9-2021

An Assessment of Storm Surge Risk in Coastal Communities in the Rio Grande Valley

Dean Kyne

The University of Texas Rio Grande Valley, dean.kyne@utrgv.edu

Recommended Citation

Kyne, D. An Assessment of Storm Surge Risk in Coastal Communities in the Rio Grande Valley. Preprints 2021, 2021090282 (doi: 10.20944/preprints202109.0282.v1).

 doi:10.20944/preprints202109.0282.v1

Article

An Assessment of Storm Surge Risk in Coastal Communities in the Rio Grande Valley

Dean Kyne[1],*

[1] Associate Professor, Disaster Studies Program Director, Department of Sociology, University of Texas Rio Grande Valley; dean.kyne@utrgv.edu
* Correspondence: dean.kyne@utrgv.edu; Tel.: (956) 656-2572

Abstract: (1) Background: Cameron County, which is located in the Rio Grande Valley, holds historical records for storm surges with noticeable property damage, fatalities, and injuries; (2) Methods: using storm surge hazard datasets from the National Oceanic and Atlantic Agency (NOAA), and American Community Survey (ACS) 2019 datasets and Geographic Information System (GIS), the study estimates at-risk population and their socio-demographic attributes; (4) Conclusions: Estimated water levels of a storm surge could be reached up to 5 feet in category 1 event, 9 feet in category 2, 17 feet in category 3, and above 20 feet in category 4 and 5. In the category 5 event, there is an estimated 37% (159,659) of the total county's population (434,294) will be under flooded water. Suggestions are made to better prepare and successfully evaluate.

Keywords: storm surge, flood risk, costal region, Rio Grande Valley

1. Introduction

Hurricanes are associated with major hazards, namely storm surge and storm tide, heavy rainfall and inland flooding, high winds, rip currents, and tornadoes [1]. Among the hazards, the storm surge and storm tide pose great threats to the lives of people who reside in the coastal regions. According to the National Hurricane Center [1], storm surge is defined as an unusual rise of water, which is caused by a speedy wind during a storm, whereas storm tide is caused by a the storm surge coupling with the astronomical tide. The storm surge which could reach to a height of more than 20 feet, in fact, could take away lives of individuals, damage buildings, and wash away roads and beaches. For example, Hurricane Charley (Category 4), which made landfall in Florida in 2004, produced a storm surge of 6 to 8 feet; Hurricane Katrina (Category 3), at landfall in Louisiana in 2005, produced a 28-foot storm surge; Hurricane Ike (Category 2), in Texas in 2008, included a 20-foot storm surge; Hurricane Irene (Category 1) at landfall in North Carolina in 2011 had a storm surge of 8 to 11 feet [2]; and Hurricane Harvey (Category 4), which made landfall in Texas in 2017, caused a 12 feet storm surge [3]. The varying amount of surge is influenced by many factors which include central pressure of the impacting hurricane, storm intensity, size of the storm, storm forward speed, angle of approach to coast, shape of the coastline, wind and slope of the ocean bottom, and local features [2]. The total water level during a hurricane storm is contributed by a storm surge, tides, waves, and freshwater input [2]. Through the years, storm surges have demonstrated their destructive power with a record of many deaths and injuries [4]. According to a study which examines the number of deaths from coastal waters during tropical cyclones in the United States in a 50-year period, about half of the fatalities were caused by the storm surge [5].

In the U.S., the coastal regions, including the Atlantic Coast, the Gulf of Mexico, and the Hawaiian Islands have been hit hard by hurricanes and storm surges. It was estimated that there are about 52% (163.8 million) of the total US population (US Census 2010) who live in 769 Coastal Watershed Counties [6]. The states that host the coastal regions which include AL, CT, DE, DC, FL, GA, LA, ME, MD, MA, MS, NH, NJ, NY, NC, RI, SC, TX, and

 doi:10.20944/preprints202109.0282.v1

VA are vulnerable to hurricanes [7]. The study's findings also reveal that all the coastal states are vulnerable to storm surge inundation, while their exposure to storm surge risk increases with the level of severity of hurricane storm. According to the National Hurricane Center, the coastal communities which are located along the Gulf of Mexico are extremely vulnerable to storm surge. Their geographical locations with unique features of flat continental shelf and low-lying land elevations exposed the communities to potential storm surges with a greater height and a wide inland extent [7]. It was observed that there were at least one major hurricane making landfall in the Gulf Coast region every two years [2]. The level of vulnerability to storm surge could be amplified by increase in ocean temperature due to climate change. According to the Fourth National Climate Assessment Report, a rise in atmospheric temperature and an increase in ocean surface temperature could result in increased wind speeds from tropical storms [8, 9]. It is projected that more frequent and intense hurricanes in the U.S. Atlantic and Gulf Coast states are likely to increase the probability of extreme flooding and storm surge risk [8]. For example, by the end of the 2018 Atlantic hurricane season, there were 15 named storms, including eight hurricanes of which Florence and Michael were major category. These statistics exceed the seasonal average of 12 named storms, six hurricanes and three major hurricanes annually [10].

Among the counties that are situated in the Gulf Coast, Cameron and Willacy are the two out of four counties that constitutes the Rio Grande Valley (RGV), which hosts a population of around 1.3 million [11]. The valley consists of four counties, namely Hidalgo (61% of the valley's total population), Cameron (32%), Willacy (5%), and Starr (2%) counties. The Cameron and Willacy counties are located adjacent to the Gulf of Mexico and prone to hurricanes and storm surges. In addition, the county that shares the border along the Rio Grande River with Mexico is exposed to risk of river flooding. Historically, the Cameron and Willacy counties have been significantly impacted by hurricanes and storm surges. On September 4th and 5th, 1933, Cameron county was inundated with a 13-foot storm surge; on September 20th to 22nd, 1967, Hurricane Beulah caused inundation in both Cameron and Willacy County with a 18 feet tides; on August 10th, 1980, Hurricane Allen (Category 5) made a landfall with one of the worst storms on record which inundated the Brownsville with 4-feet of storm surge; on September 16th and 17th, 1988, Hurricane Gilbert (Category 3), the strongest storm on record for the Atlantic basin at the time, flooded Cameron and Willacy coastal regions with a notable storm surge; on August 23rd, 1999, Hurricane Bret (Category 4) hit Brownsville are with a foot of rain fall; on July 23rd, 2008, Hurricane Dolly (Category 2) hit the residents of the Lower Texas coastline and 3 to 4 foot surge was observed in the Brownsville Ship Channel; on June 30th, 2010, Hurricane Alex caused heavy rains and severe flooding in the Lower and Middle Rio Grande Valley [12].

To better cope with the anticipated frequency and new level of intensity of hurricanes and their associated hazards including storm surge and tide, it is imperative to build disaster resiliency in the coastal communities which are at-risk of hurricanes and their repercussions. Disaster resiliency is defined as increasing the ability to understand risk and vulnerability and enhancing capability to mitigate from, prepare for, respond to and recover from natural disasters. This brings about a return to normal or better than normal conditions [13]. The current approach of relying much on response and recovery phases will not work for future disasters resulting from climate change [8]. Building disaster resiliency begins with understanding hazards, social vulnerability, and risk which is conceptualized as the intersection between storm hazards and social vulnerability. The study aims at empirically investigating spatial distribution of storm surge hazards associated with hurricanes in Cameron County, the largest coastal county in the Rio Grande Valley and assessing social vulnerability of the coastal community members who expose to the storm surge hazards.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 September 2021 doi:10.20944/preprints202109.0282.v1

2. Materials and Methods

The study utilizes a conceptual framework which consists of storm surge hazards, social vulnerability, and storm surge risk (Figure 1). Strom surge hazard is defined as a dangerous phenomenon that causes an unusual rise of water during a storm and the amount of water is caused by storm surges, tides, waves, and freshwater input. Storm surge vulnerability refers to the social characteristics of a community that are susceptible to the damage caused by a storm surge hazard. Storm surge risk or exposure to storm surge hazards refers to communities and their members that reside in storm surge hazard areas and they are subject to potential losses.

Figure 1. Conceptual Framework of Storm Surge Hazards, Social Vulnerability, and Storm Surge Risk

To examine storm surge risks, the study employs two types of datasets: storm surge hazards and social vulnerability. First, storm surge hazard datasets were obtained from the National Oceanic and Atlantic Agency (NOAA). The datasets included the National Storm Surge Hazard Maps (NSSHM) - Version 2 data from NOAA [7]. Second, socio-demographic datasets were obtained from the U.S. Census Bureau. The social datasets consisted of census block group American Community Survey (ACS) 2019 data. In addition, the county boundary shapefiles were obtained from the U.S. Census Bureau (Figure 2).

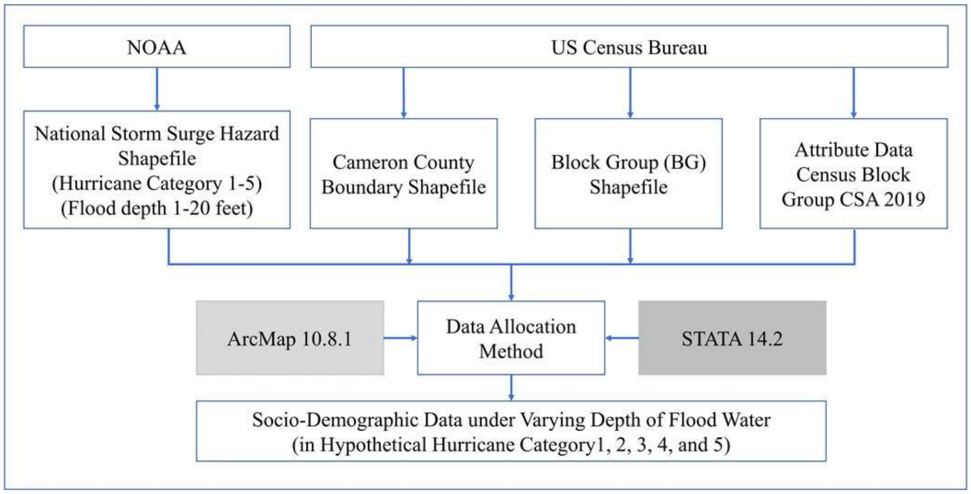

Figure 2. Data Analytics for Computing Socio-demographic Attributes Associated by Block Group which are Exposed to Strom Surge Risk under Five Hurricane Categories

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 September 2021 doi:10.20944/preprints202109.0282.v1

The NSSHM data was downloaded from the NHC, the National Oceanic and Atmosphere Administration (NOAA), website [14]. The hydrodynamic Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model was utilized to project the storm surge map in the NSSHM data. The SLOSH model, which was developed by the National Weather Service (NWS), is a numerical model that could run on computers to project storm surge heights. The model could be used to estimate storm surge heights from past hurricanes or predicting future hurricanes [15]. Specifically, the model consists of physic equations which require input information of shoreline, bay and river configurations, water depths, bridges, roads, levees and other physical features [15]. The data is in GeoTIFF format which could be used in Geographic Information Systems (GIS) software.

The attribute data of ACS 2019 at block group level include (1) total population, (2) gender, (3) age, (4) race, (5) tenure of living in the same house, (6) language, (7) total number of families, (8) educational attainment, (9) households with public assistance, (10) medium household income, (11) employment, (12) average age of buildings, (13) median value of houses, (14) total population without insurance, (15) native born, and (16) total occupied houses.

The study utilizes the areal apportionment method, which is widely used in estimating population [16, 17]. The method recalculates area of each census block group area that exists within the projected storm surge area in the NSSHM layer. When a census block group is covered by a storm surge area, then the entire population is counted toward the number exposed to storm surge risk. Similarly, when only a fraction of a census block group is exposed to a projected storm surge area in the NSSHM layer, then the fraction of the population is counted as the portion exposed to the storm surge risk.

$$P_s = P_t \times P_{cb}$$

Whereas:

P_s = the number of people potentially impacted by the storm surge,

P_t = the population type,

P_{cb} = the percentage of census block group area.

For example, 5,000 individuals live in a block group and only 10% of the block group exists in the projected storm surge area, then only 500 individuals are counted as population that is exposed to the storm surge risk. The other socio-economic variables are also recalculated using the apportionment method. One underlying assumption with this method is that the population and its socio-demographic attributes are evenly distributed in a block group, but, it is not always the case.

3. Results

Five storm surge maps for hypothetical hurricane events with category 1, 2, 3, 4, and 5 are depicted in the Figure 3.A, 3.B, 3.C, 3.D, and 3.E respectively (Figure 3). The findings indicate that estimated storm surge water could be as high as 21 feet or more during the hypothetical hurricane category 4 and 5 (Figure 3.D and 3.E). It is obvious that the area impacted by the storm surge water increases with the level of hurricane intensity.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 September 2021 doi:10.20944/preprints202109.0282.v1

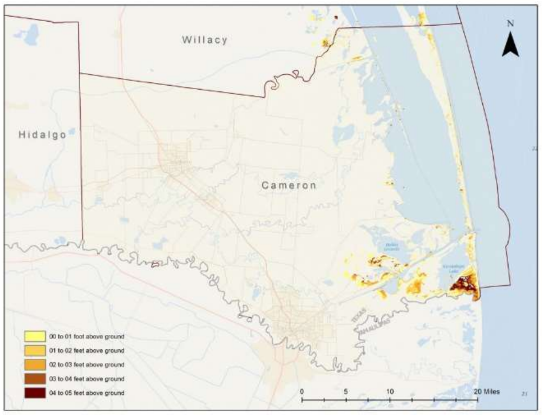

Figure 3.A Storm Surge under Hurricane Category 1 and Flood Water Level

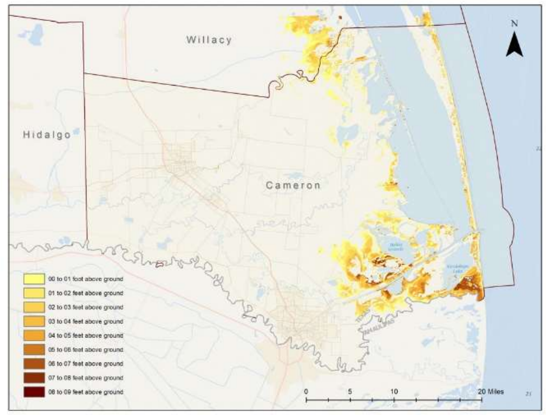

Figure 3.B Storm Surge under Hurricane Category 2 and Flood Water Level

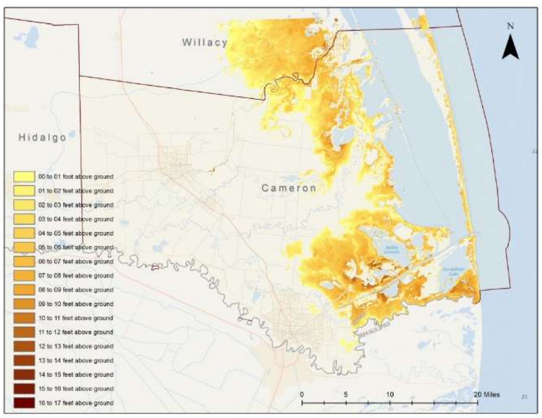

Figure 3.C Storm Surge under Hurricane Category 3 and Flood Water Level

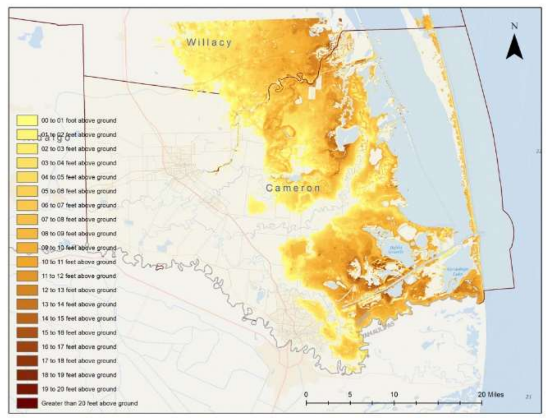

Figure 3.D Storm Surge under Hurricane Category 4 and Flood Water Level

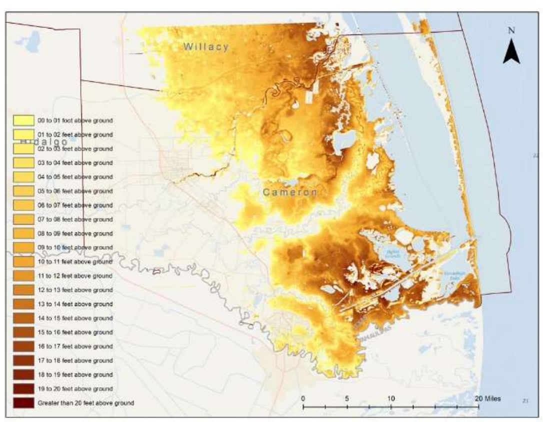

Figure 3.E Projected Storm Surge under Hurricane Category 5 and Flood Water Level

Figure 3. Data Projected Storm Surge and Flood Water Level in Five Hurricane Categories
Data Source: The National Storm Surge Hazard Maps (NSSHM)

First, estimated water levels of a storm surge could be up to 5 feet in category 1 event, 9 feet in category 2, 17 feet in category 3, and above 20 feet in category 4 and 5. The study's

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 September 2021 doi:10.20944/preprints202109.0282.v1

findings show that an estimated 36.7 % (159,659) of the county's total population (434,294) will likely be exposed to hurricane induced storm surges in a hypothetical hurricane category 5 event (Figure 4.A, Appendix A, Table A.5). Similarly, 14.39% (62,512), 3.48% (15,123), 1% (4,340), and 0.16% (711) of the county's total could be exposed to storm surge in a hypothetical hurricane category 4, 3, 2, and 1 event (Appendix A, Table A.4, Table A.3, Table A.2, and Table A.1).

Second, 23.53% of individuals who are at-risk for flooding speak only Spanish in Category 5, 21.87% in Category 4, 19.02% in Category 3, 18.15% in Category 2, and 19.24% in Category 1 (Figure 4.B, Appendix A, Table A.5, Table A.4, Table A.3, Table A.2, and Table A.1).

Third, among the at-risk individuals, an estimated 32.48% of the total had no schooling or attained less than high school education in the hypothetical hurricane category 1, 29.57% in category 2, 28.81% in category 3, 33.28% in category 4 and 35.27% in category 5 (Figure 4.C, Appendix A, Table A.5, Table A.4, Table A.3, Table A.2, and Table A.1.).

Fourth, a trend of close association among the level of education attainment and median household income was observed. The higher the percentage of no schooling and less than high school education, the lower the income. The median household income was observed as $37276 among the at-risk population in hypothetical hurricane category 1, $36454 in category 2, $37875 in category 3, $40352 in category 4, and $41384 in category 5 (Figure 4.D, Appendix A, Table A.5, Table A.4, Table A.3, Table A.2, and Table A.1.).

Fifth, about 14% and 38% of at-risk total households received public assistance in hypothetical hurricane category 4 and 5 respectively whereas lower percentage of them (0.22% in category 1, 1.31% in category 2, 4.16% in category 3) were observed as households receiving public assistance (Figure 4.E, Appendix A, Table A.5, Table A.4, Table A.3, Table A.2, and Table A.1.)

Sixth, the findings indicated that there was an estimated 42% of total at-risk individuals observed to have no health insurance who were likely to be exposed to storm surges induced by a hypothetical hurricane category 5 (Figure 4.F). Similarly, about 17%, 4%, 1% and 0.22% of the total at-risk individuals were observed in the hypothetical hurricane category 4, 3, 2, and 1 respectively (Figure 4.F, Appendix A, Table A.5, Table A.4, Table A.3, Table A.2, and Table A.1.).

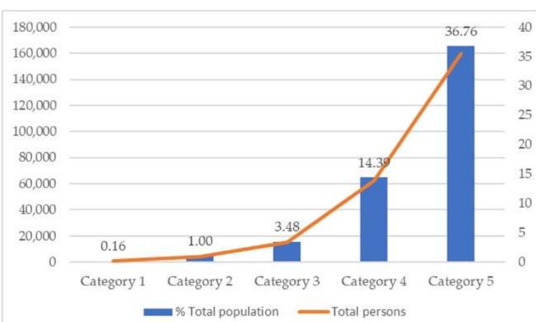

Figure 4.A Projected total population exposed to hurricane induced storm surge under five hypothetical hurricane categories

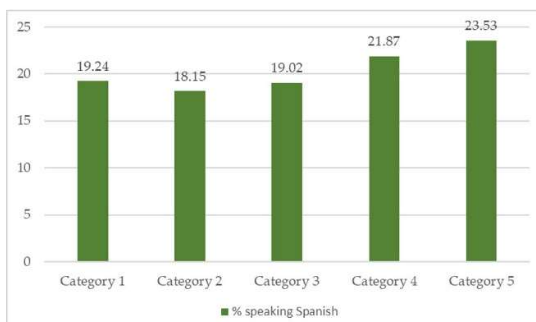

Figure 4.B Projected percent speaking Spanish of total population exposed to hurricane induced storm surge under five hypothetical hurricane categories

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 September 2021 doi:10.20944/preprints202109.0282.v1

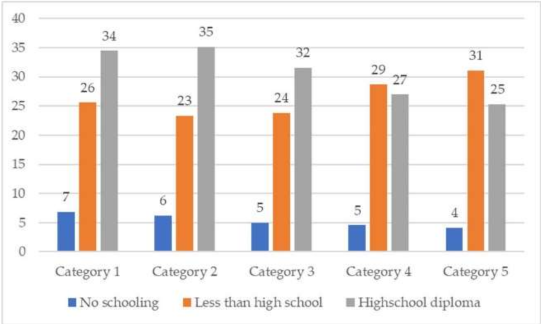

Figure 4.C Projected level of education attainment among at-risk indviduals who are likley to expose to hurricane induced storm surge under five hypothetical hurricane categories

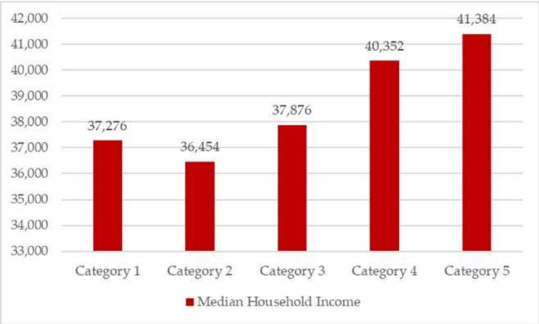

Figure 4.D Projected median household income among at-risk indviduals who are likley to expose to hurricane induced storm surge under five hypothetical hurricane categories

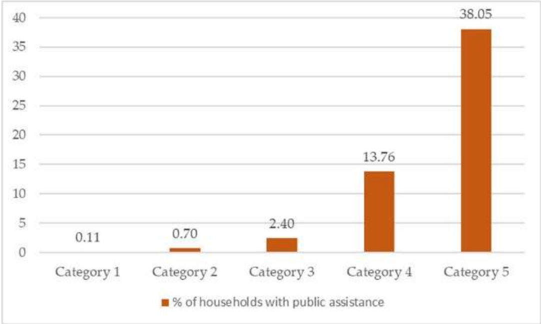

Figure 4.E Projected percent total households with received public assistance, that are likley to expose to hurricane induced storm surge under five hypothetical hurricane categories

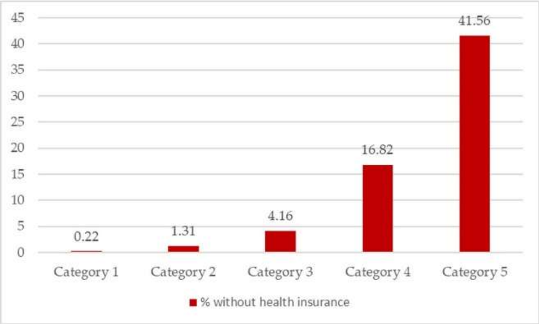

Figure 4.F Projected percent of total at-risk indivduals with no health insurance, who are likely to expose to hurricane induced storm surge under five hypothetical hurricane categories

Figure 4. Socio-demographic characteristics of population exposed to hurricane induced storm surge under five hypothetical hurricane categories

4. Discussion and Conclusions

The study's findings provide a better understanding of social vulnerability to storm surge hazards in Cameron County in the Rio Grande Valley, Texas, which is adjacent to the Gulf of Mexico and bordering with the Rio Grande River and Mexico. The county hosts a total population of 423,163 [18]. Using NOAA's storm surge projection under each of five hypothetical hurricane categories, the study finds community members who reside in the storm surge hazard areas under projected varying water depth up to 21 feet. It was alarming to notice that in a hypothetical hurricane category five event, there is an estimated 37% (159,659) of the total population (434,294) in the country that will be under flooded water (Appendix A, Table 5). The estimated population could experience the flooding water level over 21 feet high. In the event of hurricane category 5, the most daunting task for local emergency managers is to encourage at-risk individuals to leave their residence under a mandatory evacuation. This challenge was evident with previous findings that during the deathliest hurricane category 5 event, there are people who will remain in their residences in the Rio Grande Valley [19]. This daunting task could be amplified with the existing condition of low level of disaster preparedness among the residents [20].

A successful implementation of a mandatory evacuation order begins with individual preparedness. It is vital to educate the at-risk population about potential risks associated with a storm surge, its impacts on property, and potential deaths. The need for the

 doi:10.20944/preprints202109.0282.v1

educating program is justified by three reasons. First, the Saffir–Simpson scale of hurricanes does not explicitly carry the risk associated with a hurricane [21]. Second, the public does not pay sufficient attention the storm surge risk [22]. Third, the storm surge is an abstract phenomenon, and it is rare to have personal experience with during a sole lifetime [7]. Providing relevant and reliable information is associated with building trust in authorities recommendation which could in turn influence the positive evacuation-decision making among the valley residents [23].

In addition, the storm surge maps in this study were very helpful to visualize the spatial distribution of the flooding areas, but it also requires additional steps to provide an understanding on the location of individual households and impacts from the potential storm surge, including deaths [24]. Moreover, according to the findings, a larger percentage (about 23%) of the total at-risk population who speak Spanish indicates that communication in Spanish is a factor.

To respond effectively to the hurricane event, the at-risk population must be able to safely leave their residential areas to a designated location. To do so, it is essential to be familiar with the evacuation routes and estimated time to travel to their destination. There are only three primary evacuation routes from the coastal areas toward the mainland (Appendix B, Figure 1). The storm surge map shows that these primary routes originating from the coastal areas could be inundated (Figure 3). As a result, local emergency managers must make a prompt evacuation order, while evacuees must execute their evacuation plan in a timely manner. Moreover, the findings show that about 40% of the total at-risk population receive public assistance and about 42% of them do not have health insurance. These findings suggest that local authorities must prepare to provide shelters, necessities, and health care services during evacuation. Some studies suggest that those who are socially vulnerable are likely to face asset vulnerability [21]. This suggests that there is a need for better mitigation strategies for this at-risk population to mitigate potential loss of their property. Above all, the study's evidence provides a wake-up call to all key stakeholders to prepare for a potential storm surge in Cameron County.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Acknowledgement: The author would like to thank Yajaira Ayala, Diana C. Chimal, Leslie M. Cisneros, Nicolas A. Crane, Stephanie L. Kasper, Ramon Martinez, Rebecca N. Moran, Alma R. Provencio, Gabriel Rodriguez, Xochilth R. Roman, who studied in his course, namely GIS for Disaster Management, which was offered in the Disaster Studies MA program, University of Texas Rio Grande Valley.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 September 2021 doi:10.20944/preprints202109.0282.v1

A ppendix A

Table A.1 Socio-demographic characteristics of projected population who are exposed to storm surge under Hurricane Category 1

	Unflooded	Flooded	Level				Total	Flooded	Level			
			0-2'	2-3'	3-4'	4-5'			0-2'	2-3'	3-4'	4-5'
Total population	433583	711	295	188	142	86	434294	0.16	0.16	0.07	0.04	0.03
Male	211281	334	138	90	66	41	211615	0.16	0.16	0.07	0.04	0.03
Female	222303	376	157	98	76	45	222679	0.17	0.17	0.07	0.04	0.03
65 or older (female)	8121	30	12	8	5	4	8151	0.36	0.36	0.14	0.10	0.07
65 or older (male)	4323	13	6	4	2	1	4336	0.30	0.30	0.13	0.10	0.05
White	407064	694	289	183	139	84	407758	0.17	0.17	0.07	0.04	0.03
Black	2440	1	0	0	0	0	2441	0.04	0.04	0.02	0.01	0.00
Native	1069	1	0	0	0	0	1070	0.08	0.08	0.04	0.02	0.02
Asian	2967	3	1	1	1	0	2970	0.11	0.11	0.04	0.04	0.02
Other	20044	11	5	3	2	1	20055	0.06	0.06	0.02	0.02	0.01
Same house 1 year ago	389572	638	270	166	128	75	390210	0.16	0.16	0.07	0.04	0.03
Different house 1 year ago	32596	23	9	7	4	2	32619	0.07	0.07	0.03	0.02	0.01
Spanish	96601	137	55	36	28	18	96738	0.14	0.14	0.06	0.04	0.03
English Only	29524	110	48	32	19	11	29634	0.37	0.37	0.16	0.11	0.06
Total families	100101	164	68	44	32	20	100265	0.16	0.16	0.07	0.04	0.03
Families with no husband	25342	35	15	9	7	4	25377	0.14	0.14	0.06	0.03	0.03
Total population (age 25 or older)	253292	476	199	129	92	56	253768	0.19	0.19	0.08	0.05	0.04
No schooling	10752	33	14	7	7	4	10785	0.30	0.30	0.13	0.07	0.07
Less than high school	71328	122	52	29	26	15	71450	0.17	0.17	0.07	0.04	0.04
Highschool diploma	66747	164	67	44	32	20	66911	0.25	0.25	0.10	0.07	0.05
Associate degree	18335	30	12	9	5	4	18365	0.16	0.16	0.07	0.05	0.03
Bachelor degree	30218	46	19	14	8	5	30264	0.15	0.15	0.06	0.05	0.03
Professional degree	2067	2	1	1	0	0	2069	0.11	0.11	0.05	0.03	0.02
Some college	42886	61	25	19	10	7	42947	0.14	0.14	0.06	0.04	0.02
Graduate degree	10959	18	9	6	2	1	10977	0.16	0.16	0.08	0.05	0.02

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 September 2021 doi:10.20944/preprints202109.0282.v1

Medium household income ($)	39568	37276	36633	36836	37112	38523	38422					
Total household	127453	248	104	69	47	29	127701	0.19	0.19	0.08	0.05	0.04
Households with public assistance	2829	3	1	1	1	1	2832	0.11	0.11	0.03	0.03	0.02
Household without public assistance	124624	245	103	68	47	28	124869	0.20	0.20	0.08	0.05	0.04
Total population (labor force)	315546	548	226	148	107	66	316094	0.17	0.17	0.07	0.05	0.03
In labor	175675	275	114	74	54	33	175950	0.16	0.16	0.06	0.04	0.03
Unemployed	10270	6	2	2	1	1	10276	0.05	0.05	0.02	0.02	0.01
Average age of buildings	36	27	28	28	27	26	36					
Medium value of houses ($)	84754	143899	138527	141529	144387	151155	114326					
Total population without health insurance	123420	278	118	68	59	33	123698	0.22	0.22	0.10	0.05	0.05
Native	333950	528	216	145	102	65	334478	0.16	0.16	0.06	0.04	0.03
Foreign born	99634	182	80	42	40	21	99816	0.18	0.18	0.08	0.04	0.04
Total houses	154553	505	221	148	84	51	155058	0.33	0.33	0.14	0.10	0.05
Total occupied houses	127453	248	104	69	47	29	127701	0.19	0.19	0.08	0.05	0.04
Total vacant houses	27100	257	118	80	37	23	27357	0.94	0.94	0.43	0.29	0.14

Table A.2 Socio-demographic characteristics of projected population who are exposed to storm surge under Hurricane Category 2

	Unflooded	Flooded	Level				Total	Flooded	Level	(%)		
			0-2'	2-4'	4-6'	6-9'			0-2'	2-4'	4-6'	6-9'

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 September 2021 doi:10.20944/preprints202109.0282.v1

Total population	429954	4340	2815	1090	304	130	434294	1.00	1.00	0.65	0.25	0.07
Male	209584	2031	1326	505	141	59	211615	0.96	0.96	0.63	0.24	0.07
Female	220370	2309	1489	585	164	71	222679	1.04	1.04	0.67	0.26	0.07
65 or older (female)	7982	169	112	39	13	5	8151	2.08	2.08	1.38	0.48	0.16
65 or older (male)	4257	79	54	19	5	1	4336	1.83	1.83	1.25	0.44	0.12
White	403542	4216	2729	1062	297	128	407758	1.03	1.03	0.67	0.26	0.07
Black	2433	8	6	1	0	0	2441	0.31	0.31	0.24	0.05	0.01
Native	1063	7	5	2	0	0	1070	0.69	0.69	0.47	0.16	0.04
Asian	2945	25	17	6	2	0	2970	0.85	0.85	0.57	0.20	0.06
Other	19972	83	58	18	5	2	20055	0.41	0.41	0.29	0.09	0.03
Same house 1 year ago	386093	4117	2706	1013	280	118	390210	1.05	1.05	0.69	0.26	0.07
Different house 1 year ago	32517	102	58	32	10	3	32619	0.31	0.31	0.18	0.10	0.03
Spanish	95950	788	498	203	60	27	96738	0.81	0.81	0.51	0.21	0.06
English Only	28915	719	495	167	43	13	29634	2.43	2.43	1.67	0.56	0.15
Total families	99222	1043	690	255	70	29	100265	1.04	1.04	0.69	0.25	0.07
Families with no husband	25152	225	144	59	16	7	25377	0.89	0.89	0.57	0.23	0.06
Total population (age 25 or older)	250738	3030	2016	733	200	81	253768	1.19	1.19	0.79	0.29	0.08
No schooling	10597	188	112	53	14	8	10785	1.74	1.74	1.04	0.49	0.13
Less than high school	70742	708	435	194	52	27	71450	0.99	0.99	0.61	0.27	0.07
Highschool diploma	65846	1065	709	255	72	29	66911	1.59	1.59	1.06	0.38	0.11
Associate degree	18169	196	137	43	12	4	18365	1.07	1.07	0.75	0.23	0.07
Bachelor degree	30007	257	170	63	19	5	30264	0.85	0.85	0.56	0.21	0.06
Professional degree	2061	8	4	3	1	0	2069	0.37	0.37	0.19	0.13	0.04
Some college	42510	437	314	92	25	7	42947	1.02	1.02	0.73	0.21	0.06
Graduate degree	10806	171	135	30	5	1	10977	1.56	1.56	1.23	0.28	0.05
Medium household income ($)	39568	36454	37034	36265	35841	36677	38011					
Total household	126175	1526	1008	374	104	40	127701	1.20	1.20	0.79	0.29	0.08
Households with public assistance	2812	20	14	3	2	1	2832	0.70	0.70	0.51	0.12	0.06

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 September 2021 doi:10.20944/preprints202109.0282.v1

Household without public assistance	123363	1506	994	370	103	39	124869	1.21	1.21	0.80	0.30	0.08
Total population (labor force)	312713	3381	2225	829	232	95	316094	1.07	1.07	0.70	0.26	0.07
In labor	174328	1622	1038	418	116	49	175950	0.92	0.92	0.59	0.24	0.07
Unemployed	10245	31	22	7	2	1	10276	0.30	0.30	0.21	0.06	0.02
Average age of buildings	36	27	27	28	27	27	36					
Medium value of houses ($)	84754	129126	132496	130894	124630	128482	106940					
Total population without health insurance	122073	1625	1006	440	121	58	123698	1.31	1.31	0.81	0.36	0.10
Native	331227	3251	2154	782	225	89	334478	0.97	0.97	0.64	0.23	0.07
Foreign born	98727	1089	661	308	80	41	99816	1.09	1.09	0.66	0.31	0.08
Total houses	152743	2315	1427	648	182	58	155058	1.49	1.49	0.92	0.42	0.12
Total occupied houses	126175	1526	1008	374	104	40	127701	1.20	1.20	0.79	0.29	0.08
Total vacant houses	26568	789	419	275	77	18	27357	2.88	2.88	1.53	1.00	0.28

Table A.3 Socio-demographic characteristics of projected population who are exposed to storm surge under Hurricane Category 3

	Unflooded	Flooded	Level					Total	Flooded	Level				
			0-2'	2-4'	4-6'	6-9'	9-17'			0-2'	2-4'	4-6'	6-9'	9-17'
Total population	419171	15123	6082	3608	3337	1761	335	434294	3.48	3.48	1.40	0.83	0.77	0.41

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 September 2021 doi:10.20944/preprints202109.0282.v1

Male	204446	7169	2884	1745	1583	803	154	211615	3.39	3.39	1.36	0.82	0.75	0.38
Female	214725	7954	3197	1863	1754	958	182	222679	3.57	3.57	1.44	0.84	0.79	0.43
65 or older (female)	7749	402	113	110	112	56	11	8151	4.93	4.93	1.38	1.35	1.37	0.69
65 or older (male)	4128	208	60	50	67	27	3	4336	4.79	4.79	1.38	1.16	1.55	0.62
White	393262	14496	5804	3454	3213	1701	325	407758	3.56	3.56	1.42	0.85	0.79	0.42
Black	2412	29	9	7	10	2	0	2441	1.18	1.18	0.38	0.29	0.40	0.10
Native	1050	20	7	4	5	3	1	1070	1.90	1.90	0.65	0.38	0.49	0.31
Asian	2888	82	34	18	20	9	1	2970	2.75	2.75	1.13	0.62	0.69	0.29
Other	19559	496	228	125	89	45	9	20055	2.47	2.47	1.14	0.62	0.44	0.23
Same house 1 year ago	375988	14222	5612	3438	3193	1680	297	390210	3.64	3.64	1.44	0.88	0.82	0.43
Different house 1 year ago	32053	566	338	99	82	40	7	32619	1.74	1.74	1.04	0.30	0.25	0.12
Spanish	93861	2877	1255	657	571	326	68	96738	2.97	2.97	1.30	0.68	0.59	0.34
English Only	27753	1881	547	486	573	244	32	29634	6.35	6.35	1.84	1.64	1.93	0.82
Total families	96655	3610	1446	859	817	414	74	100265	3.60	3.60	1.44	0.86	0.81	0.41
Families with no husband	24598	779	341	175	152	90	19	25377	3.07	3.07	1.34	0.69	0.60	0.36
Total population (age 25 or older)	244101	9667	3656	2353	2306	1148	203	253768	3.81	3.81	1.44	0.93	0.91	0.45
No schooling	10302	483	150	110	115	89	19	10785	4.48	4.48	1.39	1.02	1.07	0.83
Less than high school	69148	2302	907	513	484	328	70	71450	3.22	3.22	1.27	0.72	0.68	0.46
Highschool diploma	63861	3050	1062	760	767	391	71	66911	4.56	4.56	1.59	1.14	1.15	0.58
Associate degree	17610	755	289	204	183	69	10	18365	4.11	4.11	1.57	1.11	1.00	0.38
Bachelor degree	29296	968	434	222	213	86	13	30264	3.20	3.20	1.43	0.73	0.70	0.28
Professional degree	2032	37	16	11	8	3	0	2069	1.79	1.79	0.75	0.51	0.37	0.14
Some college	41372	1575	636	410	375	137	18	42947	3.67	3.67	1.48	0.95	0.87	0.32
Graduate degree	10480	497	163	124	162	46	3	10977	4.53	4.53	1.48	1.13	1.48	0.42
Medium household income ($)	39568	37876	40880	39824	37646	35805	35225	38722						
Total household	122889	4812	1819	1155	1161	577	100	127701	3.77	3.77	1.42	0.90	0.91	0.45
Households with public assistance	2764	68	30	13	17	7	1	2832	2.40	2.40	1.08	0.46	0.59	0.24
Household without public assistance	120125	4744	1789	1142	1144	570	99	124869	3.80	3.80	1.43	0.91	0.92	0.46

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 September 2021 doi:10.20944/preprints202109.0282.v1

Total population (labor force)	304745	11349	4456	2752	2595	1304	242	316094	3.59	3.59	1.41	0.87	0.82	0.41
In labor	170177	5773	2373	1380	1247	647	126	175950	3.28	3.28	1.35	0.78	0.71	0.37
Unemployed	10051	225	128	50	34	9	4	10276	2.19	2.19	1.25	0.49	0.33	0.09
Average age of buildings	36	26	25	26	27	27	27	36						
Medium value of houses ($)	84754	124511	131761	135497	129572	121421	104306	104632						
Total population without health insurance	118549	5149	2007	1177	1111	709	146	123698	4.16	4.16	1.62	0.95	0.90	0.57
Native	322995	11483	4623	2816	2571	1243	231	334478	3.43	3.43	1.38	0.84	0.77	0.37
Foreign born	96176	3640	1459	792	766	518	105	99816	3.65	3.65	1.46	0.79	0.77	0.52
Total houses	148373	6685	2314	1608	1721	900	142	155058	4.31	4.31	1.49	1.04	1.11	0.58
Total occupied houses	122889	4812	1819	1155	1161	577	100	127701	3.77	3.77	1.42	0.90	0.91	0.45
Total vacant houses	25484	1873	495	453	560	323	42	27357	6.84	6.84	1.81	1.65	2.05	1.18

Table A.4 Socio-demographic characteristics of projected population who are exposed to storm surge under Hurricane Category 4

	Unflooded	Flooded	Level						Flooded	Level				
			0-2'	2-4'	4-6'	6-9'	9-21'	Total		0-2'	2-4'	4-6'	6-9'	9-21'

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 September 2021 doi:10.20944/preprints202109.0282.v1

Total population	371782	62512	22389	17916	10346	7786	4076	434294	14.39	14.39	5.16	4.13	2.38	1.79
Male	181536	30079	10991	8525	4922	3757	1883	211615	14.21	14.21	5.19	4.03	2.33	1.78
Female	190245	32434	11398	9391	5423	4029	2193	222679	14.57	14.57	5.12	4.22	2.44	1.81
65 or older (female)	7297	854	194	203	165	181	110	8151	10.48	10.48	2.38	2.50	2.03	2.23
65 or older (male)	3882	454	109	118	80	85	62	4336	10.47	10.47	2.51	2.72	1.85	1.97
White	347728	60030	21476	17219	9946	7471	3918	407758	14.72	14.72	5.27	4.22	2.44	1.83
Black	2245	196	90	59	28	12	8	2441	8.04	8.04	3.68	2.40	1.13	0.48
Native	943	127	74	25	10	10	8	1070	11.84	11.84	6.91	2.34	0.92	0.89
Asian	2675	295	110	88	48	30	19	2970	9.92	9.92	3.71	2.97	1.61	1.01
Other	18190	1865	639	525	315	264	122	20055	9.30	9.30	3.19	2.62	1.57	1.32
Same house 1 year ago	332991	57219	20176	16253	9535	7385	3870	390210	14.66	14.66	5.17	4.17	2.44	1.89
Different house 1 year ago	28605	4014	1727	1347	603	237	100	32619	12.31	12.31	5.29	4.13	1.85	0.73
Spanish	83065	13673	5154	4095	2193	1489	743	96738	14.13	14.13	5.33	4.23	2.27	1.54
English Only	25966	3668	715	828	727	843	556	29634	12.38	12.38	2.41	2.79	2.45	2.84
Total families	85745	14520	5165	4170	2398	1817	970	100265	14.48	14.48	5.15	4.16	2.39	1.81
Families with no husband	22004	3373	1249	1000	550	379	196	25377	13.29	13.29	4.92	3.94	2.17	1.49
Total population (age 25 or older)	217562	36206	12418	10179	6113	4874	2622	253768	14.27	14.27	4.89	4.01	2.41	1.92
No schooling	9125	1660	524	439	282	239	177	10785	15.39	15.39	4.86	4.07	2.62	2.21
Less than high school	61062	10388	3831	3004	1694	1173	685	71450	14.54	14.54	5.36	4.20	2.37	1.64
Highschool diploma	57153	9758	3039	2631	1703	1532	853	66911	14.58	14.58	4.54	3.93	2.54	2.29
Associate degree	15745	2620	873	741	437	377	191	18365	14.27	14.27	4.75	4.04	2.38	2.06
Bachelor degree	25768	4496	1715	1365	720	471	224	30264	14.86	14.86	5.67	4.51	2.38	1.56
Professional degree	1878	191	69	54	30	27	11	2069	9.25	9.25	3.35	2.60	1.46	1.31
Some college	37337	5610	1889	1554	1001	820	346	42947	13.06	13.06	4.40	3.62	2.33	1.91
Graduate degree	9494	1483	477	391	245	235	135	10977	13.51	13.51	4.35	3.56	2.23	2.14
Medium household income ($)	39568	40352	42815	41936	41142	39719	36150	39960						
Total household	110190	17511	5929	4973	2942	2352	1315	127701	13.71	13.71	4.64	3.89	2.30	1.84
Households with public assistance	2442	390	159	113	62	38	18	2832	13.76	13.76	5.62	4.00	2.18	1.33

Household without public assistance	107747	17122	5770	4860	2881	2314	1297	124869	13.71	13.71	4.62	3.89	2.31	1.85
Total population (labor force)	271194	44900	15736	12813	7531	5806	3014	316094	14.20	14.20	4.98	4.05	2.38	1.84
In labor	151041	24909	9059	7153	4110	3068	1519	175950	14.16	14.16	5.15	4.07	2.34	1.74
Unemployed	8904	1372	568	398	226	145	35	10276	13.36	13.36	5.52	3.87	2.20	1.41
Average age of buildings	36	25	25	25	25	26	27	36						
Medium value of houses ($)	84754	122405	######	125236	126742	126220	114419	103579						
Total population without health insurance	102893	20805	7342	5899	3478	2606	1480	123698	16.82	16.82	5.94	4.77	2.81	2.11
Native	288127	46351	16358	13174	7802	6041	2977	334478	13.86	13.86	4.89	3.94	2.33	1.81
Foreign born	83654	16162	6031	4742	2544	1746	1099	99816	16.19	16.19	6.04	4.75	2.55	1.75
Total houses	133903	21155	6672	5764	3583	3202	1935	155058	13.64	13.64	4.30	3.72	2.31	2.06
Total occupied houses	110190	17511	5929	4973	2942	2352	1315	127701	13.71	13.71	4.64	3.89	2.30	1.84
Total vacant houses	23714	3643	743	791	641	850	619	27357	13.32	13.32	2.72	2.89	2.34	3.11

Table A.5 Socio-demographic characteristics of projected population who are exposed to storm surge under Hurricane Category 5

	Unflooded	Flooded	Level						Flooded	Level				
			0-2'	2-4'	4-6'	6-9'	9-21'	Total		0-2'	2-4'	4-6'	6-9'	9-21'
Total population	274635	159659	45007	37197	28893	28947	19615	434294	36.76	36.76	10.36	8.56	6.65	6.67

 doi:10.20944/preprints202109.0282.v1

Male	133715	77900	22105	18319	14197	13966	9313	211615	36.81	36.81	10.45	8.66	6.71	6.60
Female	140919	81760	22902	18878	14697	14982	10301	222679	36.72	36.72	10.28	8.48	6.60	6.73
65 or older (female)	5833	2318	743	513	304	346	412	8151	28.44	28.44	9.12	6.29	3.73	4.25
65 or older (male)	3126	1210	368	267	172	190	213	4336	27.90	27.90	8.49	6.16	3.96	4.39
White	255340	152418	42798	35418	27658	27761	18783	407758	37.38	37.38	10.50	8.69	6.78	6.81
Black	1551	890	251	288	154	121	77	2441	36.46	36.46	10.26	11.80	6.30	4.96
Native	684	386	140	85	79	59	23	1070	36.10	36.10	13.10	7.94	7.34	5.56
Asian	2056	914	242	254	159	161	98	2970	30.76	30.76	8.14	8.56	5.35	5.41
Other	15004	5051	1577	1151	844	845	634	20055	25.19	25.19	7.86	5.74	4.21	4.21
Same house 1 year ago	246214	143996	39864	33403	26118	26342	18270	390210	36.90	36.90	10.22	8.56	6.69	6.75
Different house 1 year ago	20799	11820	3885	2731	2198	2069	936	32619	36.24	36.24	11.91	8.37	6.74	6.34
Spanish	59165	37573	10963	9188	6855	6564	4003	96738	38.84	38.84	11.33	9.50	7.09	6.79
English Only	23186	6448	1406	977	866	1355	1844	29634	21.76	21.76	4.74	3.30	2.92	4.57
Total families	63524	36741	10199	8544	6690	6721	4587	100265	36.64	36.64	10.17	8.52	6.67	6.70
Families with no husband	16152	9225	2832	2129	1632	1603	1029	25377	36.35	36.35	11.16	8.39	6.43	6.32
Total population (age 25 or older)	162228	91540	25346	21415	16368	16542	11869	253768	36.07	36.07	9.99	8.44	6.45	6.52
No schooling	6986	3799	1024	858	641	682	595	10785	35.23	35.23	9.50	7.95	5.94	6.32
Less than high school	42960	28490	8756	6821	4933	4832	3149	71450	39.87	39.87	12.25	9.55	6.90	6.76
Highschool diploma	43761	23150	6309	5121	3931	4281	3508	66911	34.60	34.60	9.43	7.65	5.88	6.40
Associate degree	12142	6223	1575	1405	1140	1198	906	18365	33.89	33.89	8.58	7.65	6.21	6.52
Bachelor degree	18828	11436	2846	2729	2359	2241	1261	30264	37.79	37.79	9.41	9.02	7.79	7.40
Professional degree	1499	570	173	153	102	86	57	2069	27.57	27.57	8.35	7.39	4.94	4.15
Some college	28585	14362	3833	3530	2569	2555	1875	42947	33.44	33.44	8.92	8.22	5.98	5.95
Graduate degree	7468	3509	829	798	694	669	519	10977	31.97	31.97	7.56	7.27	6.32	6.09
Medium household income ($)	39568	41384	43205	42152	42090	41199	38275	40476						
Total household	83194	44507	12486	10292	7818	8008	5902	127701	34.85	34.85	9.78	8.06	6.12	6.27
Households with public assistance	1755	1077	361	261	186	179	91	2832	38.05	38.05	12.75	9.22	6.56	6.31
Household without public assistance	81440	43429	12125	10031	7632	7830	5811	124869	34.78	34.78	9.71	8.03	6.11	6.27

Total population (labor force)	200937	115157	32376	27052	20628	20749	14352	316094	36.43	36.43	10.24	8.56	6.53	6.56
In labor	111628	64322	17634	15405	11971	11701	7611	175950	36.56	36.56	10.02	8.76	6.80	6.65
Unemployed	6467	3809	1080	959	750	668	351	10276	37.07	37.07	10.51	9.33	7.30	6.50
Average age of buildings	36	27	28	27	26	26	27	36						
Medium value of houses ($)	84754	113604	102289	108756	117159	121693	118123	99179						
Total population without health insurance	72291	51407	14252	11752	9178	9528	6697	123698	41.56	41.56	11.52	9.50	7.42	7.70
Native	217687	116791	32655	27014	21079	21334	14709	334478	34.92	34.92	9.76	8.08	6.30	6.38
Foreign born	56947	42869	12352	10183	7814	7614	4906	99816	42.95	42.95	12.38	10.20	7.83	7.63
Total houses	103548	51510	14111	11610	8795	9295	7699	155058	33.22	33.22	9.10	7.49	5.67	5.99
Total occupied houses	83194	44507	12486	10292	7818	8008	5902	127701	34.85	34.85	9.78	8.06	6.12	6.27
Total vacant houses	20354	7003	1624	1317	978	1287	1797	27357	25.60	25.60	5.94	4.82	3.57	4.71

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 September 2021 doi:10.20944/preprints202109.0282.v1

Appendix B

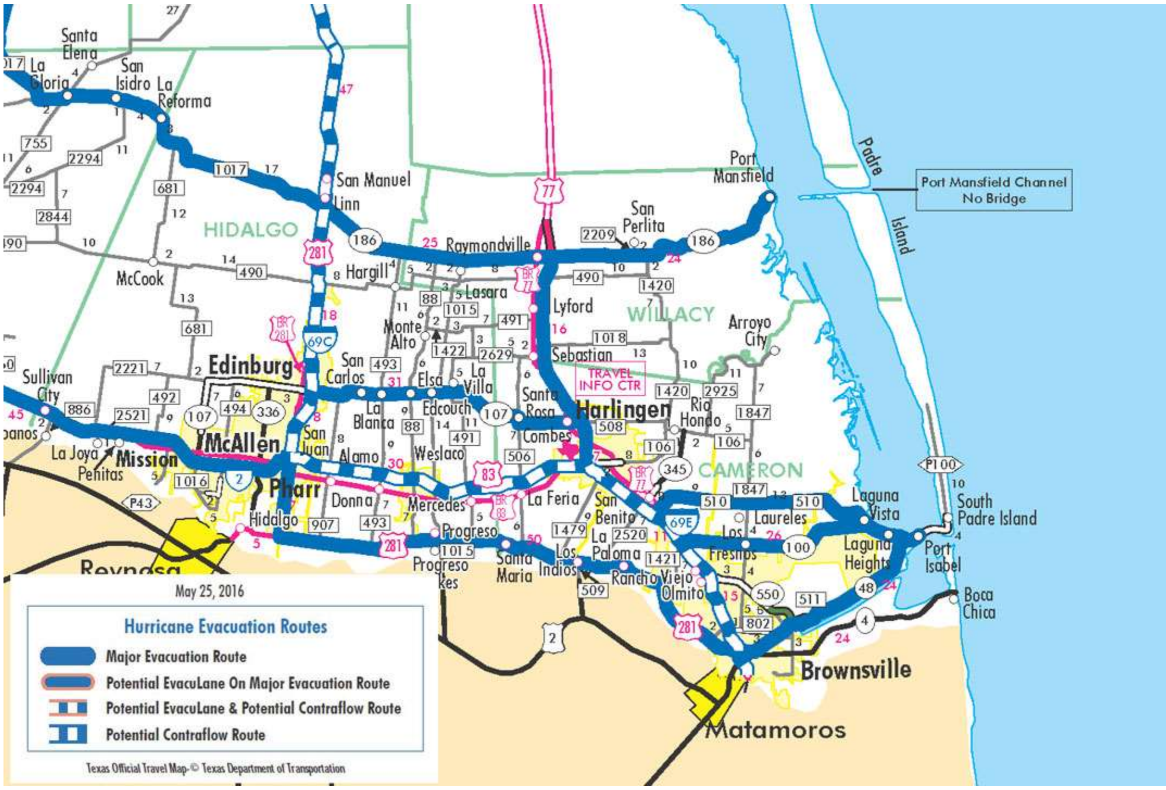

Figure 1. Hurricane Evacuation Routes in Brownsville and Rio Grande Valley
Source: Texas Department of Transportation (TxDOT) [25]

References

1. NHC *Hurricane Preparedness - Hazards*; Online, 2017.
2. National Hurricane Center Introduction to Storm Surge. https://www.nhc.noaa.gov/surge/
3. Natoinal Weather Service Major Hurricane Harvey - August 25-29, 2017. http://www.weather.gov/crp/hurricane_harvey
4. Morrow, B. H.; Lazo, J. K.; Rhome, J.; Feyen, J., Improving Storm Surge Risk Communication: Stakeholder Perspectives. *B Am Meteorol Soc* **2014,** 96, (1), 35-48.
5. Rappaport, E. N., Fatalities in the United States from Atlantic Tropical Cyclones: New Data and Interpretation. *B Am Meteorol Soc* **2013,** 95, (3), 341-346.
6. NOAA *National Coastal Population Report: Population Trends from 1970 to 2020*; Online, March 2013, 2013.
7. Zachry, B. C.; Booth, W. J.; Rhome, J. R.; Sharon, T. M., A National View of Storm Surge Risk and Inundation. *Weather Clim Soc* **2015,** 7, (2), 109-117.
8. USGCRP, *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. U.S. Global Change Research Program: Washington, DC, USA, 2018; p xxx.
9. GFL Global Warming and Hurricanes: An Overview of Current Research Results. https://www.gfdl.noaa.gov/global-warming-and-hurricanes/ (03/26/2019),
10. NOAA, Destructive 2018 Atlantic hurricane season draws to an end. In 11/28/2018 ed.; National Oceanic and Atmospheric Administration (NOAA): 2018.
11. US Census, United States Census 2010 Data. In United States Census Bureau: Online, 2010.

 doi:10.20944/preprints202109.0282.v1

12. National Weather Service, Hurricane Preparedness, Rio Grande Valley: Hurricane History. In 2017.
13. US NRC, *Disaster resilience: a national imperative.* . US National Research Council, The National Academies Press: Washington, 2012.
14. NHC *National Storm Surge Hazard Map-Version 2*; Online, 2018.
15. NHC *Sea, Lake, and Overland Surges from Hurricanes (SLOSH)*; Online, 2018.
16. Goodman, K. Environmental Justice and GIS: A Comparison of Three GIS Methods for Estimating Vulnerable Population Exposed to Brownfield Pollution in Portland, Oregon. Kyle Goodman, Portland State University, Jiunn-Der (Geoffrey) Duh, 2017.
17. Maantay, J.; Maroko, A.; Porter-Morgan, H., *Research Note—A New Method for Mapping Population and Understanding the Spatial Dynamics of Disease in Urban Areas: Asthma in the Bronx, New York*. 2008; Vol. 29, p 724-738.
18. Census Bureau, QuickFacts. In 2019.
19. Kyne, D., Lomeli, A., Donner, W.,Zuloaga, E., Who Will Stay, Who Will Leave: Decision-Making of Residents Living in Potential Hurricane Impact Areas During a Hypothetical Hurricane Event in the Rio Grande Valley. *J Homel Secur Emerg* **2018**.
20. D Kyne, L. C., J Delacruz, B Lopez, C Madrid, R Moran, A Provencio, F Ramos, MF Silva, Empirical evaluation of disaster preparedness for hurricanes in the Rio Grande Valley. *Progress in Disaster Science* **2019,** 5, 1-12.
21. Felsenstein, D.; Lichter, M., Social and economic vulnerability of coastal communities to sea-level rise and extreme flooding. *Nat Hazards* **2014,** 71, (1), 463-491.
22. Morss, R. E.; Demuth, J. L.; Lazo, J. K.; Dickinson, K.; Lazrus, H.; Morrow, B. H., Understanding Public Hurricane Evacuation Decisions and Responses to Forecast and Warning Messages. *Weather Forecast* **2016,** 31, (2), 395-417.
23. Kyne, D.; Donner, W., Kyne–Donner Model of Authority's Recommendation and Hurricane Evacuation Decisions: A Study of Hypothetical Hurricane Event in the Rio Grande Valley, Texas. *Popul Res Policy Rev* **2018,** 37, (6), 897-922.
24. Arlikatti, S.; Lindell, M. K.; Prater, C. S.; Zhang, Y., Risk area accuracy and hurricane evacuation expectations of coastal residents. *Environ Behav* **2006,** 38, (2), 226-247.
25. Texas Department of Transportation Hurricane Evacuation Routes. https://www.brownsvilletx.gov/DocumentCenter/View/5715/Hurricane-Evacuation-Routes-TxDOT