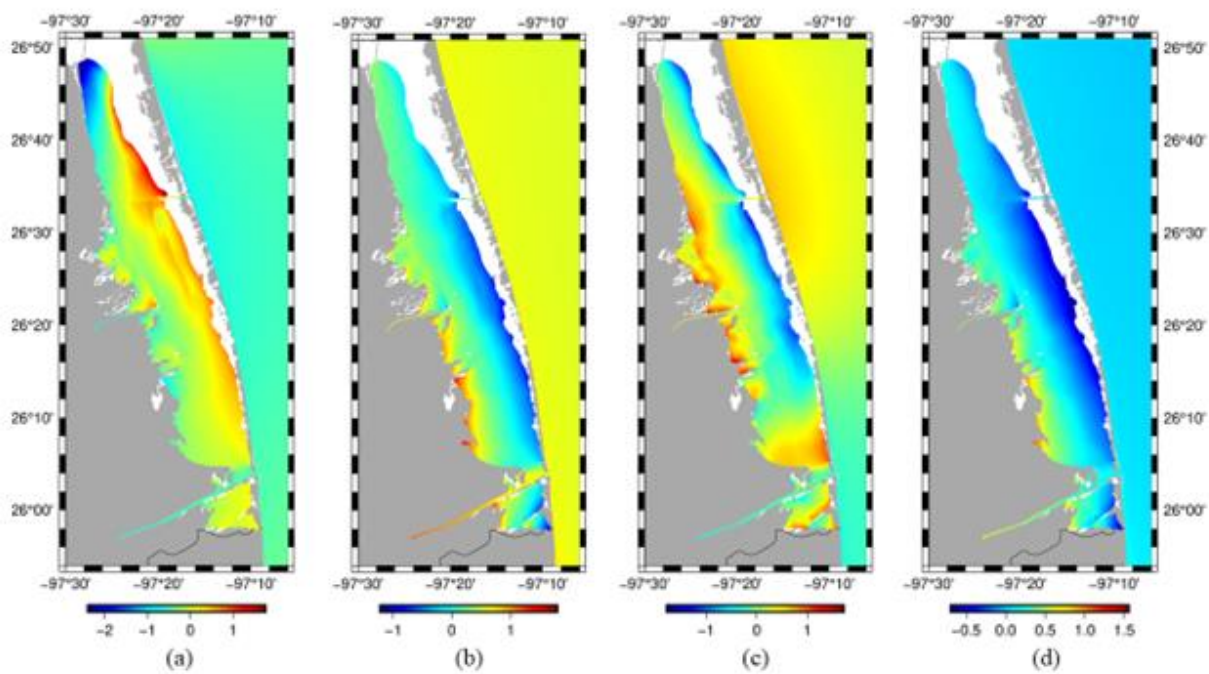

Figure 6: Computed water surface elevation in meters of (a) Hurricane Bret (1999), (b) Hurricane Emily (2005), (c) Hurricane Dolly (2008), and Hurricane Alex (2010) (Davila, Garza, & Ho, 2018).

After creating the storm simulations, the scenarios were run multiple times with different tidal constituents and manning's roughness coefficients to note which provided the most accurate results. The tidal constituents represent elements of the mathematical formula representing the tidal current based on the relative position of the Earth, Moon, and Sun (National Oceanic and Atmospheric Administration, n.d.); playing a major role on the simulation patterns. Each scenario was compared to the historic water surface elevation to check for accuracy. Seven tidal constituents were selected (K1, O1, P1, Q1, M2, S2, and N2) and the roughness coefficient varied between .067 and .02 according to the distance from sea level of each nodal attribute.

Once the stability was corroborated by comparing the modeled elevation with the existing peak heights of the buoy station recording, 5 different scenarios were developed to account for each hurricane category based on Saffir Simpson Scale (Roth, 2010). The parameters established in order to simulate the previously mentioned scenarios included: date/time, coordinate location, hurricane direction, wind speed, atmospheric pressure, speed of hurricane and pressure of hurricane (Nunez, 2019). These new scenarios were developed following historic data provided by NOAA of hurricanes that have come in contact with the South Texas area. The storms selected and the used parameters are denoted in Table 2.

Table 2: Storms Selected for Simulation.

Storm Name	**Category**	**Year and Location**	**Direction and Duration**	**Max Wind Speed (km/h)**	**Min. Atmospheric Pressure (mb)**
UNNAMED	1	1886, Brownsville	N, 5 days	158	979
Dolly	2	2008, Arroyo Colorado	W/NW, 10 days	153	967
Bret	3	1999, Kennedy County	N/NW, 5 days	225	952
Allen	4	1980, Brownsville	NW, 10 days	225	931
Beulah	5	1967, Brownsville	N/NW 15 days	257	923

After assignments through SMS, the ADCIRC simulations were exported and simulated with the use of Linux compatible applications. The exporting process was required given the extent of the model and the lengthy simulation process. Figure 3 illustrates the water surface levels from the scenarios evaluated for 4 different hurricane events, which depict peak surges along the coastal area, with the most severe inundation locations noted in red. The speed of the storm transition plays a significant role on how the storm surge propagates (Davila, Garza, & Ho, 2018).

Model Calibration and Validation

The model calibration and validation were done to corroborate the accuracy of the results and ensure the simulations of hypothetical scenarios provided similarly accurate water depths and extensions. Given the usage of historical storms and available data from NOAA, the validation process consisted of comparing the computational results and the NOAA provided water surface elevations. The hydrographs used for comparison are denoted in Figure 7. Through this comparison, it was noted that tidal constituents played an essential role in the accuracy of the simulation. Constituents, such as M2, are stable in the deep ocean conditions but lacked efficient resolution for the coastal areas; therefore, the combination of constituents used are essential to the simulation. After conducting a statistical index to quantify the accuracy of the hydrodynamic model, the number tidal constituents were evaluated. Ultimately it was determined that the use of 7 constituents provided the most accurate results. Furthermore, this statistical index noted that the use of a constant manning's roughness was more accurate than the use of a specified value varying by elevation on each node. With the use of the determined nodal attributes and constant roughness coefficient, the modeled storm surges closely matched the measured peak heights of the buoy station recordings.

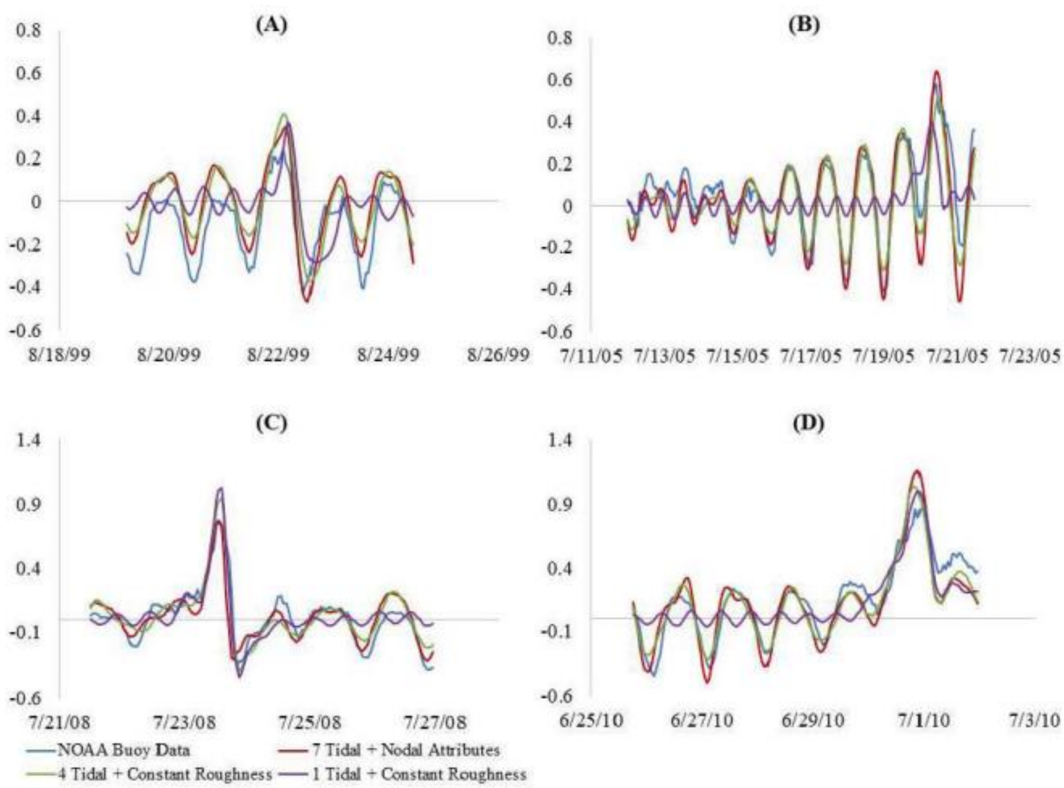

Figure 7:Hydrographs comparing simulations and existing NOAA data.

GIS Analysis

The GIS analysis was conducted based on the data gathered and the information discerned from the literature review, applying past research with the aim of obtaining a similar analysis for the North Mexico-South Texas area. The geospatial analysis required the usage of both model results and the obtained geographical data sourced during the data gathering portion of the work; this data was processed through the use of ArcMap 10.7. The hurricane water surface elevations used for the geospatial analysis were based on the peak hurricane storm surge resulting from each hurricane category simulation and are listed in table 3. It should be noted that elevations were converted into meters due to the elevation datum used for most of the geospatial data utilizing SI units..

Table 3: Peak hurricane storm surge used.

Hurricane Category	**Elevation (ft)**	**Elevation (m)**
Category 1	3.5	1.0668
Category 2	6.8	2.0726
Category 3	14.2	4.3282
Category 4	21.5	6.5532
Category 5	30	9.144

A combination of high-resolution digital elevation models sourced from USGS, alongside the national elevation model sourced from INEGI were cropped and merged into a single elevation model with the use of the mosaic tool. This newly merged DEM was then modified in the symbology tab to showcase the general extension of flooding based on the elevations denoted previously. It should be noted that this DEM's accuracy is affected by the coastal resolution, as parts of it are completely cropped out when considered to be part of the ocean.

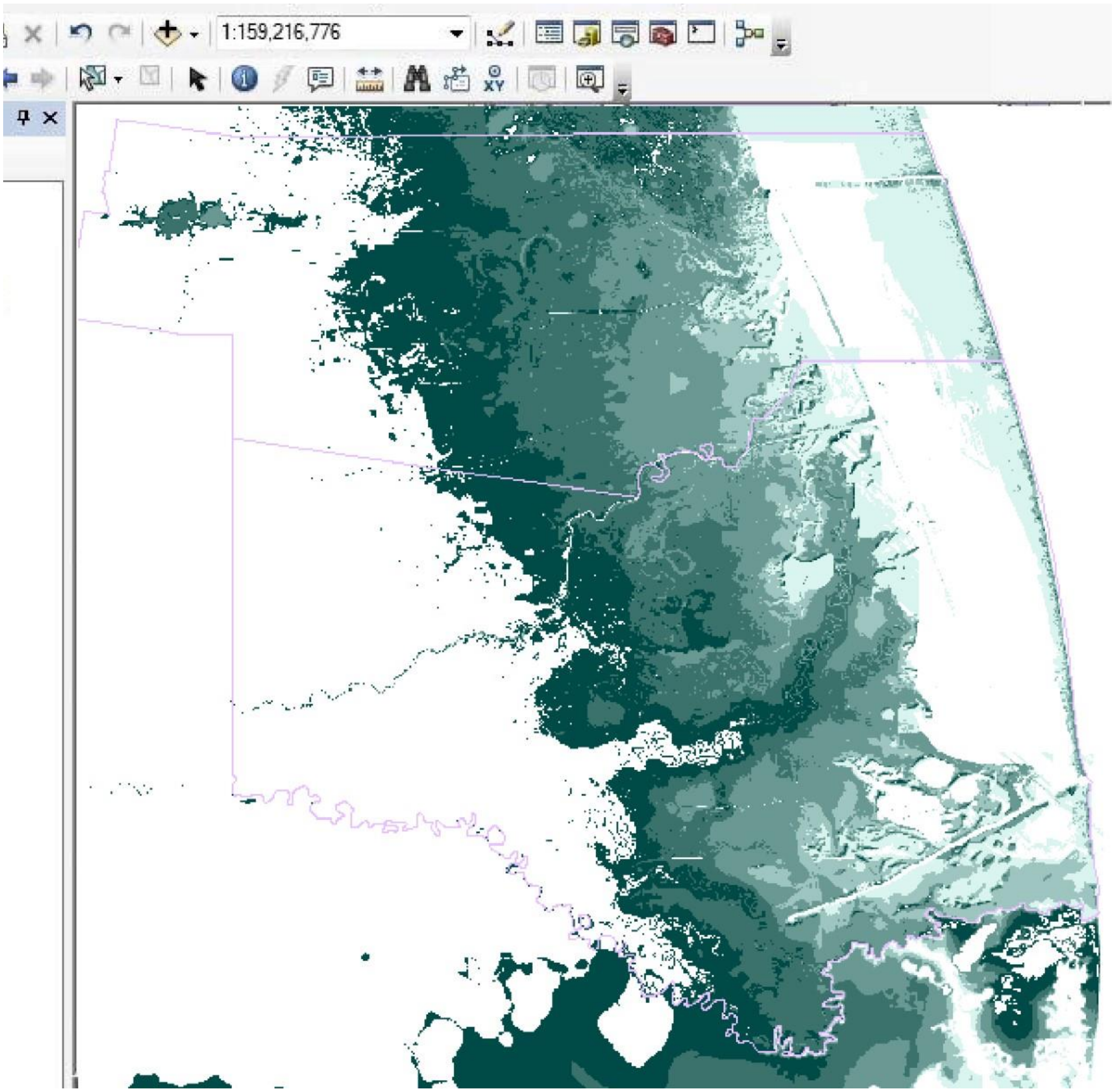

Figure 8: Preliminary flooding extension based on hurricane storm surge.

In order to obtain the actual water surface elevation, the determined heights from the model were subtracted from the previously developed DEM. This process was conducted five times to account for each hurricane category and resulted in five different rasters that showcased the actual elevation of flooding in each hurricane scenario to be used as one of the resulting deliberates of this work.

In order to conduct an analysis on what features would be affected due to each flooding scenario, the extension of flooding rasters had to be converted into shapefiles. This is due to the current existing features to be analyzed (such as urban extension and evacuation routing) existing as shapefiles as well. The created rasters of each hurricane extension were reclassified into single class rasters, omitting any values outside of the flooding extension. This resulted in five different hurricane shapefiles that showcased the extension of flooding in each scenario without actual depth.

As previously noted, the DEM resolutions of the coastline appear to have issues when delineating the ocean boundary. In order to address this issue, An existing ocean shapefile sourced from NOAA was incorporated. This shapefile was edited and refined to follow the coastline of the study area to a better match, including features such as the Brownsville Ship Channel.

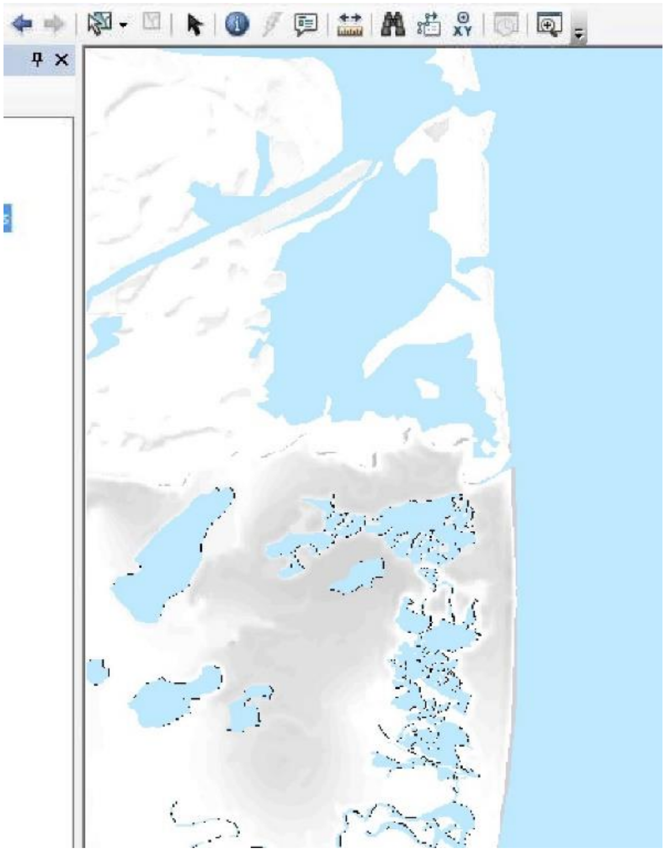

Figure 9: Adjusted Shapefile of water boundaries.

The data to be analyzed first was Urban Outlines as shown in figure 10. This was done to obtain an approximate area of how much of the urban municipalities would be affected during each hurricane scenario. Data used was sourced from INEGI's census data of 2010 (INEGI, 2010) and Texas City limits as of 2016 (ArcGIS, 2016), these shapefiles were cropped to only denote the relevant urban locations in the study area. Similarly, to previous work, these shapefiles were merged into a single shapefile to help improve work efficiency. Population data was attached to the attribute data of the shapefile. Population from Mexico was sourced from the same INEGI census data, while the population of Texas municipalities were sourced from Texas Demographics (CUBIT, 2021). Emergency evacuation routes sourced from the Texas Department of Transportation were also included for the analysis of this work, shown on figure

11 (Texas Department of Transportation, 2016). In order to analyze the effect of flooding on these areas, the Clip Tool was utilized to clip the extension of flooding out of each element to be analyzed. This procedure resulted in new shapefiles that denoted the extension that would be affected under the effects of each hurricane category. Through the use of the Geospatial Calculator and the tabulated data available in each shapefile, the extension of flooding was analyzed numerically as well.

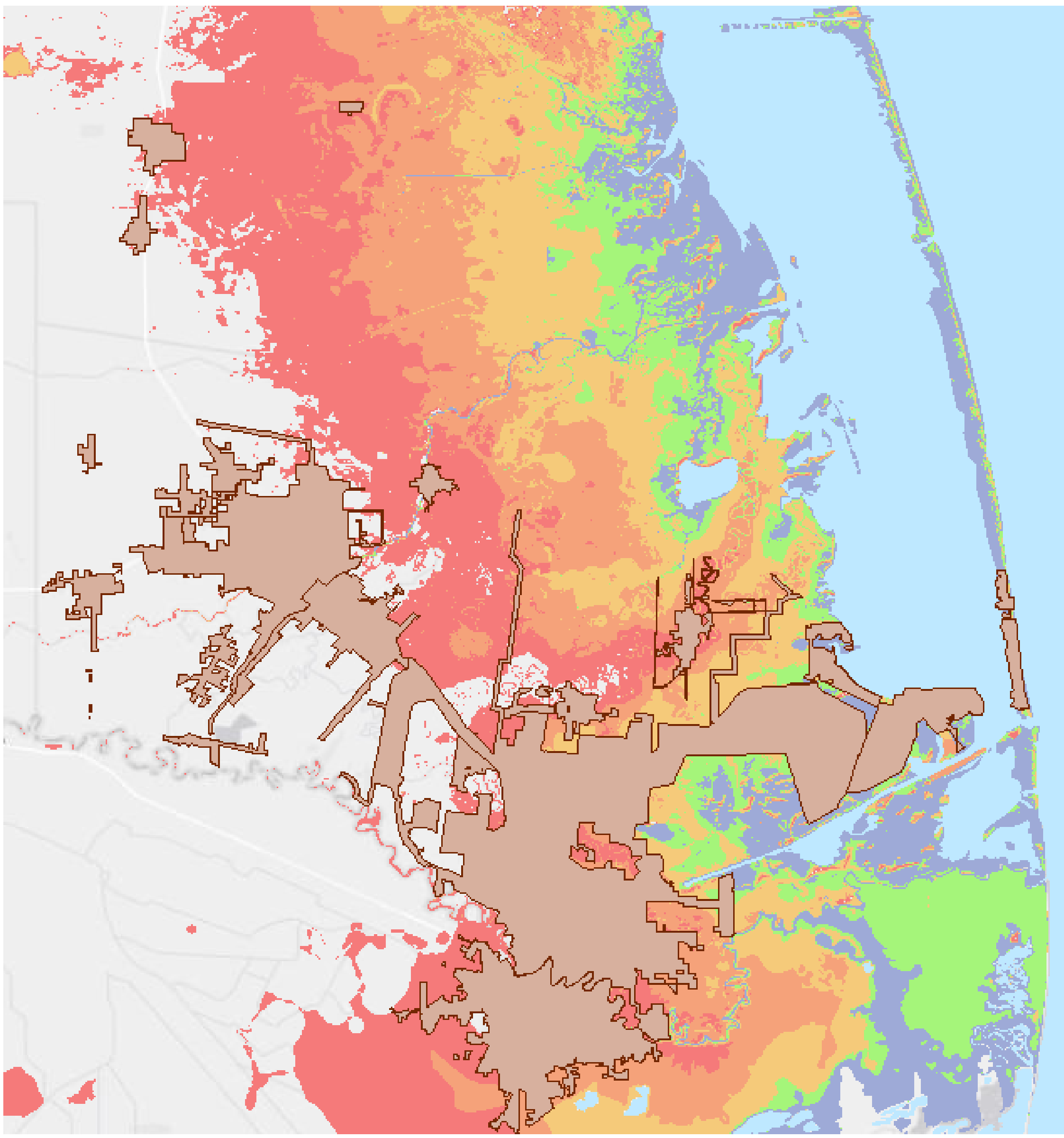

Figure 10: Urban Outline Extension.

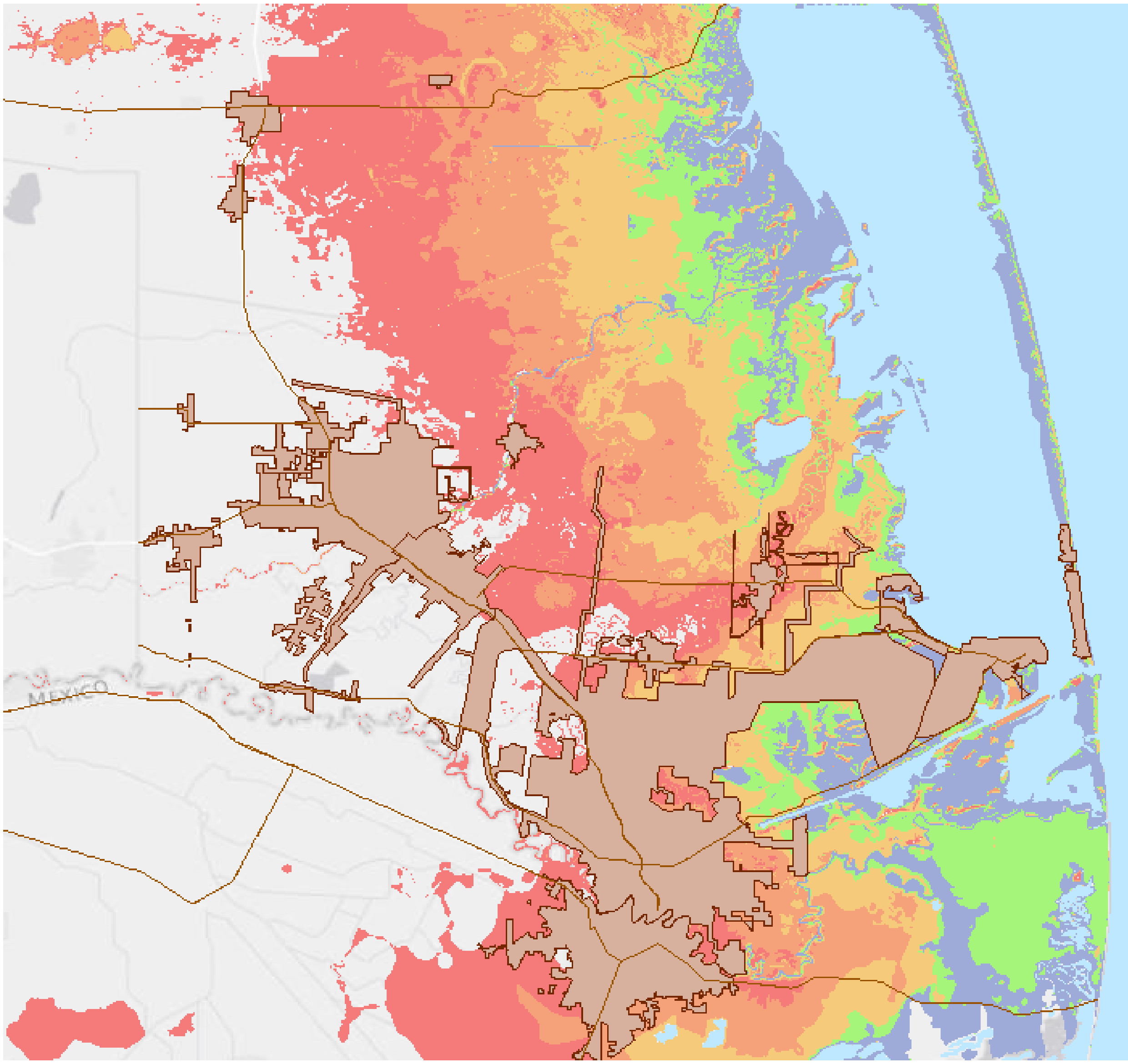

Figure 11: Evacuation routing over urban outlines.

It should be remarked that, despite the use of evacuation routing and population data, there were certain limitations for the geospatial analysis. Population data was considered directly proportional to the area of the urban location due to the lack of urban density mapping that was compatible with the resolutions of shapefile of this study. Similarly, the evacuation routing analysis was limited to the extension of the United States, due to Mexico's lack of set evacuation routing in the study area.

The numerical analysis of the data results sourced from the GIS work was conducted through the use of Microsoft Excel. The work consisted of tabulating the names of all the urban population utilized and connecting them to the sourced population indexes linearly. Based on this analysis, the percentage of areas affected from the hurricane scenarios was assumed to affect the same percentage of population living in each urban area. Graphical representations of the areas affected contrasted were developed to remark the difference between each hurricane category scenario side by side. The urban locations used with the total population sourced can be found in table 4.

Table 4: Urban locations (2016), population (2010), and area.

Name	**Area (meter squared)**	**Area (hectares)**	**Population**
Bayview	11844810.86	1184	605
Brownsville	372384129.2	37238	185,849
Combes	8314495.091	831	2,998
Harlingen	104293405.1	10429	71,124
Indian Lake	699473.0692	70	1,143
La Feria	11302863.39	1130	6,894
Laguna Vista	12700941.76	1270	3,506
Los Fresnos	11007395.92	1101	8,023
Los Indios	4833170.123	483	829
Lyford	4644687.895	464	2,494

Table 4: Urban locations (2016), population (2010), and area (cont.)

Name	Area (meter squared)	Area (hectares)	Population
Palm Valley	1569421.308	157	1,644
Port Isabel	35411586.49	3541	5,208
Primera	7131992.3	713	5,167
Rancho Viejo	5922926.157	592	2,804
Rangerville	9063015.1	906	122
Raymondville	10593639.05	1059	10,574
Rio Hondo	4660995.412	466	2132
San Benito	41414087.21	4141	24812
San Perlita	1334323.605	133	697
Santa Rosa	1981676.608	198	2873
South Padre Island	9133998.17	913	2138
Matamoros	107478661	10749	541,979

CHAPTER IV

RESULTS AND DISCUSSION

Flooding Extension and Severity

As part of the established parameters of this work, the flooding simulations conducted required GIS processing in order to obtain the final surface elevation and extension. The overall flooding extension based on the hurricane intensities are shown in figure 12, and the waster surface elevation reached in case of a category 5 hurricane is shown in figure 13. Maps showcasing the flooding severity of each hurricane scenario are presented in appendix B. These maps denote the major flooding severity affecting the closer proximity towards the coast, which is expected when considering the hurricane paths all originate from the coast. Through the presentation of these developed maps, question 1 and 2 of the problem statement introduced in this thesis are answered.

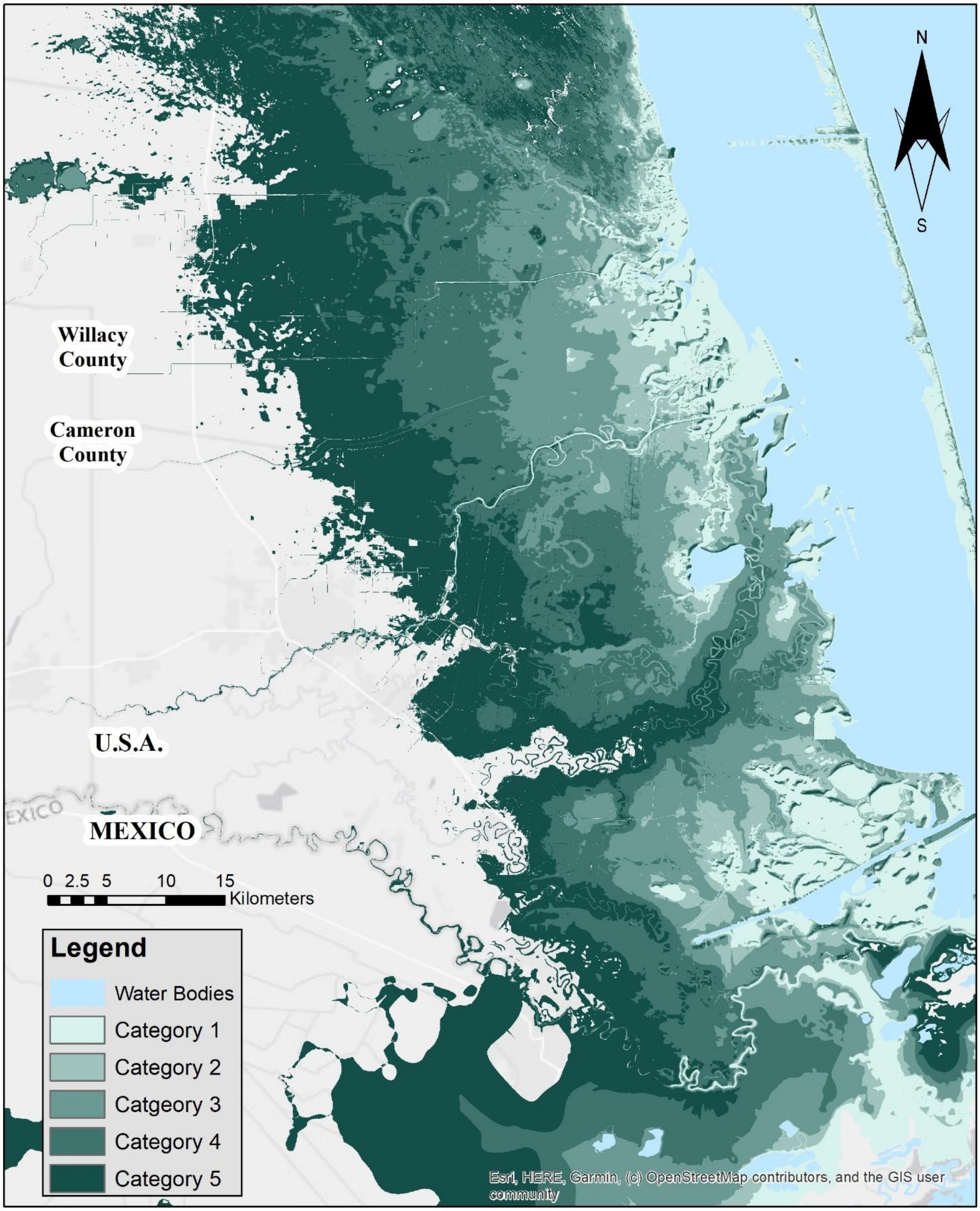

Figure 12: Flooding Extension based on hurricane categories.

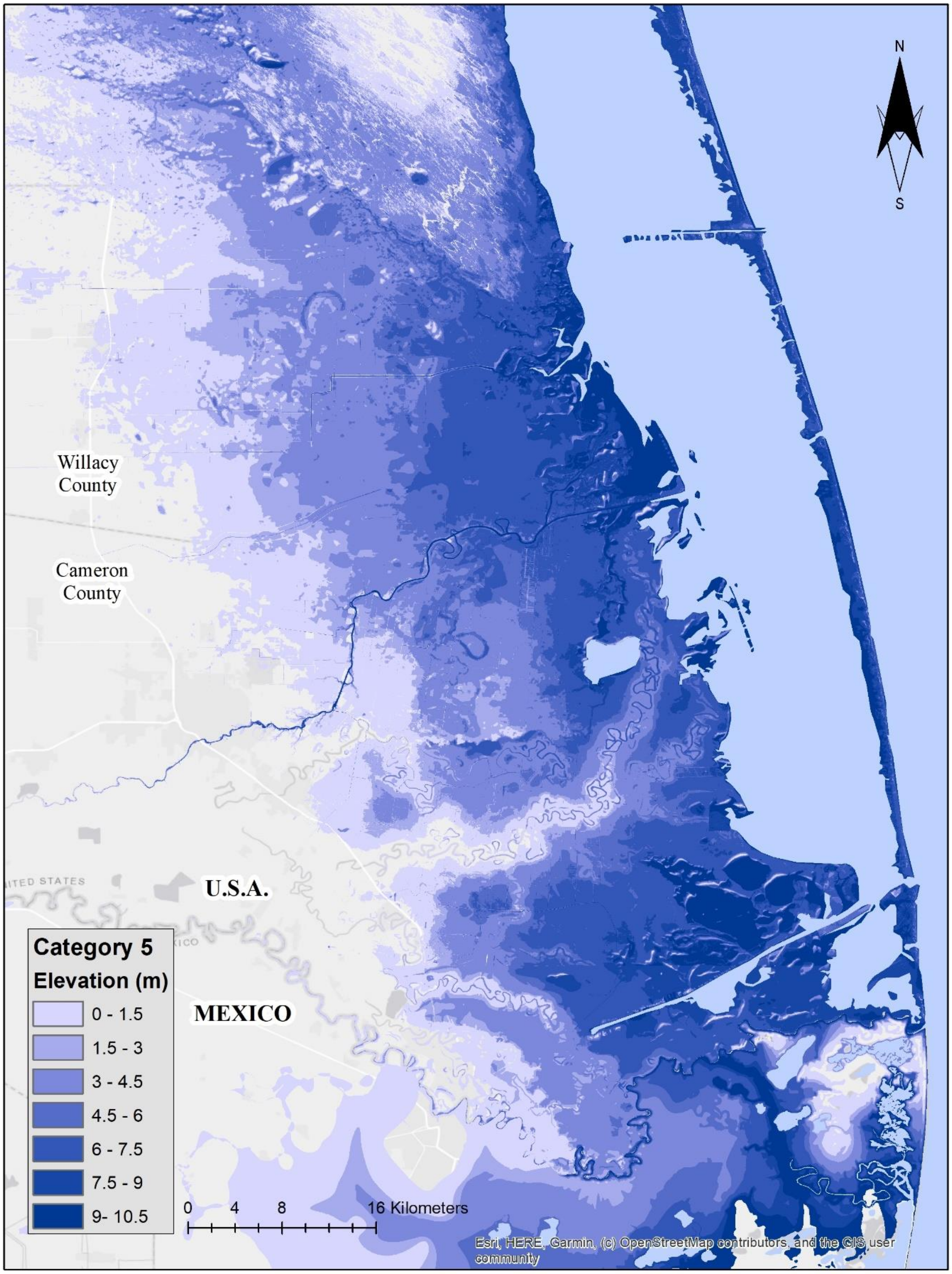

Figure 13: Water Elevation in case of Category 5 hurricane.

Urban Extension and Population

As a response to question 5 of the problems studies for this thesis, the urban locations affected by each hurricane scenario were compiled in figure 14. Higher resolution versions of each individual map can be observed in Appendix B. The numerical analysis relating to the urban areas affected is summarized in table 5. This table includes the percentage of areas affected based on each hurricane scenario simulated and was also illustrated graphically to show the contrasting difference of flooding per scenario.

Table 5: Percentage of Urban Extension affected by hurricane categories.

Hurricane Categories	Category 1	Category 2	Category 3	Category 4	Category 5
Percentage Affected	9.24%	13.56%	23.77%	37.14%	61.98%

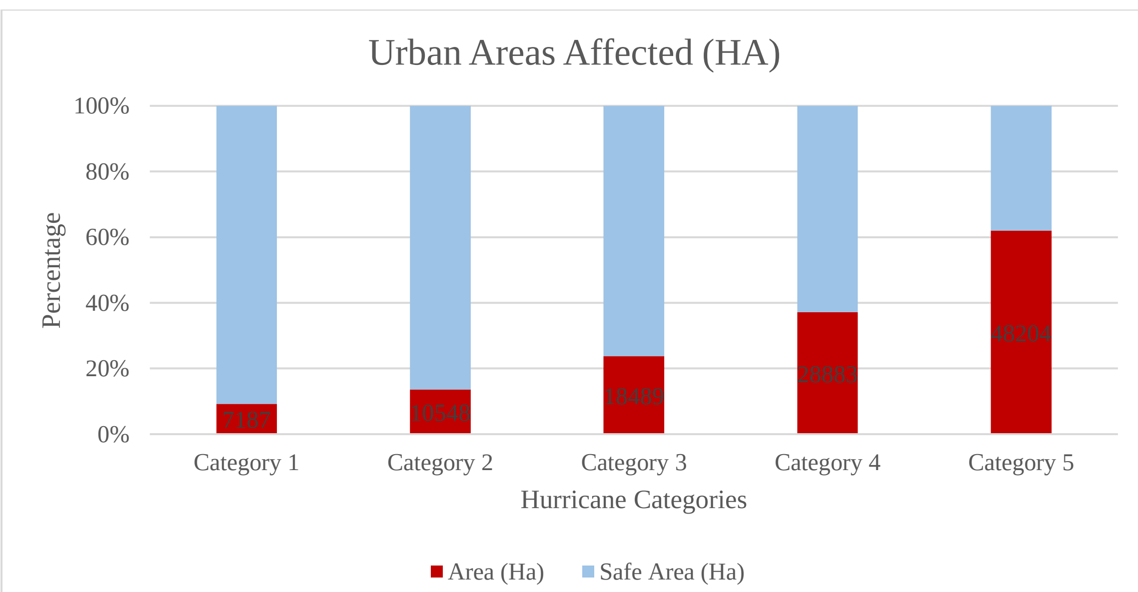

Figure 14: Graph of areas affected by hurricane scenarios.

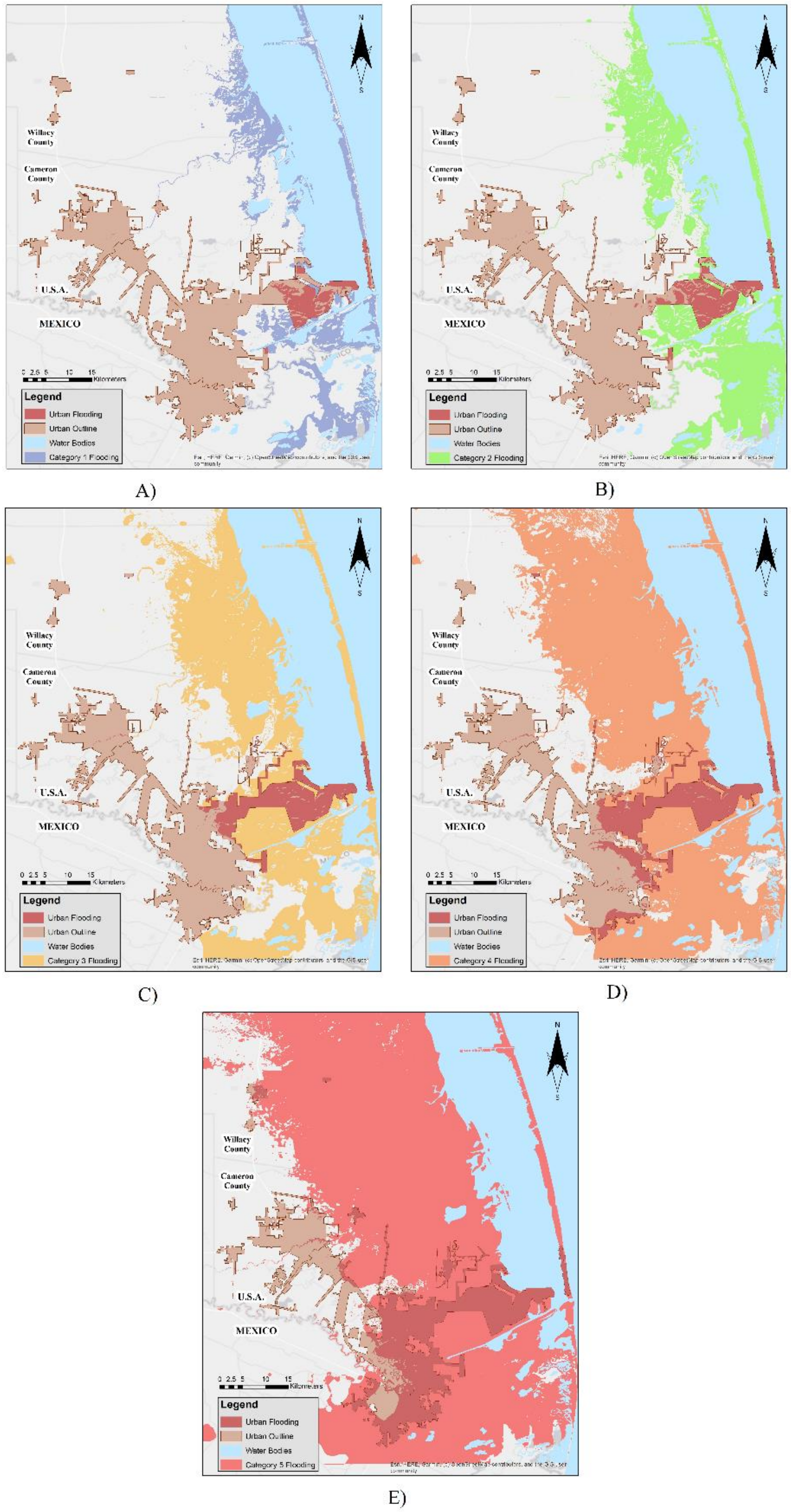

Figure 15: Map showcasing the flooding extension based on: A) Category 1, B) Category 2, C) Category 3, D) Category 4, and E) Category 5.

The severity of flooding is correlated to the intensity of the hurricane simulated. However, it is important to note that despite the flooding extending further westward in the Mexico area, parts of the city of Matamoros remain relatively untouched. This is due to the elevation in Mexico which, in contrast to the flat elevation of south Texas, plays a factor in the water runoff direction. However, it should be important to remark that the resolution noted from the North Mexico Digital Elevation Model was of lower quality compared to the resolution used for Texas. Digital Elevation Model resolution plays an important role on modelling works, and the development of higher resolution data should continue to be advocated for to ensure the best preventive analysis possible (Leitão, Boonya-aroonnet, Prodanović, & Maksimović, 2009).

Regarding the population analysis, the linear correlation between affected area and population drawn resulted in the numbers presented in figure 15.

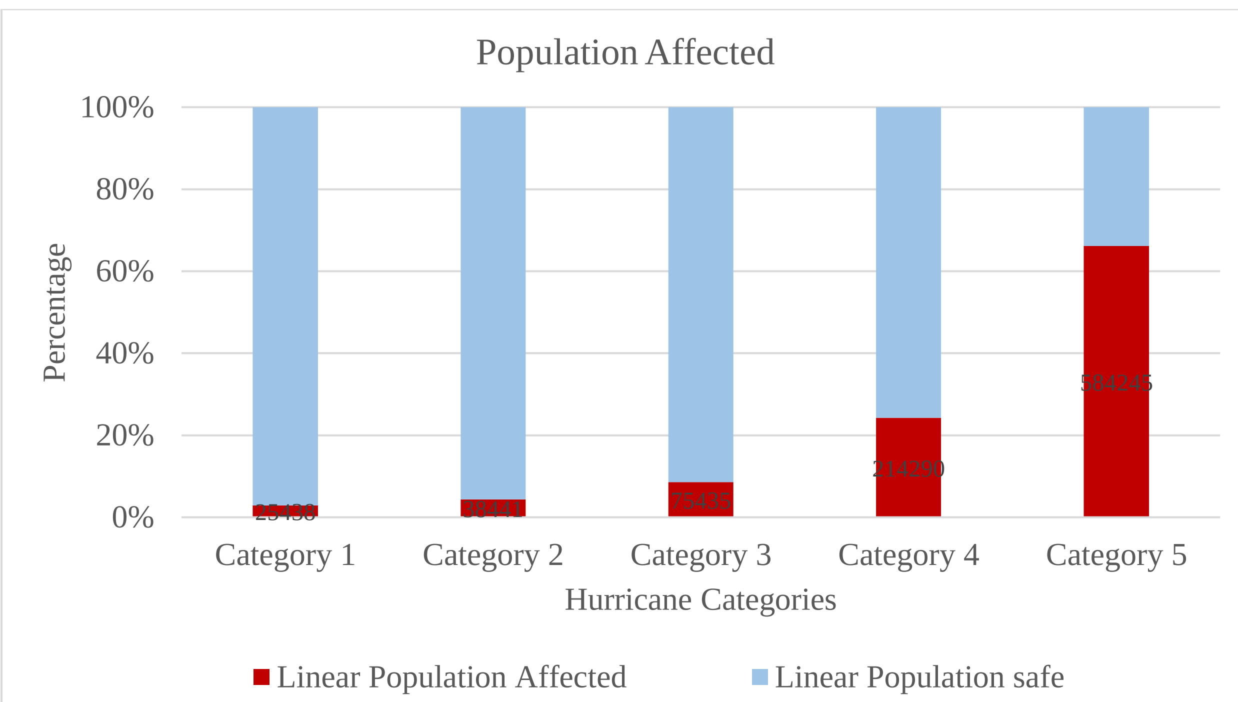

Figure 16: Population affected by linear correlation.

When analyzing the actual percentage of population affected, it should be noted that, according to the U.S. Census Geography of 2020, the total population in Cameron and Willacy counties is 341,551; meaning that in the most severe scenarios such as the category 5 hurricane over 60% of the total population in the area will be affected. This could represent even further issues when considering that most of the drainage channels alongside the study area extend further east and accumulate debris that could potentially affect the drainage rates and lead further damages (Reyna, 2022).

Evacuation Routes and Transportation

Through the use of GIS data attributes, the percentage and location of the affected evacuation routes were distinguished. The following figure and tables showcase the report in case of each hurricane category and the effect on the evacuation routes determined by TxDOT.

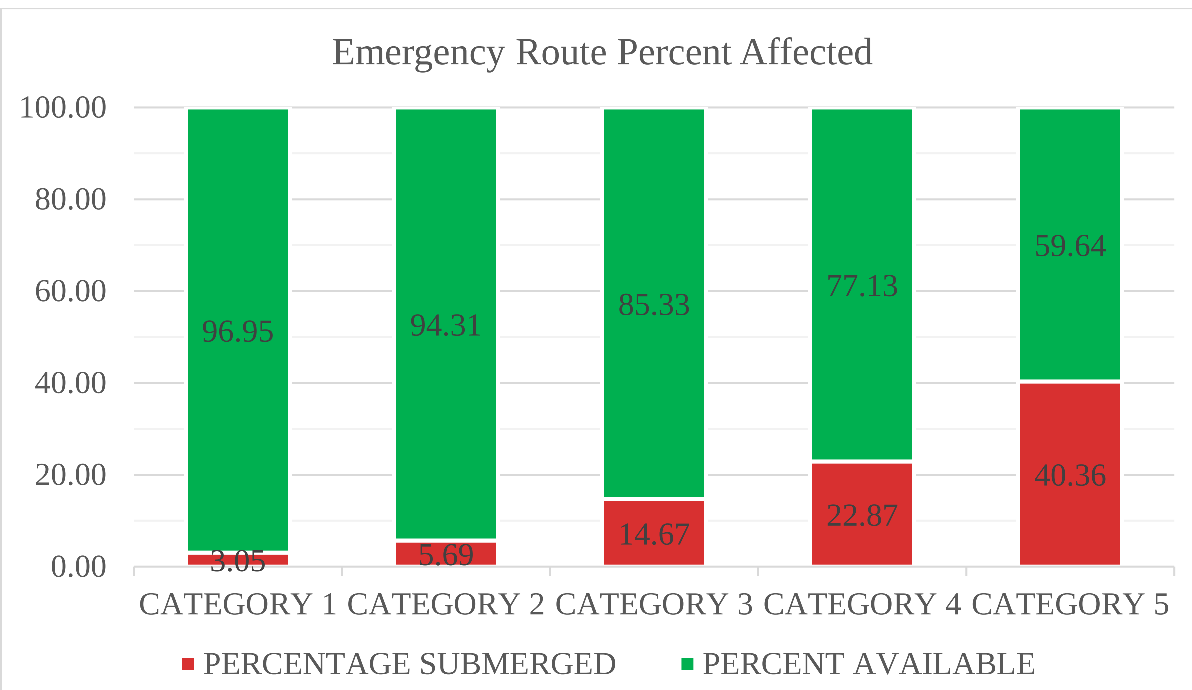

Figure 17: Evacuation routes affected based on hurricane categories. (Spor Leal, Ho, & Davila, 2023)

Table 6 - Evacuation routes affected summary.

Total Length (m)	Category 1 Affected Length	Category 2 Affected Length	Category 3 Affected Length	Category 4 Affected Length	Category 5 Affected Length
510774.24	15593.74	29061.98	74946.59	116824.69	206125.83

The increase of submerged highways between a category 1 and category 5 hurricane is over 4 times greater based on the length shown by table 6. As previously discussed, the extent of hurricane flooding is related to the fact that hurricane storm surge is not tied to the extension of drainage channels and can affect any area that has proximity to the coast. This extensive flooding due to hurricane storm surge represents an issue not only during but after the flooding as well given that the water damage on the asphalt of most evacuation routes will affect their future usage. An illustration of the extension of evacuation routing flooding in case of a category 3 hurricane can be seen in figure 17; other scenarios can be found on Appendix B. This evacuation routing analysis answers question 4 of the problem statement section established for this work.

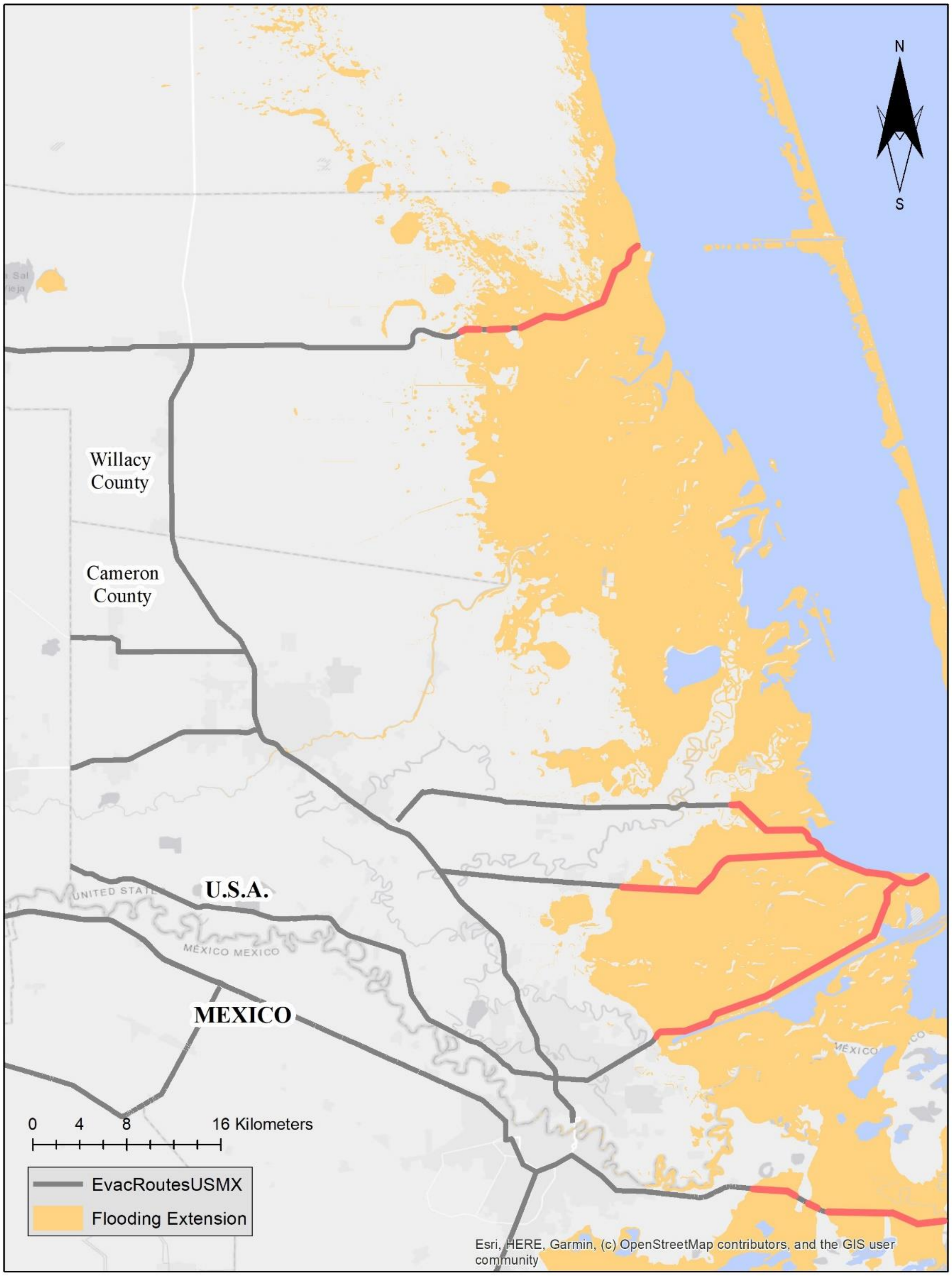

Figure 18: Map of Category 3 hurricane effects of evacuation routes.

An important aspect affected by the flooding extension of these hurricane simulations is the border crossing points that would be deemed inaccessible for evacuation. According to the extension noted and the location of border crossing bridges, most international bridges located in Matamoros would be affected in case of a Category 5 hurricane. Through figure 18, it can be noticed that the Veterans, Gateway, and Matamoros-Brownsville Express International Bridges would be affected by the darkest flooding extension. These are some of the most important features affected in the study area, answering the third question established by the problem statement of this thesis.

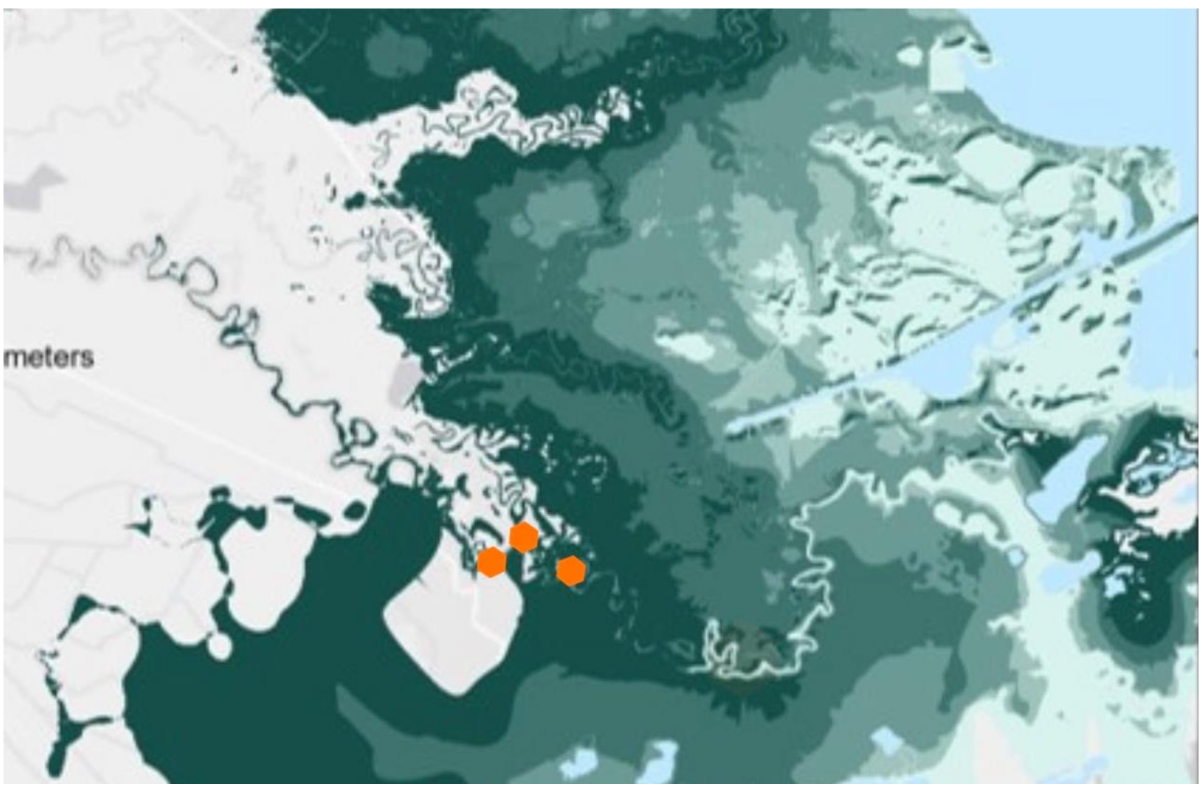

Figure 19: International Bridges located on flooding extension.

Brownsville has been listed as one of the top 5 international bridges when it comes to international travel entry numbers. According to the 2022 data published by the U.S. department of transportation, the monthly average personal vehicle inflow resulted in over 376,690 (U.S. Department of Transportation, 2023); Further data related to pedestrian, busses, and trucks crossing can be found in appendix C. With such an inflow of traffic present in the area, potential access issues to the international bridges in case of flooding should be preemptively addressed to maximize safety and efficiency.

CHAPTER V

CONCLUSION

By analyzing the effects of flooding due to hurricane storm surge, an analysis of the possible consequences can be conducted. The combination of hurricane categories provided a variety of locations and flooding depths that can denote the specific areas susceptible to flooding. According to the used digital elevation models, coastal areas in the Lower Rio Grande Valley are highly susceptible to flooding, and the extensive water channels lead to potential risk around most urban areas. Furthermore, the relatively flat and low elevation can lead to potential prolonged flooding as there is nowhere for the excess runoff to evacuate.

This flooding risk leads to a variety of complications which include up to 60% of the population being affected according to the area of surface that would be affected; alongside over 40% affected evacuation routes in the Willacy and Cameron county. The effects on the evacuation routes are a notable prolonged issue given that asphalt is susceptible to water damage, indicating that the issue may continue after evacuation efforts in case of an emergency. In addition to this damage, it is important to denote that even in less severe scenarios, such as a category 1 hurricane, only 3% of the Evacuation routes in the LRGV are denoted as flooded. Despite this, according to the developed geographical scenarios it is noted that most of the affected routes are in urban locations like Brownsville and Raymondville. Given their nature as urban locations, this flooding indicates that most population are located around these areas and increases the amount of population that will be affected by these relatively small percentages. The effects on international border crossing access points should also be considered as evacuation in a binational emergency is not limited to the extension of a county. Ultimately, this data represents possible risks that will affect the people living in the Cameron and Willacy counties and could be used to plan in case of future emergencies. Flooding simulations, such as the one conducted in this study, can be used to plan upcoming urban development, and renovate existing pathways for the safety of everyone. Ultimately, the variety of results drawn from a limited simulations prove to show the efficiency of geospatial analysis, answering the final question posed as a problem statement for this thesis.

REFERENCES

ArcGIS. (2016). *Texas City Limits*. Retrieved from Koordinates: https://koordinates.com/layer/15266-texas-city-limits/history/

Brown, C., Czerniak, R., & Buscaglia, C. (n.d.). GIS Mapping of Areas of Critical Ecological Concern on the U.S.-Mexican Border: Selected Binational Watersheds. *Transboundary Ecosystem Management*. Retrieved from https://trw.sdsu.edu/English/Projects/Docs/Chapter_3.pdf

Center for International Earth Science Infromation Network. (2017). *Georeferenced Population Data sets of Mexico*. Retrieved from Socioeconomic Data and Applications Center: https://sedac.ciesin.columbia.edu/data/collection/geo-mex

CUBIT. (2021). *Texas Cities by Population*. Retrieved from Texas Demographics: https://www.texas-demographics.com/cities_by_population

Davila Hernandez, C., Davila, S., Flores, M., Ho, J., & Kim, D.-C. (2022). Automation and Coupling of Models for Coastal Flood Forecasting in South Texas. *Journal of Extreme Events, 8*. Retrieved from https://doi.org/10.1142/S2345737622500014

Davila, S., Garza, A., & Ho, J. (2018). Development of hurricane storm surge model to predict coastal highway inundation for South Texas. *AIMS Geoscience*, 522-527.

de Vries, A., Tyrlis, E., Edry, D., Krichak, S., Steil, B., & Lelieveld, J. (2013). Extreme precipitation events in the Middle East: Dynamics of the Active Red Sea Trough. *Journal of Geophysical Research: Atmospheres, 118*(13), 7087-7108. doi:10.1002/jgrd.50569

Elston, D., & Buckland, S. (1993). Statistical modelling of regional GIS data: an overview. *Ecological Modelling, 67*(1), 81-102. Retrieved from https://doi.org/10.1016/0304-3800(93)90100-7.

Environmental Protection Agency. (2015). *Plan De Contingencia Entre Fronteras Ciudades Hermanas Mexico-EEUU*. City of Brownsville, City of Harlingen, City of Matamoros, City of Valle Hermoso: United States Environmental Protection Agency.

Freimund, C. A., Garfin, G. M., Norman, L. M., Fisher, L. A., & Buizer, J. L. (2022). Flood resilience in paired US–Mexico border cities: a study of binational risk perceptions. *Natural Hazards, 112*, 1247-1271. Retrieved from https://doi.org/10.1007/s11069-022-05225-x

Ho, J., Kim, D., & Oubeidillah, A. (2021). *Storm Surge Flood Maps Development for the Lower Laguna Madre Coastal Emergency Management.* Texas General Land Office.

Hu, X., Wang, X., Zheng, N., Li, Q., & Shi, J. (2021). Experimental investigation of moisture sensitivity and damage evolution of porous asphalt mixtures. *Materials*.

INEGI. (2010). *Mapas*. Retrieved from INEGI: https://www.inegi.org.mx/app/mapas/?t=0710000000000000&tg=3604

Leitão, J. P., Boonya-aroonnet, S., Prodanović, D., & Maksimović, Č. (2009). The influence of digital elevation model resolution on overland flow networks for modelling urban pluvial flooding. *Water Science and Technology*, 3137-3149.

Lysaniuk, B., Cely-García, M. F., Giraldo, M., Larrahondo, J. M., Serrano-Calderón, L. M., Guerrero-Bernal, J. C., . . . Ramos-Bonilla, J. P. (2021). Using GIS to estimate population at risk because of residence proximity to asbestos, processing facilities in Colombia. *International Journal of Environmental Resources and Public Health*. Retrieved from https://doi.org/10.3390/ijerph182413

Murphy, C., Creamer, C., McClelland, A., & Boyle, M. (2017). The value of cross border emergency management in adapting to climate change. *Borderlands: The Journal of Spatial Planning in Ireland*, 34-46.

National Oceanic and Atmospheric Administration. (n.d.). *Coastal Elevation Models*. Retrieved from National Centers for Environmental Information: https://www.ncei.noaa.gov/products/coastal-elevation-models

National Oceanic and Atmospheric Administration. (n.d.). *NOAA Historical Hurricane Tracks*. Retrieved from National Oceanic and Atmospheric Administration: https://coast.noaa.gov/hurricanes/

National Oceanic and Atmospheric Administration. (n.d.). *Tidal Constituent, also known as a Constituent Tide*. Retrieved from Tides and Currents: https://tidesandcurrents.noaa.gov/constitu.html#:~:text=Tidal%20Constituent%2C%20also%20known%20as,the%20Earth%2C%20Moon%20and%20Sun.

National Weather Service. (n.d.). *Hurricane Bret: August 22 1999*. Retrieved from National Weather Service: https://www.weather.gov/crp/Hurricane_Bret

Nunez, C. (2019, May 3). *Here's how hurricanes form—and why they're so destructive*. Retrieved from National Geographic: https://www.nationalgeographic.com/environment/article/hurricanes

Ozcelik, C., Gorokhovich, Y., & Doocy, S. (2012). Storm surge modelling with geographic information systems: Estimating areas and population affected by cyclone Nargis. *International Journal of Climatology, 32*, 95-107. Retrieved from https://doi.org/10.1002/joc.2252

Reyna, A. L. (2022). *Hydrologic modeling study to determine hydrologic impact of Resacas on the Lower Laguna Madre watershed.* The University of Texas Rio Grande Valley.

Rosa, M. (2020). Binational Climate Vulnerability Assessment for Cross-Border Adaptation Planning in the San Diego-Tijuana Region. *UC San Diego: Climate Science and Policy*. Retrieved from https://escholarship.org/uc/item/08z4f8tn

Roth, D. (2010). *Texas Hurricane History.* https://weather.gov/media/lch/events/txhurricanehistory.pdf: National Weather Service.

Sebastian, A., Proft, J., Deitrich, J. C., Du, W., Bedient, P. B., & Dawson, C. N. (2014). Characterizing hurricane storm surge behavior in Galveston bay using the SWAN+ADCIRC model. *Coastal Engineering, 88*, 171-181. Retrieved from https://doi.org/10.1016/j.coastaleng.2014.03.002

Secretaria de Relaciones Exteriores. (2014). Frontera Mexico - Estados Unidos. (pp. 1-30). Secretaria de Relaciones Exteriores.

Shao, W., Si, X., Lu, J., Liu, J., Yang, Z., Cao, Y., . . . Wang, K. (2021). The application of big data in the analysis of the impact of urban floods: a case study of Qianshan River Basin. *Journal of Physics: Conference Series*.

Spor Leal, L. B., Ho, J., & Davila, S. (2023). Geospatial analysis of impact on evacuation routes and urban areas in South Texas due to flood events. *Urban Resilience and Sustainability*, 20-36.

Texas Department of Transportation. (2016, August 12). *TxDOT Evacuation Routes*. Retrieved from ArcGIS Online: https://gis-txdot.opendata.arcgis.com/maps/f2e4fdd46b764af4a514ce6391900d21

Texas Department of Transportation. (2020). *Texas-Mexico Border Transportation Master Plan.* Texas Department of Transportation.

Texas Parks and Wildlife. (n.d.). *The State of Water in the South Texas Brush Country*. Retrieved from Texas Parks and Wildlife: https://tpwd.texas.gov/landwater/water/environconcerns/regions/southtexas.phtml

U.S. Department of Commerce. (2020). Flood Safety Awareness for the Lower Rio Grande Valley. *National Weather Service NOAA*. Retrieved from https://www.weather.gov/bro/floodsafety

U.S. Department of Transportation. (2023). *Border Crossing Entry Data | Monthly Data*. Retrieved from Border Crossing Entry Data: https://explore.dot.gov/views/BorderCrossingData/Monthly?%3Aembed=y&%3AisGuestRedirectFromVizportal=y

Zerger, A. (2002). Examining GIS decision utility for natural hazard risk modelling. *Environmental Modelling and Software, 17*(3), 287 - 297. Retrieved from https://doi.org/10.1016/S1364-8152(01)00071-8

Zhang, H., Zhang, M., Zhang, C., & Hou, L. (2021). Formulating a GIS-based geometric design quality assessment model for Mountain highways. *Accident Analysis and Prevention, 157*. Retrieved from https://doi.org/10.1016/j.aap.2021.106172.

APPENDIX A

APPENDIX A

ATTEMPTED EXPANSION OF ADCIRC FINITE ELEMENT MESH

As part of the methodology of this research, the mesh developed for model simulation was attempted to be refined. Due to issues with existing data and newer resolution work, the process was ultimately discontinued. The process taken for the development of the mesh focused on the inclusion of the Rio Grande River extension and is detailed in the following section.

In order to include Rio Grande Valley extension, coastal bathymetry data was sourced from the U.S. Geological Survey. This data was cropped to focus on the extension of the Rio Grande, without extending too far past the coastline due to the coastal simulation nature of the model. Through the use of SMS, the bathymetric data was traced over as an arc with redistributed vertices, transformed into a polygon and converted into a 2D Mesh. This mesh was interpolated with the map elevation of the bathymetric data in order to reach the required elevations and successfully adding a third dimension; this mesh would be ultimately converted into a set of scatter points. The previous existing mesh (noted as fort 14 for ADCIRC) was extracted and converted into a set of scatter points as well and merged with the newly developed set of scatter points. The boundary conditions of the existing mesh were combined with the traced polygon previously developed for the Rio Grande section, creating a newer boundary. Utilizing the scatter set and the newer boundary conditions, the mesh generation tool was used, successfully developing a new 3D mesh with the Rio Grande Extension. Boundary conditions data was added to match the previous mesh. However, after attempting to simulate with the newly developed data, boundary conditions developed were not compatible with the storms to be simulated. Ultimately deeming the work unusable for the time constraints of the project.

APPENDIX B

APPENDIX B

MAPS DEVELOPED FOR GEOSPATIAL ANALYSIS

The following figures include the individual maps summarized throughout the results and discussion section.

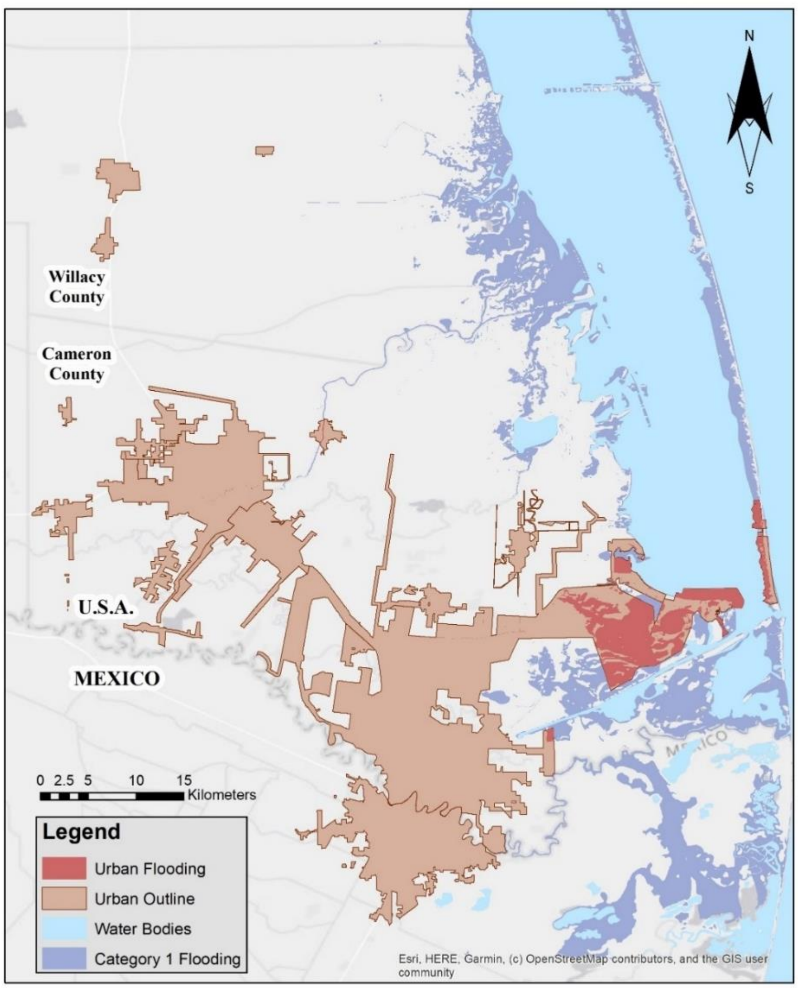

Figure 20: Urban flooding extension - Category 1 Hurricane.

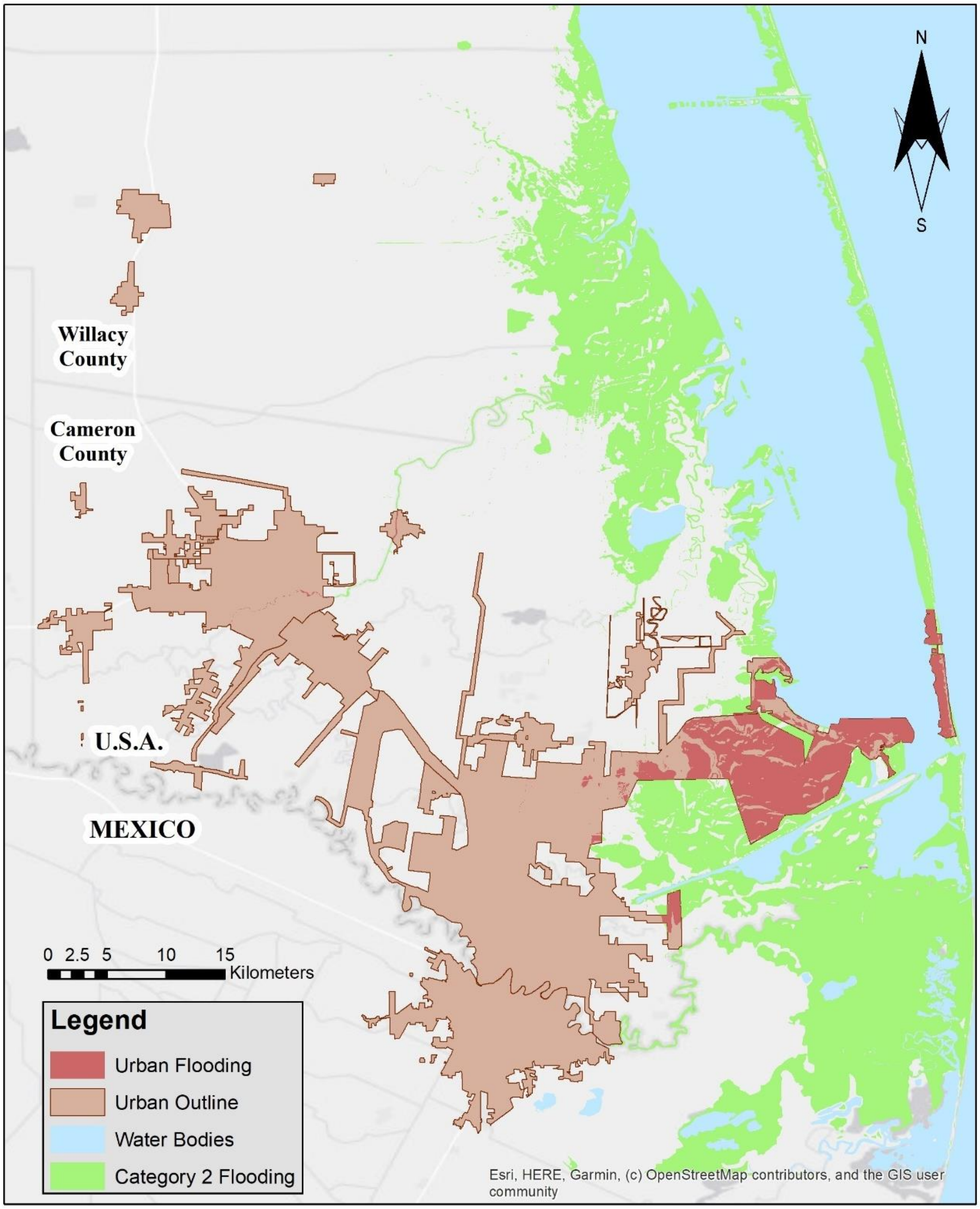

Figure 21: Urban flooding extension - Category 2 Hurricane.

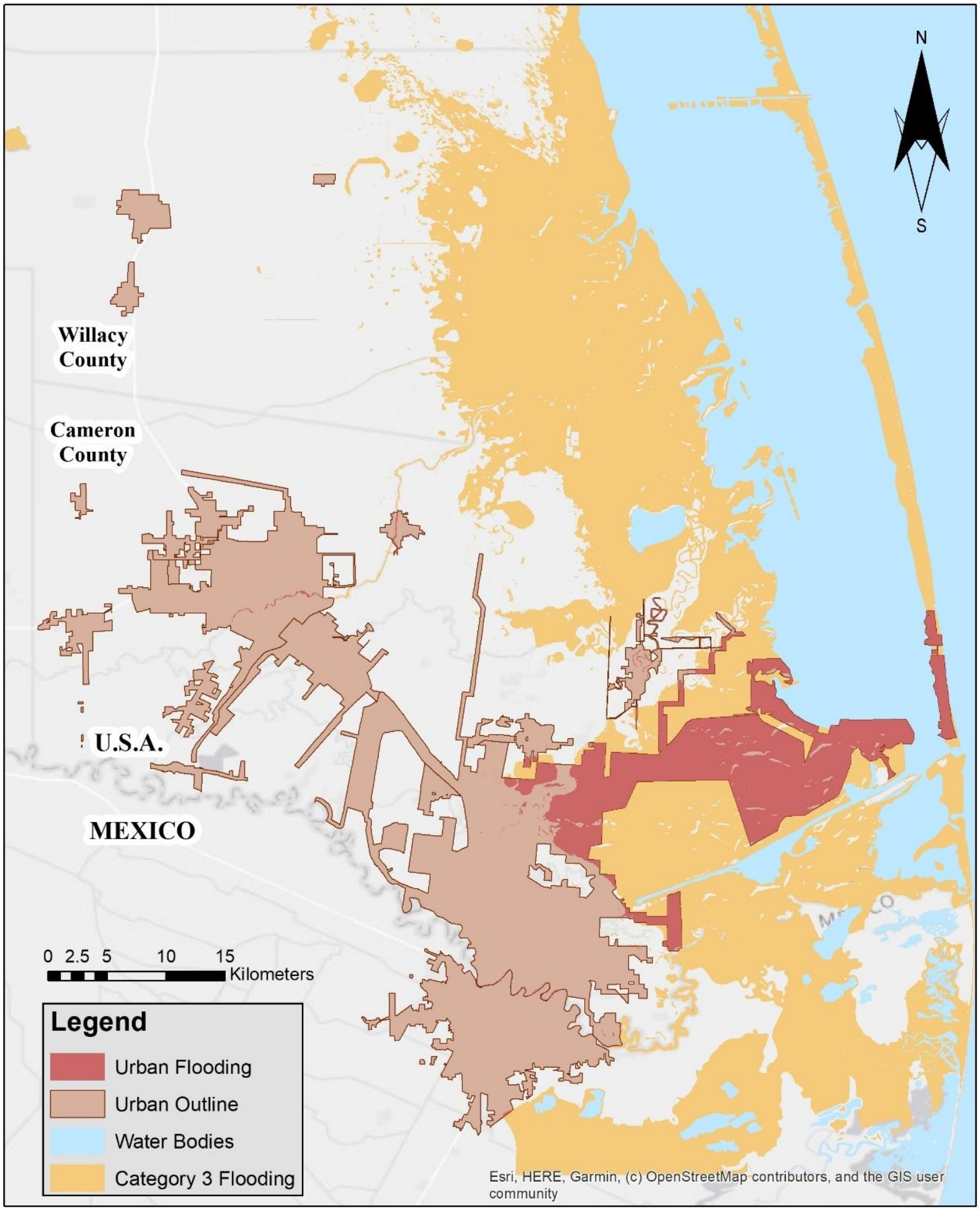

Figure 22: Urban flooding extension - Category 3 Hurricane.

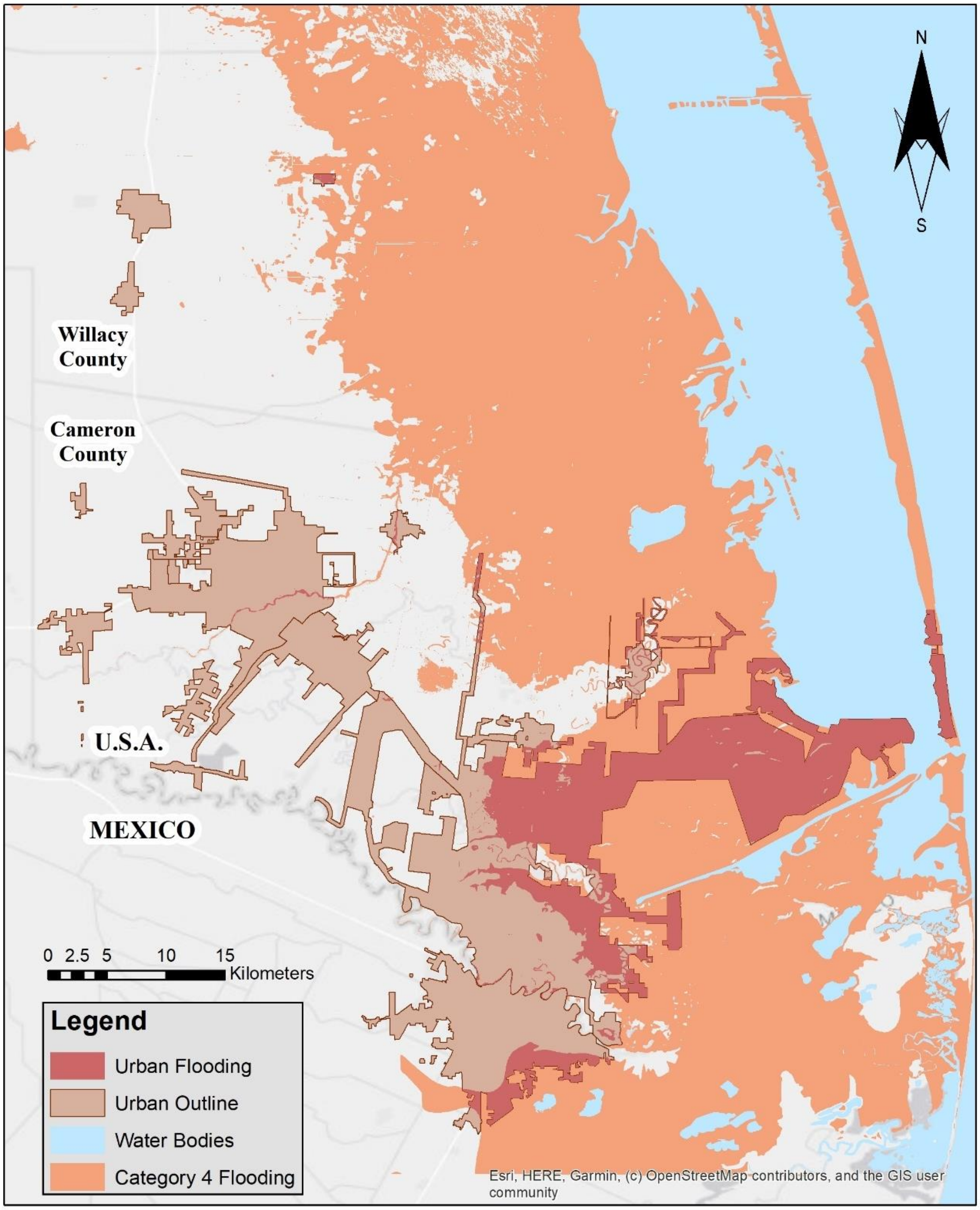

Figure 23: Urban flooding extension - Category 4 Hurricane.

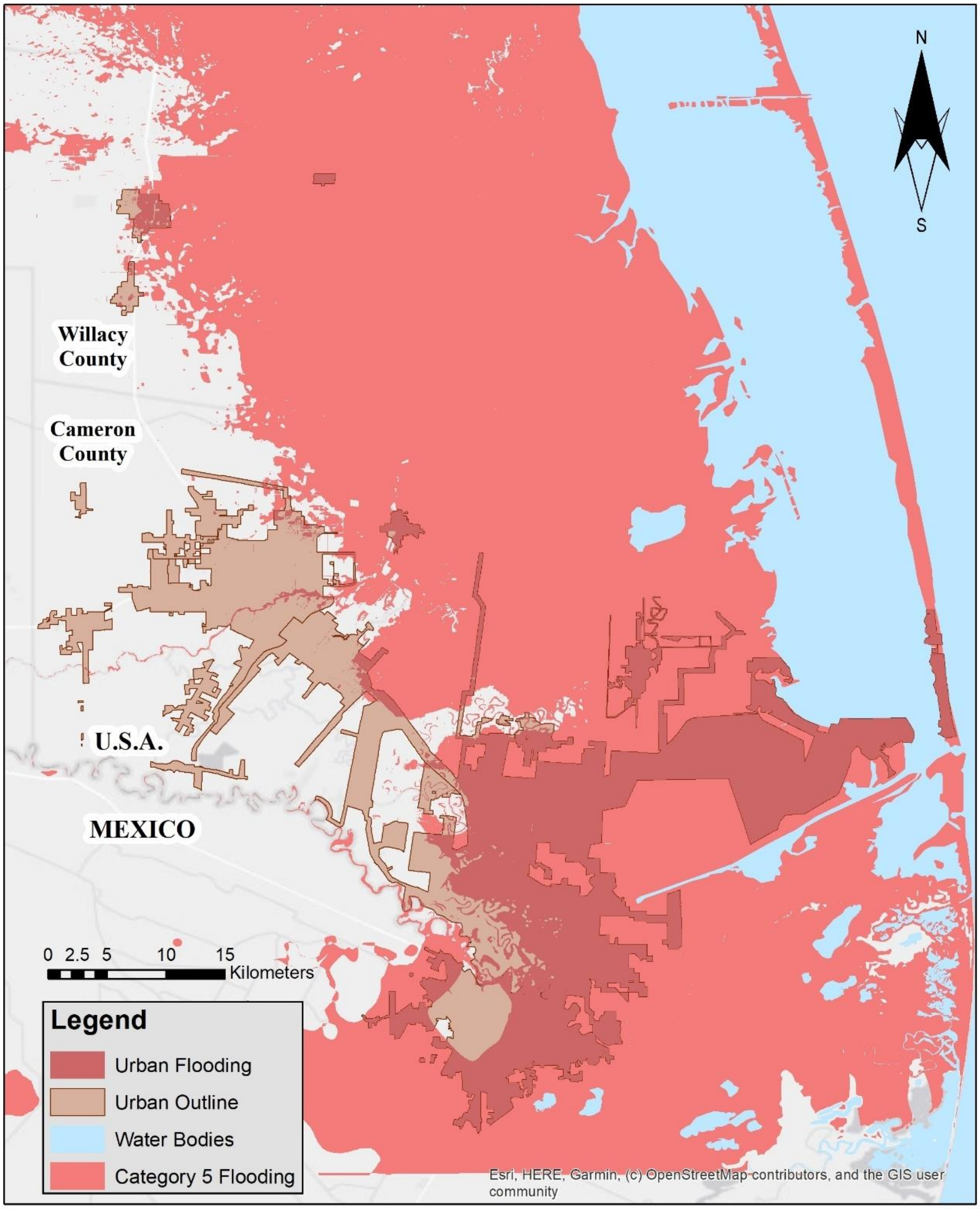

Figure 24: Urban flooding extension - Category 5 Hurricane.

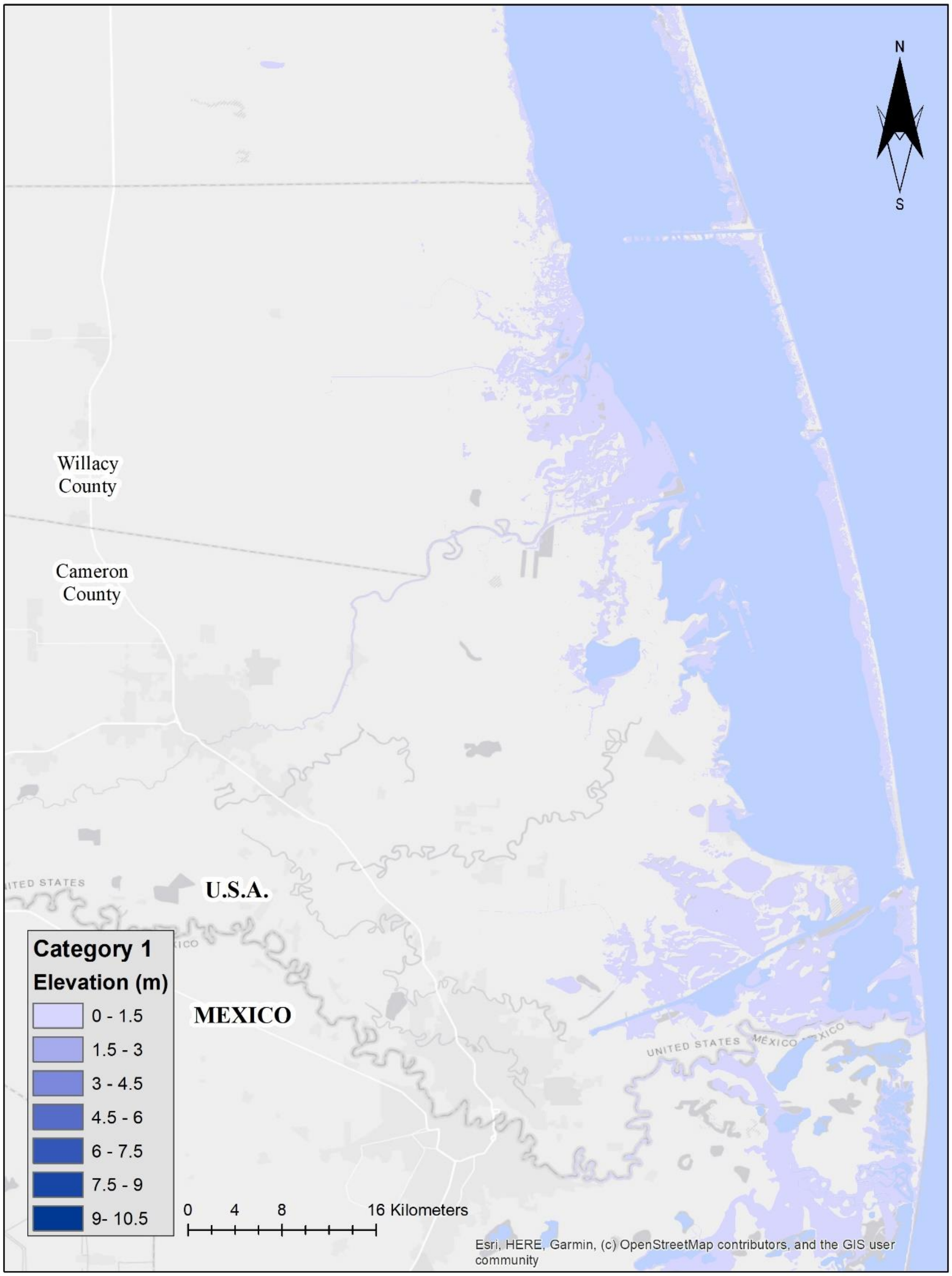

Figure 25: Water Elevation reached in case of Category 1 Hurricane.

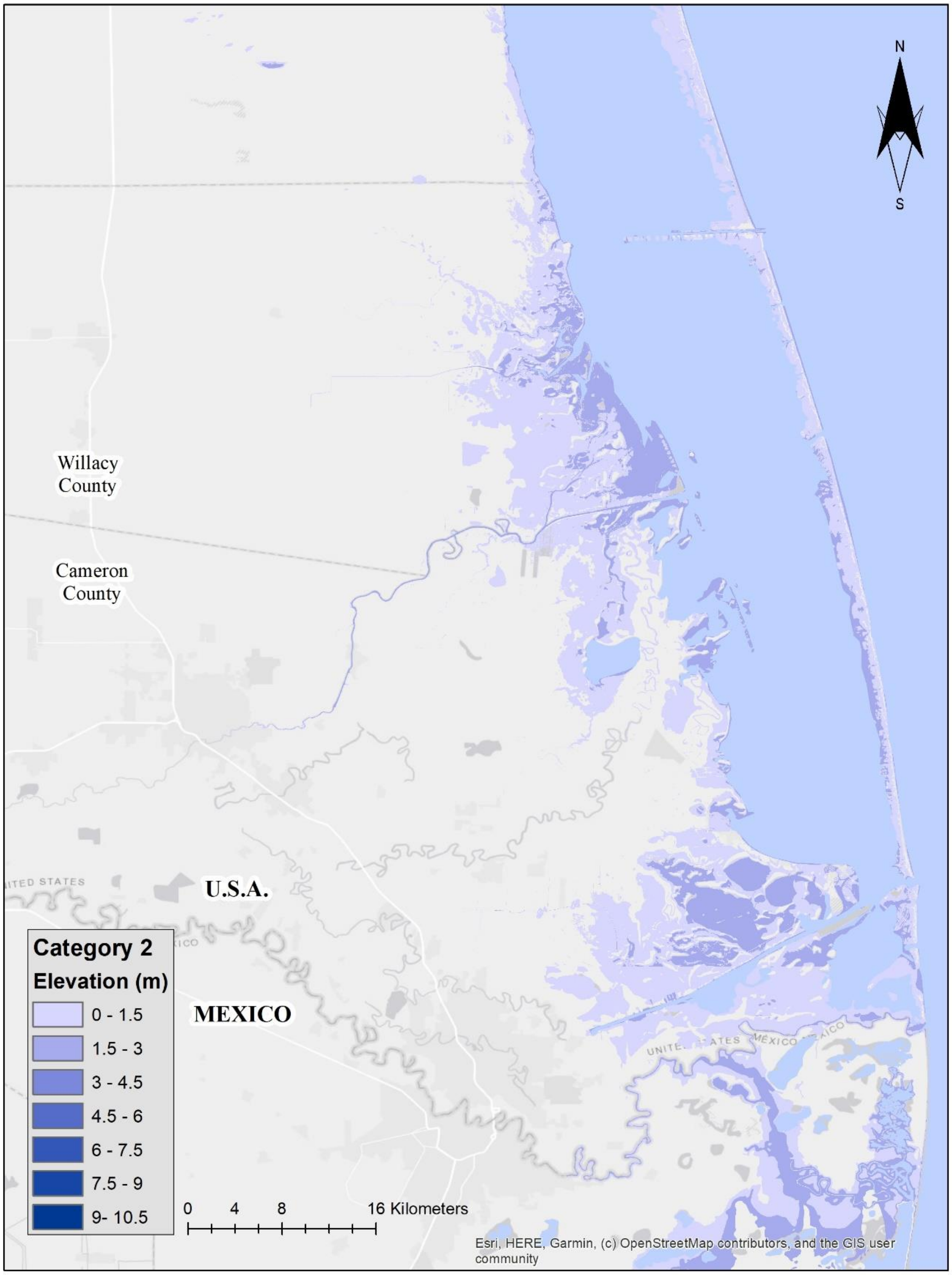

Figure 26: Water Elevation reached in case of Category 2 Hurricane.

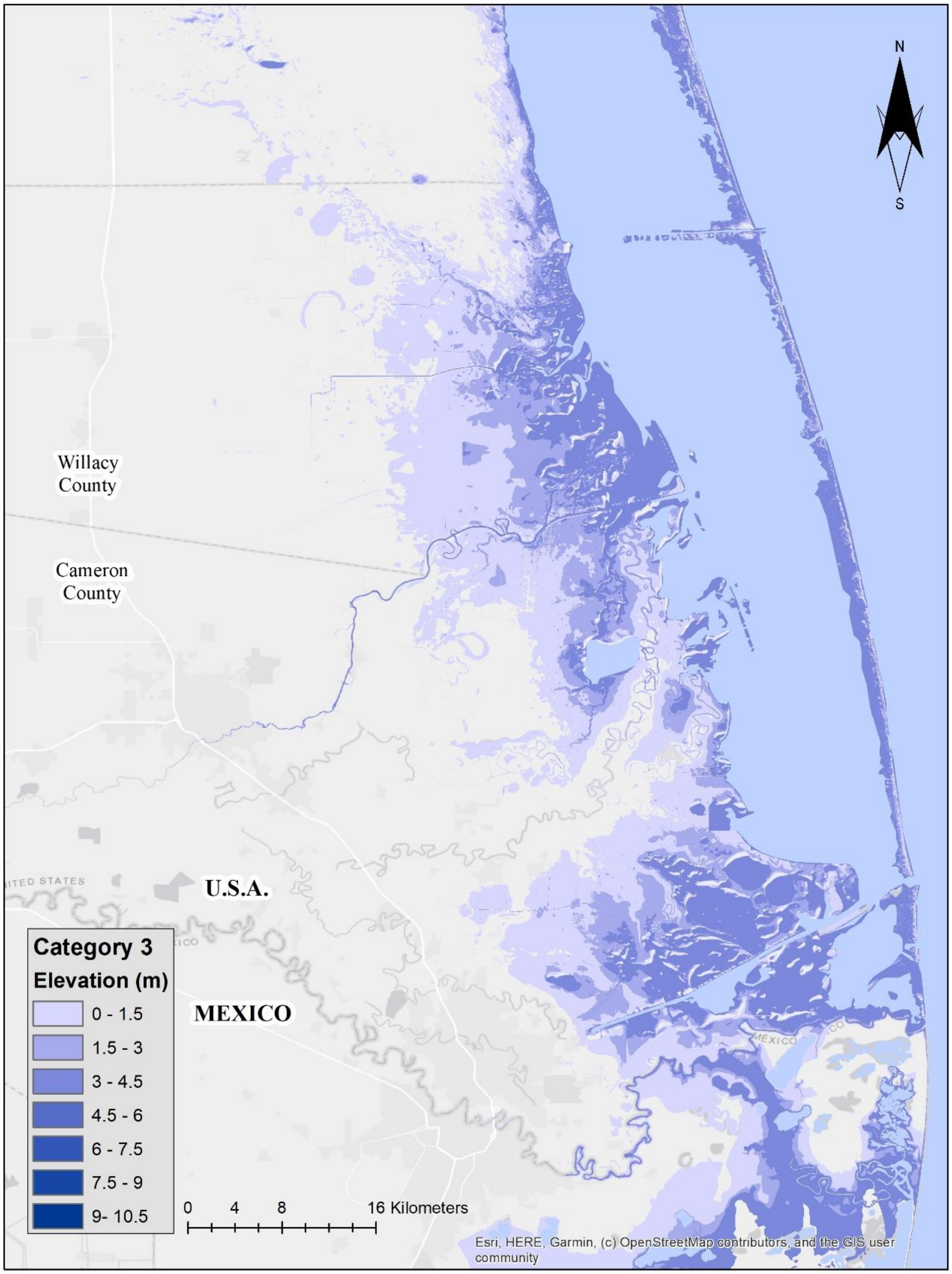

Figure 27: Water Elevation reached in case of Category 3 Hurricane.

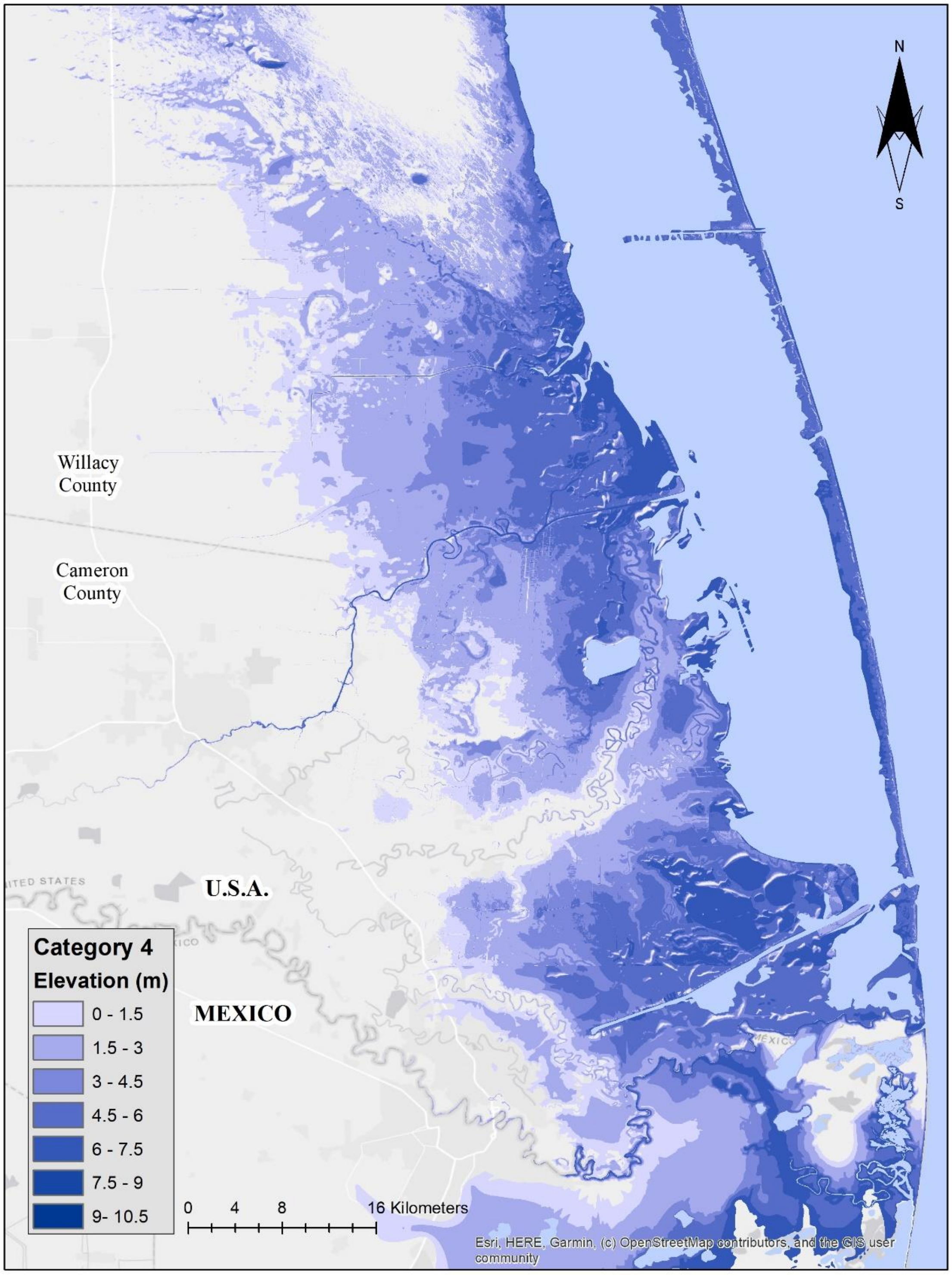

Figure 28: Water Elevation reached in case of Category 4 Hurricane.

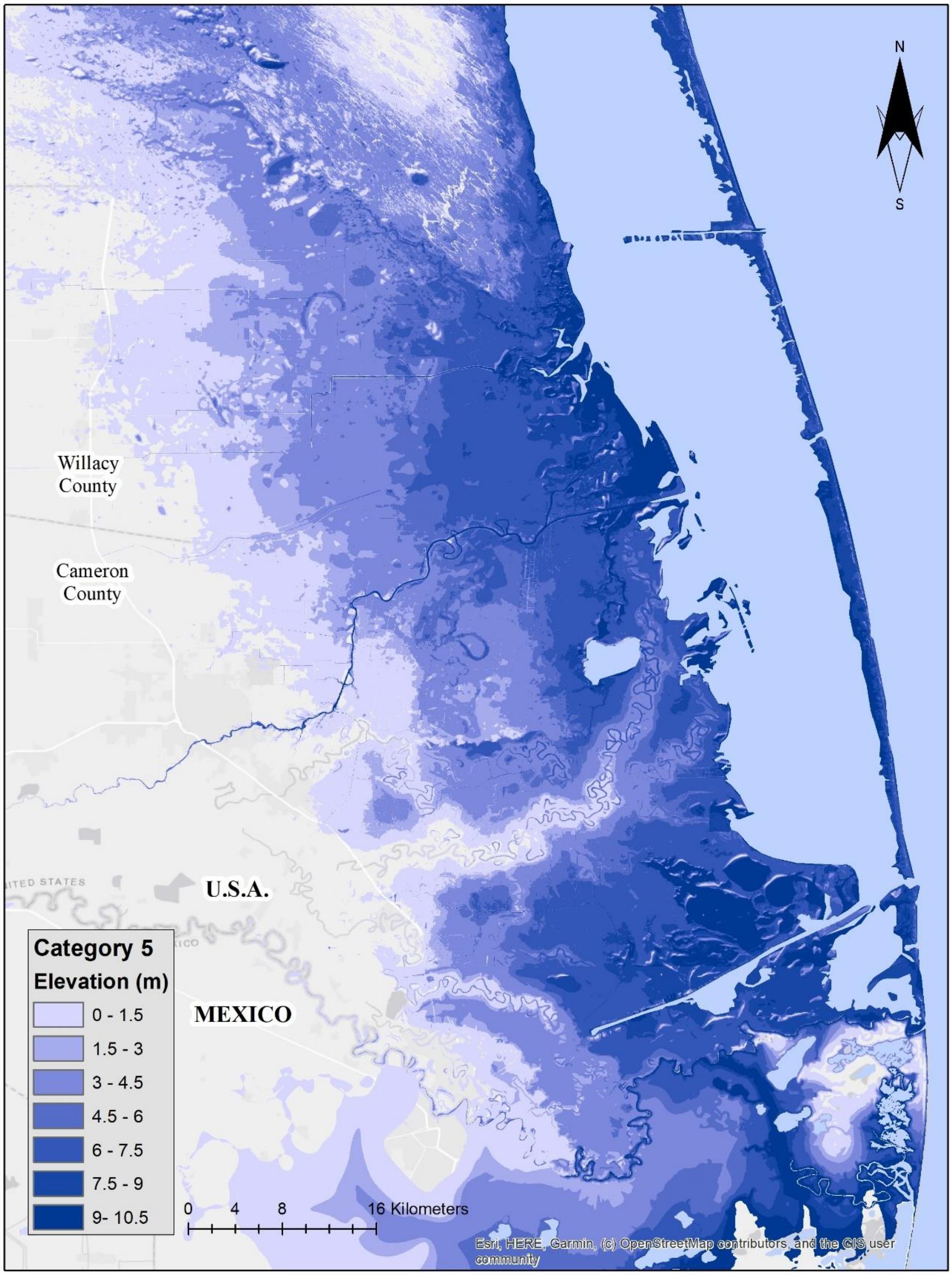

Figure 29: Water Elevation reached in case of Category 5 Hurricane.

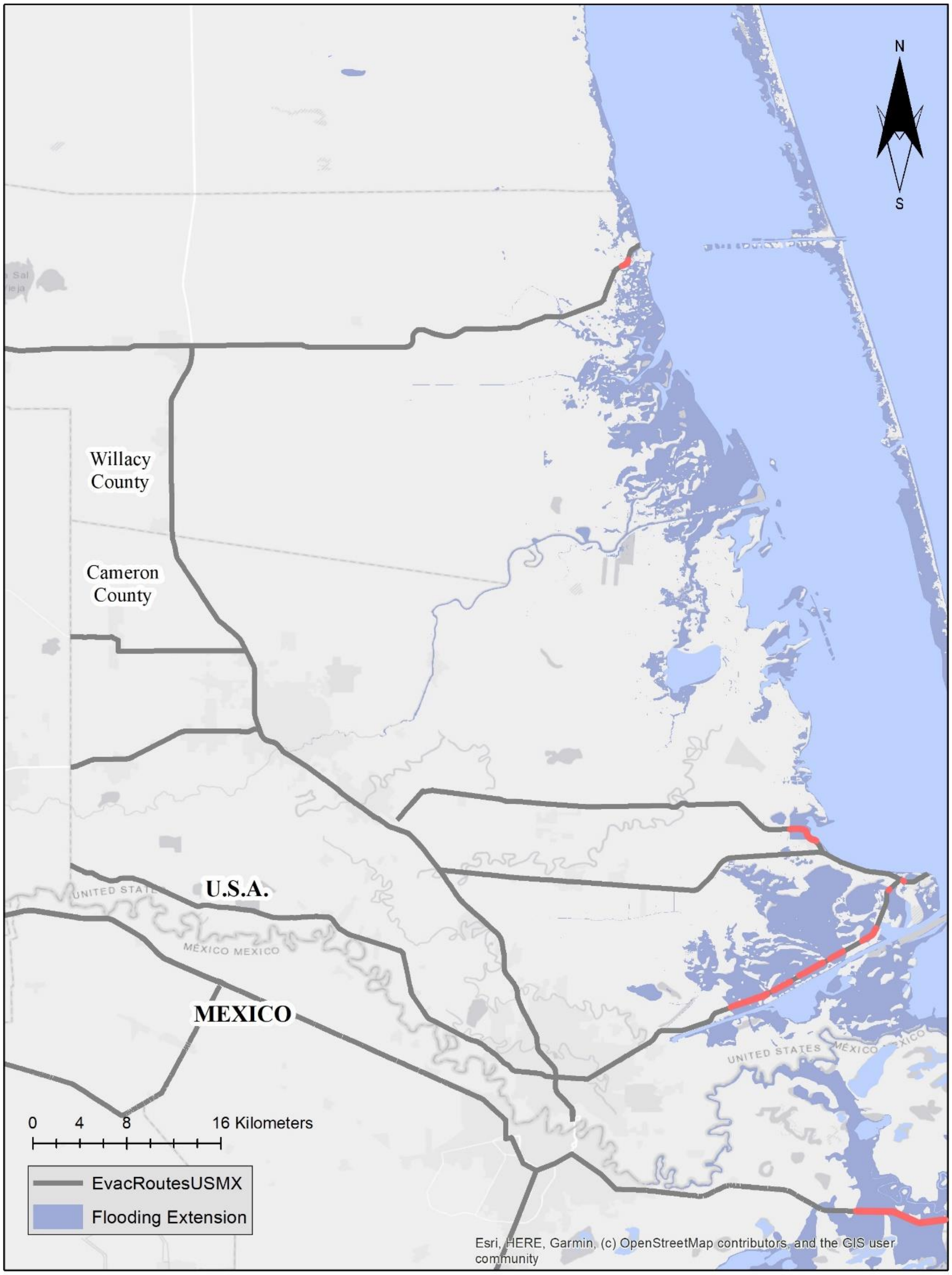

Figure 30: Roads Submerged - Category 1 Hurricane.

Figure 31: Roads Submerged - Category 2 Hurricane.

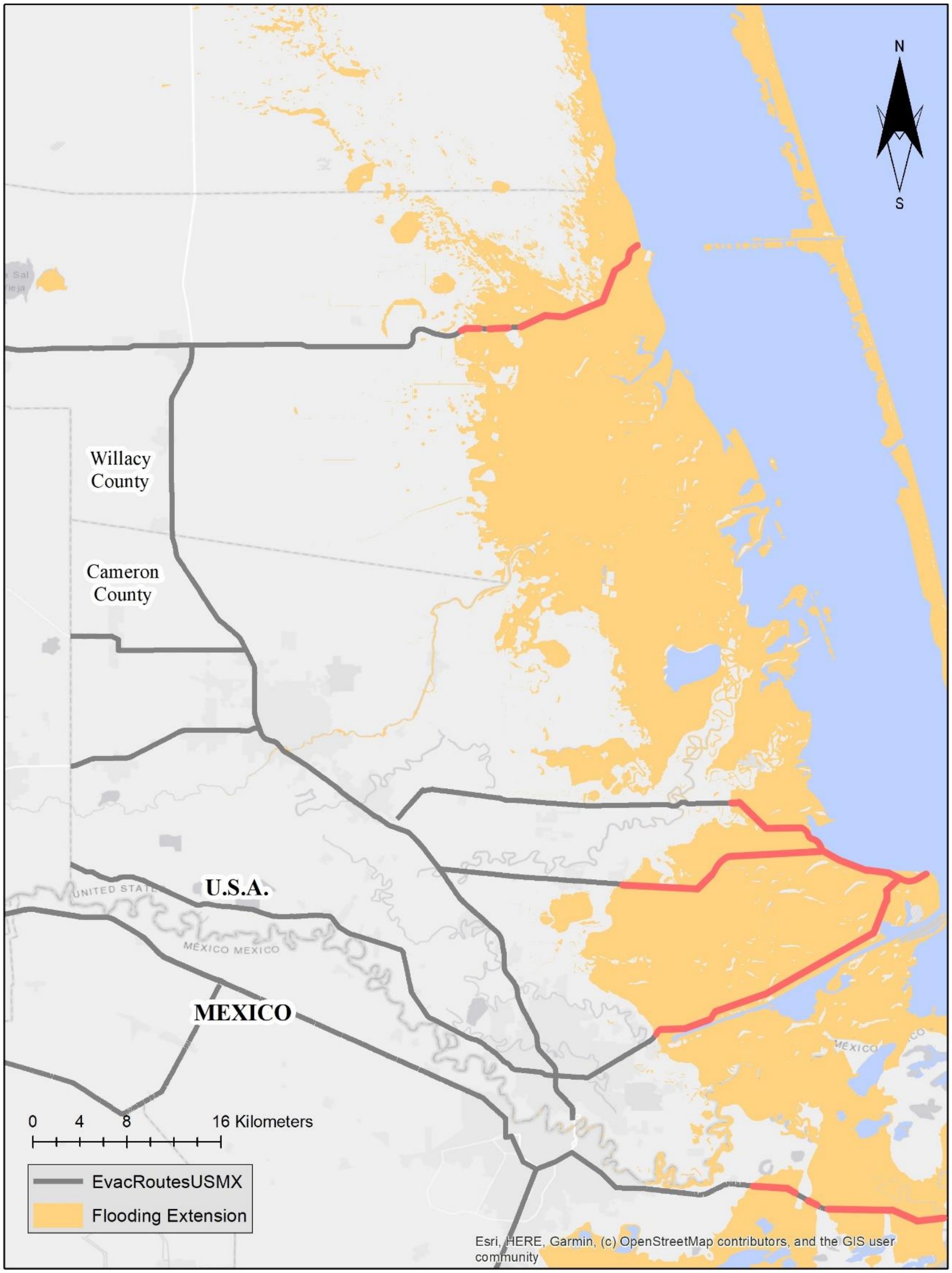

Figure 32: Roads Submerged - Category 3 Hurricane.

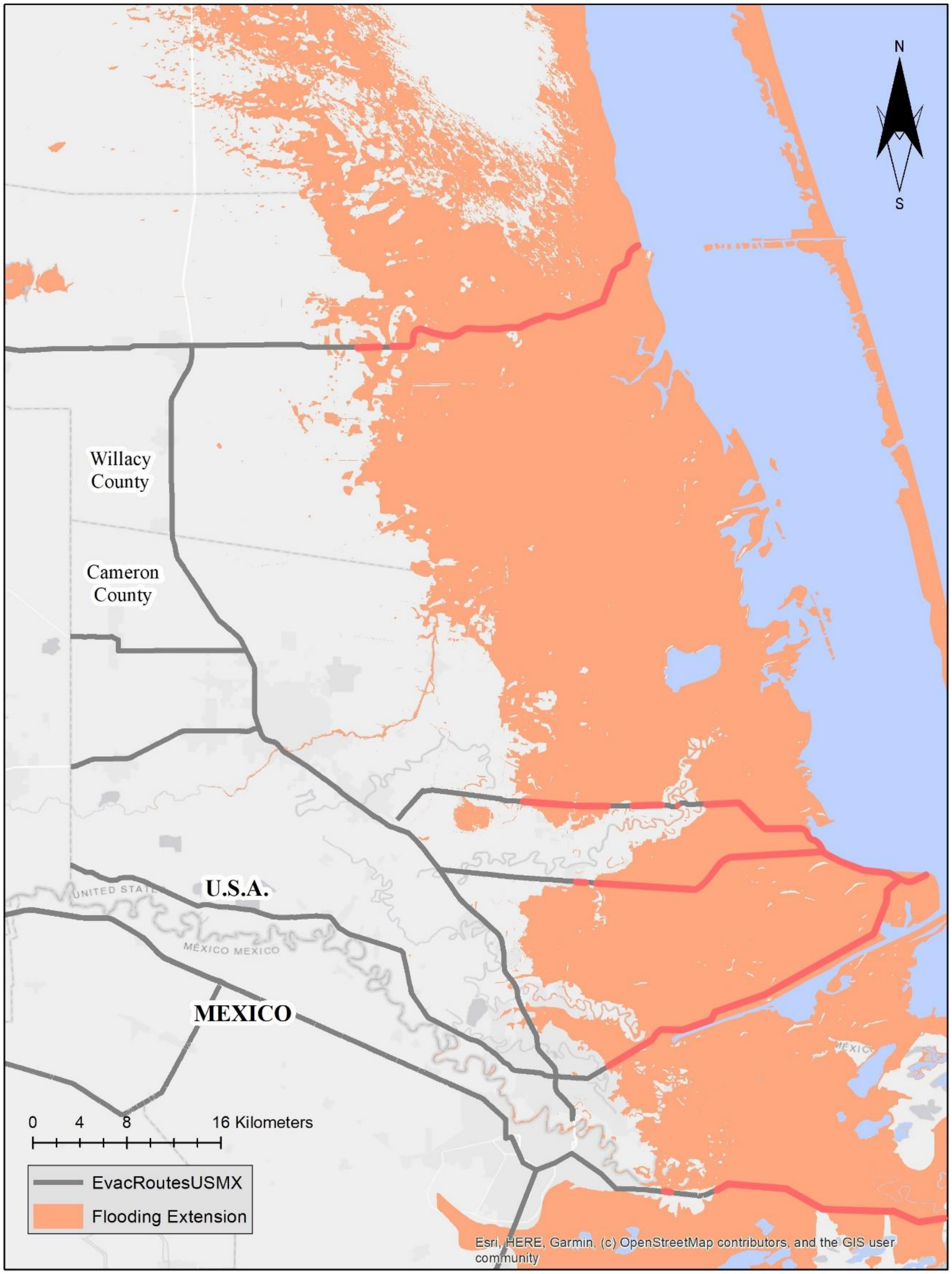

Figure 33: Roads Submerged - Category 4 Hurricane.

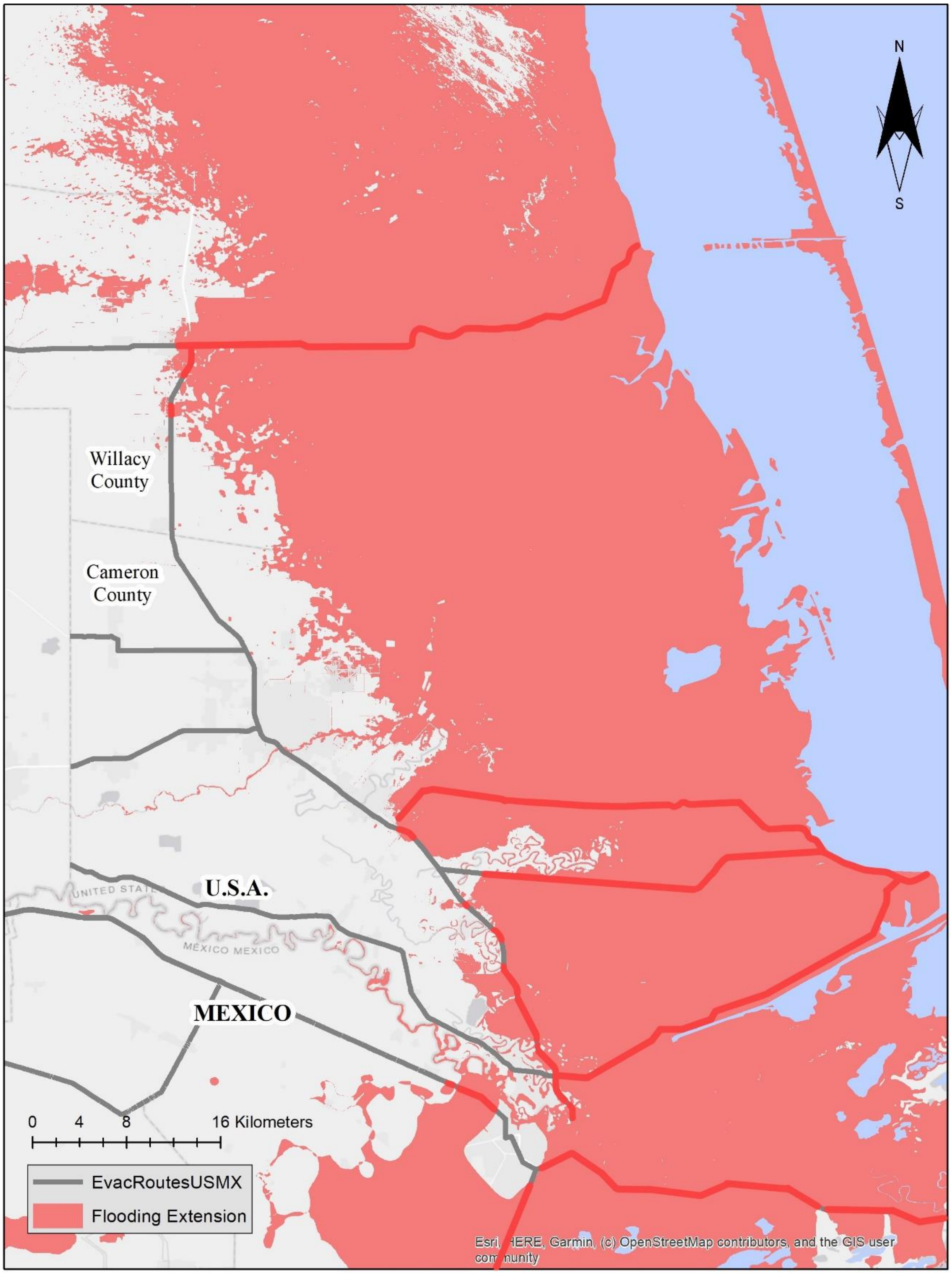

Figure 34: Roads Submerged - Category 5 Hurricane.

APPENDIX C

APPENDIX C

NUMERICAL ANALYSIS FOR GEOSPATIAL ANALYSIS

The following tables contain the tabulated data used for the numerical analysis of the areas affected by different flooding scenarios.

Table 7: Affected area - Numerical analysis.

Urban Location	**Total Area (He)**	**Category 1 Affected Area**	**Category 2 Affected Area**	**Category 3 Affected Area**	**Category 4 Affected Area**	**Category 5 Affected Area**
Bayview	1184		10	137	530	1184
Brownsville	37238	3928	6026	12605	20187	30093
Combes	831					9
Harlingen	10429	9	33	80	128	609
Indian Lake	70					18
La Feria	1130					4
Laguna Vista	1270	310	603	1215	1244	1270
Los Fresnos	1101			62	257	855
Los Indios	483					
Lyford	464					67

Table 7: Affected area - Numerical analysis (cont.)

Urban Location	**Total Area (He)**	**Category 1 Affected Area**	**Category 2 Affected Area**	**Category 3 Affected Area**	**Category 4 Affected Area**	**Category 5 Affected Area**
Palm Valley	157					
Port Isabel	3541	2319	3055	3424	3507	3541
Primera	713					
Rancho Viejo	592					75
Rangerville	906					
Raymondville	1059					648
Rio Hondo	466	23	25	38	55	443
San Benito	4141					420
San Perlita	133				98	133
Santa Rosa	198					
South Padre Island	913	598	796	913	913	913
Matamoros	10749			15	1964	7922

Table 8: Affected population - Numerical analysis.

Urban Location	Category 1 Affected population	Category 2 Affected population	Category 3 Affected population	Category 4 Affected population	Category 5 Affected population
Bayview	0	5	70	271	605
Brownsville	19604	30075	62910	100750	150189
Combes	0	0	0	0	32
Harlingen	61	225	546	873	4153
Indian Lake	0	0	0	0	294
La Feria	0	0	0	0	24
Laguna Vista	856	1665	3354	3434	3506
Los Fresnos	0	0	452	1873	6230
Los Indios	0	0	0	0	0
Lyford	0	0	0	0	360
Palm Valley	0	0	0	0	0
Port Isabel	3411	4493	5036	5158	5208
Primera	0	0	0	0	0
Rancho Viejo	0	0	0	0	355
Rangerville	0	0	0	0	0
Raymondville	0	0	0	0	6470
Rio Hondo	105	114	174	252	2027

Table 8: Affected population - Numerical analysis (cont.)

Urban Location	Category 1 Affected population	Category 2 Affected population	Category 3 Affected population	Category 4 Affected population	Category 5 Affected population
San Benito	0	0	0	0	2517
San Perlita	0	0	0	514	697
Santa Rosa	0	0	0	0	0
South Padre Island	1400	1864	2138	2138	2138
Matamoros	0	0	756	99028	399438

Table 9: Affected evacuation routes - Numerical analysis.

Total Length (M)	**Category 1 Affected Length**	**Category 2 Affected Length**	**Category 3 Affected Length**	**Category 4 Affected Length**	**Category 5 Affected Length**
39652.16	293.22	4792.58	22957.79	28478.08	33581.71
35430.13	8248.21	16752.75	25866.81	31475.59	33235.71
36153.37	1745.20	2043.27	8097.83	19827.40	34958.78
14453.81	556.12	556.12	556.12	556.12	556.12
15861.64	21.69	187.95	12738.73	24740.09	39676.92
61691.74	1007.05	1007.05	1007.05	2414.20	12619.21
77341.51	564.84	564.84	564.84	564.84	191.03
42552.04	789.36	789.36	789.36	2192.10	564.84
15860.91	789.36	789.36	789.36	2192.10	12685.38
42944.24	789.36	789.36	789.36	2192.10	12685.38
42944.24	789.36	789.36	789.36	2192.10	12685.38
42944.24					12685.38
42944.24					

Table 10: Average monthly international crossing.

Measure	January	February	March	April	May	July	June
Buses	537	505	543	502	504	506	507
Pedestrians	233073	235337	256192	269464	261873	311597	238032
Personal Vehicles	398495	344903	384475	307136	367141	391050	369607
Trucks	22372	21590	24008	25775	26248	26508	23449

Table 10: Average monthly international crossing (cont.)

Measure	August	September	October	November	December	Average
Buses	523	506	493	495	507	510.6666667
Pedestrians	265214	249583	256951	260826	285701	260320.25
Personal Vehicles	398131	384121	389573	380549	05153	376694.5
Trucks	26195	23551	25702	22197	19942	23961.41667

BIOGRAPHICAL SKETCH

Layda Belia Spor Leal was born on October 30th, 1997, in Ciudad Victoria, Tamaulipas Mexico. She is the second child of Mrs. Layda Beatriz Leal Perales and Dr. Manuel Ramon Spor Galarza.

After commencing her studies at UTRGV in 2016, she decided to pursue a degree in Civil Engineering with the hopes of pursuing a career in construction and design. However, due to the influence of her professors, at the end of her bachelor's degree she decided to change her focus towards Water Resources and Environmental Engineering. In order to emphasize her specialties in the new field selected, Layda pursued a master's degree in civil engineering with a concentration in Water Resources and Environmental Engineering. Working under the supervision of Dr. Jungseok Ho, she was able to participate in multiple educational opportunities, becoming part of the U.S. Department of Transportation Dwight David Eisenhower Transportation Fellowship for two years in a row starting 2022. She also received the honor of obtaining the Terracon Graduate Scholarship in Engineering in 2022. Her work was published in a scientific journal, granting her recognition from both the university and local news networks. Layda was awarded her Master of Science in Civil Engineering in May 2023.

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