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Research article

Geospatial analysis of impact on evacuation routes and urban areas in South Texas due to flood events

Layda B. Spor Leal, Jungseok Ho* and Sara Davila

Department of Civil Engineering, University of Texas Rio Grande Valley, TX 78539, USA

* **Correspondence:** Email: Jungseok.ho@utrgv.edu.

Abstract: The Lower Rio Grande Valley has historically faced a variety of hurricanes and tropical storms that have led to sever flooding. As a consequence, waves of mass evacuation of the local population with the means of transportation occur frequently. While evacuation is encouraged in some cases of disaster, the routing is not always available as water takes to roads and drainage capacities are overwhelmed. In order to dissert the most appropriate evacuation routes, it is necessary to analyze the areas that will be affected in the future based on urban locations, elevation, and historical information. This project utilizes a semi-coupled hydrodynamic modeling approach that combines the overall spectrum of hurricane storm surge and rainfall induced flooding. The combination of models provide data that can be analyzed with Geographical Information Systems to illustrate the severity of flooding. This analysis can be used to denote the location of the affected evacuation routes and an estimation of population affected in various storm scenarios. The estimated results of this project can be used to not only plan future evacuation routes but denote what areas will possibly require road maintenance after certain flooding scenarios.

Keywords: emergency evacuation route; affected highway coverage and population; coastal hurricane storm surge; South Texas

1. Introduction

The Lower Rio Grande Valley Area (LRGV) is located in the Southmost area of the state of Texas, facing the Gulf of Mexico eastward and denoting major water bodies in the area such as the Laguna Madre and the Rio Grande. Due to constant economic developments, the LRGV has faced an influx of population in the area and as such, an increase of road usage across the region [1]. However, given the geographical location of the newly developed work sectors (such as the SpaceX South Texas launch site at Boca Chica), it is imperative to consider the possible issues that arise as consequence of the coastal proximity. According to the University of Texas Rio Grande Valley's Office of Emergency Management, Hurricane season runs between June 1st through November 30th [2]; leading to potential tropical storms and hurricanes to flood the area with a relatively high frequency. This potential flooding has already occurred in the past, such as back on September 20th, 2013, where 3 inches of rain caused water to overflow in the Starr County, affecting the U.S. Highway 83 between Rio Grande City and Roma [3].

Given that flooding is a major threat in the LRGV, it is imperative to analyze the potential storm scenarios and the extent of damage that they can have; denoting the combination of rainfall runoff and storm surge and the potential evacuation routes affected. Previous studies have denoted that the use of Geographic Information Systems (GIS), alongside potential natural risks simulations can be used to achieve accurate results for urban planning and emergency routing development [4,5]. As such, with the aid of the Coastal Management Program [6] led by various professionals at the University of Texas Rio Grande Valley have developed a forecasting model based on the existing Mesh created by the National Oceanic and Atmospheric Administration. This mesh denotes the bathymetric characteristics of the Gulf of Mexico and was refined based on existing data to highlight the geography of the Laguna Madre with the purpose of obtaining a more accurate flooding prediction in the Willacy and Cameron County.

These flooding simulations supported by attentive analysis with the use of GIS can help denote multiple risk affects besides the extent of flooding. The LRGV is home to over 1 million people across different cities [6]. With such a notable amount of population and the present risk of flooding, analyzing the percentage of the population that will be affected can be used to highlight the human risk of flooding. Studies conducted previously have denoted that the use of GIS can be helpful at estimating the number of people in close proximity to a variety of risks [7,8].

Furthermore, as with most natural dangers, the location and usage of evacuation routes should be denoted. In the LRGV, the prominent evacuation route consists of a network of highways across the area [9]. Most highways across the United States are made of asphalt and water damage is one of the greatest degraders in asphalt, creating cracks and failures as it seeps into the material, which can potentially aggravate in case of salt water [10]. Therefore, since the use of GIS can help identify the area affected by flooding, the extension of emergency routing can be analyzed too; the percentage affected can help denote possible future transportation issues and help design newer routing options.

The limited available flooding prevention analysis for the LRGV area, combined with the high risk that is present due to hurricane and flooding across the coastal counties denote a need for this study. Through flooding simulation and analysis with the use of GIS, the amount of population and emergency routing that would be affected by various possible flooding scenarios can be highlighted. In order to make this information useful for a variety of entities, the final results were chosen to be represented in both numerical and graphical ways, allowing the use of multiple maps for future transportation and urban development decision making.

The modelling and analysis conducted for this research focuses on the Willacy and Cameron County located on the east side of the Lower Rio Grande Valley Area. Due do this, the flooding extents predicted, the populated areas affected, and the emergency routing at risk are presented as percentages of the overall that exists in these two counties. The flooding model developed for this study accounts for both in-land runoff (with the use of watershed hydrologic modelling and two-dimensional flood modelling [11,12]) and storm surge with the use of ADCIRC (https://adcirc.org/) in order to provide a more accurate extension of possible flooding. The data used for this study is sourced from a variety of reliable sources and have been verified by different organizations; data accounting for more recent years was prioritized for results to mimic that of the current state of the study area. It is important to highlight that while the model was evaluated for accuracy, GIS analysis provide an estimation that may vary from real results as urban growth and movement is not a static variable.

As previously established, the focus area of this study is the Lower Rio Grande Valley located in the state of Texas, with a priority on Cameron and Willacy counties due to their proximity to the coast. Given the nature of the modelling work conducted, it is important to not only be aware of the coastal geography of the counties but to also be aware of the multiple watersheds located in the area (Figure 1). While not the purpose of this study, the Mexican drainage channels are incorporated as well since over 90% of the population in the LRGV are Hispanic/Latino [6]; out this percentage, those with connections in the southern country may consider evacuating to Mexico in case of emergency as noted by the evacuation routes. As it will be noted during the population analysis, the LRGV has large percent of its population in the coastal area and given the historical occurrence of tropical storm (and consequent damage), it is imperative to be aware of the dangers that may continue to occur.

2. Methods and data sources

The methodology for this procedure consists of two major sections: the model development and the data analysis of the model results. The data used for this study originated from a variety of reputable sources such as the National Oceanic and Atmospheric Administration NOAA (https://coast.noaa.gov/) and the United States Census Bureau (https://data.capitol.texas.gov/), among further supplementary sources.

2.1. Hurricane storm surge and inland rainfall-runoff modeling

2.1.1 Hurricane storm surge model development

The model used to simulate the multiple flooding scenarios is composed of three elements of the storm surge model, watershed hydrologic, and coastal flood model. Surface Water Modeling System (SMS) software is utilized for the development of the finite element mesh which represents the geographical characteristics of the study area. Alongside SMS, ADCIRC is used to simulate the different storm scenarios. 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 [13]. 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.

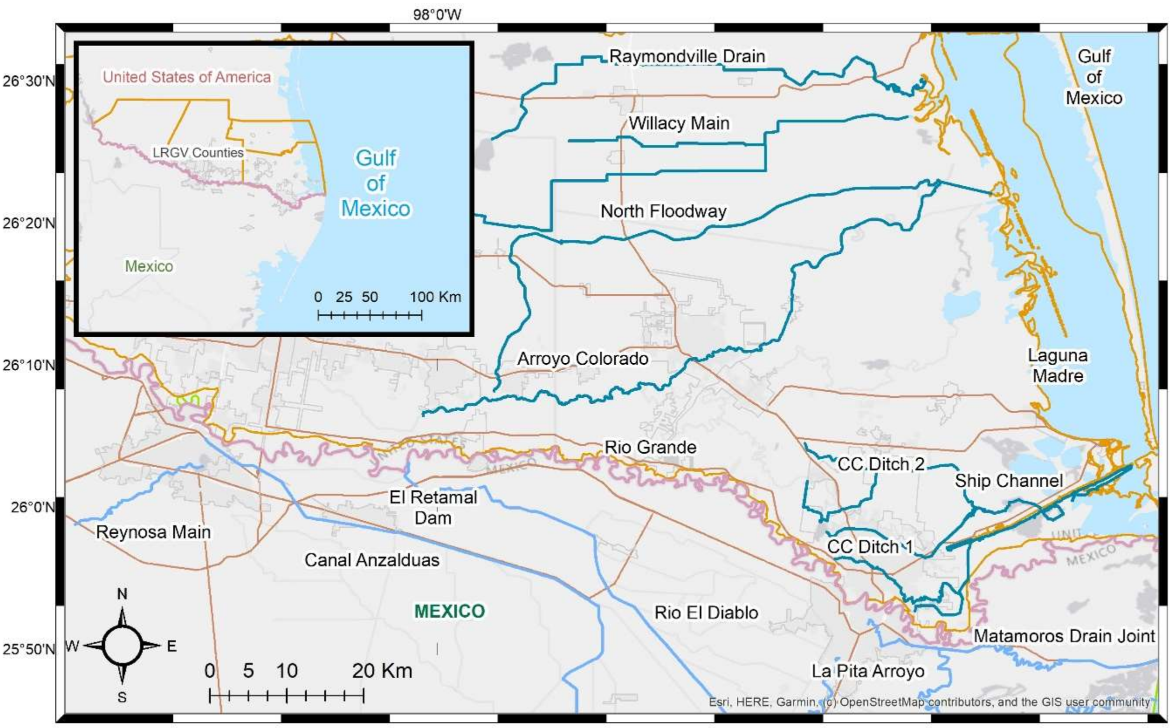


Figure 1. Map of the LRGV location and the existing drainage channels.

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. Figure 2 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.

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 (https://www.weather.gov/), Hurricane Emily, Hurricane Dolly, and Hurricane Alex (https://coast.noaa.gov/hurricanes/). 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.

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. Each scenario was compared to the historic water surface elevation to check for accuracy. Seven tidal constituents were selected (K_1, O_1, P_1, Q_1, M_2, S_2, and N_2) and the roughness coefficient varied between .067 and .02 according to the distance from sea level of each nodal attribute.

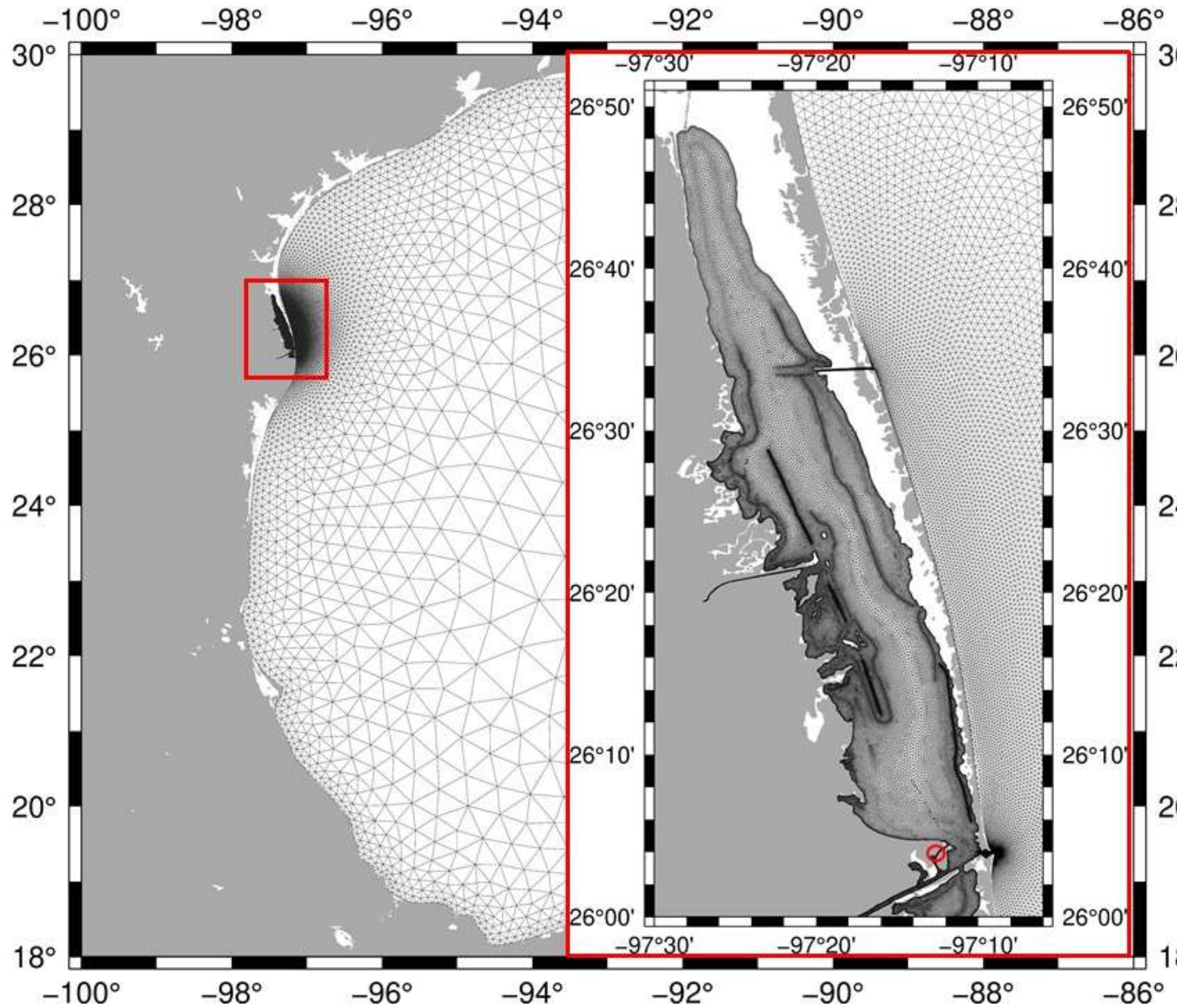


Figure 2. Finite element mesh focusing on the Lower Laguna Madre Coast [14].

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 [15]. 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 [16]. 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 1.

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 [14].

Table 1. Evacuation Route (km) affected according to storm frequency and category.

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

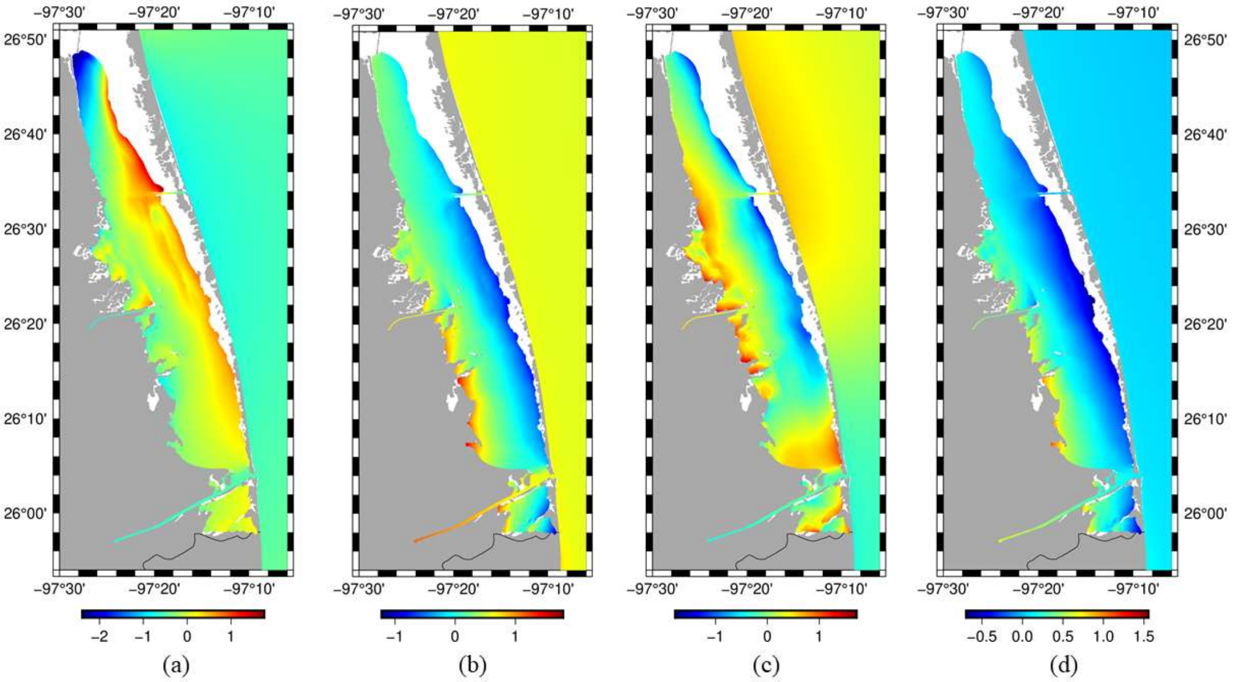


Figure 3. Computed water surface elevation in meters of (a) Hurricane Bret (1999), (b) Hurricane Emily (2005), (c) Hurricane Dolly (2008), and Hurricane Alex (2010) [14].

2.1.2. Inland Rainfall-Runoff Model Development

The inland rainfall runoff was developed with a combination of the watershed hydrologic model and the coastal flood model. The HEC-HMS model was adopted to estimate the hydrologic transition between rainfall and runoff process by creating watershed terrain and hydrologic characteristics. This program is used to simulate the different hydrologic processes of watershed systems, such as infiltrations, hydrographs, and hydrological routing [11]. The model was developed by creating terrain information for the South Texas area. Digital elevation models and land cover information for this modeling part were sourced from USGS's National map (https://www.usgs.gov/) and the Natural resources conservation service by the USDA (https://www.nrcs.usda.gov/). ArcGIS was used to develop this terrain information. Then, the Sixteen and thirty-five watersheds that compose Cameron and Willacy County, respectively, were illustrated with the use of the HMS software. These watershed models executed hydrologic computations with hypothetical storm events of a matrix of five frequency storm events (10, 25, 50, 100, and 500-years) and two precipitation durations (1-day and 2-day). The

Precipitation Frequency Data Server (PFDS) developed by the Hydrometeorological Design Studies Center NOAA National Weather Service was adopted for the frequency of rainfall depths per duration [17]. The simulation results were detailed through runoff hydrographs, which illustrate flow versus time data.

Based on the information provided by the HEC-HMS model, the second part of the modeling was conducted with the use of Hydrologic Engineering Center River Analysis Systems HEC-RAS. The model illustrated the three major drain channels in Cameron County and two major channels in Willacy County: Brownsville Ship Channel; Arroyo Colorado, North Floodway, Hidalgo Main, and Raymondville Floodway. HEC-RAS's Two-dimensional hydrodynamic modeling enables combined 1-D channel/floodplains with 2-D flow areas behind levees. This suits the watershed flood modeling objective. 2-D flow modeling is accomplished by adding 2-D flow area elements into the model in the same manner as adding a storage area. A 2-D flow area is added by drawing a 2-D flow area polygon, developing the 2-D computational mesh, then linking the 2-D flow areas to 1-D model elements [12].

A terrain model was developed by using HEC-RAS Mapper for detailed 2-D hydraulic computations and result in visualization. In this study, NAD 1983 State Plane was selected for spatial reference projection. RAS Mapper was also used for visualization of computation results, time series plots, and generation of map layers, such as depth of water, water surface elevation, and inundation boundary. After refinement, fifty runs were conducted to simulate the combination of the 5 main channel geometries and the 10 possible storm scenarios. This resulted in 50 different maps that showcased the depth and boundary of flooding in each specified scenario which would be used later for further analysis.

2.2. Model calibration and validation for hurricane storm surge and inland rainfall-runoff

Given the usage of multiple models for the calibration and validation process was conducted twice. This was done to corroborate the accuracy of the results and ensure the simulations of hypothetical scenarios provided similarly accurate water depths and extensions. The first validation and calibration were done to the SMS-ADCIRC Hurricane Storm Surge model. 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 4. Through this comparison, it was noted that tidal constituents played an essential role in the accuracy of the simulation. Constituents, such as M_2, 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 tested. 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.

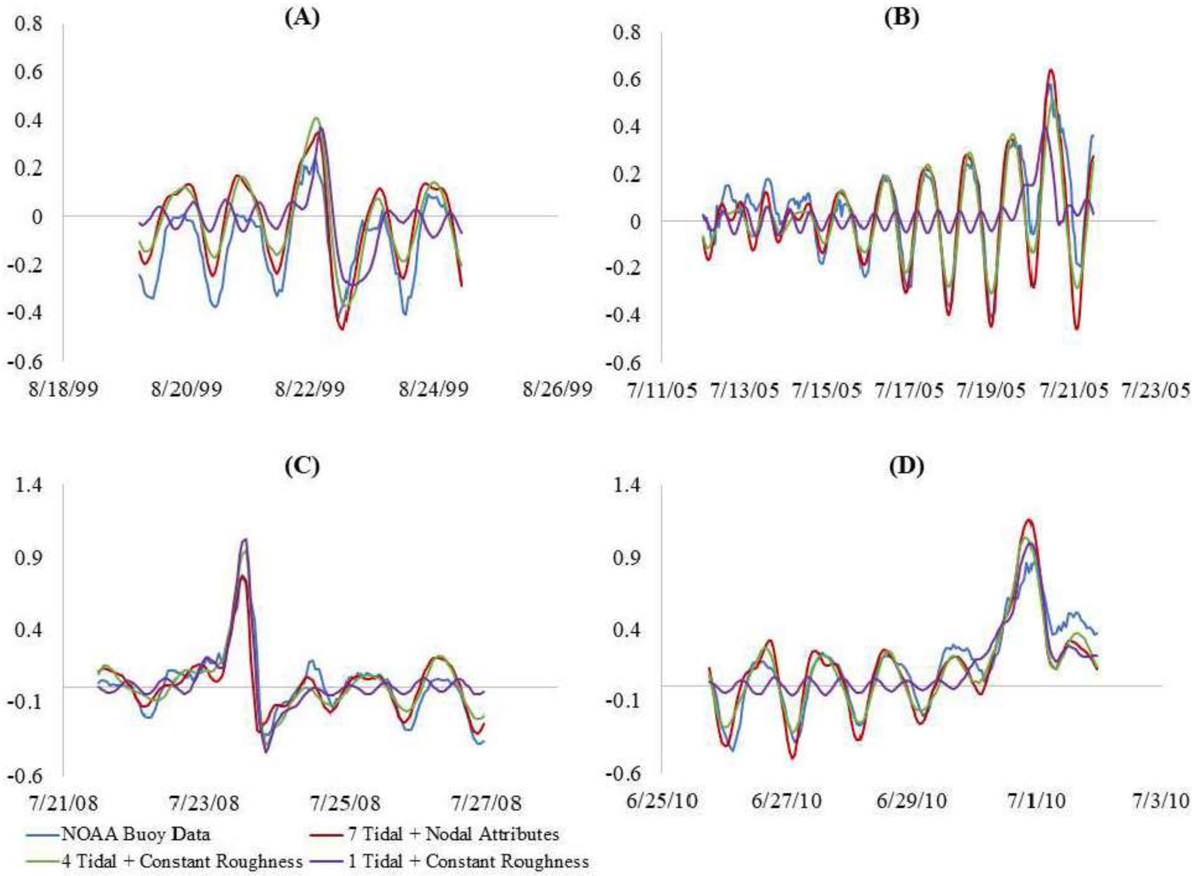


Figure 4. Hydrographs comparing simulations and existing NOAA data [14].

The Inland Rainfall Runoff model was validated and calibrated through HEC-RAS, since the final output was processed through this software. Given that the scenarios simulated correspond to frequency storms, the corroboration of results was different from that of the hurricane storm surge. In this case, the peak flooding extensions denoted by the RAS Mapper were compared to the existing Flood Insurance Rate Maps (FIRM) of the region, obtained from the Federal Emergency Management Agency (https://msc.fema.gov/). A zoomed in version of the comparison is showed in Figure 5, which denotes the flooding areas obtained after the simulation of a 100-year storm and the extension of flooding according to the FIRM map of the LRGV. A small deviation from the flooding extension was considered acceptable since the available FIRM maps were created in 1982 and lack crucial urban development that is present in the area. The HEC-RAS 2-D mesh was refined in order to increase the accuracy of the flooding extension. This was done by creating break lines and refining regions to increase the stability of the model. Shallow channels and oxbow lakes were delineated with finer meshes since computational results would vary rapidly and an increased accuracy was required.

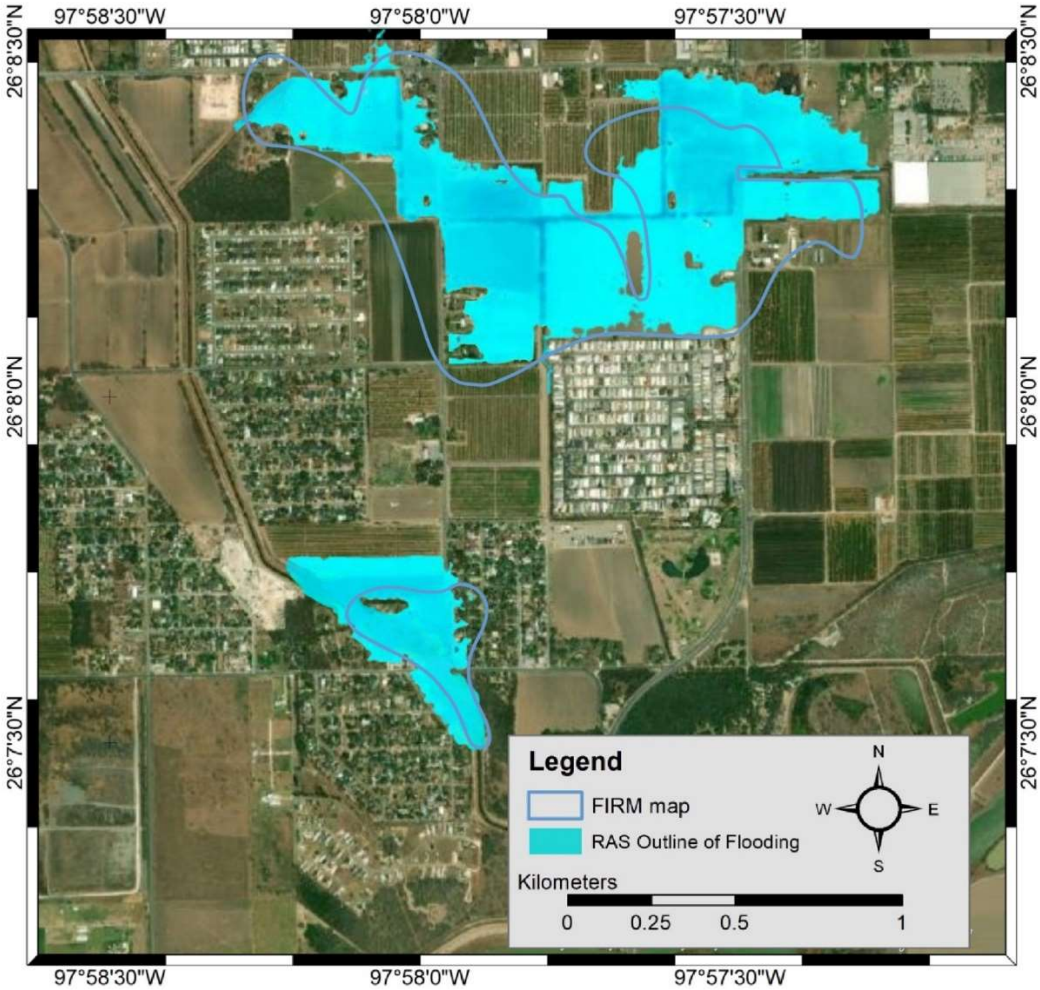


Figure 5. Outline of FIRM flooding extension in case of a 100-year frequency storm over extension of computed results.

2.3. Coupled model coastal storm surge flood map development

The ADCIRC storm surge model was coupled with the 2-D HEC-RAS flood model to develop more realistic coastal storm surge flood maps. The abnormal coastal water surface level, i.e., hurricane storm surge, computed by ADCIRC was inputted as the HEC-RAS model downstream boundary conditions to estimate the storm surge impact on the coastal flood. Given the dynamic nature of these models, the results that presented the maximum water level were used, denoting the most severe extension of flooding. Based on the elevation results from the coupled HEC-RAS, Digital Elevation Model rasters were developed to denote the elevation of water caused by flooding. With the use of GIS ArcMap tools, the raster calculator can be used to sum the flooding due to Inland rainfall runoff and Hurricane storm surge, merging together each hurricane category and each storm scenario to illustrate the possible outcomes. 40 maps were developed combining category 1 through 5 hurricanes with the storm frequency of 10, 25, 50, 100, and 500 years for 1–2 d. Figure 6 includes the developed map in case of a category 5 hurricane, a 500-year frequency storm for 2 d.

As shown in orange, the evacuation routes in the LRGV are highlighted, and it is clear that a high percentage of it would be affected by flooding. In order to analyze the exact percentage affected, a shapefile of the flooding extent of each scenario was created. By overlapping the extent of the flooding shapefiles over the evacuation routes polyline, the evacuation route can be clipped and then through the attributes table the length affected can be analyzed. The evacuation routing polyline was sourced from previous reports of evacuation navigation [9]. The length of the original evacuation route and the affected routes were extracted and compared to show the percentage of highways that will be ultimately affected.

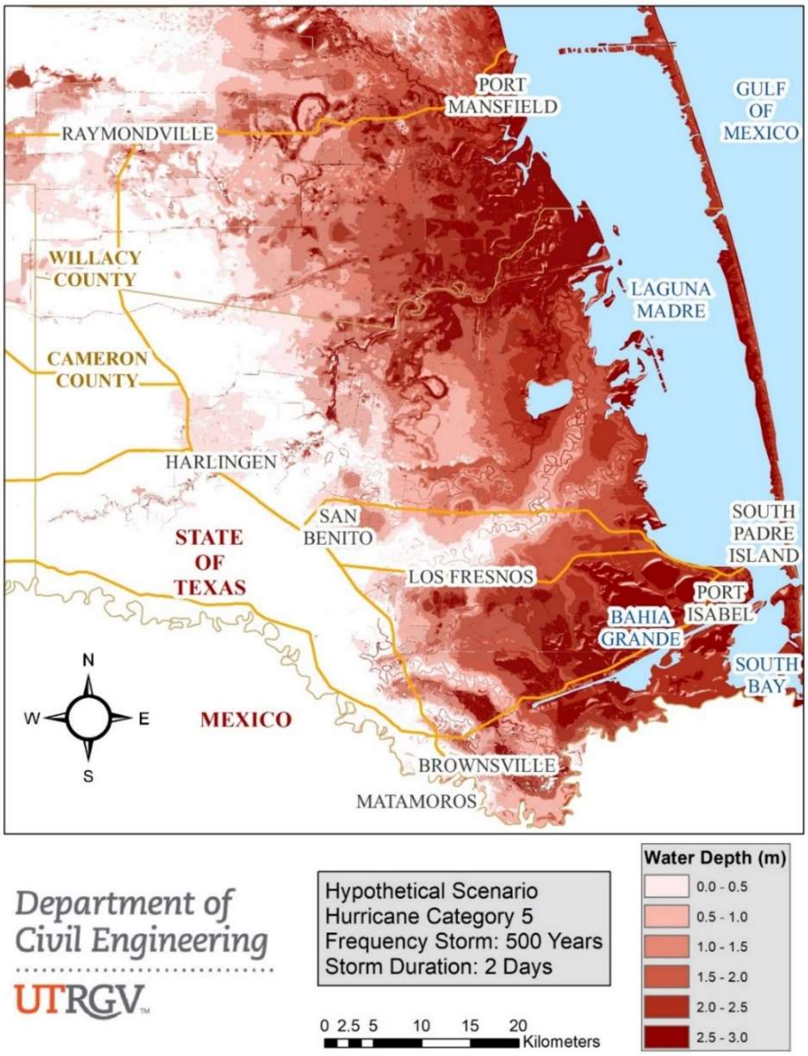


Figure 6. Developed Map based on combined model data.

Regarding the population analysis, the process is rather similar to that of the highway analysis. Shapefiles detailing the population attribute information were used and overlapped with the flooding extension shapefiles. After clipping the affected areas, the remaining of the polygon was used to calculate the remaining area. Due to the lack of population density information in each specific urban area provided by the Census Geography of 2020 (https://data.capitol.texas.gov/), an even distribution was assumed and as such, the population affected was inferred from the area percentage that was affected.

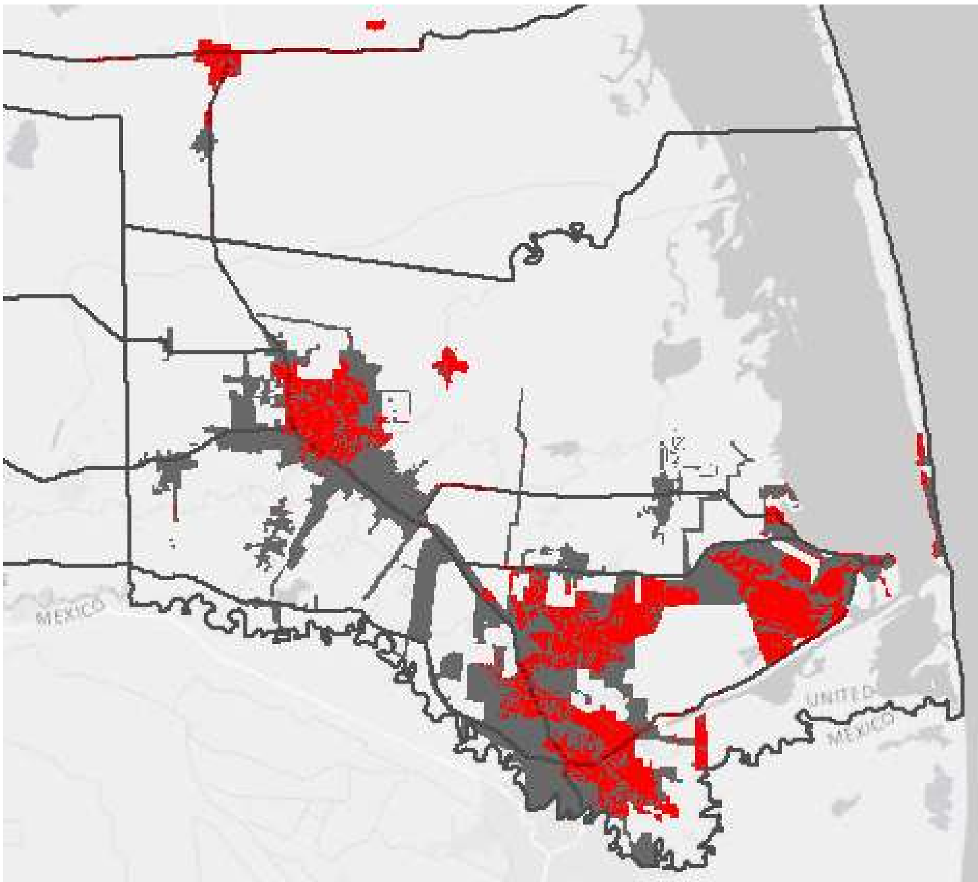


Figure 7. Map showcasing the extension of the multiple urban areas in the LRGV, and the areas affected in case of a category 1 hurricane alongside a 500-year frequency storm.

3. Results and discussion

To present the information in a manner that clearly illustrates the difference in damage severity between scenarios, the storm frequencies of 10, 50 and 500 years were chosen alongside all 5 possible hurricane categories. These three storm scenarios were selected due to 10-year frequency storm being a relatively common scenario with a 10% probability of occurring any year [18], 50-year scenario being commonly used for transportation flooding studies [16], and 500-year storm being a relative recent incident to affect the LRGV area [20]. The following tables contain the population affected and highway extension in kilometers that would be affected according to the described procedures.

Table 2. Evacuation Route (km) affected according to storm frequency and category.

Storm Frequency	Category 1	Category 2	Category 3	Category 4	Category 5
10 Year	16	29	75	117	206
50 Year	37	50	94	133	211
500 Year	52	66	110	147	213

As it is expected, the amount of population and highways affected are proportional to the severity of the storm/ hurricane category; but more specific trends can be denoted as well. Regarding the evacuation routes affected, while the increment is linear to that of the storm frequency/hurricane category severity, the hurricane storm surge plays a proportionate greater role. According to the Texas Department of Transportation [9], the evacuation routes across the Cameron and Willacy County have about 510 km of length. When comparing the percentages affected as shown on Table 2, it is noticeable that the amount of affected evacuation routes is not too different between frequency storms, but the increase based on hurricane category is notable. The percentage increase between 50-year storm and a 500-year storm in case of a Category 5 scenario is less than 1%; and the increase in case of a Category 1 is 3.1%. This increase is not as dramatic as the increase per hurricane category despite the fact that the severity of a 500-year storm is much greater than that of a 50-year scenario. The increase of submerged highways between a category 1 and category 5 hurricane is over 4 times greater in both scenarios (5.7 times in the case of the 50-year scenario and 4.1 times in the 500-year scenario). As previously discussed, the extent of hurricane flooding is much greater than that of the storm scenarios. This is due to the fact that hurricane storm surge is not tied to the extension of drainage channels and can affect any area that has a proximity to the coast. This extensive flooding represents a major issue for LRGV population since, according to the Federal Highway Association, transportation networks are key when evacuating people out of harm's way [21]; with such percentages of evacuation routes being affected, evacuation operations can be severely affected.

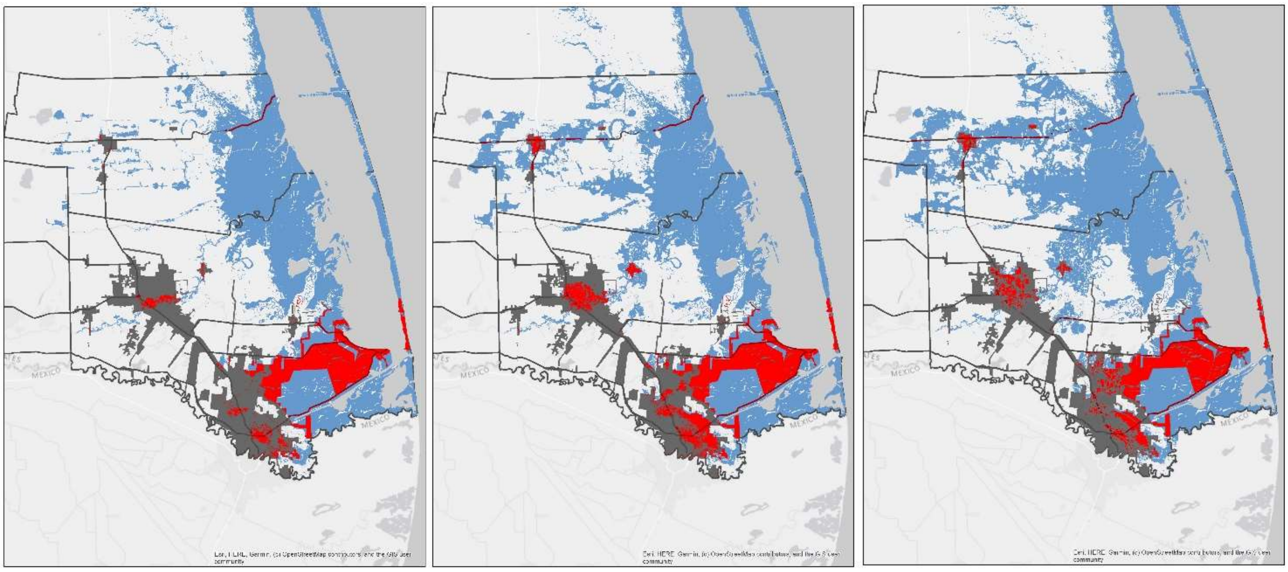
Furthermore, it should be noted that the reason why the Storm frequency effect on evacuation routes is more noticeable in less severe hurricane scenario is due to the fact that most of the rainfall runoff overlaps with the hurricane storm surge in areas closer to the coast and given that the percentage represents the surface area affected and not the severity of flooding, the overlap is not accounted for. Since the flooding extent of a category 5 hurricane covers the majority of the flooding due to the storm scenarios, it explains why the percentage of submerged highways does not vary that much.

Table 3. Highway percentage affected according to storm frequency and category.

Storm Frequency	Category 1	Category 2	Category 3	Category 4	Category 5
10 Year	3.1%	5.7%	14.7%	22.9%	40.4%
50 Year	7.2%	9.8%	18.5%	26.0%	41.3%
500 Year	10.3%	12.9%	21.5%	28.7%	41.7%

Table 4. Population affected according to storm frequency and category.

Storm Frequency	Category 1	Category 2	Category 3	Category 4	Category 5
10 Year	43,266	51,012	91,025	129,843	179,228
50 Year	83,086	90,179	125,793	153,005	194,063
500 Year	119,626	126,667	150,508	170,750	206,553

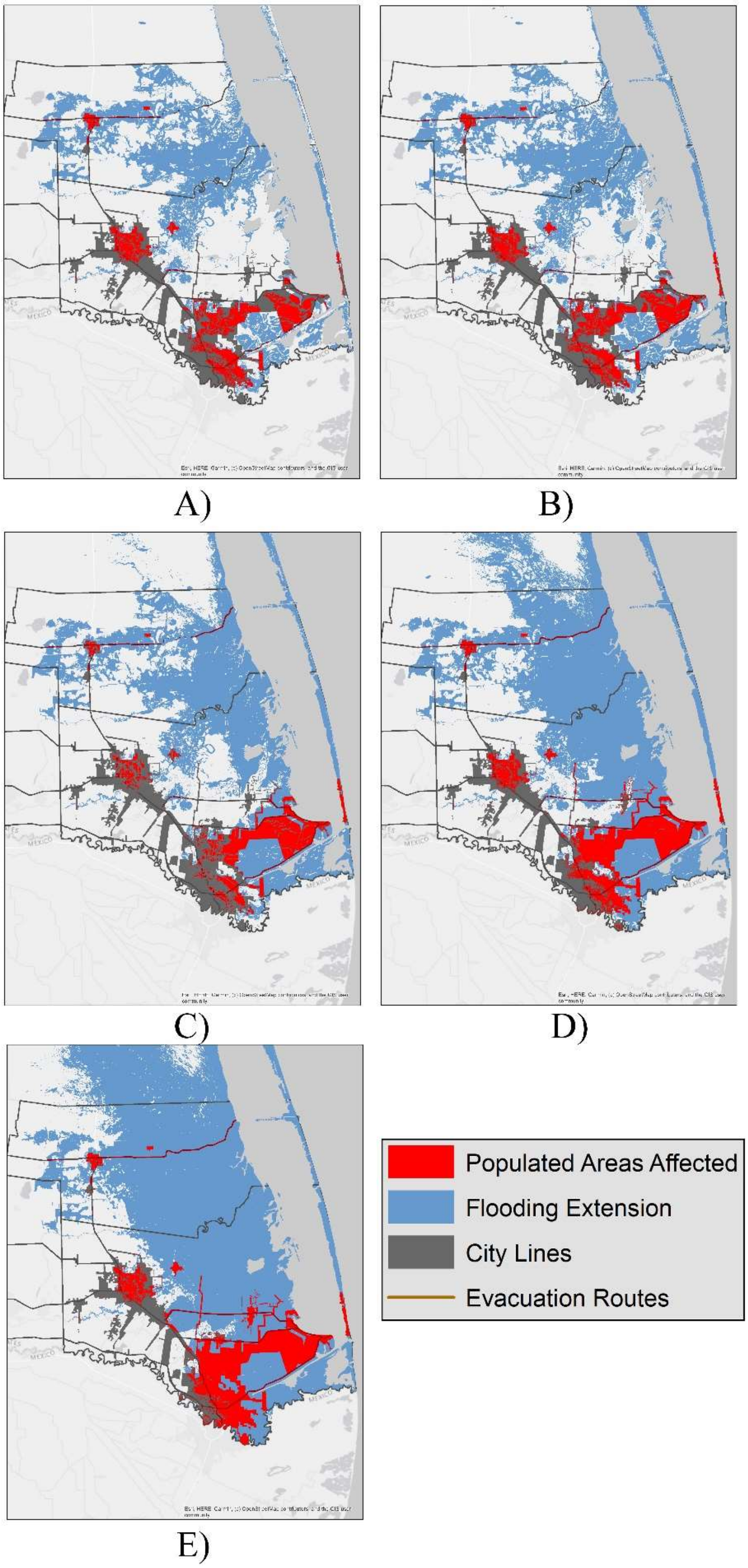


Evacuation Percentage Affected	
Storm Frequency	**Category 3**
10 Year	14.7%
50 Year	18.5%
500 Year	21.5%

Population Affected by Area	
Storm Frequency	**Category 3**
10 Year	91,025
50 Year	125,793
500 Year	150,508

Figure 8. Areas affected in case of an (A) 10-year frequency storm; (B) 50-year frequency storm; and (C) 500-year frequency storm.

Regarding the population affected, both the inland rainfall runoff and hurricane storm surge played a major role on the areas affected due to the specific locations of urban areas and drain channels. As it can be shown in Figure 9, the increase in hurricane categories increases the coastal surface area that is affected, which consequently leads to effects on any areas in closer proximity to the coast. On the other hand, the increase of frequency storm intensity, as shown in figure 8, leads to an increase in damage alongside the drainage channels. Given that urban areas must have connection to a drainage channel (https://www.susdrain.org/), the inland rainfall runoff will have an effect on the surrounding population that is as comparable to that of the hurricane storm surge. When analyzing the actual percentage of population, it should be noted that the accor 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 gory 5–500-year frequency combination, 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 [22].



Population Affected by Area	
Storm Frequency	**500 Year**
Category 1	119,626
Category 2	126,667
Category 3	150,508
Category 4	170,750
Category 5	206,553

Highway Percentage Affected	
Storm Frequency	**500 Year**
Category 1	10.3%
Category 2	12.9%
Category 3	21.5%
Category 4	28.7%
Category 5	41.7%

Figure 9. Areas affected in case of (A) Hurricane Category 1; (B) Category 2; (C) Category 3; (D) Category 4; (E) and Category 5; combined with a 500-year frequency storm.

4. Conclusion

By analyzing the effects of flooding through a combination of hurricane storm surge and rainfall runoff modelling, an in-depth analysis of the possible consequences can be conducted. The combination of hurricane categories alongside the multiple storm scenarios provides 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's important to denote that even in more frequent and less severe scenarios, such as a category 1 hurricane with a 50-year storm scenario, only 7.16% 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 this relatively small percentages. 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.

Acknowledgments

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Conflict of interest

The authors hereby declare no conflicts of interest in this research.

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