Transportation Consortium of South-Central States

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Portable Roadway High Water Detection System for Driver Safety and Infrastructure Assessment

Project No. 18SATSA05

Lead University: University of Texas at San Antonio

Final Report

August 2019

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16. Abstract

The state of Texas, local governments, and community groups are adopting several initiatives to address this problem. The main goal of this project is to develop an approach to enhance prediction and detection of roadway flooding and help efforts to prevent driving into flood roadways. The motivation of this work was initiated by the alarming number of vehicle related flood fatalities in Texas, mostly at low-water crossings. Texas leads the nation in the number of flood fatalities and about 77% of flood fatalities in Texas are motor vehicle-related. This percentage is much higher than the national percentage reported in several previous studies. Motor vehicle-related flood fatalities in Texas are generally correlated with monthly climate, topography, and population density. For example, about half of the fatalities caused by Hurricane Harvey were transportation-related. The presence of numerous low water crossings throughout Texas contribute to the higher recurrence rates of floods that pose a danger to vehicles. The research team has been challenged to identify effective measures to improve safety at low-water crossings. Therefore, the research team developed an approach that combines data analysis, modeling, and high water detection and communication to improve safety at low-water crossings. Researchers conducted the following tasks: literature review, vehicle-related flood fatality analysis, review of transportation fatalities cause by Hurricane Harvey, and proposed the design of a warning systems at low-water crossings that can detect and predict water depth and velocity at these locations. It was suggested that flood detection and warning can be significantly augment by using sensing technologies that can detect not only the water depth but also the water velocity in combination with a physically-based hydrologic modeling system that can provide forecasts of water depth and velocity at locations of interest. The results of the model and information of the sensors can be used to provide timely and adequate warning to approaching motorists that flooded roadway conditions exist further up the road.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

FHWA	Federal Highway Administration
GIS	Geographic information system
IoT	Internet of Things
NOAA	National Oceanic and Atmospheric Administration
TxDOT	Texas Department of Transportation
USDOT	United States Department of Transportation

EXECUTIVE SUMMARY

The dense road networks and numerous low water crossings throughout Texas may be contributing to the higher recurrence rates of floods that pose a danger to vehicles. Several ephemeral streams in Texas have steep slopes. The highly intermittent flow of these streams reduces the overall financial efficiency of such large, expensive structures at road-stream crossings. Therefore, many crossings are constructed as armored sag vertical curves, often with a small corrugated metal culvert pipe as a relief structure to prevent long-term ponding of water upstream of the roadway embankment. These low-water crossings pose immediate danger to vehicles that try to cross during flooding conditions. It is at these crossings where most motor vehicle-related flood fatalities happen.

This study reviewed motor vehicle-related flood fatalities in Texas between 1959 and 2016. Review of the data indicates that about 77% of the fatalities with known circumstances are motor vehicle-related. Review of ages of the victims of motor vehicle-related flood fatalities indicates that all age groups are at risk of dying from floods, including significant numbers of victims of ages below 20 years or above 60 years. More males die in a motor vehicle crashes during a flood than females. The main recommendation of our study is that efforts to reduce flood fatalities in Texas should employ a combination of improved road flooding forecasting and detection, educational programs aimed at enhancing the public awareness of flood risk and the seriousness of flood warnings, and timely and appropriate action by local emergency and safety authorities.

Analysis of vehicle-related flood fatalities caused by Hurricane Harvey and believed to have occurred at low-water crossings reveals that most fatalities were due to drowning, particularly in and around vehicles. Male victims and those over 50 years old were overrepresented in the dataset compared to their proportions in the general population. More than half of the fatalities occurred in Harris County, where heavy rainfall and dam releases caused unprecedented urban and road flooding. The impacts of Harvey can also be utilized to evaluate and improve the performance of the low-water crossing warning systems and emergency management for Region 6.

Road flood detection and warning can be significantly augment by using sensing technologies that can detect not only the water depth but also the water velocity in combination with a physically-based hydrologic modeling system that can provide forecasts of water depth and velocity at locations of interest. The results of the model and information from on ground sensors can be used to provide timely and adequate warning to approaching motorists that a flooded roadway conditions exist further up the road.

It is recommended that strategic low-water crossings have flood warning and detection systems that can benefit from recent advance in the sensing and flood prediction technologies. The warning systems are especially needed where traffic volumes are sufficiently high so as to create a significant risk exposure to drivers. Every low-water crossing should be equipped with a depth and flow detection system along with an advance warning sign. The water depth and velocity allow safety officials to determine the hazard magnitude at crossing and display the appropriate warning of the advance warning sign to alert drivers. Moreover, there is a need to identify locations where there is a history of vehicles becoming trapped or washed away due to rapidly rising water and emphasize safe driving behaviors during hazardous weather conditions in teenager driver education courses and defensive driving courses. Social media friendly information highlighting the statistics of injuries and fatalities during hazardous weather conditions will also be helpful.

1. INTRODUCTION

The motivation of this work was initiated by the alarming number of vehicle related flood fatalities in Texas, mostly at low-water crossing. Flood fatalities in Texas are generally correlated with extreme events, topography, and population density and most of these fatalities are vehicle-related. For example, about half of the fatalities caused by Hurricane Harvey, were transportation-related. The presence numerous low water crossings throughout Texas contribute to the higher recurrence rates of floods that pose a danger to vehicles. The state of Texas, local governments, and community groups are adopting several initiatives to address this problem. The research team has been challenged to identify effective measures to improve safety at low-water crossings. Therefore, the research team developed an approach that combine data analysis, modeling, and high-water detection and communication to improve safety at low-water crossings.

In Texas, the influence of physiography, precipitation, and temperature results in unpredictable climatic weather cycles that vary widely across the state *(1)*. The combination of these factors may result in extreme hydrologic conditions such as floods and droughts *(2)*. In recent years, the frequency and duration of heavy storms have detrimentally increased in Region 6. Similarly, flash flooding has increasingly become a common occurrence. For instance, from April 17th to April 18th, 2016, an exceptional rainfall of 17 inches has caused widespread flooding in the city of Houston and surrounding areas killing 9 people, all of whom died while driving into flooded roadways. According to the National Oceanic and Atmospheric Administration (www.ncdc.noaa.gov/billions/events) this flooding represents the most severe flooding event in Houston since Tropical Storm Allison in 2001, and its estimated damage was $1.2 Billion. Just one year after, these records were completely shattered by Hurricane Harvey with over 40-inches of torrential rainfall causing extreme flood damage in excess of $150 billion to south-central and the loss of tens of lives *(3)*.

When the flooding occurs, roads are impassable. Thus, the impacts of road flooding are broader and go beyond simple economic aspects as it effects on population mobility and travelers' safety. Furthermore, flooding represents a serious threat for the durability of road infrastructures. Hence, road flooding is an undesirable naturally occurring phenomenon that often results in damaging and costly impacts on both the transportation infrastructure and motorist/public safety. The resulting emergency road works after the floods recede can be a costly drain on the State dollars and are undesired. Commonly reported floodwater related damage includes some road sections being completely washed away, bridge/drainage damage, and increased manifestation of pavement distresses such as pot holing, aggregate loss, cracking, etc. Motorist safety related issues include damage or knocking down of road safety fixtures and water ponding on the pavement surface that renders driving a safety hazard.

Several streams in Texas, especially along the Balcones Escarpment, have steep slopes. Extended periods of drought reduce the overall financial efficiency of such large, expensive structures at road-stream crossings. As a result, many crossings are simply armored sag vertical curves, often with a small corrugated metal culvert pipe as a relief structure to prevent long-term ponding of water upstream of the roadway embankment. The primary conveyance becomes over-the-road flow. Differing road networks and numerous low water crossings throughout Texas contribute to the higher recurrence rates of floods that pose a danger to vehicles (Figure 1). According to the Federal Emergency Administration *(4)*, six inches (0.15 m) of water will reach the bottom of most passenger cars causing loss of control and possible stalling, and two feet (0.61 m) of rushing water

can carry away most vehicles including sport utility vehicles and pickups. Many municipalities in Region 6 installed sophisticated road flood warning systems at problematic Low Water Crossing sites to prompt motorists to avoid flooding, saving lives and property. These systems are expensive and require continuous maintenance.

Figure 1. Low-water crossings across Texas.
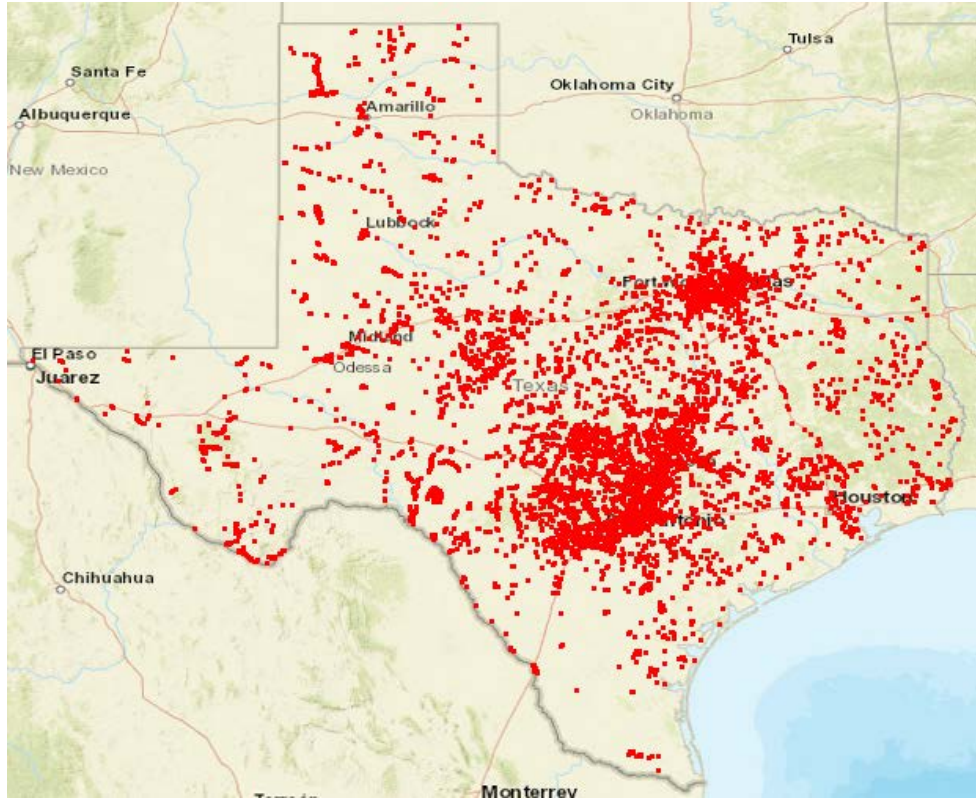
2. OBJECTIVES

The main goal of this project examine the impacts of flooding on transportation safety and to describe how flood safety data analysis, modeling, and high-water detection and communication can be utilized to improve safety at low-water crossings, enhance prediction and detection of roadway flooding, and help efforts to prevent driving into flood roadways.

3. LITERATURE REVIEW

3.1. Flood Impacts on Transportation Safety

Road safety is significantly affected by weather conditions. In fact, weather conditions are reported to be responsible for up to 25% of crashes on the United States (U. S.) highways *(5)*. The effects of weather on road safety include reduced visibility, reduced pavement friction, malfunctioning of traffic control devices, and flood water on the road *(6)*. Rainfall and subsequent flood are reported to have more impact on road safety the than other weather-related factors. For instance, Goodwin *(7)* found out that rainfall accounted for 80% of the injuries and 69% of the fatalities on U.S. highways that were caused by poor weather conditions. Other studies reported that rainfall increases the number of road crashes by 100% or more *(8-10)*. An interesting finding of empirical studies is that rainfall leads to a stronger increase in the number of fatal crashes when it comes after a dry spell *(11)*. Eisenberg and Warner *(12)* also found that although precipitation, including rainfall and snow, significantly increases the number of crashes, it appears to reduce the severity of crashes.

Flooding is the most damaging consequence of rainfall. Floods, in general, are naturally occurring events dependent not only on rainfall rates and durations, but also on other factors such as the topography, land use, soil types of the catchment area, and antecedent moisture conditions *(13)*. A flash flood is a short-term flood event that occurs in less than 6 hours after heavy rainfall has ended and requires immediate action to protect life and property. In contrast to a flash flood, a typical river flood usually occurs beyond 6 hours after heavy rainfall has ended. Flood-related fatalities in the U.S. have been the topic of several studies. The Federal Emergency Management Agency (FEMA) considers flooding "America's Number One Natural Hazard" *(14)*. Moreover, floods are the most common and widespread of all weather-related natural disasters. Between 1983 and 2003, flooding caused an average of 98 deaths and $4.5 billion in property damage per year in the U.S. *(15-16)*. Despite flood management efforts in many communities, U.S. flood damages remain high, largely due to increasing population and property development in flood-prone areas *(17-19)*. Although the dominant characteristic of hurricanes is their strong winds, most fatalities and damage are caused by flooding due to high runoff produced by torrential rains and storm surge propelled by these winds. Research for the US East Coast and Gulf area shows that the effects on transport and transport infrastructure is substantial *(11)*.

The most serious and irreversible consequence of flooding is the number of flood-related fatalities. French et al. *(20)*, in one of the first published studies examining flood fatalities in detail, found that most of the flash floods during 1969–81 occurred during the warm season spanning July–September, with September representing the peak fatality month. They also found over 90% of flash flood fatalities were due to drowning, and of those 42% were vehicle-related. Most flood-related deaths are due to drowning, which can be caused by several actions such as driving into the flood or trying to save a person from a flood. In the U.S., over half of these casualties involve people driving into flooded roads, and then either drowning in their vehicles or escaping only to perish in the open water *(21)*. Ashley and Ashley *(22)* reported 4,586 flood fatalities in the U.S. between 1959 and 2005. They found that the number of fatalities varied from year to year, with anomalously high years coinciding with either tropical system–produced floods or sudden flash floods, often associated with structural failures of dams or levees. Ruin et al. *(23)* used cognitive mapping to identify several factors influencing motorists' flash flood risk perception. Younger drivers underestimate flood risk, as do drivers of lower income and drivers with no children. They

found that urban people underestimate the risk for a car to be swept away by running water and are relatively more threatened by walking and driving in flood conditions than are people living in rural areas.

The impact of flooding depends on the interaction of any components of the environment with the flood. Direct flood impacts occur when the exposed components has physical contact with the floodwater. One of the most serious direct consequences of flooded roadways is the high proportion of flood victims that lose their lives attempting to drive through the flooded roads. In the U.S. more than half of the flood victims perish in their vehicles with a staggering 70% in Texas *(1)* and the ration may be higher in Region 6. One would expect that safety concerns should prompt drivers to avoid driving into flooded roads and turn around to seek safe routes to their destinations. However, that will also adversely affect the transportation network and lead to indirect impacts on certain dynamics in the network without physical contact with floodwaters. Such impacts typically evolve into a larger area and last for a longer period of time than the flood itself *(24)*. Resulting traffic jams will lead to delays that will impact many road users.

Several descriptive studies have assessed the consequences of past flood events on a transportation network *(25)*. Department for Transport of the United Kingdom *(26)* reported that just one single day of flooding on the transportation network in the United Kingdom accounted for 2% of the annual delays in the whole country. McDermott et al. *(27)* estimated the cost of Storm Desmond (December 2015 – January 2016) due to traffic flow disruption in Ireland to be 3.8 million British Pounds. These studies demonstrate the catastrophic impacts of flooding on the transportation infrastructure and roadway users. Suarez et al. *(28)* estimated that climate change could potentially double both travel time and travel most through intensifying storms. Chang et al. *(29)* demonstrated that traffic delays to be a more significant consequence of road flooding than the longer routes that driver need to take to avoid flooded roadways. It is intuitive to expect that the urban environment has many rerouting options, so the travel distance should not be increased as much as the travel delays due to traffic jams. Other studies assessed the vulnerability and performance robustness of transportation systems during flooding events *(30-32)*.

Pregnolato et al. *(33)* suggested a flood depth – speed reduction function to quantify the impacts of flooded roadways on the system's performance. They also compared traffic flow data between dry conditions and flood conditions in several locations. Vehicles' stability in flooded waters is becoming an increasingly relevant topic in the context of growing urbanization and intensification of storms. Smith et al. *(34)* demonstrated through field experiments that a compact car should completely float in less than two feet of standing water while an SUV started to float in three feet of standing water. This and other studies suggested that half of these depths should seriously affect the stability of the vehicle if the water is moving *(34-36)*.

3.2. Low-Water Crossings

The amount of water required to wash away a vehicle depends on a number of variables, including the speed of the current, the design of the vehicle, whether the vehicle is sideways or end-to-end of current, and the type of surface over which the water is flowing. As a rule of thumb, each foot of water pushes against the broad side of a typical car with approximately 500 ft-lb of force and can displace about 1,500 lb. Therefore, it only takes about two feet of water to float most cars and, in some cases, less. For example, where the current is swift, the bottom being hard and smooth, and the car's body being low to the ground, as little as one foot of water with a speed of 6 mph

will move most cars. The road network is often connected to the natural drainage network in a hydrological/hydraulic sense, and the greater the road/stream density, the greater the connection *(37)*. In Texas, low-water crossings are present in any location where unimproved roads and trails intersect ephemeral streams (streams with temporary flow during or after a precipitation events) and stream channel is small enough to permit the use of a simple fording structure.

The Main designs of low-water crossing include unvented (ford) and vented (using a pipe or culvert) crossings and low water bridges (bridges capable of handling overtopping water flow). Unvented crossings are usually selected on ephemeral streams or streams with shallow flows that are safe to drive through. The crossings can be either at or above-grade of the stream bed. At grade is typically chosen if any concern about wildlife or erosion exists. Figure 2 shows an unvented cable-concrete crossing that is at grade. Vented crossings keep the vehicles out of the water most of the year as long as the flows are low. The number and size of culverts depends on the geometry of the stream and the flow characteristics. The crossings are designed to be low and overtop during extreme storms (Figure 3). It is less likely that a vented crossing will be used on military training lands due to its life-cycle cost. However, the road network that accesses these areas may have vented fords at locations crossing large or frequent streamflow where traffic volume, vehicle type, and personnel safety require them. Low-water bridges are the third type of low-water crossing. Low-water bridges are very similar to other bridges except they are built lower (Figure 4). Similar to the vented crossings, the water level can rise above the driving surface. These structures typically have a bridge deck and footings if the stream is wide enough.

Figure 2. Unvented low-water crossing *(38).*

Figure 3. Vented low-water crossing *(39).*

Figure 4. Low-water bridge *(39).*

3.3. Effective Safety Strategies

The consequences of rainfall and flooding on transport safety are well studied. However, motor vehicle-related flood fatalities have received little attention in the transportation literature. There is evidence that rainfall intensity and flooding frequency are increasing in many regions around the globe. In addition, studies predict that the intensity and frequency of storms and hurricanes in Texas will rise due to climate change and variability *(40)*. Although rainfall and flooding are believed to reduce the severity of traffic crashes *(11)*, they cause significant motor vehicle fatalities in Texas. Attention to this problem may help reduce these fatalities. In addition, physical and hydraulic field investigation is needed to better understand the factors that lead to the high frequency of these events in Texas and the impact on climate change on these factors. That the Flash Flood Alley region of Texas is experiencing unprecedented urbanization and population growth, leading to an increase in the impervious areas and reduction in infiltration, suggests that the flood fatality rate will become even higher if the issue is not given due attention.

3.3.1. Warning and Education

Texas Department of Transportation realizes the seriousness of driving into floodwater. Therefore, different types of warning signs that can be used at low-water crossings and flood-prone areas are included in Texas Manual on Uniform Traffic Control Devices (TxMUTCD) (Figure 5). For example, WATER CROSSING (W8-13T) is intended to be used at crossings where water is continuously present. The WATCH FOR WATER ON ROAD sign (WB8-15) is a permanent sign that can be placed at locations that occasionally flood. The WATER OVER ROAD sign (W8-14) is intended to be used at locations that occasionally experience flooding - these are locations where drivers may not be aware of the presence of fast-moving water. TxMUTCD recommends posting this sign only when the roadway is flooded, indicating that the sign is temporary in nature and would only be used during flooding events. This would require manual placing of the sign near the flooded crossing, although in some cases, fold-out signs had been used at known flood-prone locations. Unfortunately, the wording is so similar among all these signs, drivers may not be able to discriminate the different circumstances and situations for which these signs are intended.

WATER CROSSING — W8-13T	The WATER CROSSING (W 8-13T) sign should be used to warn of a dip or ford where the roadway is normally underwater. It should not be used where water only occasionally and temporarily crosses the roadway due to heavy local rains or flash floods.
WATER OVER ROAD — W8-14	The WATER OVER ROAD (W8-14) sign should be displayed to warn of a temporary condition when a low area may flood or fill with water. The sign is normally posted only when water is actually over the roadway.
WATCH FOR WATER ON ROAD — W8-15	The WATCH FOR WATER ON ROAD (W8-15) sign should be displayed at all times to warn of locations where wet-weather conditions normally result in a temporary condition of ponding or flowing water on the roadway.

Figure 5. Examples of the low-water crossing warning signs in TxMUTCD.

Several studies *(1)* report that human behavior may be associated with majority of the flood fatalities in Texas. These statistics highlight the need for increasing public awareness of the dangers of driving and walking into flood waters although it is difficult to understand about why people tend to walk into or drive through flooded roads or walk into flood waters *(41)*. Nonetheless, we believe that a combination of improved hydrometeorological forecasting, educational programs aimed at enhancing public awareness of flood risk and the seriousness of flood warnings, and timely and appropriate action by local emergency and safety authorities may help reduce flood fatalities in Texas. Proactive efforts from regional groups such as the Texas Flash Flood Coalition (TFFC), which consists of stakeholders from academia, local, state and federal government and private business, are expected to help reduce the impact of flooding in Texas. The TFFC serves as a comprehensive flood resource council for the prevention of flooding injuries and deaths; to prepare Texans for adverse flash flood events; and to make recommendations to stakeholders to promote relevant research, education and communications that will save the lives and property of Texans. Another effort is "Turn Around Don't Drown ®", which is a National Weather Service campaign to warn people of the hazards of walking or driving a vehicle through flood waters. Several studies suggested that education, awareness and warning are key to preventing flood mortality (e.g., *42, 43*). It was recommended that people should avoid entering floodwaters, either by vehicle or on foot, and other risk-taking activities, generally associated with males, should be curtailed *(43)*. This should include all phases of the flood: before the water rises, during the event, and especially after the storm system has passed but water levels remain high and dangerous. However, more evidence is needed to identify the underlying causes of death and the vulnerabilities. Nonetheless, lack of adequate data is not an appropriate excuse for lack of action *(42)*. The fact that flood water could continue to rise well after the storm has passed should be emphasized. Finally, in addition to flood characteristics, flood safety programs should take into account socioeconomic factors *(42-43)* and language barriers.

3.3.2. Flooding Prediction

The foundation of the scientific approach to flood warning and prediction systems was established during the 1970s and early 1980s. Most U.S. operational flash flood warning methodologies do not involve a forecast, but rely on monitoring rainfall accumulation using radar and rain gauges. A flood runoff prediction model requires reliable precipitation estimates and forecasts. However, the time scales for some floods are too short for a meaningful application of synoptic and mesoscale models. Additionally, the spatial scale of heavy rainfall that results in flash floods typically occurs on the order of tens of kilometers *(44)*. Factors that influence or control the evolution and motion of these storms are often of similar space and time scales.

Hydrologists have recognized the inability of point precipitation estimates to capture the high variability of rainfall in both space and time *(45)*. Numerous studies have evaluated the effects of such variabilities and sampling errors on hydrograph simulations. Catchment sensitivity to temporal and spatial rainfall variability was examined by Bras and Rodriguez-Iturbe *(46)*, Wood et al. *(47)*, and Julien and Moglen *(48)*, among others. The sensitivity of distributed hydrologic models to spatial and temporal rainfall variability and sampling resolution was examined by Wilson et al. *(49)*, Kouwen and Garland *(50)*, Ogden and Julien *(51)*, and Ogden et al. *(52)*. Sharif et al. *(53)* discussed the propagation of radar rainfall uncertainty in runoff predictions. Only distributed models take advantage of high resolution precipitation data and model river flows at basin interior points.

Advance in hydrologic modeling enables flood prediction systems to seamlessly ingest high-resolution radar and multi-sensor products available in real-time from National Weather Service (NWS) servers, process and quality-control the data, and merge it with ground observations in real time. Such systems can provide current and predicted flood depths and velocities along all channels in the area and over the land surface at very high spatial resolution (as fine as 10-m grids overland, and continuously along channels) and temporal resolution (15 min. intervals, or shorter). This means that water depths and velocities will be calculated everywhere including streams, low-water crossings, flooded roadways, and commercial and residential areas at 15-min intervals (or shorter). Moreover, these systems can easily assimilate water levels available at high water monitoring stations. The systems' output can be provided in a format accessible to non-technical users at county and city emergency management offices, and transportation officials. Customized output can be accessed by workstations, laptops, tablets, and smart phones, and other devices, via the cloud. Support software can be installed and operated at multiple sites and can be accessed by multiple users and devices via the cloud. Maintenance of the proposed predictive flood modeling system will be free and is continuously supported by the Army Corps of Engineers researchers and the hydrologic community. The predictive flood modeling systems are extremely fast as they can be run in distributed mode, with varying resolution, and over multiple processors via the cloud. The customized outputs can be available at multiple resolutions providing accurate estimates of flow depths and velocities over the model domain, showing current condition, predicted conditions, and predictions of how and when the flood water will recede, which is vital information for flood emergency crews.

4. METHODOLOGY

The stated problem was addressed by conducting a comprehensive analysis of flood fatalities in Texas over a 50-year period highlighting fatalities involving driving into flooded roads. As a case study, a detailed analyses of fatalities caused by Hurricane Harvey is provided. A high-resolution flood prediction model was developed for a catchment in San Antonio, Texas to demonstrate the utility of its predicted outputs as input to a road flooding warning system. Finally, we describe road flooding detection device that can be part of the warning system.

4.1. Flood Fatality Data

Texas is the second largest state in the U.S., both in terms of population and area, with a population of 27,862,596 and a land area of 695,662 km2. The southeast of Texas shares 591 km (367 miles) of coastline with the Gulf of Mexico and is susceptible to hurricanes and coastal flooding. A major topographical feature that affects the number of flooding events in Texas is the Balcones Escarpment that consists of a series of cliffs dropping from the Edwards Plateau to the Balcones Fault Line. As noted in an article from the Texas Hill Country magazine published in 2016, "This outer rim of the Hill Country is the formation point for many large thunderstorms, which frequently stall along the uplift and then hover over this region" *(54)*. The "Flash Flood Alley" includes counties having the fastest population growth rates in Texas.

The Texas vehicle-related flood fatality information reviewed in this study was extracted from the National Oceanic and Atmospheric Administration (NOAA) "*Storm Data*" reports for the period January 1959 through December 2016 *(55)*. From 1959–1995, the data were only available via PDF files. Data from 1996–2016 were available via the NOAA searchable database. The data in the "*Storm Data*" publication relies on self-reporting from individual states and counties and is dependent upon the verification and validation of the reporting agency. The "*Storm Data*" had some inconsistencies from year to year and county to county in the classification of the causes of fatalities. The "*Storm Data*" reports include narratives that describe some the circumstances that lead to fatalities including time, location, age, and environmental conditions.

"*Storm Data*" lists each incident with the date, time, the number of people who died in the incident, the number of people injured, and a brief description of the event. The descriptive narratives provided along with each event were used to get information related to the gender, age, activity, mode of transport, and location of the individual who died. In 1996 and after, the database provided an accompanying chart of the victims. The chart listed the victim's age, gender, and location. If there was a disparity between the description and the accompanying table, the information in the description was used since the descriptions were often retrieved from the police report that was filed with the death.

4.2. Safety Enhancement

4.2.1. Analysis of Low-Water Crossings Safety Data

The data analysis includes temporal and spatial trending using linear trendlines and correlation analysis to verify statistical significance. Spatial analysis by county used the ArcGIS (v.10.4) (Esri, Redlands, CA, U.S.) to generate thematic maps. Fatality rates were normalized by annual population for temporal trends and by the study period median population for the spatial distribution by county. Percentages were generally rounded to the nearest whole number unless

otherwise necessary for comparative analysis. Only roadway fatalities that were reports as being directly caused by road flooding are included in the analysis.

4.2.2. Hurricane Harvey Case Study

Hurricane Harvey, which made landfall on August 25, 2017 near Rockport, Texas as a Category 4 hurricane with maximum sustained winds of approximately 200 km/hour, was one of the largest storms to hit the US in the past century. With its record-setting rainfall totals and flood-related damages, it resulted in the evacuation of more than 100,000 residential properties and caused numerous fatalities. A detailed analysis of the fatalities caused by the hurricane is presented as a case study.

4.2.3. Flooding Prediction

The need for flood prediction as part of a low-water crossing system is demonstrated through a case of study where a physically based, distributed flood model is used to predict discharge resulting from a 2007 storm over a watershed in San Antonio, Texas. The two-dimensional, fully-distributed, physically-based hydrologic simulation tool Gridded Surface Subsurface Hydrologic Analysis (GSSHA), developed by the U.S. Army Corps of Engineers, will be used to predict floodwater depth and velocity at low-water crossing. GSSHA offers a multidimensional modeling technology that fully couples overland, surface, and subsurface flow for highly accurate watershed simulations. It can incorporate fully dynamic pipe networks and the relevant hydraulic structures for urban drainage systems (e.g., detention basins, culvers, weirs, etc.). GSSHA can be used as an event-based or continuous model where overland flow, soil surface moisture, groundwater levels and stream interactions are continuously simulated. The fully coupled groundwater-surface-water interaction capability also allows GSSHA to accurately estimate aquifer recharge. Open-source software tools can be used to provide access to multiple data sources (e.g., real-time remotely sensed rainfall estimates or forecasts, ground flood sensors) and lower the barriers for users in management agencies at the local level. GSSHA can fully be integrated with other hydraulic models if needed. The Army Corps of Engineers personnel and other hydrologists have used GSSHA in hundreds of real-life applications, including preparation for major storms such as Katrina and Sandy.

4.2.3. Flooding Detection and Communication

Recent development in sensor technology demonstrated the feasibility of using this technology for improving roadway warning and assessment systems, which is particularly beneficial in high-risk areas that are impacted by hurricanes and tropical storms. There are several available sensing technologies that can report via wireless means to a base station for operation and control. Suitable sensor types are Pressure Transducer, Bubbler Sensor, Radar Sensor, or Laser Sensor. The sensor selected has a reliable industry proven design and commercial availability, with resolution of not less than 0.1 foot and uses a Pressure Transducer, Bubbler Sensor, and Ultrasound Sensor in order to support providing meaningful water level and trend data. The system reports water level in near real-time without significant delay. The water level sensor system can record the depth and duration of road flooding and communicate the information. The recorded data can be used, in conjunction with post-event road inspection, to assess the impact of the flooding on the road integrity.

5. ANALYSIS AND FINDINGS

5.1. Flood Fatalities at Low-Water Crossings

By far, Texas leads the nation in flood fatalities. From 1959 through 2008 there were three times more fatalities in Texas (839) than in the next leading state, Pennsylvania (265). The distribution of flood fatalities in Texas with known activity/location from NCDC "*Storm Data*" is shown in Table 1 - The activity/location is not provided in "*Storm Data*" for 223 fatalities. "In water" describes the case when a person intentionally walked into the floodwater. Review of the data indicates that 77% (471 out of 616) of the fatalities with known circumstances are motor vehicle-related. According to the Flood Safety Website (https://www.weather.gov/safety/flood), nationwide, most flood drownings are vehicle related, and in Texas, 76% of flood deaths are vehicle related.

Table 1. Texas flood fatalities classified by activity/location.

Activity/location	Fatalities	Percentage
Boat	21	3%
In Water	100	16%
Mobile Home	6	1%
Permanent Home	18	3%
Vehicle	471	77%

Review of NCDC "*Storm Data*" records reveals that Texas is the only state that reported flood-related fatalities every single year of the 1959-2008 record. The circumstances of death (i.e., whether the death was motor vehicle-related or not) are not described in "*Storm Data*" for 26% (223 out of 839) of the cases. Confirmed motor vehicle-related flood fatalities were reported for every year of the record as seen in Figure 6. The 50-year average number of confirmed fatalities is 9.42 per year. The graph of monthly distribution of motor vehicle-related flood fatalities (Figure 7) is bimodal with peaks in May and October. The graph of mean monthly distribution of rainfall in the major urban area with highest flood fatalities has similar features with peaks in May and October (Figure 8).
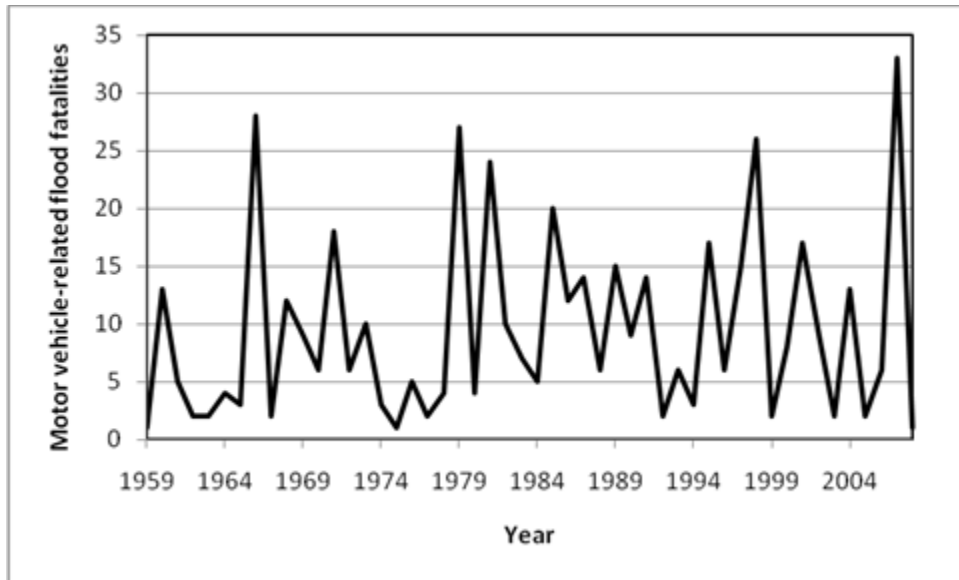
Figure 6. Motor vehicle-related flood fatalities in Texas (1959 – 2008).
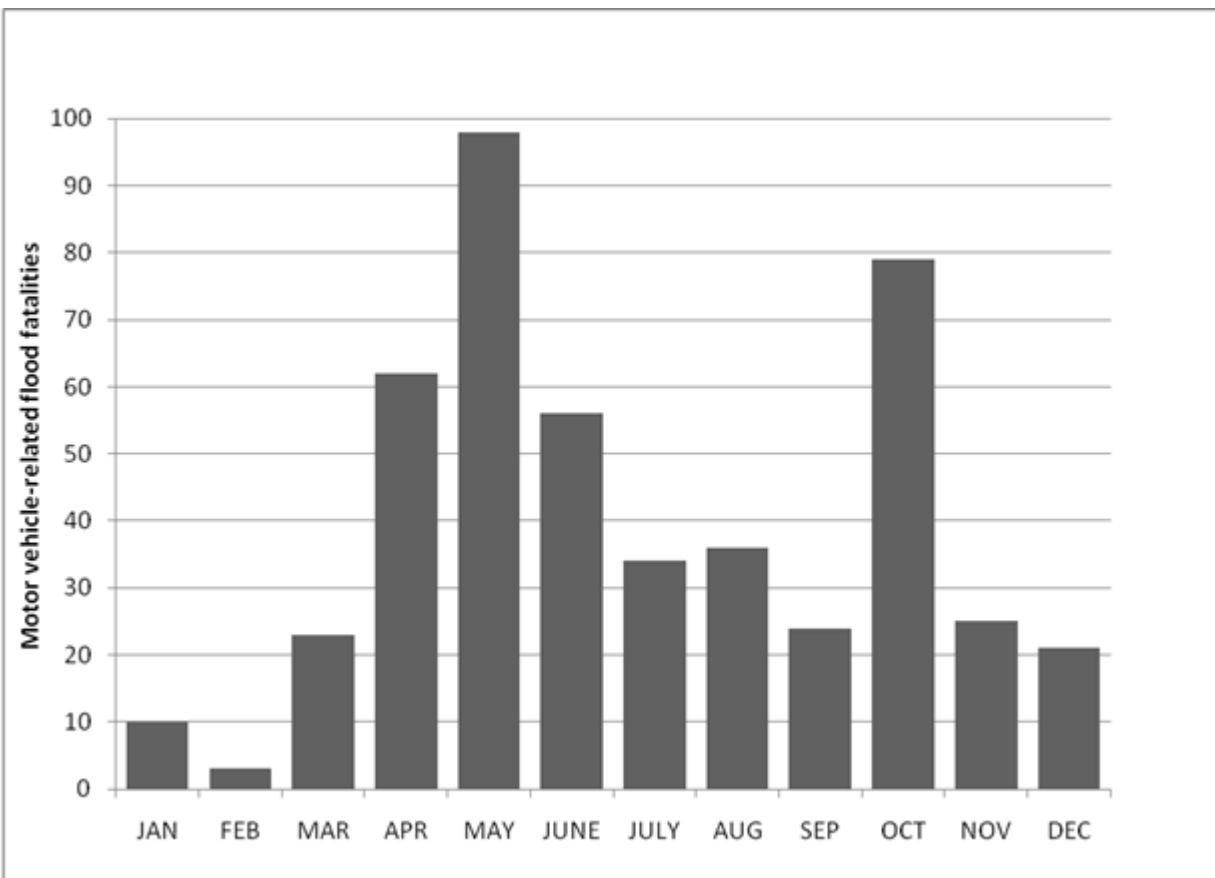

Figure 7. Monthly distribution of motor vehicle-related flood fatalities in Texas.
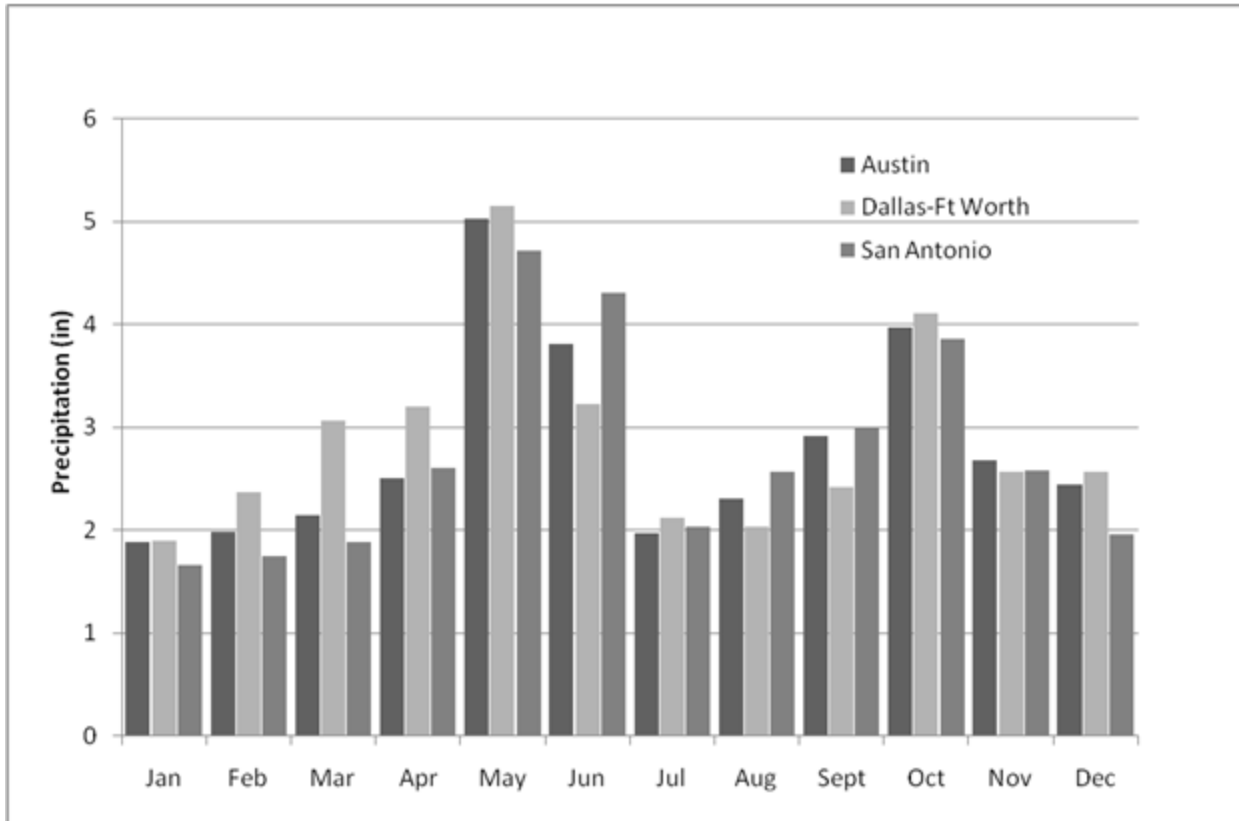
Figure 8. Monthly rainfall for three major urban areas in Texas Flash Flood Alley.

As seen in Table 2 "*Storm Data*" reports the time of deaths for 346 (out of 472) of the victims. It is not clear whether the time reported in "*Storm Data*" is the time of the incidents or the time of death. Review of these 346 reports indicates that 56% of the motor vehicle-related fatalities took place at night.

Table 2. Motor vehicle-related flood fatalities with known time of occurrence.

Time	Fatalities	Percentage
Morning	92	27%
Afternoon	59	17%
Night	195	56%

"*Storm Data*" provides gender of only 81% (383 out of 471) of motor vehicle-related flood victims and the ages of only 58% (272 out of 471) of the victims. For cases when the gender of the victim is known, the ratio of males to females is 1.76 to 1 (244 to 139). The age distribution for victims with known age is shown in Table 3. The age group with the most fatalities is young adults (52 known victims). Infants, children, teenagers, and the elderly (less than 20 years of age and more than 59 years) represent about half of the victims (132 out of 272). A significant number of the victims are infants or children (32).

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Table 3. Motor vehicle-related flood fatalities with known age.

Age Group	Fatalities	Percentage
0-9	31	11%
10--19	32	12%
20-29	52	19%
30-39	26	10%
40-49	27	10%
50-59	35	13%
60-69	33	12%
70-79	24	9%
80-89	12	4%

Motor vehicle-related flood fatalities in Texas far exceed total flood fatalities in any other state between 1959 and 2008. Review of the data indicates that 77% (471 out of 616) of the fatalities with known circumstances are motor vehicle-related. The number of those fatalities in Texas is expected to be higher than 471, as we expect that a significant number among the 223 fatalities whose circumstances are not provided to be also motor vehicle-related. Some earlier studies reported that 75% of flash-flood deaths occurred during the hours of twilight and darkness *(56)*.

Younger drivers underestimate flood risk, as do drivers of lower income and drivers with no children. It was found that urban people underestimate the risk for a car to be swept away by running water and are relatively more threatened by walking and driving in flood conditions than people living in rural areas. Review of ages of motor vehicle-related flood victims indicates that all age groups are at risk of dying from floods, including significant numbers of victims of ages below 20 years or above 60 years. More males die in a motor vehicle crashes during a flood than females. This agrees with studies that addressed vehicle-related fatalities in general. McKenna et al. *(57)*, for example, suggested that the presence of a female passenger reduces the likelihood of a crash, and Chen et al. *(58)* reported that the presence of a male passenger almost doubles the per capita death rate, regardless of the driver.

There is a strong similarity between the monthly distribution of motor vehicle-related flood fatalities and the monthly distribution of rainfall in the flash flood region. This indicates that the frequency of storms plays an important role in increasing the flood hazard. Although Texas accounts for more than 17% of the total U. S. flood fatalities (841 out of 4841), it is interesting to note that none of the top major US deadliest flood events occurred in Texas. For some states flood mortality was dominated by catastrophic flood events. For example, out of the 244 deaths in South Dakota for the 1959-2008 period, 237 resulted from a single event.

Several factors influence the way an individual responds to a hazardous situation such as driving while the road is flooded. According to Kates *(59)*, factors that may affect risk perception include the nature and features of the natural hazard (its magnitude, duration, frequency, and temporal spacing), and the recency, frequency, and intensity of personal experience with past events of similar nature. More than 60% (288 out of 471) of floods that result in motor vehicle-related fatalities in Texas are flash floods, which typically arrive immediately after the storm with little or no warning. Tropical systems, although they are associated with very intense rainfall and ensuing floods, result in a very small number of fatalities (less than 3% of the fatalities). The reason may

be that these systems are typically forecasted with very long lead times (many hours or days), and that warnings of these systems are widely broadcasted. Also, these events are less frequent. A third reason can be the heightened alertness and involvement of emergency personnel during these events. Most motor vehicle-related flood deaths in Texas appear to have occurred at night (Table 3). This trend may be attributed to people not being able to see or estimate the depth and speed of the flood water in inadequate lighting.

Motor vehicle-related flood fatalities are related to topography and climate. This is evidenced by the fact that fatalities are clustered in counties located along the Balcones Escarpment and those that include major urban centers. The fatality numbers in Harris County are much smaller than those for counties along the Balcones Escarpment although it is one of the counties with highest numbers of flood fatalities in general. Highly populated counties outside the escarpment, such as Hidalgo, did not witness significant number of fatalities. Another factor is the climate: very few fatalities occurred in counties with dry climate even when the population density is high. El Paso County is one such example.

5.2. Analysis of Harvey Data

Hurricane Harvey, a category 4 major hurricane event, that hit Texas coast late August 2017, is considered the most damaging storm in U.S. history according to a 2018 report from the National Oceanic and Atmospheric Administration *(60)*. According meteorologist Jeff Lindner's final report on Harvey for Harris County Flood Control District (HCFCD), Harvey caused about $125 billion in damages in Harris County alone, with over 150,000 homes being flooded as well as thousands of businesses *(61)*. Harvey's damage exceeded that of Hurricane Katrina. Harvey revealed the full extent of the damage that can be caused by extreme precipitation on the transportation infrastructure.

Disruptions of the transportation network resulted in wide ranging impact. Roadway flooding halted traffic and inflicted severe damage on roads, suspended rail service, forced closures of regional shipping terminals and ports in Houston, Galveston, Texas City and Freeport and interrupted supply chains. Major oil companies Valero Energy, ExxonMobil, Motiva, and Royal Dutch Shell shut down their operations in southern Texas, and almost one-third of U.S. refineries have been affected by Harvey.

The impact on air transport ranged from destroyed weather reporting services (Corpus Christi airport), flight cancellations to unusable runways (102 flights cancelled at Houston William P. Hobby airport, runways closed). Airline had to provide clean drinking water, cots and food to stranded passengers, allow people to pick up their cars from parking lots that had been flooded, or offer waivers to passengers whose flights were cancelled. Indirect effects were also identified: supply roads were flooded and impassable, so employees could not reach the airport for work**.**

High water detection systems are designed to warn driver they are approaching a flooded road when the water depth and speed are high enough to potentially wash the vehicle away. We could not find any reliable information on the performance of high water detection systems during Harvey event. There were various understandable reasons for that including legal issues and the fact that the storm was so devastating that hardly anybody could pay attention to the performance of the warning systems since vast areas were completely flooded. Information about vehicle-related fatalities during Harvey appeared mostly on local news websites. Confirmed cases were published later by the National Weather Service. Although the larger part of the casualties fell

during or directly after Harvey made landfall, even four weeks later, newly discovered casualties were mentioned in the media. Data sources included various media reports and data from six of the counties affected by Harvey. Official reporting on fatalities and the level of detail varied greatly between counties. Only Harris County, where most of the fatalities occurred, has published an official and public list of casualties.

Harvey resulted in, at least, 78 fatalities, of which 29 may be attributed to flooded roads. The fatalities were scattered over 14 counties but about half of the fatalities occurred in Harris County (38 out of 78). Locations of fatalities believed to have occurred at flooded roads as extracted from a published fatality database *(62)* are shown in Figure 9. The fatalities include vehicle fatalities (23) and pedestrians who walked into flooded roads (6). Vehicle fatalities include those who were killed inside vehicles swept away by floodwater (17) and those swept away by the current while getting out of a vehicle (6). A heartbreaking example is a case were six family members, including four children, drowned when their van was swept away by fast moving water in east Houston. Many of the victims were not found until the floodwaters had receded. A significant part of the victims drowned as a result of driving a vehicle into floodwaters or getting (confirmed for 18 of 54 drowning victims). Figure 9 and 10 show the locations of fatalities believed to have occurred at low-water crossing in Texas and Harris County as a result of Hurricane Harvey. Figure 11 shows the classification of victims by gender and age group. We believe that fatalities occurred at locations where there were no high-water detection systems or at location where the road flooding detection and warning systems were malfunctioning.
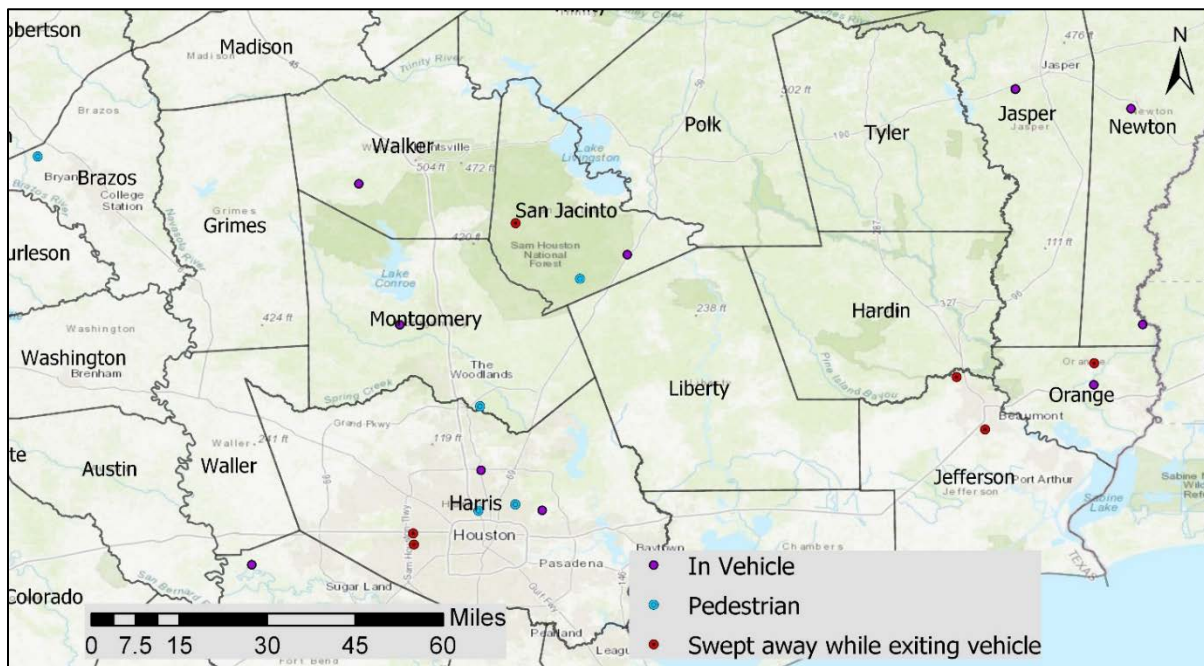

Figure 9. Harvey fatalities believed to have occurred at low-water crossings.
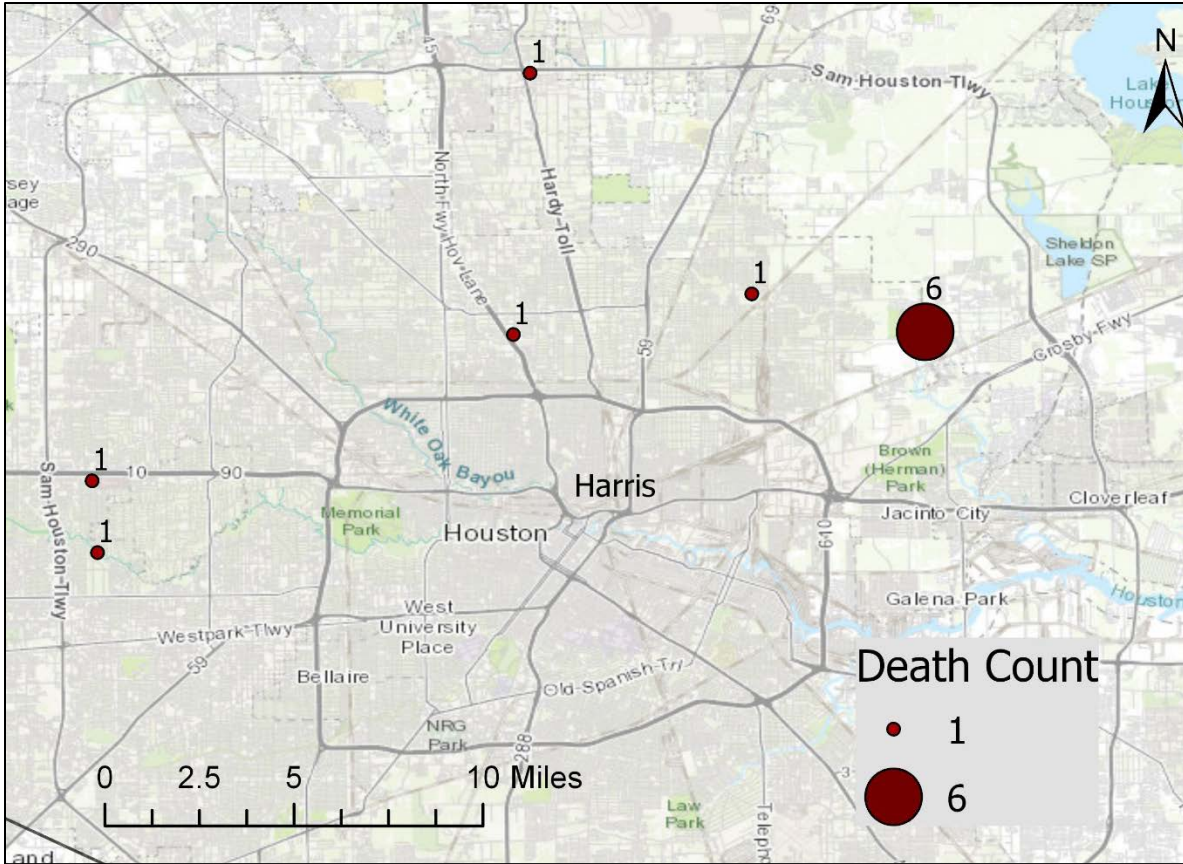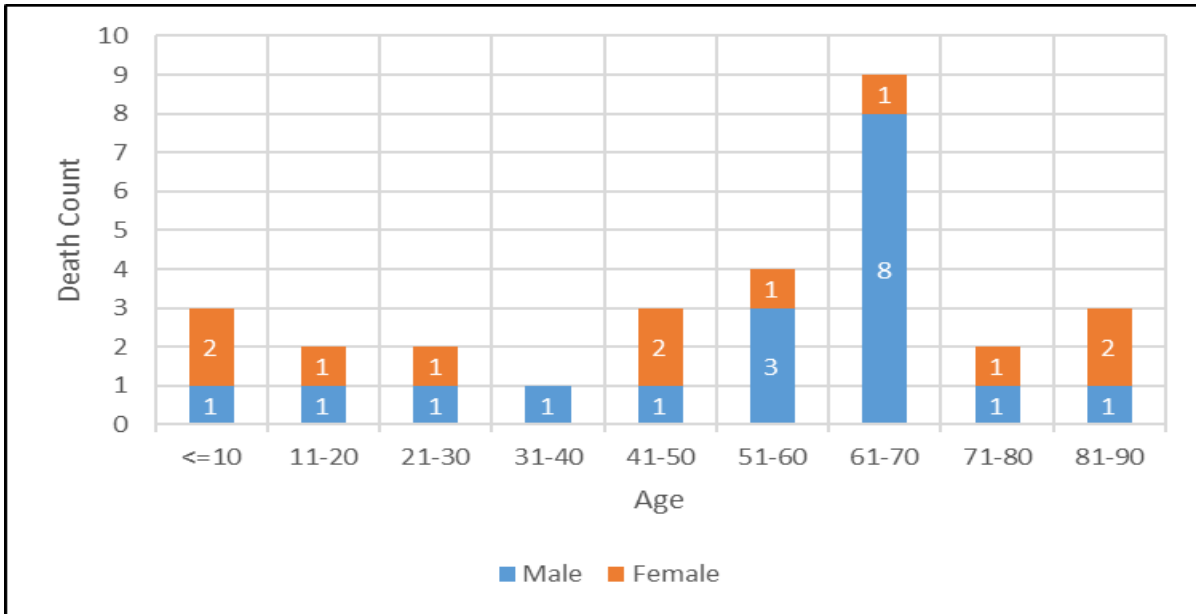
Figure 10. Fatalities in Harris County.

Figure 11. Fatalities by age and gender.

5.3. Flood Prediction and Warning

5.3.1. Prediction

For emergency personnel to take necessary measures to prevent driving into flooded roads, time is the most needed resource. It is impossible to detect flooding at every location and issue warning or block flooded roads in time. If road flooding can be predicted with any lead time, this will allow emergency personnel to prepare and deploy resources and issue warnings. Fortunately, the availability of high-resolution remotely sensed precipitation data in real time and quantitative precipitation estimates and the recent advances in physically based distributed hydrologic modeling, make possible to predict flooding at high resolution with reasonable lead time. The resolution of the flood prediction can be high enough to enable prediction of water depth and velocity at any location of the road network. The predicted flood maps can be sent to any device over the Internet. In this section, we describe the results of high-resolution hydrologic model simulations that provide information on flow depth and velocity at every point over urban areas in San Antonio. The inputs to such a model are rainfall observation as estimated by a radar and the outputs are the predicted flood water level and velocity at any point in the catchment including roads.

The results shown below are for the partially-urbanized Culebra Creek watershed in northwest San Antonio, Texas (Figure 12). The watershed is part of Leon Creek watershed. The land use of the watershed is mixed, with approximately 90 percent preserved as open space. About 65 percent of the watershed is forested. Several roads pass through the watershed, especially the urbanized portion of the watershed. The topography is varied and includes gradually sloped plateaus and steep-sloped canyons. Multiple storm water detention structures exist on the watershed. Two flood events were simulated: A late August 2007 major flood event with a peak discharge of 9,125 cubic feet/second (cfs) and another event in October 2015 with a peak discharge of 6,215 cfs.
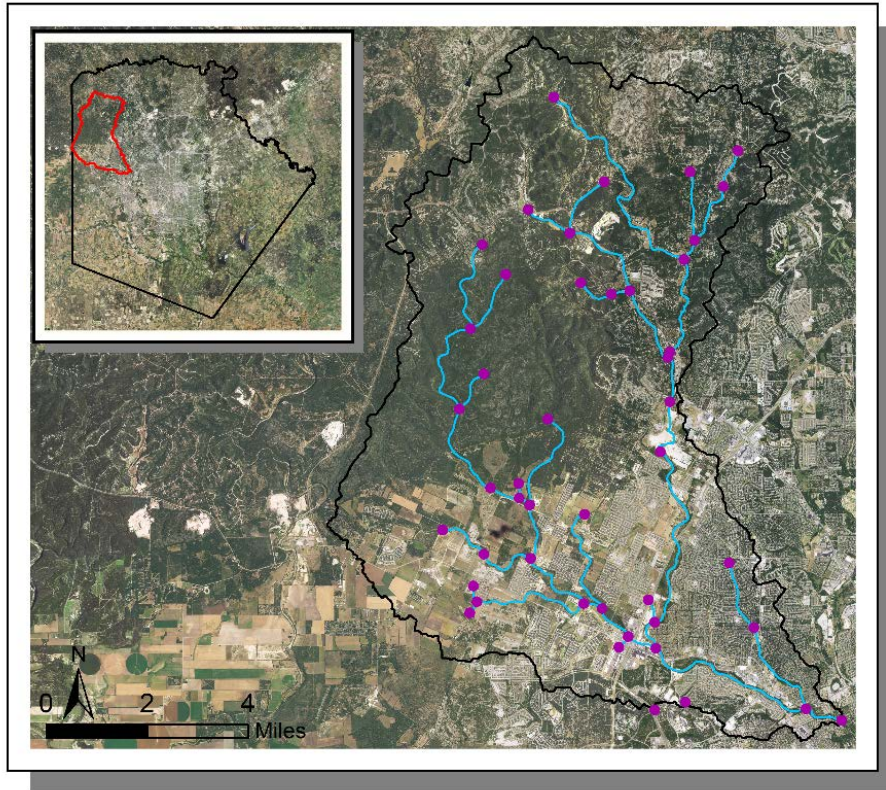
Figure 12. Location of the study area (Culebra Creek) in Bexar County.

5.3.2. Radar Rainfall Data

Next Generation Radar (NEXRAD) preprocessed precipitation products were used in this study. Multi-sensor precipitation data for the two storm events were obtained from the National Weather Service West Gulf River Forecast Center online archive (http://dipper.nws.noaa.gov/hdsb/data/nexrad/wgrfc_mpe.php). MPE, developed by the National Weather Service (NWS) Office of Hydrology in March 2000, is a product that merges rainfall measurements from rain gauges and rainfall estimates from the NEXRAD network and the Geostationary Operational Environmental Satellite (GOES) products. The NWS West Gulf River Forecast Center (WGRFC) switched from Stage III to MPE as the preferred precipitation estimation program in October 2003 and ended Stage III in December 2004. Thus, since January 1, 2005, only MPE has been produced and distributed by the WGRFC. MPE rainfall products are available at 4 km and hourly resolution. The National Weather Service Austin/San Antonio region WSR-88D (Weather Surveillance Radar, 1988-Doppler) located in New Braunfels, Texas, approximately 70 km from the Culebra Creek Watershed, is the primary source of radar estimates used in the MPE product for the watershed area.
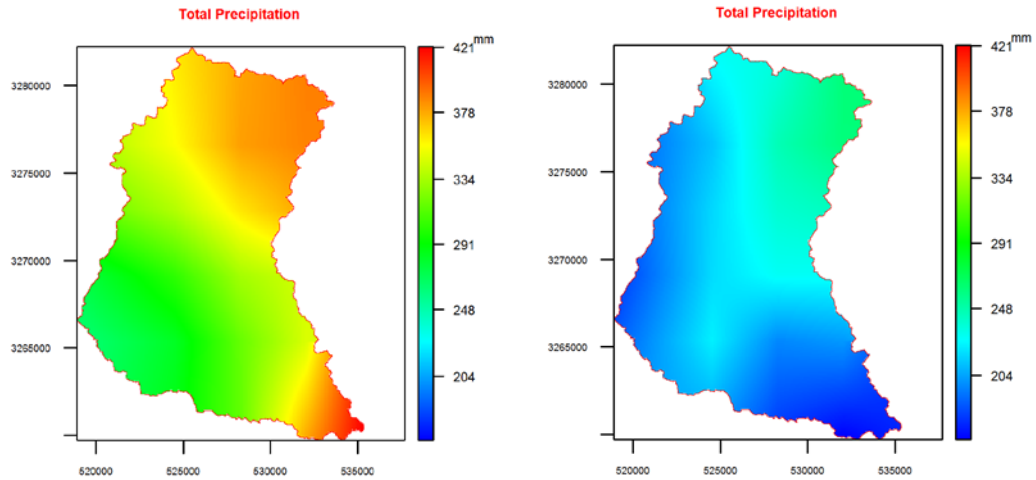
Figure 13. Radar rainfall accumulation for the two main floods of 2007(left) and 2015 (right).

5.3.3. Watershed Terrain Processing

U.S. Geological Survey (USGS) 10 m digital elevation models (DEM) were downloaded from http://seamless.usgs.gov for the Culebra Creek watershed. DEM data were processed using Watershed Modeling System (WMS) version 10.2. Using the WMS watershed processing tools, including the USDA topographic analysis program TOPAZ, the watershed basin and stream arcs were delineated from the DEM (Figure 14). This process resulted in a 212-km^2 drainage basin. Pits, or digital dams, in the DEM were filled using the Cleandam algorithm distributed with the GSSHA model. Cleandam uses a stochastic search process to determine the most likely flow path from a digital dam to a lower elevation *(63)*.
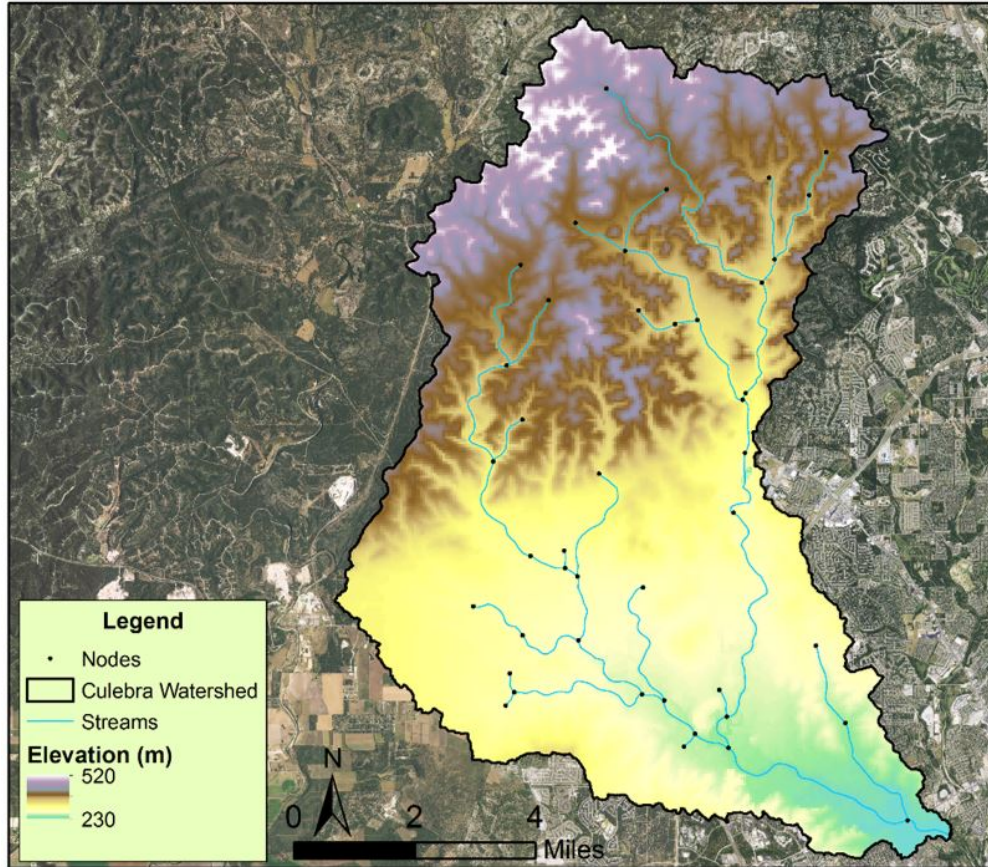
Figure 14. Culebra Creek topography.

5.3.4. Watershed Physical Characteristics

Land use/land cover and soil type GIS shapefiles, obtained from the National Land Cover Dataset (NLCD), and the Natural Resource Conservation Service (NRCS) Soil Survey Geographic Database (SSURGO), respectively, were processed using AWMS to create GSSHA input files modeling the physical characteristics of the watershed. NRCS soil types were assigned a USDA soil texture classification as well as a classification based on land uses where natural infiltration processes are altered by the presence of impervious areas due to urbanization. These soil types associated with urbanized portions of the watershed are referred to as "developed" soil texture classifications. The dominant natural soil texture classifications are bedrock and silty clay (Figure 15).
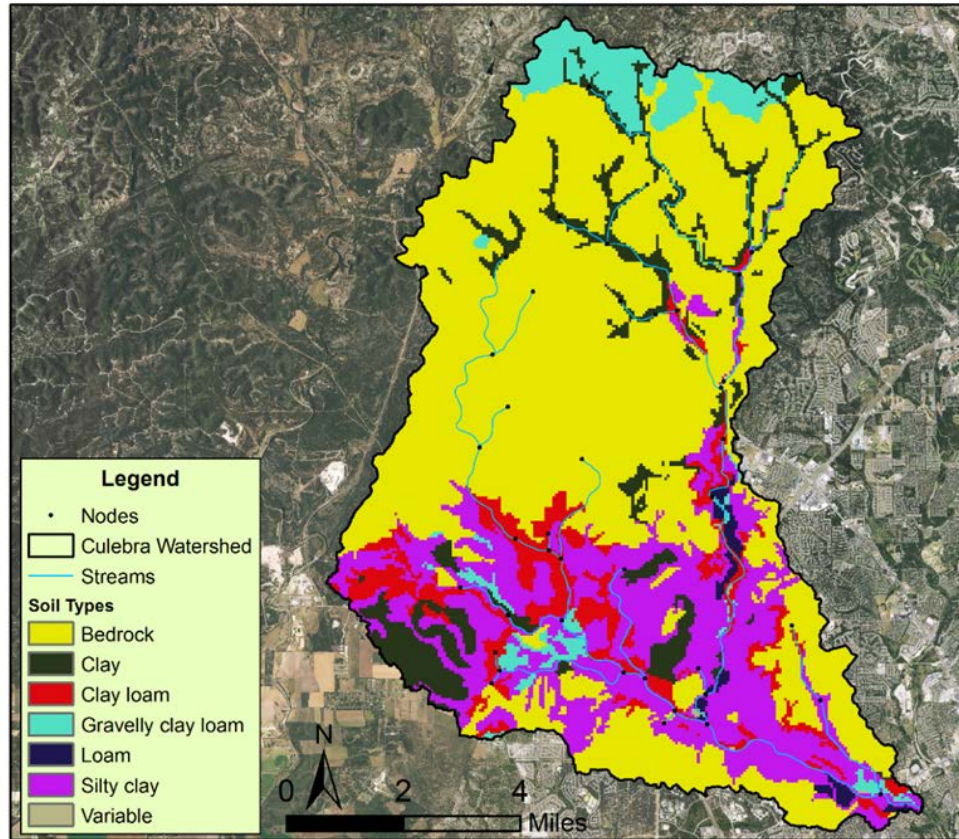
Figure 15. Culebra Creek soil types.

Green-Ampt infiltration parameters, including saturated hydraulic conductivity (K_s cm/hr), capillary suction head (ψf, cm) and effective porosity (θe), were assigned using the soil type index map. Applied values were based on published average estimates for the soil texture classifications by Rawls et al. *(64)*. In order to model the reduced infiltration caused by development, the applied value of hydraulic conductivity for developed soil texture classifications was reduced in an amount proportional to the computed fraction of impervious cover. Uniform values of initial soil moisture (θi) were assigned based on antecedent soil conditions at the time of the storm event. Simulations were started at least one week before the event to spin-up the model and thus eliminate initial soil moisture uncertainties. Overland flow Manning's roughness coefficient values for the developed portion of the watershed were assigned based on the land use and cover index map. The most dominant land cover types are forest and pasture (Figure 16).
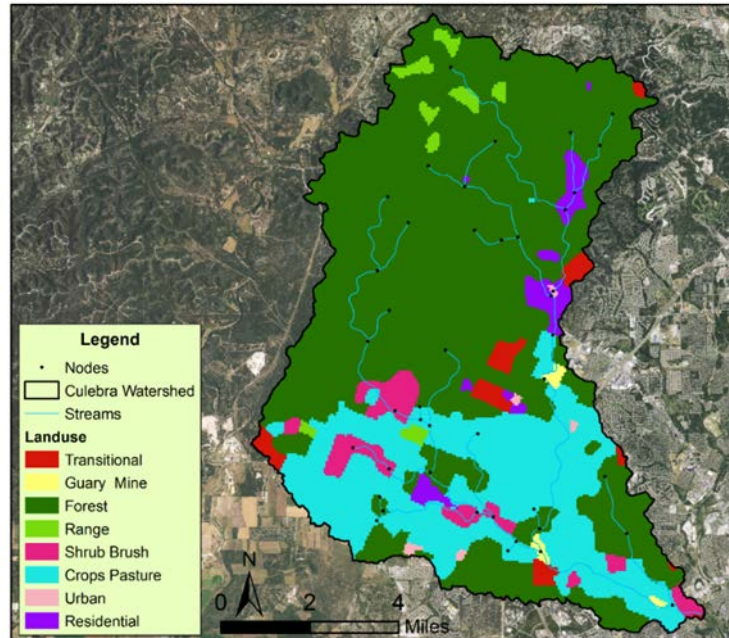
Figure 16. Culebra Creek land use types.

5.3.5. Stream Channels

Delineation of the channel network was based on the topography data. Minor adjustment was needed when the delineated network was compared to aerial photographs of the catchment. Stream channels were modeled using irregular cross sections and reach-specific Manning's *n* values at five locations along the main stream channel. Manual adjustment of stream channels using the WMS "smoothing" feature was required to remove some regions of adverse (negative) channel slope resulting from errors in the DEM.

5.3.6. Simulation Results

GSSHA model was run in continuous mode on a 75-m grid with all the watershed characteristics described above used to assign model parameter values. These parameters include soil hydraulic conductivity, soil initial water content, porosity, Green and Ampt capillary head parameter, Manning's roughness coefficient (*n*), seepage coefficient, and overland retention depth. The overland roughness coefficient and flow retention depth are a function of the land use/cover. Impervious areas were assigned soil hydraulic conductivity values of 0.0. Culebra Creek streamflow data was obtained from USGS 08181400 Helotes Creek station at Helotes, TX, which provides archived 15 min flow data. Simulated and observed hydrographs are plotted below for the two periods that include two major events simulated. Helotes Creek has a drainage area of about 15 square miles. Figure 17 shows the observed and simulated hydrographs for the 10-day period (10/21-10/31/2015). The simulation was started 10-days before the major event to spin up the model and make sure that the initial moisture conditions are as accurate as possible. The model was able to reasonably simulate the observed hydrographs with moderate calibration. All hydrographs are show for the USGS 08181400stream gauge station, which drains an area about 15 mi^2.

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The model could have been further calibrated to more closely match the observed data, but since details of the detention ponds in the catchment were not available, it is better to use the current model and include the detail of the pounds and channel cross-sections in a more detailed study. To illustrate the power of model optimization, we employed the automated calibration method that is embed in GSSHA [the Shuffled Complex Evolution method (SCE, *65*)] on the 2007 flood season. SCE is intended to both ease the burden of manual calibration and increase the user's ability to explore the parameter space (i.e., the range of possible parameter values) and search for the optimal solution as defined by the user. Figure 18 shows the calibrated hydrograph of the main event of 2007 after 100 iterations of the calibration algorithm.
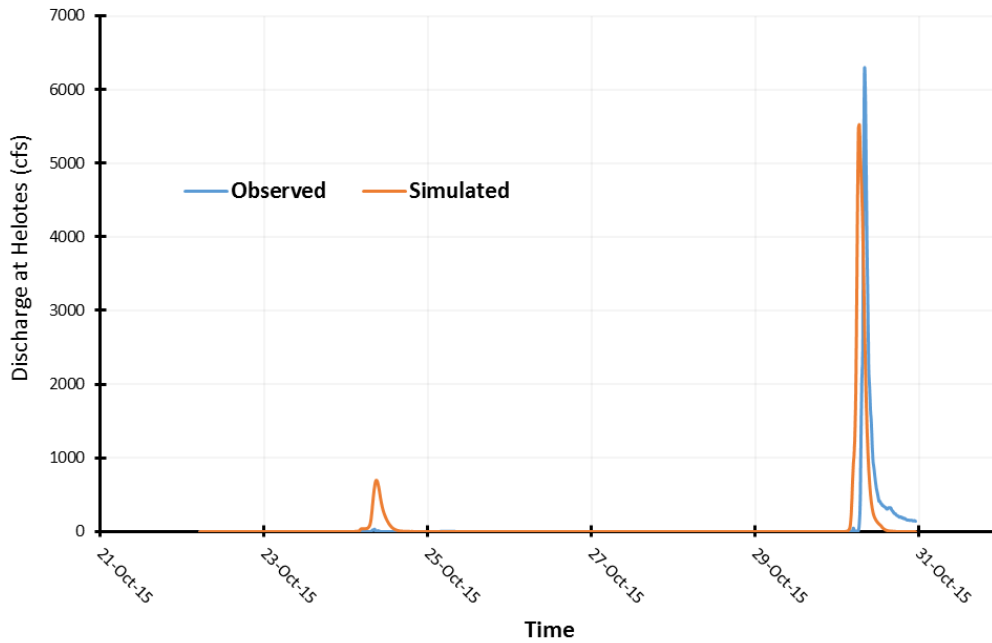

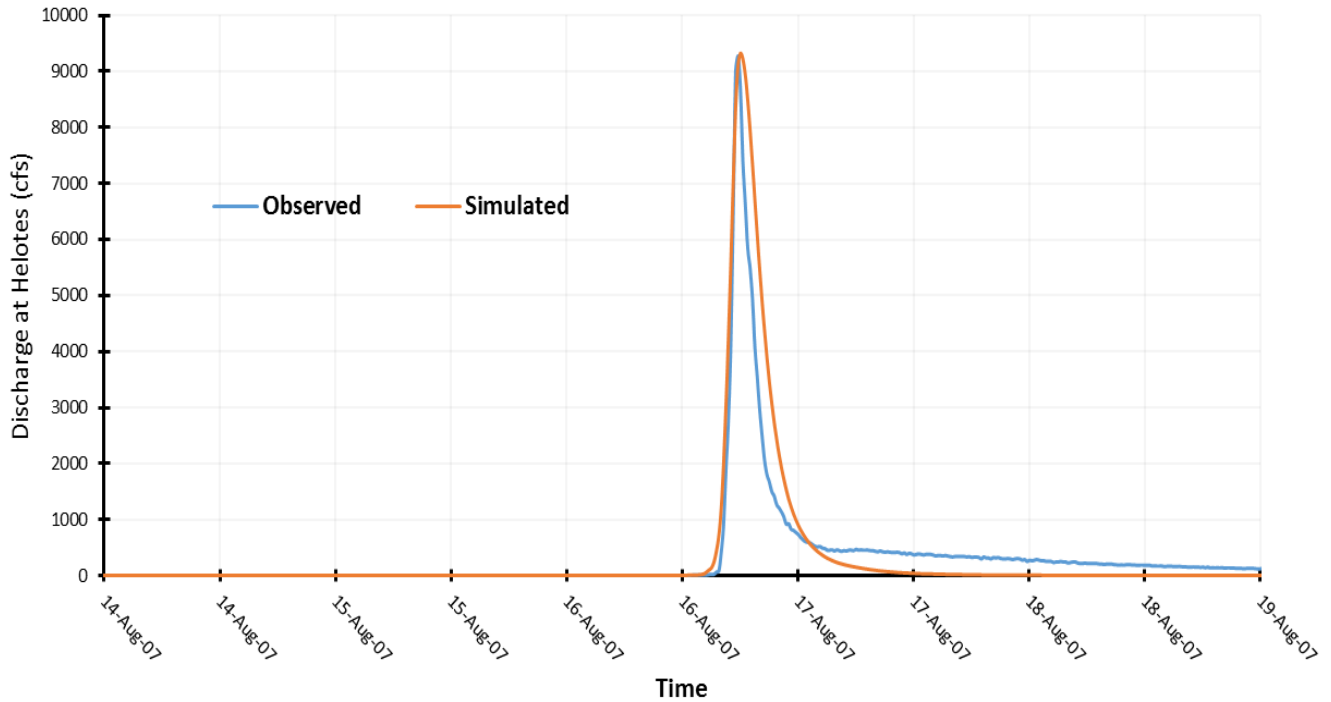**Figure 17. The observed and simulated hydrograph of the 2015 flood.**

Figure 18. The observed and calibrated hydrograph of the 2007 main event (calibrated using SCE).

The main advantages of using a physically-based model to predict flow depth and velocity at low-crossings is that the model outputs can be available at multiple resolutions providing accurate estimates of flow depths and velocities over the model domain "the entire drainage area and depths over which the model is being applied" showing current condition, predicted conditions, and predictions of how and when the flood water will recede, which is vital information for flood emergency crews. Figure 19 shows the maximum inundation caused by the 2007 event over Culebra Creek. The model can provide an output map of flood depth and velocity for every point in the catchment at every time step while the model is running.
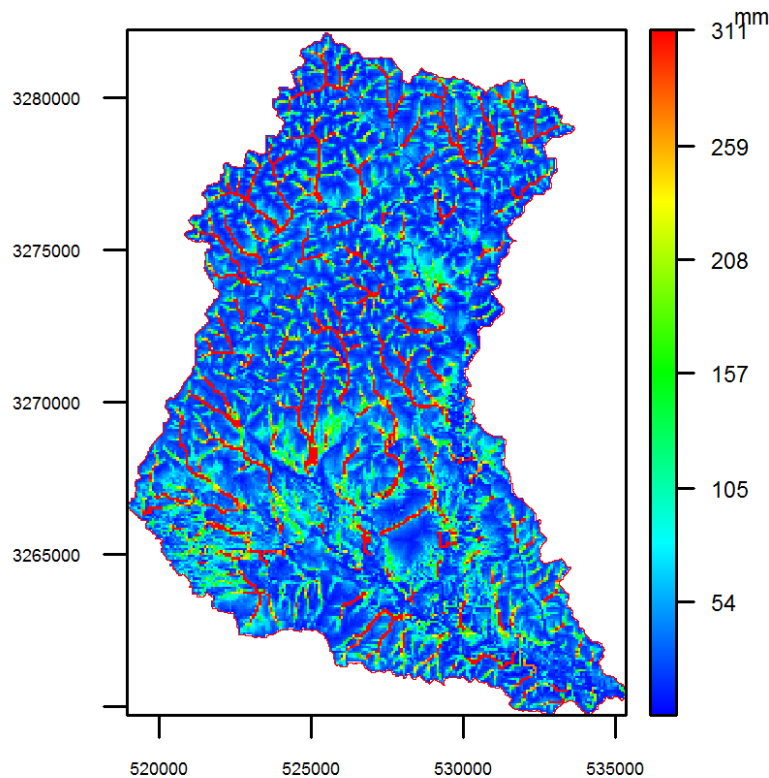
Figure 19. Maximum inundation depth caused by the 2007 flood event.

5.3.7. Detection and Warning

Recent development in sensor technology demonstrated the feasibility of using this technology for improving roadway warning and assessment systems, which is particularly beneficial in high-risk areas that are impacted by hurricanes and tropical storms. After evaluation of numerous devises available in the market and discussions with colleagues at other universities, we selected a water level and flow sensor and installed it on a small watercourse inside the main campus of the University of Texas at San Antonio. The flow (or water velocity) is needed for safety because the power needed to washout a vehicle depends on the water depth and velocity. The Signature flowmeter (Figure 20), tested on campus (Figures 21-22), is designed for water depth and flow monitoring applications. It supports depth and flow measurement technologies including bubbler, non-contact laser area velocity, submerged Doppler ultrasonic area velocity, and ultrasonic. In addition to the depth, the flowmeter can calculate flow using standard open channel level-to-flow and area velocity conversions, as well as user-defined equations, level to area data points, or level to flow data points, depending on the application need.

The flowmeter sensor technology has a resolution of much better than .04 inch in order to support providing meaningful water level and trend data. The system reports water level in near real-time without significant delay. An internal CDMA or GSM cellular modem enables long distance, remote programming, data retrieval, and alarms. Data can be automatically sent to server at set time intervals. The water level sensor system can record the depth and duration of road flooding while communicating with an Advance Warning Station (connected to flashing beacons and gates).

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The recorded data can be used, in conjunction with post-event road inspection, to assess the impact of the flooding on the road integrity. This technology can be adapted to inexpensively develop warning systems that can be easily deployed where and when needed. The proposed system will use sensing technology to trigger just-in-time deployment to increase effectiveness of the warning system, save operation costs, and nullify false alarm probability. It will allow transportation departments and municipalities to inexpensively expand the effectiveness of their safety countermeasures.
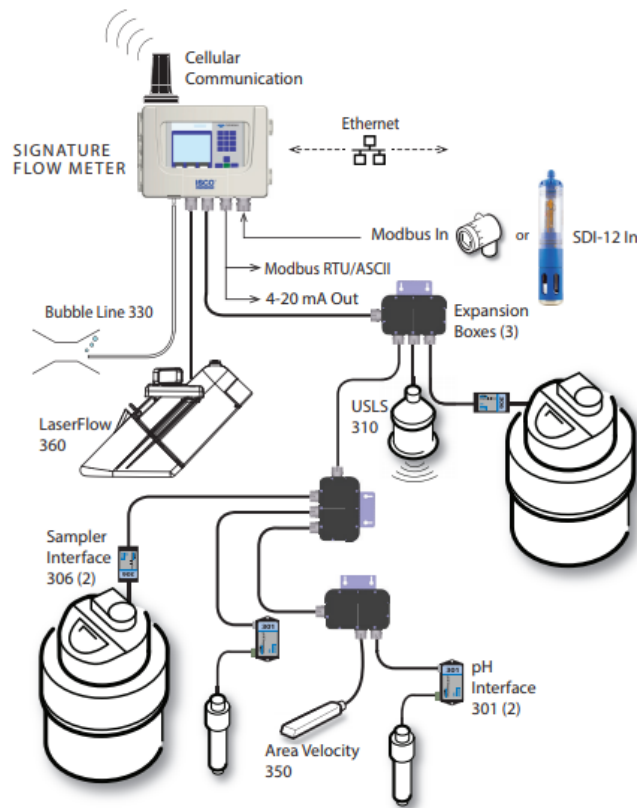
Figure 20. A schematic of the Signature flowmeter.

Figure 21. Control box of the Signature flowmeter installed on campus.

Figure 22. Connection of the area velocity component of the Signature flowmeter.

Another excellent and affordable water level sensor is the Hydra-Pulse 235 (Figure 23), which is a continuous non-contact water level measurement sensor that is versatile, easy to use and program. Installation is simple and since the sensor measurement is non-contact (installed above

the water) accurate water level measurements can be taken even in flood conditions without possibility of damage to the sensor. The next generation Hydra-Pulse has a proven mean time between failure (MTBF) of more than 50 years, and is the most accurate in the industry with a measurement accuracy of 2mm up to 115 ft (35 m). An internal CDMA or GSM cellular modem enables long distance, remote programming, data retrieval, and alarms. Data can be automatically sent to server at set time intervals.

Figure 23. The Hydra-Pulse 235 radar water level sensor.

5.4. Communication

New communications technologies with the potential to greatly improve safety, system efficiency, and traffic are emerging in a very fast manner. However, the possibility of exceeding the design and capacity of existing wireless communications networks can limit the potential mobility and safety benefits of their applications. The master station can accurately capture data from up to two flood sensors of similar or differing technologies in near real-time, and stores the data for transmission by wireless or wired connection. The automated equipment can alternately activate and de-activate a traffic control system remotely and/or locally as the master station itself, when water reaches operator pre-set threshold levels. Any controller that enables an operator to activate and de-activate the traffic control system can be used. The controller will report the status of the traffic control system and flood sensor in real time. The controller will report its current state, including battery level at a programmable self-report interval. The controller will report each change of state, when it occurs. Communications engineered to provide dependable service; especially in times of hazardous weather or power/infrastructure outage are becoming available. The communication can be compatible with the emerging technology of Internet of Things (IoT). The IoT describes an interconnected network of physical objects (e.g., buildings, vehicles, and devices) that can collect, share, and exchange data. This system allows for better incorporation of the physical world into computer-based systems.

5.5. Key Findings

Today's advanced manufacturing tools can produce lightweight, cheap, internet-connected sensors to improve flood detection, monitoring, and local flood safety programs. Road flood detection and warning can be significantly augment by using sensing technologies that can detect not only the water depth but also the water velocity in combination with a physically-based hydrologic modeling system that can provide forecasts of water depth and velocity at locations of interest. The sensors can be designed to be modular, allowing maximum flexibility for authorities to configure the sensors to meet specific needs. A scalable IoT network of highly-reliable sensors with wide-area wireless coverage and cloud sensor data processing can be used. The results of the model and information of the sensors can be used to provide timely and adequate warning to approaching motorists that a flooded roadway conditions exist further up the road.

6. CONCLUSIONS

Motor vehicle-related flood fatalities in Texas far exceed total flood fatalities in any other state between 1959 and 2016. Review of the data indicates that about 77% of the fatalities with known circumstances are motor vehicle-related. The number of those fatalities in Texas is expected to be actually higher than, as we expect that a significant number flood fatalities whose circumstances are not provided in the "*Storm Data*" publications to be also motor vehicle-related. Review of ages of victims of motor vehicle-related flood fatal crashes indicates that all age groups are at risk of dying from floods, including significant numbers of victims of ages below 20 years or above 60 years. More males die in a motor vehicle crashes during a flood than females. Differing road networks and numerous low water crossings throughout Texas contribute to the higher recurrence rates of floods that pose a danger to vehicles.

Motor vehicle-related flood fatalities are a serious threat to transportation safety and in many cases, they can be prevented. In addition, physical and hydraulic field investigation is needed to better understand the high frequency of these events. If no action is taken, flood fatalities, specifically in Texas, are expected to rise due to several factors. The main recommendation of our study is that efforts to reduce flood fatalities in Texas should employ a combination of improved road flooding forecasting and detection, educational programs aimed at enhancing the public awareness of flood risk and the seriousness of flood warnings, and timely and appropriate action by local emergency and safety authorities.

An analysis was performed on the vehicle-related flood fatalities caused by Hurricane Harvey and believed to have occurred at low-water crossings. Information was collected for the fatalities that occurred due to the event and were recovered within the first 2 weeks after landfall. In general, most fatalities were due to drowning, particularly in and around vehicles. Male victims and those over 50 years old were overrepresented in the dataset compared to their proportions in the general population. More than half of the fatalities occurred in Harris County, where heavy rainfall and dam releases caused unprecedented urban and road flooding. We believe that fatalities occurred at locations where there were no high-water detection systems or at locations where the road flooding detection and warning systems were malfunctioning. The impacts of Harvey can also be utilized to evaluate and improve the performance of the low-water crossing warning systems and emergency management for Region 6.

For emergency personnel to take necessary measures to prevent driving into flooded roads, time is the most needed resource. It is impossible to detect flooding at every location and issue warning or block roads in time. If flooding can be predicted with any lead time, this will allow emergency personnel to prepare and deploy resources and issue warnings. Fortunately, the availability of high-resolution remotely sensed precipitation data in real time, quantitative precipitation forecast, and the recent advances in physically based distributed hydrologic modeling can make it possible to predict flooding at high resolution with reasonable lead time. The resolution of the flood prediction can be high enough to enable prediction of water depth and velocity at any location of the road network. The predicted flood maps can be sent to any device over the Internet.

Recent development in sensor technology demonstrated the feasibility of using this technology for improving roadway warning and assessment systems, which is particularly beneficial in high-risk areas that are impacted by hurricanes and tropical storms. This technology can be adapted to inexpensively develop warning systems that can be easily deployed where and when needed. The systems proposed in this study can use sensing technology to trigger just-in-time deployment to

increase effectiveness of the warning system, save operation costs, nullify false alarm probability, and allow transportation departments and municipalities to inexpensively expand the effectiveness of their safety countermeasures.

Communications engineered to provide dependable service; especially in times of hazardous weather or power/infrastructure outage are becoming available. The communication system can be compatible with the emerging technology of Internet of Things (IoT). The IoT describes an interconnected network of physical objects (e.g., buildings, vehicles, and devices) that can collect, share, and exchange data. This system allows for better incorporation of the physical world into computer-based systems.

6.1. Recommendations

Following the study carried out on the vehicle-related flood fatalities that occurred from 1959 – 2016 in Texas, the following actions are hereby recommended to further enhance the safety of low-water crossings:

6.1.1. Low-Water Crossing Warning Systems Should have a Forecasting Capability

Time is the most crucial factor to emergency personnel for taking necessary and immediate steps to prevent driving into flooded roads. The recent advances in physically based distributed hydrologic modeling in conjunction with real-time high-resolution remotely sensed precipitation data and quantitative precipitation forecast can bolster the prediction of flooding at high resolution with reasonable lead time. At any location of the road network, the depth and velocity of water can be predicted using the high-resolution flood prediction. Predicted flood maps can be shared in real time over internet to facilitate immediate measures.

6.1.2. Low-Water Crossing Warning Systems are Absolutely Necessary for Certain Locations

The warning systems are especially needed where traffic volumes are sufficiently high so as to create a significant risk exposure to drivers, where there is a history of vehicles becoming trapped or washed away due to rapidly rising water, where roadway geometry and/or other factors (e.g., vegetation, obstruction) reduces sight distance and visibility to the crossing, and where crossings are located in isolated locations where a significant delay may exist before the crossing.

6.1.3. Every Low-Water Crossing Should have a Water Depth/Flow Detection Device and an Advance Warning Sign

Every low-water crossing should be equipped with a depth and flow detection system along with an advance warning sign. The water depth and velocity allow safety officials to determine the hazard magnitude at crossing and display the appropriate warning of the advance warning sign to alert drivers.

6.1.4. An Ample Stopping Sight Distance to Maximum Water Height Approaching Crossing

For maximum safety, it is recommended that all warning signs be located such that an ample stopping sight distance is provided. This should allow drivers to stop well before entering the water.

6.1.5. Educational Campaign Programs

1. Publicize locations where there is a history of vehicles becoming trapped or washed away due to rapidly rising water.
2. Improve and emphasize safe driving behaviors during hazardous weather conditions in teenager driver education courses and defensive driving courses.
3. Create educational graphics and social media friendly information highlighting the statistics of injuries and fatalities during hazardous weather conditions.
4. Publicize programs such as "Turn Around Don't Drown".

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