Asset Management, Extreme Weather, and Proxy Indicators Pilot Final Report

February 2019

Notice

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Executive Summary

Introduction

The Federal Highway Administration (FHWA) selected the Texas Department of Transportation (TxDOT) to pilot the development of an extreme weather event risk framework. The TxDOT Houston District was used as the case study to develop a framework for understanding and integrating extreme weather risk into asset management because of:

- Houston's large population, housing an estimated 2.4 million people in 2017.
- The District's extensive transportation network, which includes 10,077 lane-miles of state-maintained highways/roads.
- Houston's contribution to the State Gross Domestic Product, specifically its critical economic role in the chemical and mining sectors.
- Historical exposure to extreme weather events and the large number of climate factors that are of concern.

Methods/Technical Approach

Texas A&M Transportation Institute (TTI) researchers performed the following tasks:

- Conducted a literature review to identify the climate factors of concern to TxDOT's Houston District.
- Conducted a workshop to focus the pilot effort on the climate factor of most concern to stakeholders. Based on the input received, researchers focused on characterizing inland flooding and its impact on Houston's road infrastructure.
- Reviewed data resources and information potentially useful for characterizing flooding in Houston.
- Translated spatial information of 100- and 500-year flood zones into a spatial view of inundation characterized by flood height.
- Analyzed Light Detection and Ranging (LiDAR) data to provide information on the elevation of road infrastructure (pavements) in Houston.
- Calculated the potential impacts of flooding on Houston's pavement infrastructure and calculated the potential loss in service life.
- Calculated the potential systems impacts of flooding on Houston's road infrastructure in terms of infrastructure impacts (loss in pavement service life) and disruption impacts (road closures due to flooding).
- Identified potential mitigation measures and investment priorities to increase the resiliency of Texas's road system to flooding in Houston.
- Identified potential proxy indicators that the agency can track in the future.

Results and Potential Mitigation Measures

There are 10,077 state-maintained lane miles in the TxDOT Houston District. The findings of the pilot project showed that almost 75 percent of the state-maintained lane-miles (i.e., 7,069 pavement lane miles) are at minimal risk from flooding (based on Federal Emergency Management Agency (FEMA) flood plain data). The pilot project also provided insight into the long-term impact of flooding on the service life of inundated flexible pavements — historically the vulnerable components of the Houston network. Three pavement structures were analyzed in this study (see Figure ES-1). In this figure:

- Pavement structure 1 corresponds to Pavement Type 5.
- Pavement structure 2 corresponds to Pavement Type 10.
- Pavement structure 3 corresponds to Pavement Type 6.

I (Pavement Type 5) II (Pavement Type 10) III (Pavement Type 6)

Notes: AC = asphalt concrete, CTB = cement treated base, LTSG = lime treated subgrade, FB = flexible base, and SG = subgrade
In the case of Structure II (Pavement Type 10), the surface layer is a surface treated layer.

Figure ES-1. Pavement Structures.

Structure I with 4 in. asphalt concrete and 12 in. cement treated base is the strongest among the considered structures, while Structure II, which is comprised of a surface treatment placed over flexible base and lime treated subgrade, is the weakest structure. Structure III is stronger than II but weaker than I.

The analysis of the potential pavement damage from floods showed that Pavement Types 06 and 10 are prone to flood damage (specifically rutting) and may need to be reconstructed to the specifications of Pavement Type 5 (i.e., an asphalt concrete–surfaced pavement structure) to withstand future flooding events. There are approximately 110 state-maintained lane-miles of Pavement Type 6 and 10 in the TxDOT Houston District. However, almost 50 percent of the lane-miles (i.e., 53 lane miles) are at minimal risk of flooding. Since these Pavement Types represent a relatively small percentage of the Houston state-maintained network, the worst-case scenario, hardening all the Pavement Type 6 and 10 sections, will cost the agency $17.2 million.

Based on the pavement analysis, it can therefore be concluded that thinner pavement structures, particularly those without treated subgrades and less than two inches of asphalt are particularly vulnerable to flooding. Strengthening unbound layers such as subgrades and base materials with stabilization techniques helps mitigate pavement damage caused by flooding. If thinner pavement sections are furthermore heavily trafficked during flood response, immediate pavement damage should be expected that will likely require immediate reconstruction.

The findings of the pilot project also highlighted the potential disruptive effects of flooding and the significant cost of elevating susceptible roads. The analysis revealed that almost 12 percent of the state-maintained lane-miles in Harris County are at risk of flooding in the case of 100-year events. Most of the impacts will lead to disruptions in travel rather than chronic damage to the pavement structure since very few lane-miles in Harris County are Pavement Types 6 and 10. Slightly more than 5 percent, or 254, of the lane-miles in Harris County will be inundated with 20 or more inches of water in a 100-year flood event (Figure ES-2). Although beyond the scope of this analysis, it is evident that even small amounts of surface water on the roadway places drivers at a safety risk from, for example, hydroplaning. Water depths of between four and 20 inches are likely to limit visibility of lanes, road boundaries, and the road surface, while depths of greater than 20 inches are likely to be impassable even to emergency response vehicles. The spatio-temporal pattern of water depths is also relevant to the ”recovery” time of the system as it is related to the time taken for the flood to dissipate.

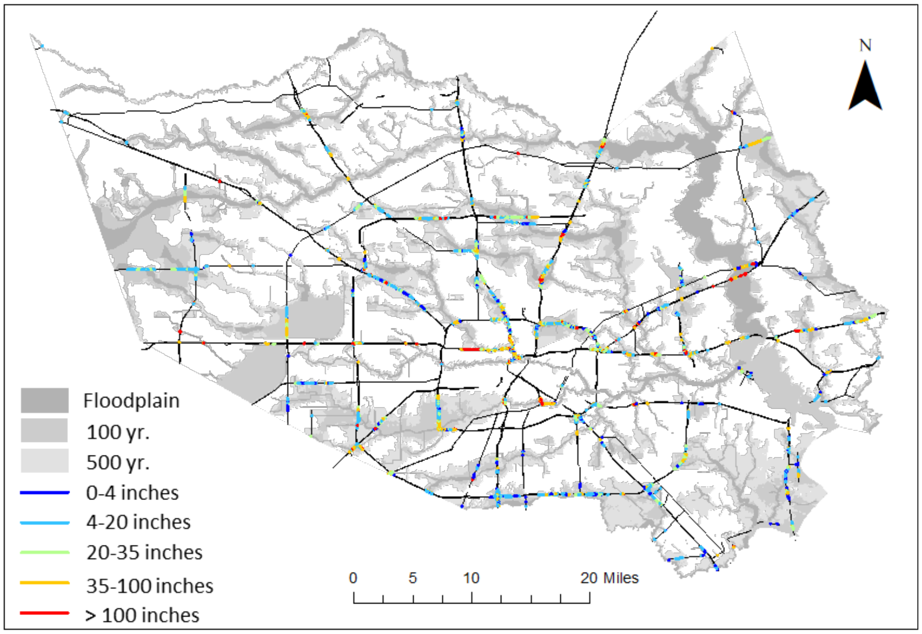


Figure ES-2. Estimated 100-Year Water Inundation Levels of TxDOT State-Maintained Network in Harris County.

This pilot study evaluated the impact of flooding on pavement structures in terms of rutting. A lack of robust models prevented the evaluation of the impact of flooding on other distresses or the evaluation of alternative measures (e.g., more frequent maintenance of culverts, improved drainage, addition of shoulders, or roadside vegetation/stabilization) on the pavement service life given a flooding event.

Furthermore, no tools currently exist to conduct a robust analysis of the inundation impacts of measures to increase the resiliency of pavements to flooding: flood defenses, higher flood walls, levees, and additional pumping stations; the creation of wetlands and marsh rehabilitation; and green infrastructure to deal with rainfall events and to capture storm water. Road closures of the state-maintained network can impose a cost to the local road system if these road closures result in damage to the county and city network from diverted traffic onto roads with weaker pavement structures. These costs were not considered in this pilot study.

Proxy Indicators

For the purposes of this study, a *proxy indicator* was defined as an indirect measure of a phenomenon that approximates a direct measure of the same phenomenon. In this way, proxy measurements are useful whenever a direct measurement of a phenomenon is difficult or even impossible to obtain. A good proxy indicator is a practically useful substitute for a direct measurement or observation.

The work performed during this study provides the following insight into the utility of proxy indicators:

- The Federal Emergency Management Agency (FEMA) floodplains, LIDAR data and pavement deterioration simulations used in this study are all examples of proxy indicators useful for estimating flood risk. They are routinely available, indirect measurements of the system, which when integrated using simple models provide insight into the location, frequency and severity of future flood events. The simulations also offer insight into the pavement network that will likely be impacted by flood events.
- The causes of flooding are complex, but rainfall intensity/duration curves linked to historical patterns of flooding may prove to be useful proxy indicators.
- Travel cost impacts could be assessed (by proxy) using novel Global Positioning System (GPS) transportation data sets (e.g., INRIX data). These data could be leveraged to estimate changes in travel patterns, such as diversions or changes in traffic volumes.
- Useful proxy indicators could be developed by linking easily measurable surface characterization of pavement condition to subsurface structures or by developing sampling methods that use subsurface measurements to infer pavement performance over the entire network.

Lessons Learned

The methods and analyses adopted in this study use publicly available data and readily available software and analysis. The outputs of the study and the methods to derive these outputs can be easily modified and improved. Specific findings of the study are as follows:

- The LIDAR data and analyses could be modified to more accurately determine the profile of selected road infrastructure. The road topography layer can be further analyzed to explore the impacts of local topographic features on flood risk. The exploration and further improvements to the analyses presented in this study may be useful for transportation engineers to formulate hypotheses about the relationships between topography, roads and flooding.

- The road topography data generated using LIDAR could be useful for extending the flood risk assessment methodology. Combined with routing information and traffic volumes, road topography data could be used to explore interactions among traffic volumes using the roads following flooding and pavement damage.
- The methods and data sets generated through this study provide pavement engineers with the potential to analyze the interactions between floodwater depth and pavement damage.
- Pavement engineers provided additional information on the design characteristics of each pavement link to explore the impacts of different levels of floodwater on pavement damage. These methodologies could be extended by estimating the rate at which floodwater levels recede following flooding and exploring how different levels of flood inundation (i.e., interpolating and extrapolating beyond 100- and 500-year flood levels) may impact road infrastructure.
- Direct engagement of other agencies and of other domain expertise within transportation is essential for developing vulnerability assessments. Many of the data, models and expertise required to refine and mitigate flood risk already exist. One of the challenges for transportation professionals is incentivizing experts in other fields to share data, models and knowledge; and to develop a system-level approach to predict, assess the impact of, and mitigate flood risk. To this end, the stakeholder meeting conducted at the beginning of this project identified key reciprocal interactions that could benefit all agencies involved in predicting and mitigating floods.

Transferable Successes

Researchers adopted a pragmatic approach to risk assessment in line with the probabilistic and uncertain nature of risk. The goal was to provide the best estimates of flood risk given currently available data and knowledge. The methods, data and analyses adopted in this study therefore used publicly available data and readily available software and analysis. The outputs of the study and the methods to derive these outputs can be easily modified and improved as new data or knowledge becomes available. Refinement can occur in several ways, for example through:

- More accurate characterization of the probability of adverse events occurring. This may occur because of the availability of more or improved data, or improved analyses.
- More useful information or variables associated with adverse events.
- Better models to translate the impacts of adverse events into estimates of damage.

These refinements usually occur iteratively. For example, improving the characterization of flood events should inform improved methods for estimating damage impacts. Similarly, improved models of pavement damage should inform improvements in methods used to characterize flood events and report flood variables that are more useful to the risk assessment process.

Benefits to the Pilot Agency

Researchers translated FEMA flood maps describing the extent of 100- and 500-year floods into maps estimating local flood water levels/heights. Researchers also developed a novel data set describing the elevation of road infrastructure relative to sea level. Used together, the data helped assess inundation of road infrastructure during floods and refine estimates of the risk of floods on road infrastructure. The results of this study also added to the understanding of the long-term impacts of flooding events on the serviceability of flexible pavements. The results can be employed in life-cycle plan analysis and resilience assessment of pavement networks to extreme weather events in the update of the TxDOT Transportation Asset Management Plan (TAMP).

Finally, the pilot project built and continued the dialogue among various TxDOT divisions and districts that started with the development of the TAMP. For example, TTI researchers presented the initial pilot findings to representatives from TxDOT's Environmental Affairs, Bridge, and Transportation Planning and Programming Divisions. Researchers also made several presentations to the FHWA Texas Division. The pilot project therefore provided an additional opportunity to enhance awareness of extreme weather events and the potential impacts to the transportation system. The outcome of this pilot project will therefore inform and be considered in future agency actions, such as the development of the agency's statewide long-range transportation plan.

Recommendations for Future Work

The following are recommendations and opportunities for future work:

- Flood risk mapping is a specialized area involving complex models with both temporal and spatial dimensions. Although the analysis presented in this study reproduces the spatial extent of FEMA-predicted flooding fairly accurately, improved results could be obtained by working with the original hydrological models, which explicitly translate rainfall frequencies and intensities into flood depth maps.
- The characterization of floodwater heights and road elevations investigated in this study also illustrates another important relationship between flooding and road infrastructure. While transportation engineers may be predominately concerned about the impacts of flooding on roads, road surfaces also alter the topography of an area and play an important role in determining the nature of surface water flow. This requires improved collaboration among climatologists, hydrologists, pavement engineers and other transportation domain specialists.
- This pilot study evaluated the impact of flooding on pavement structures in terms of rutting. Further work is needed to convert the rutting impact into the distress and condition scores used in TxDOT's Pavement Analyst because the condition score is the performance measure used by the agency in evaluating maintenance measures and

managing its assets. Besides rutting, water inundation can also lead to stripping of AC layers, creating the potholing effect often seen after heavy rain events. More robust tools are needed to simulate this impact. A lack of robust models also prevented the evaluation of alternative measures (e.g., more frequent maintenance of culverts, improved drainage and hydrological solutions, or addition of shoulders or roadside vegetation/stabilization) on the pavement service life given a flooding event.

- The findings of the pilot project highlighted the potential disruptive effects of flooding and the significant cost of elevating impacted roads. Lifecycle planning analysis typically does not consider the cost and disruption of road closures. No tools currently exist to conduct a robust analysis of the inundation impacts of measures to increase the resiliency of pavements to flooding. Additional work is also needed to understand the routing decisions and the impact of road closures of the state-maintained network that result in the diversion of traffic onto roads with weaker pavement structures in cities and counties.
- The framework developed in this pilot study provides a repeatable process for risk assessment of the extreme weather event threats to the agency’s assets. The work can be extended to develop a resilience index for the state-maintained system in terms of both potential infrastructure damage and disruptive impacts. Such a resilience index can ultimately be used to inform and prioritize investment decisions.

Introduction

The United States experienced 227 (Texas experienced 98) weather and climate disaster events that resulted in more than $1 billion in losses per event between 1980 and 2017. Of concern is that more than one-third of these weather and climate disaster events happened in the last seven years (i.e., between 2010 and 2017). Between 2010 and 2017, the United States experienced 91 (Texas experienced 43) weather and climate disaster events that resulted in more than $1 billion in damage per event.[1]

Extreme weather events can be devastating for a region. In some instances, communities never recover. Resilient transportation systems can, however, temper the impacts on communities and are vital in response and recovery operations. The Federal Highway Administration (FHWA) has therefore identified the creation of a more resilient transportation system as a priority. In 2011, the U.S. Department of Transportation (DOT) released a policy statement addressing climate adaptation planning, which stated that the DOT should integrate climate change impacts and adaptation into planning, operations, policies, and programs.[2] During implementation, the DOT committed to adhering to the following guiding principles:

- Adopt integrated approaches by incorporating climate change strategies in planning, operations, policies, and programs.
- Prioritize the most vulnerable people, places, and infrastructure.
- Use best-available science in understanding risks, impacts, and vulnerabilities.
- Build strong partnerships with a wide range of stakeholders.
- Apply risk-management methods and tools to assess and respond to climate change.
- Apply ecosystem-based approaches to build resilience and reduce vulnerability.
- Maximize mutual benefits by adopting strategies that complement or support other initiatives.
- Continuously evaluate performance toward achieving desired outcomes.[2]

FHWA Order 5520, Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events (2014) established that FHWA will "strive to identify the risks of climate change and extreme weather events to current and planned transportation systems, and to integrate consideration of these risks into its planning, operations, policies, and programs to promote preparedness and resiliency."[3]

Finally, the 2015 Fixing America's Surface Transportation Act (Pub. L. No. 114-94) requires transportation agencies to address resiliency in their transportation planning processes and to develop a Transportation Asset Management Plan (TAMP) that integrates climate change and extreme weather event resilience approaches into transportation asset management.

Although a few transportation agencies have started to apply climate change and extreme weather event information into asset management and plan development, most State DOTs require guidance on how to incorporate information on vulnerability assessment and mitigation strategies into asset management practices.

Project Purpose

FHWA selected the Texas Department of Transportation (TxDOT) to pilot the development of an extreme weather event risk framework using the TxDOT Houston District as a case study. The pilot project deliverables will be used to inform TxDOT's asset management practices.

The purpose of the risk assessment framework is to understand extreme weather event threats and their potential impact on the transportation network, and to provide a data-driven approach to identify risk mitigation strategies and prioritize investment decisions.

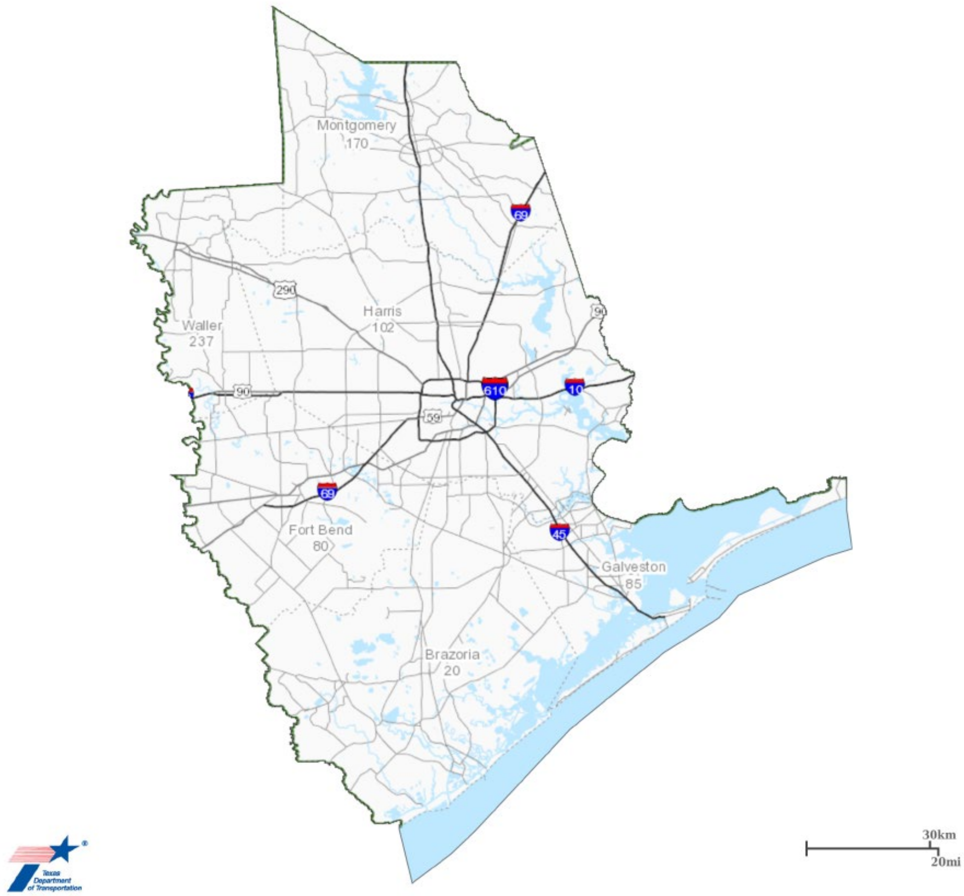
Pilot Goals

This pilot project deals with the risk of extreme weather events (specifically, inland flooding risk) to road infrastructure in Houston, Texas. The goal of the pilot is to characterize flood risk in Houston to provide better inputs for pavement engineers to estimate the damage caused by these events. The latter ultimately informs the development of appropriate mitigation measures and investment priorities in managing the agency's assets.

Scope

The TxDOT Houston District (see Figure 1) was used as the case study to develop a framework for understanding and integrating extreme weather risk into asset management because of:

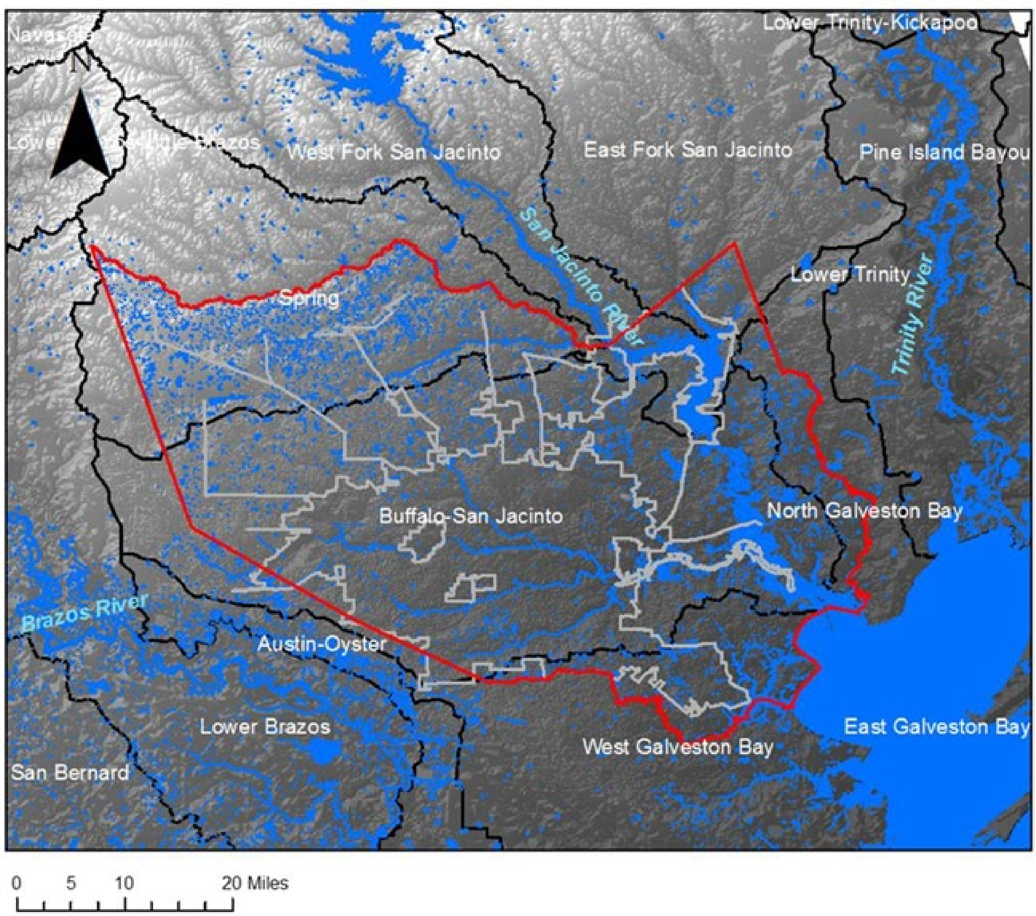
- Houston's large population, housing an estimated 2.4 million people in 2017.
- The District's extensive transportation network, which includes 10,077 lane-miles of state-maintained highways/roads, the second largest marine port in the U.S. in terms of total tonnage handled, the 17th largest airport in the United States in terms of landed weight, and three Class I railroads.
- Houston's contribution to the State Gross Domestic Product, specifically, its critical economic role in the chemical and mining sectors.
- The District's historical exposure to extreme weather events (e.g., 2015 Memorial Day flooding, 2016 Tax Day flooding, 2017 Hurricane Harvey) and the large number of climate factors that are of concern to the Houston District that will affect the performance of the transportation network and impact state budgets for repair and maintenance of transportation assets. Specifically, most of Houston is situated on low lying land in what was once a coastal marsh; making the area prone to inland flooding (see text box).



Source: Base maps compiled, developed, and maintained by the Transportation Planning and Programming Division. PMIS data are maintained by the Maintenance Division, Pavement Preservation Branch.

Figure 1. TxDOT Houston District.

Houston's Drainage System and Topography
The figure illustrates the hydrology of Harris County and Houston metropolitan area plotted on a Digital Elevation Model, and with U.S. Geological Survey watersheds also delineated. The figure maps Houston's drainage system (blue lines and areas) and topography (hill shade map). The red and grey outlines define the study areas of Harris County and Houston, respectively. Most of Houston is situated on low lying land in what was once a coastal marsh. The map also shows that most of Houston is located in the Buffalo-San Jacinto watershed, whose rivers, bayous, and drainage channels drain water from the northwest to the southwest. To the east of Houston, the San Jacinto River runs approximately north to south, draining a large area of land north of the city. To the west of Houston and Harris County, the Brazos River drains a large area of land northwest of Houston, and enters the gulf approximately 50 miles southwest of Houston at Freeport.



This pilot project focused on the TxDOT maintained network in the agency's Houston District to develop the extreme weather event risk framework. In some cases, the proposed methodology and data for framework elements were focused on smaller geographic areas (for example, Harris County) because of data availability and time constraints.

Background

A review of the literature at the outset of the pilot project revealed several studies that addressed various elements in developing extreme weather vulnerability frameworks. Examples that informed researchers' approach include:

- FHWA's Vulnerability Assessment and Adaptation Framework: Third Edition published in 2017. The FHWA's Vulnerability Assessment and Adaptation Framework defined vulnerability in terms of exposure (whether an asset or system is in an area affected by climate variables), sensitivity (how an asset or system responds when exposed to a climate variable), and adaptive capacity (how the system will adjust or cope with existing climate variables or future climate events).
- The 2013 American Association of State and Highway Officials (AASHTO) national symposium reported several best management practices that were implemented by State DOTs to prepare for, protect against, and recover from the impacts of extreme weather events.[4]
- The 2014 USDOT report detailed a *General Process of Transportation Facility Adaptation Assessments,* as part of a study investigating climate change impacts on the Central Gulf Coast region.[5] The process is meant to address vulnerabilities due to climate change, developing adaptation options to mitigate the risks of expected impacts, and choosing a course of action.
- The Transportation Climate Change Sensitivity Matrix developed by FHWA[6] and used by Rowan et al in *Assessing the Sensitivity of Transportation Assets to Extreme Weather Events and Climate Change*. The matrix highlights which infrastructure components are impacted by which types of extreme weather.[7]
- The 2016 report by Kiel et al. on the INTACT project, which aimed to address the challenges posed by extreme weather events on infrastructure.[8]
- The policy insights documented by the International Transport Forum (2016) in a report entitled *Adapting Transport to Climate Change and Extreme Weather*.[9]
- The framework proposed by Williams and Rushall (2014) for managing asset performance that unifies the related fields of climate change risk assessment, asset management, and resilience/risk management.[10]

In addition, TxDOT considered the occurrence of an unanticipated weather event or natural disaster, such as a hurricane resulting in system damage, as a risk to the performance of the National Highway System (NHS) in the agency's TAMP. Previous experience has demonstrated that flooding and storm surges pose risks to Texas's pavements. TxDOT used Federal Emergency Management Agency (FEMA) floodplain data to identify transportation assets vulnerable to flooding in the development of the Texas TAMP (see Figure 2). TxDOT conducted a geospatial analysis to determine NHS segment lengths that crossed or were contained in the 100-year floodplain. Using this method, TxDOT, for example, determined that 4,811 lane-miles of the NHS are at risk of (and therefore vulnerable to) experiencing physical damage in the event of a 100-year flood event.

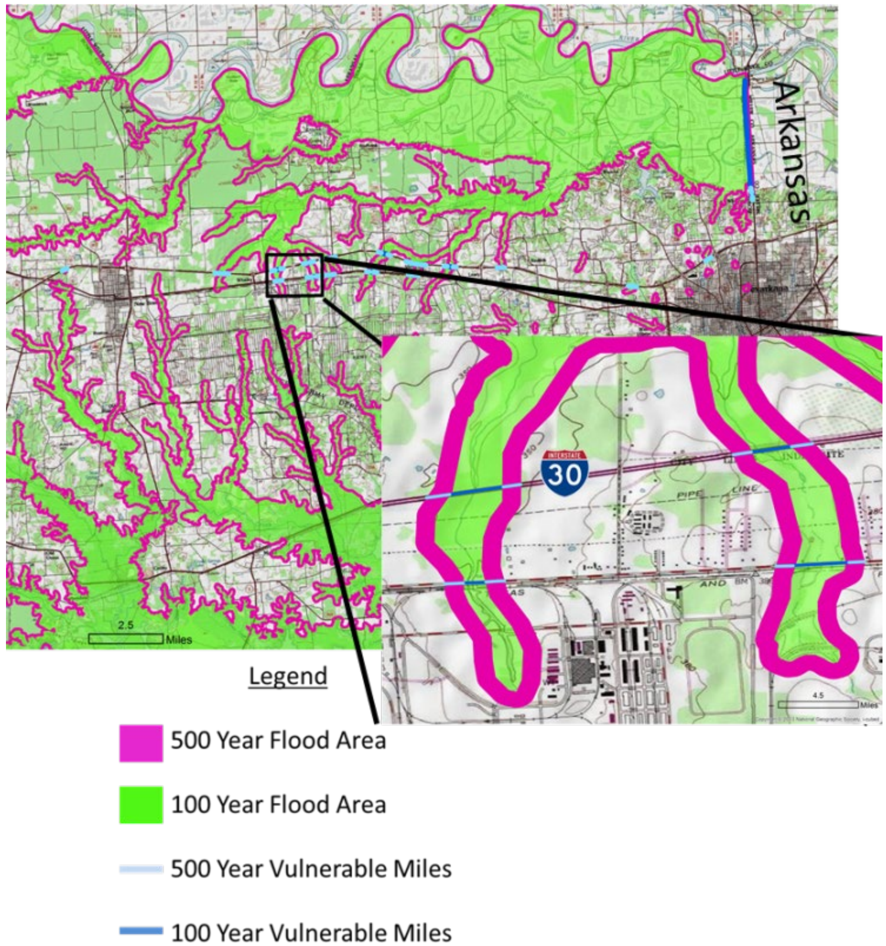


Figure 2. Example FEMA Flood Plain Map.

Similarly, TxDOT used the National Oceanic and Atmospheric Administration (NOAA) storm surge data as of May 9, 2016 for coastal regions to identify transportation assets exposed to storm surge for each hurricane category in the development of the Texas TAMP.[11] TxDOT conducted a geospatial analysis to determine NHS segment lengths vulnerable for each hurricane category.

Finally, TxDOT's new pavement management system (i.e., Pavement Analyst) has the capability to conduct lifecycle planning analysis by considering forecasted pavement condition, various treatment options, treatment costs, and the lifecycle of treatments under different scenarios for funding levels or specified requirements for pavement condition. The Texas TAMP includes a system-wide lifecycle planning analysis given different funding and pavement condition requirements.

Context of Pilot

The objective of the Texas pilot project was to develop a risk assessment framework to understand flood risk and the potential impact on the Houston state-maintained network, and to provide a data-driven approach to identify mitigation strategies and prioritize investment decisions.

To accomplish the pilot project objective, the Texas A&M Transportation Institute (TTI) researchers performed the following tasks:

- Conducted a literature review to identify the climate factors of concern to TxDOT's Houston District.
- Conducted a stakeholder workshop to focus the pilot effort on the climate factor of most concern to stakeholders. Based on the input received, researchers focused on characterizing inland flooding and the impacts on the Houston's road infrastructure.
- Reviewed data resources and information potentially useful for characterizing flooding in Houston.
- Translated spatial information of 100- and 500-year flood zones into a spatial view of inundation characterized by flood height.
- Analyzed Light Detection and Ranging (LiDAR) data to provide information on the elevation of road infrastructure (pavements) in Houston.
- Calculated the potential impacts of flooding on Houston's pavement infrastructure and calculated the potential loss in service life.
- Calculated the potential systems impacts of flooding on Houston's road infrastructure in terms of infrastructure impacts (loss in pavement service life) and disruption impacts (road closures due to flooding).
- Identified potential mitigation measures and investment priorities to increase the resiliency of Texas's road system to flooding in Houston.
- Identified potential proxy indicators that the agency can track in the future.

Figure 3 illustrates the tasks performed as part of this pilot project.

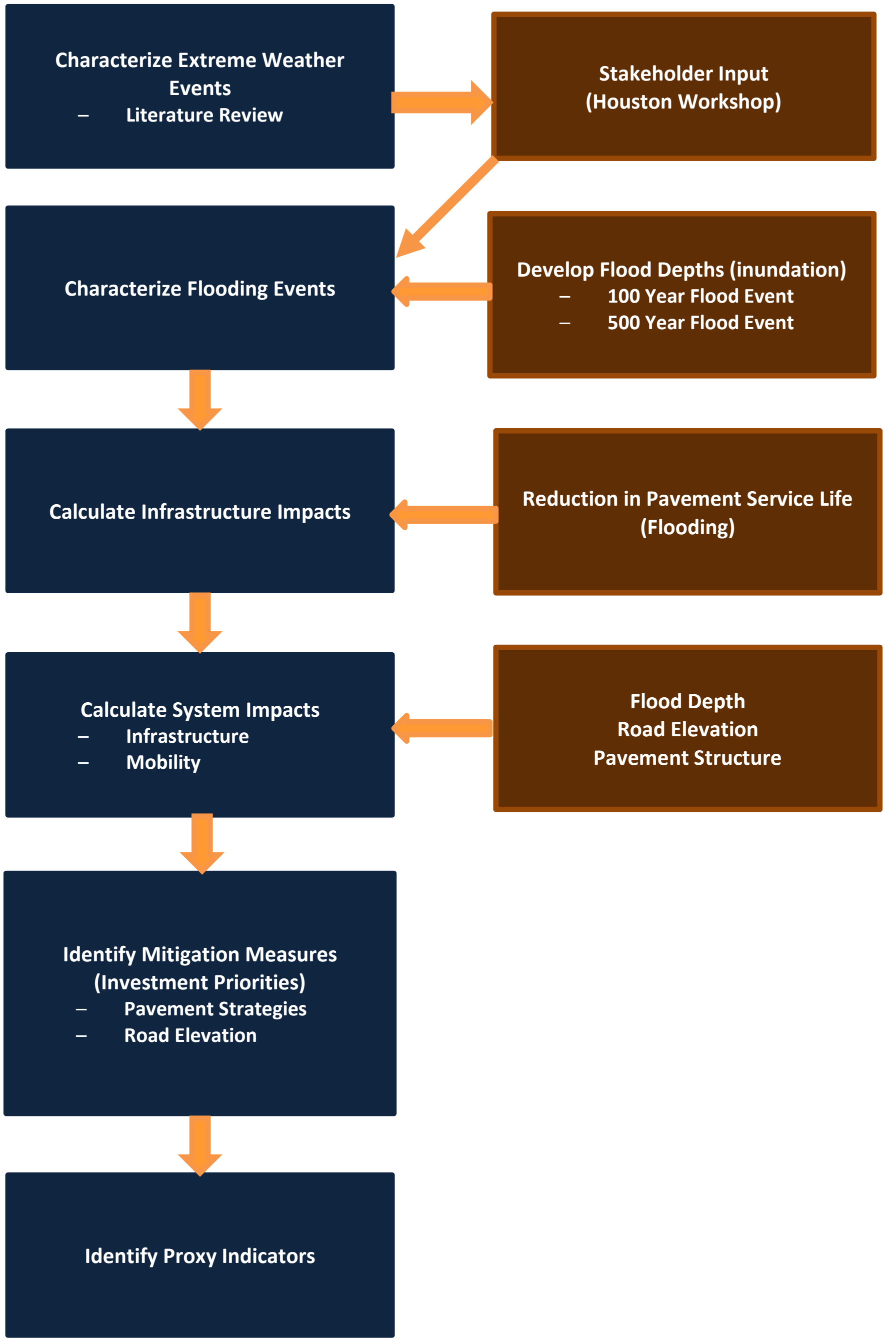


Figure 3. Pilot Project Tasks.

This report documents the study team's efforts in conducting the pilot project tasks. The outcome of this effort provides TxDOT with an improved framework (methodology) to identify pavement sections vulnerable to flooding and a better understanding of the potential long-term impacts of flooding on pavement service life. The framework can be applied to other TxDOT districts and extreme weather threats, which can ultimately be used to determine vulnerability of the agency's state-maintained system to extreme weather threats and to manage risks. The results can therefore contribute to the more efficient management of the system while minimizing costs. Specifically, the results can be used to inform decisions about mitigation strategies (e.g., thicker pavement structures, road elevations) and investment priorities to make the system more resilient to extreme weather events.

Extreme weather poses a threat to transportation infrastructure. Events like floods, storms, and fires have increased in frequency and intensity in recent years, and the impacts on transportation infrastructure can be devastating. In August 2017, Hurricane Harvey hit the coast of Texas, causing $190 billion in damage—the most expensive damage by a storm in U.S. history.[12] The impacts on the transportation system were extensive. For example, the Port Houston, the second busiest port by tonnage in the United States, was closed for eight days (i.e., from August 25 to September 1).[13]

Hurricane Harvey (2017) caused $190 billion in damages and had the largest recorded impact (including debris removal) on the TxDOT maintenance budget.[14]

Preparing transportation infrastructure for extreme weather events is a challenge, because of the uncertainty associated with the types of events, uncertainty on the frequency and intensity of future events, and how to prepare for the events.

This section of the report documents:

- The stakeholder outreach that was conducted in TxDOT's Houston District to obtain input on the pilot project.
- The data and method used to determine flood heights associated with the likelihood of floods occurring in Houston, or in other words the spatio-temporal pattern of flood events.
- The infrastructure impacted by such floods, which is a function of the location of road infrastructure relative to flood zones, and elevation of both road surfaces and flood water.
- The impacts of flooding on Houston's road pavements.

Stakeholder Outreach

Researchers hosted a one-day workshop with stakeholders in Houston to share the goals of the pilot project; discuss extreme weather resiliency in the context of transportation infrastructure; and obtain early input and commitment from stakeholders on the study approach, potential data sources that can inform the study activities, and on the identification of critical elements of the TxDOT Houston District transportation network (essential corridors). Researchers hosted the workshop on Wednesday, February 21, 2018, at the offices of the Houston Galveston Area Council (H-GAC).

Workshop Participants

Researchers initiated the development of the stakeholder list by reaching out to the TxDOT District Engineers from Houston, Beaumont, Corpus Christi, and Yoakum, the TxDOT Pavement Asset Management section in Austin, and the agencies that supported the TxDOT application for conducting the study (i.e., H-GAC, Greater Houston Port Bureau, and The Gulf Coast Rail District). The final contact list developed was a combination of the suggested stakeholders supplemented by researchers' contacts representing other Texas modes, local officials, and transportation agencies. Email invitations were subsequently sent to 114 stakeholders. In total, 31 stakeholders participated in the workshop. Appendix A provides the list of stakeholders that participated.

Workshop Structure

The workshop consisted of two sessions. Five presentations comprised the morning session:

- Researchers reviewed the objectives of the study and the scope of services with workshop participants.
- TxDOT's Director of Maintenance for the Houston District discussed the agency's response during and in the aftermath of Hurricane Harvey.
- The H-GAC discussed the agency's response to Hurricane Harvey and some of the challenges during and in the aftermath of Hurricane Harvey.
- The Harris County Engineer discussed the damage to the county's transportation infrastructure and how the county is recovering.
- Researchers concluded the morning presentation by defining extreme weather resiliency in the context of transportation. The presentation defined key concepts and provided background to the afternoon's small group discussions.

For the afternoon session, workshop participants were divided into three groups. Participants were pre-assigned to one of the three groups to ensure a diverse perspective on the information presented in the morning sessions and to gather input on:

- Climate Factors/Extreme Weather Events of Concern (see Appendix A).
- Transportation Challenges/Issues of Concern.
- Houston's Critical Transportation Infrastructure.
- Mitigation Measures.
- Available Data/Information and Gaps.
- Study Approach.

One researcher facilitated the group discussions and a second member recorded the discussion. Appendix A summarizes the important findings from the small group discussions.

Workshop Outcome

During the workshop, participants agreed that the main extreme weather events in Houston are associated with water/flooding, whether from tropical storms of hurricanes or a high rainfall event. Subsequent efforts of this study therefore focused on developing a methodology to determine the vulnerability or risk of Houston's road infrastructure to inland flooding, to determine the incidence of flooded areas with road infrastructure, and the potential infrastructure impacts attributable to flooding.

Risk and Vulnerability

Risk is a concept useful for understanding and quantifying the likely impact of certain (defined) events on a specific entity such as a system, object, or person. Usually, the events of interest are uncertain and often adverse (i.e., are associated with a cost to the risk assessor). FHWA defines risk as "the positive or negative effects of uncertainty or variability upon agency objectives."[14]

Risk assessment is the process of estimating risk, in the absence of full knowledge of when, where, or how an uncertain event will impact a defined entity. In a scientific context, risk assessment uses knowledge of the processes that drive adverse events and/or the history of defined events to estimate probabilities of similar events occurring in the future. Risk assessment also uses methods to estimate the likely impacts of events on the entity of interest. Colloquially and scientifically, risk and risk assessment involve concepts of probability. That is, they assume that the future events of interest are somewhat unpredictable in relation to the time-line of interest. This unpredictability can be incorporated into both the probability of events occurring, and the likely damage occurring from such events.

In this pilot project, researchers defined and assessed risk using the following framework:

$$\text{Risk} = P_{\text{Occurrence}} \times P_{\text{Damage}} \qquad \text{Equation (1)}$$

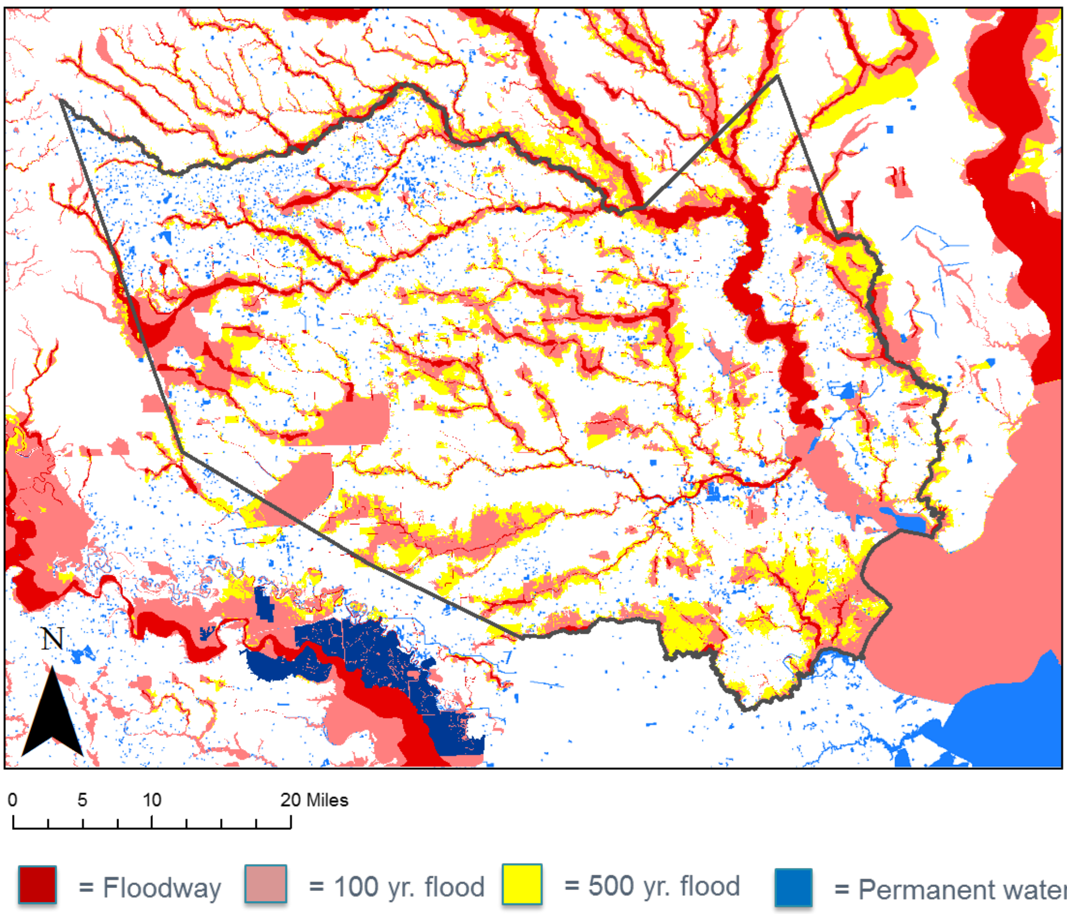
Where $P_{\text{Occurance}}$ represents the probability of an adverse event occurring through space and time; and P_{Damage} represents an estimate of damage if a flood event occurs. Note that Equation 1 provides a conceptual model of risk – useful for partitioning a risk analysis into processes that drive the occurrence of an adverse event and factors that influence the damage resulting from such an event. Equation 1 therefore provides the conceptual model used in this study to assess flood risk to infrastructure.

The framework outlined in Equation 1 is useful because it allows risk to be partitioned into two largely dependent components: the probability of an event occurring and the likely damage that results from such an event. Often, different skills and expertise are required to evaluate and estimate these quantities. For example, in the context of this study, flooding occurs because of complex environmental processes (e.g., rainfall intensity and duration, proximity to water channels); while flood damage is largely driven by factors such as extra moisture, pavement design, and traffic volumes. Partitioning these estimates of overall risk allows researchers and engineers in each area to concentrate on providing the best quality information available to conduct a full risk assessment.

Calculating Flood Heights in Houston

This section describes a method for mapping the spatial and temporal pattern of floods and the height of local floodwater. Two sources of GIS data were used to perform the analysis: FEMA flood risk maps and Digital Elevation Models (DEM) of Harris County. In addition, data on the location of rivers and water bodies, United States Geological Survey (USGS) watershed maps, and stream gage measurements were also useful for the study.

Figure 4 shows a map of FEMA flood risk areas for Harris County and Houston. FEMA flood maps are developed as part of FEMA's flood hazard mapping program. FEMA identifies flood hazards, assesses flood risks, and partners with states and communities to provide accurate flood hazard and risk data to guide them to mitigation actions.[15] Because FEMA flood hazard mapping is used for the National Flood Insurance Program to determine insurance required for businesses and homeowners, it is both widely available and frequently updated.



Note: The black outline delineates Harris County.

Figure 4. FEMA Flood Risk Zones in Houston.

FEMA flood maps are derived from complex, space- and time-dependent hydrological models, which translate historical spatial-temporal patterns of rainfall to hydrological processes such as soil storage, surface run off, channel flow, and tidal information. The development of such models is time consuming and requires specialized skills and knowledge. FEMA works with local partners such as the Harris County Flood Control District to develop models according to national guidelines, maintain the information required to validate these models, and report local flood risk maps to the Federal mapping program.

Despite the complexity of the models used to generate the FEMA maps, the reported information is relatively simple. This is understandable given the fact that the maps are designed to be nationally consistent and useful to various stakeholders. Primarily, the maps delineate areas of 100- and 500-year flood risk and the location of flood plains.

TTI researchers used the information from the FEMA flood maps (2015 release[1]) and USGS DEMs to estimate flood depth, and to understand the influence of topography on flood risk. The rationale for this analysis is that estimates of the local height of floodwater and an understanding of how local topography affects the incidence and duration of standing water is important for assessing damage to pavements in and around flooded areas. The analysis was conducted for Harris County FEMA flood data as follows:

1. FEMA flood zone areas were aggregated into polygons delineating the floodplain, 100-year flood areas, and 500-year flood areas. Polygons were aggregated to form continuous boundaries for each flood zone. The polygons therefore varied in size depending on the size and shape of drainages to which they belonged.
2. A USGS 10 m DEM was used to determine the elevation of the outer boundary of each polygon within the two flood risk categories. Elevations were calculated at each vertex of each flood risk polygon within Harris County. This yielded a boundary representing the maximum local elevation (relative to sea level[2]) associated with 100- or 500-year flood event.
3. The flood elevation boundaries were spatially interpolated (using Environmental Systems Research Institute [ESRI] ArcMap topographic interpolations) to provide a continuous surface of the elevation of local floodwater heights. The interpolation yielded a spatially continuous estimate of floodwater elevation, relative to sea level, for each risk category.
4. The floodwater elevations (relative to sea level) were overlaid onto the DEM to yield estimates of the depth of floodwater relative to the underlying topography of the area. Floodwater depth was calculated as the difference between floodwater elevation and the elevation of the underlying topography.

Figure 5, Figure 6, and Figure 7 show the outcomes of the flood depth analysis for Harris County. The methodology provides estimates of flood depth consistent with the original FEMA maps.

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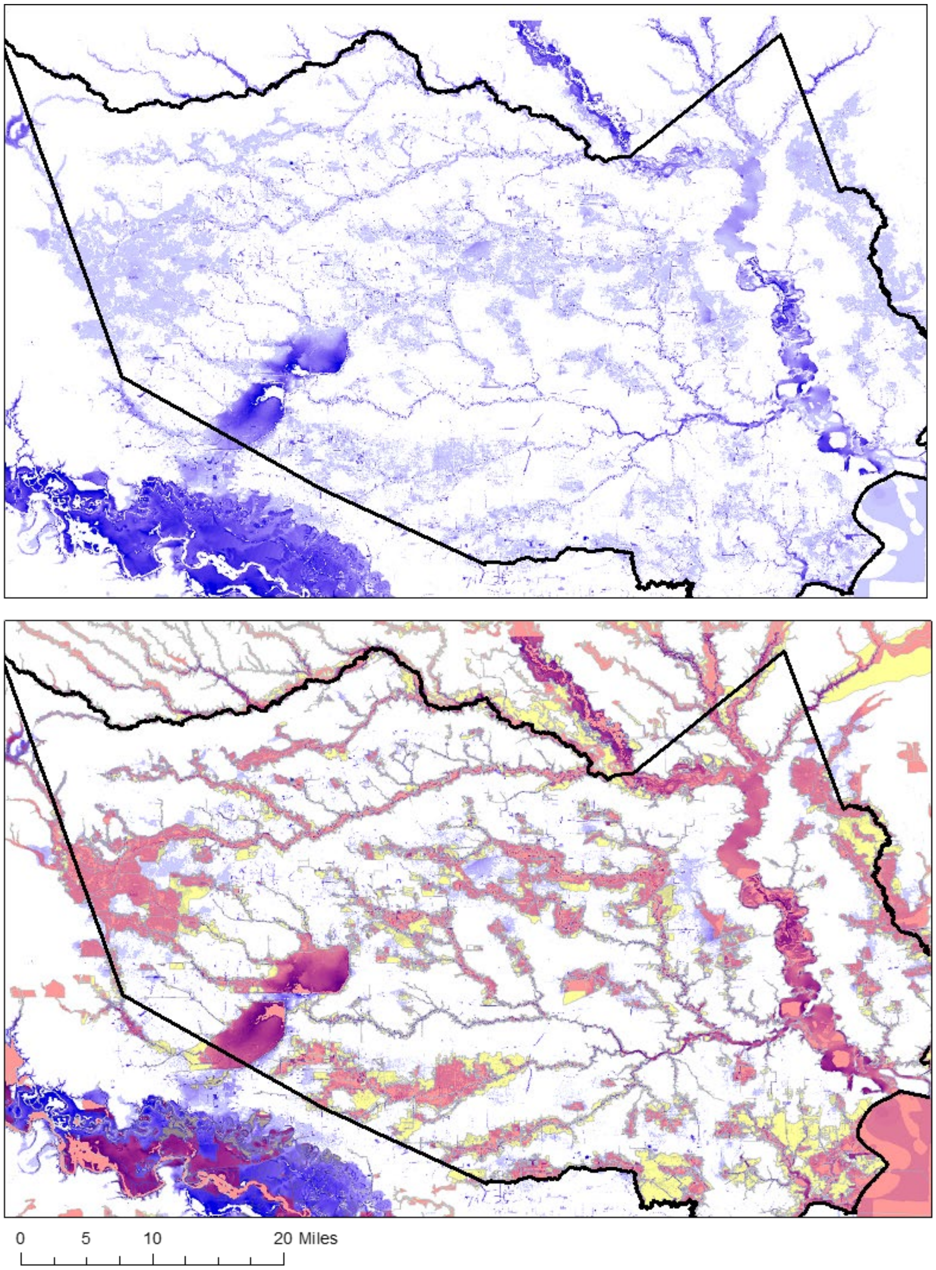
1 Official 2015 maps were used for most of the Houston District region. However, official maps were not available for parts of Galveston and Brazoria Counties. For these areas, unofficial maps were downloaded from the county GIS data warehouses.

2 The analysis did not include changes in sea level.

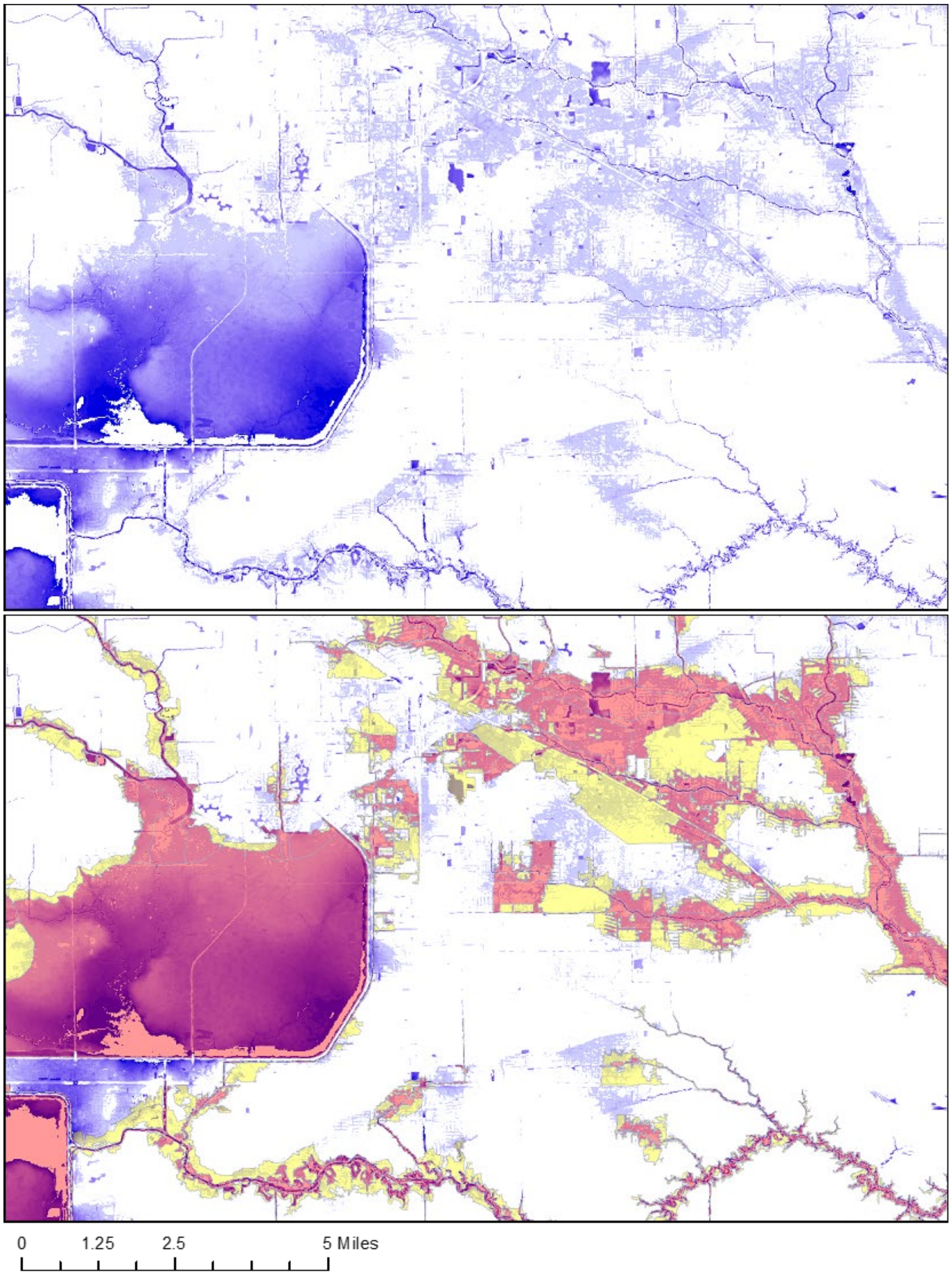
In Figure 5, the top map shows the floodwater depth predictions based on an analysis of the FEMA 100-year flood risk areas (light blue < 20 cm, dark blue > 5 m flood depth). The bottom map overlays the FEMA flood map zones: red = 100-year risk; yellow = 500-year risk. In both maps, the study area is outlined in black (areas outside this boundary were not explicitly modeled).



Note: Floodwater depth is represented as blue shading (light blue < 20 cm, dark blue > 5 m flood depth). The top map shows floodwater depth only. The lower map overlays this floodwater depth on FEMA flood zones (red =100-year risk, yellow = 500-year risk.

Figure 5. Results of Floodwater Depth Mapping for Harris County

In Figure 6, the top map shows the floodwater depth predictions based on an analysis of the FEMA 100-year flood plain locations. In this map, flood water depth is illustrated by blue areas (light blue < 20 cm, dark blue > 5 m flood depth). The bottom map overlays the FEMA flood map zones: red = 100-year risk; yellow = 500-year risk. The center of the map is approximately -95.50° longitude and 29.84 latitude.



Note: Floodwater depth is represented as blue shading (light blue < 20 cm, dark blue > 5 m flood depth). The top map shows floodwater depth only. The lower map overlays this floodwater depth on FEMA flood zones (red =100-year risk, yellow = 500-year risk.

Figure 6. Detail of Flood Depth Mapping Outputs (for a Portion of the Study Area).

This method of refining flood probabilities (i.e., flood depth) can be used to investigate flooding scenarios based on any estimate of local floodwater levels. For example, Figure 7 illustrates the extent of flooding that may occur with a 1 m increase in flood depth.

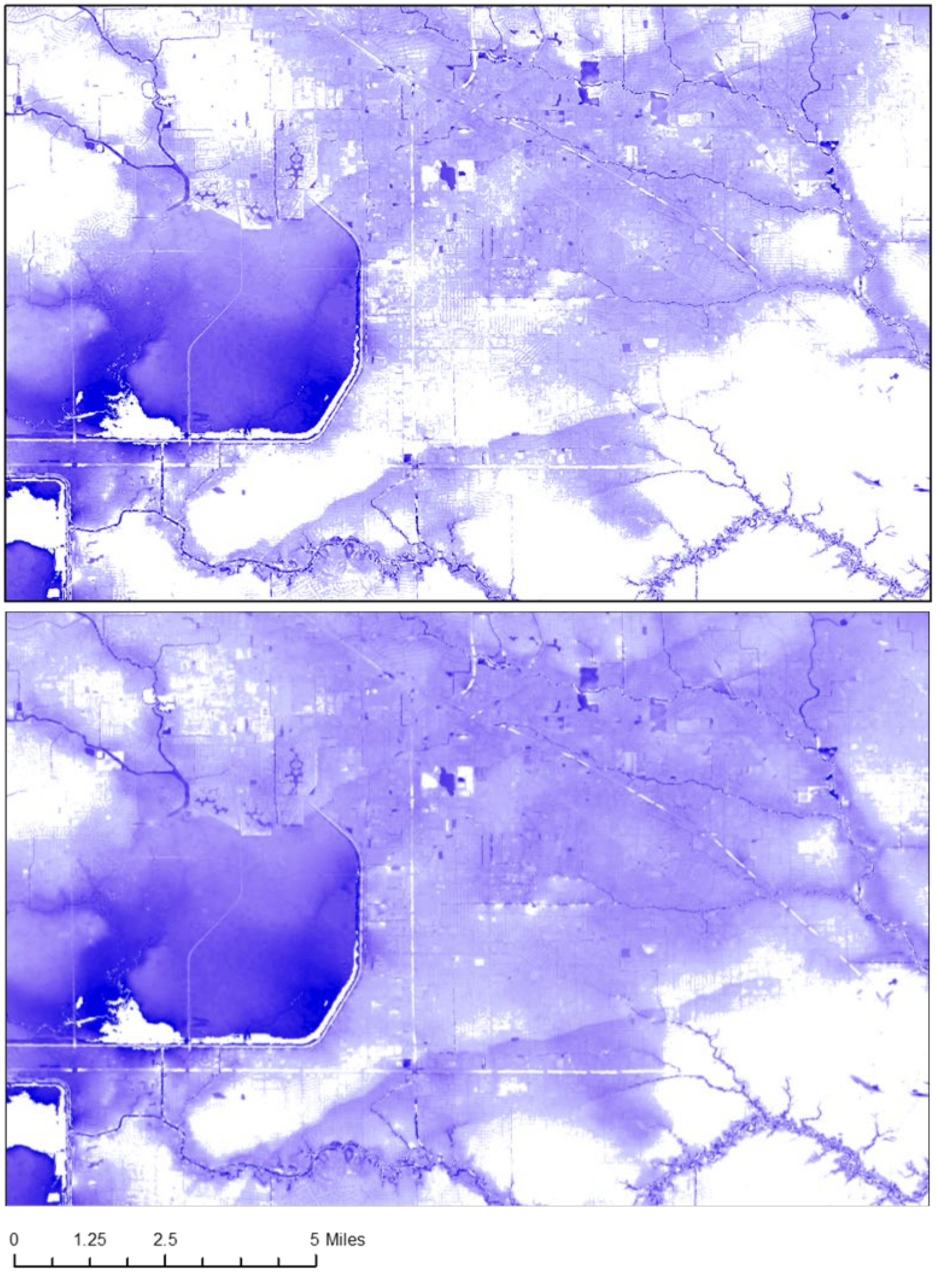


Figure 7. 100-Year Flood Level Analysis Modified to Increase Floodwater Depth.

Estimating Road Infrastructure Elevation

In this section, TTI researchers describe an analysis that uses aerial LIDAR data to estimate the elevation of road surfaces and surrounding infrastructure within Harris County. Aerial LIDAR is obtained using aircraft fitted with LIDAR equipment. The aircraft fly along regular flight paths covering a study area, while the onboard LIDAR equipment emits large numbers of LASER pulses toward the ground. Some of these pulses are reflected to the LIDAR receiver, and the time elapsed between the pulse being sent and pulse received is used to estimate the height of the object from which the pulse was reflected. This height data are then linked to accurate GPS data (longitude, latitude, and altitude of the aircraft) to provide an accurate assessment of the three-dimensional location of the surface from which the pulse was reflected.

The large numbers of pulses per unit time result in large numbers of returns per unit surface area, referred to as a point cloud. LIDAR pulses can be reflected from any solid object including building materials, water, vegetation, bare earth, but the nature with which pulses are reflected varies according to the object or material in question. For example, trees may return a point cloud signature with many returns from the top of the canopy, but with some penetration to the ground beneath (LIDAR is often used to distinguish tree species in forest mapping studies). On the other hand, pavements and the surfaces of buildings are relatively solid, resulting in LIDAR returns with more uniform elevation. Raw LIDAR data (point clouds) usually require statistical analysis to obtain useful information on the types and elevations of objects present on the ground surface.

The methodology used to analyze the Harris County LIDAR is relatively simple, but involves considerable computing time:

- Harris County LIDAR data (obtained in 2001) were downloaded in their original LAZ format, a specialized data format designed to efficiently store the large numbers of data points associated with LIDAR studies.[16]
- A 5 m × 5 m grid (or output raster) was created to cover the extent of Harris County and the LIDAR data.
- Computer code was written to sequentially open each file in the data set and extract the data points. Each point was assigned to a cell in the raster layer based on its Cartesian coordinates (longitude and latitude).
- The mean, minimum, and maximum height of all points in each cell in the output raster were calculated, yielding the mean, minimum, or maximum height of LIDAR returns for every 5 m × 5 m cell within Harris County.

Computations and code to perform the analyses were written in the R software language. Figure 8, Figure 9, and Figure 10 show the results of the LIDAR analysis. The figures demonstrate the utility of aerial LIDAR data for mapping road elevation.

Figure 8 shows four views of the intersection at I-10 and North Loop Freeway, near Jacinto City, Houston. The top left map shows elevation of the intersection and surrounding roads estimated using LIDAR. The top right map shows the same information with road line work overlaid, demonstrating the spatial accuracy of the approach. The bottom left map shows the same view mapped using a conventional USGS Digital Elevation Model. The bottom right panel shows an aerial image of the same location.

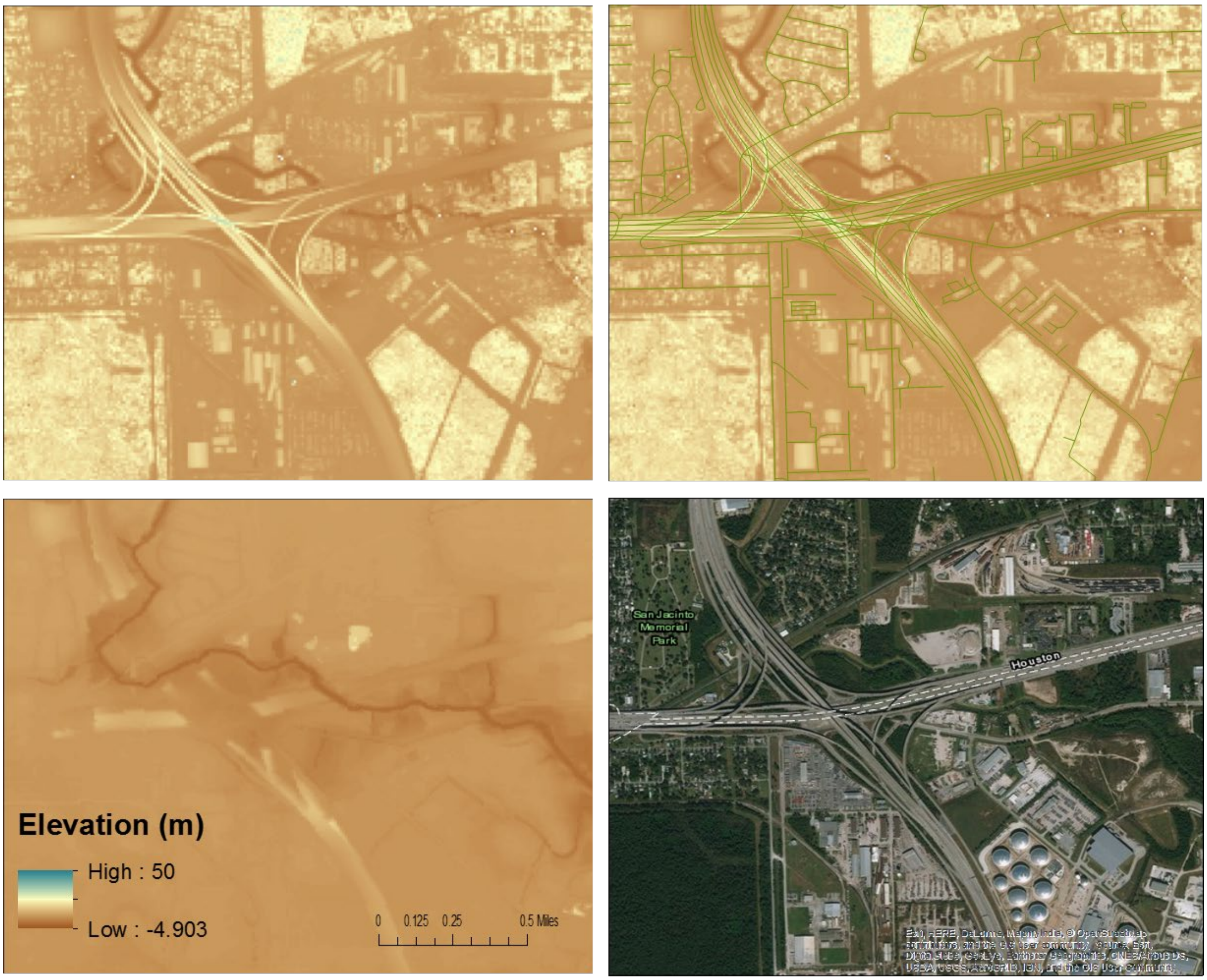


Figure 8. Four Views of the Intersection at I-10 and North Loop Freeway.

Figure 9 shows four views of the interchange at I-610 and US-59 near Jacinto City, Houston. The top left map shows elevation of the intersection and surrounding roads estimated through LIDAR. The top right map shows the same information with road line work overlaid, demonstrating the spatial accuracy of the approach. The bottom left map shows the same scene mapped using a conventional USGS Digital Elevation Model. The bottom right panel shows an aerial image of the same location.

Figure 9. Four Views of the Interchange at I-610 and US-59.

Figure 10 shows four views of the interchange between I-10 and I-45 near downtown Houston. The top left map shows elevation of the intersection and surrounding roads estimated through LIDAR. The top right map shows the LIDAR elevation with road line work overlaid, demonstrating the spatial accuracy of the approach. The bottom left map shows the same scene mapped using a conventional USGS Digital Elevation Model. The bottom right panel shows an aerial image of the same location. The visibility of the drainage channels is clear in all the elevation model maps.

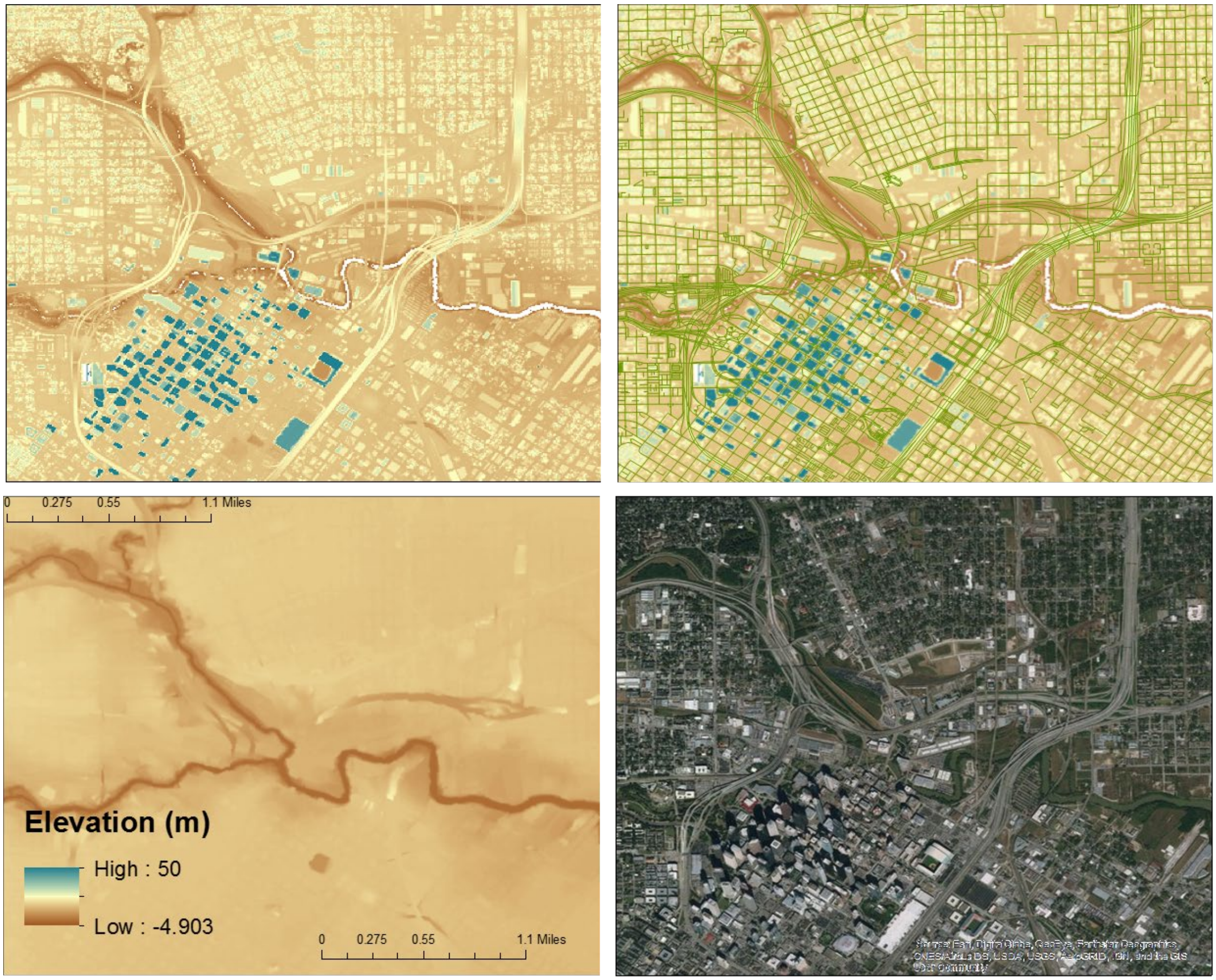


Figure 10. Four Views of the Interchange between I-10 and I-45.

Assessing Infrastructure Impacts

Flooding has the potential to cause damage to pavement structures. The structural capacity of pavements can be affected by flooding mainly due to inundation of unbound layers. When flooding occurs, the subsurface water level rises above the normal level, saturating unbound layers. An increase in the moisture content of unbound layers can notably reduce layer stiffness. Loading weakened pavements in the immediate aftermath of a flood event can lead to sudden failure or severe damage. In addition, an increase in the number of emergency and non-emergency vehicles to expedite recovery and rebuilding efforts may exacerbate the damage. The extent of the damage depends on several factors, including:

- Material properties of unbound layers.
- Pavement structure.
- Traffic volume.
- Frequency and severity of flooding events.

For this pilot, researchers evaluated the effects of flooding on the service life of flexible pavements. A simulation study was conducted to assess the performance of water inundated flexible pavements in TxDOT's Houston District given different scenarios of traffic levels, pavement structures, and flooding events. The potential long-term impacts of flooding on these pavements were presented in terms of the pavement service life reductions. The analysis results showed that the thinner pavement types are vulnerable to flood damage (specifically rutting) and may need to be hardened to withstand future flooding events. Appendix B provides a brief reference to studies conducted on the effects of flooding on pavements, the simulation approach adopted (models used), and the collection of simulation inputs. The simulation results and the major contributions are presented in this section.

TxDOT Houston District's Pavement Structures

The TxDOT Houston District's state-maintained road network comprises 10 different pavement structures/types. Table 1 summarizes the roadbed section lengths by pavement type.

Table 1. TxDOT Houston District Pavement Types.

Pavement Types (Codes)	Road Bed Section Length (Miles)	% of Total Road Bed Section Length
Continuously Reinforced Concrete Pavement (1)	1,902.5	44.9%
Jointed Reinforced Concrete Pavement (2)	185.3	4.4%
Jointed Plan Concrete Pavement (3)	15.8	0.4%
Thick Asphaltic Concrete Pavements (greater than 5-1/2") (4)	0.5	0.0%
Intermediate Thickness Asphaltic Concrete Pavement (2-1/2" to 5-1/2") (5)	1,512.6	35.7%
Thin Surfaced Flexible Base Pavement (less than 2-1/2") (6)	5.8	0.1%
Asphalt Surfacing with Heavily Stabilized Base (7)	1.0	0.0%
Overlaid and/or Widened Old Concrete Pavement (8)	205.5	4.9%
Overlaid and/Widened Old Flexible Pavement (9)	338.1	8.0%
Thin Surfaced Flexible Base Pavement (Surface Treatment-Seal Coat Combination) (10)	66.3	1.6%
Total	4,233.4	100.0%

Simulating Flooding Events

The first step in estimating the effects of flooding on pavements was to identify the potential pavement structures in TxDOT's Houston District that would be sensitive to flooding. Unfortunately, pavement work history and the ability to identify the actual age of the pavement is not readily available. This information is often institutionally held by local network managers. Therefore, simulations were performed using generic timeframes with conclusions determined in a way that would help network managers better understand the impacts of flooding. Local managers with significant historical knowledge of the network will be able to further apply the results of the simulations. Based on the observed performance of pavement structures in the Houston District after Hurricane Harvey, the pavement structures currently used by the Houston District for reconstructing roadways perform well in the event of extreme weather (see Appendix C). In general, the pavement structures can be categorized as follows:

- Not vulnerable to flooding – Pavement Types: 1, 2, 3, 4, 7, 8, and 9.
- Potentially vulnerable to flooding – Pavement Type 5
- Vulnerable to flooding – Pavement Types: 6 and 10.

Specifically, thinner pavement types were considered more vulnerable and are often used by local municipalities. Three pavement structures were therefore considered in this study (see Figure 11). In this figure:

- Pavement structure 1 corresponds to Pavement Type 5.
- Pavement structure 2 corresponds to Pavement Type 10.
- Pavement structure 3 corresponds to Pavement Type 6.

I (Pavement Type 5) II (Pavement Type 10) III (Pavement Type 6)

Notes: AC = asphalt concrete, CTB = cement treated base, LTSG = lime treated subgrade, FB = flexible base, and SG = subgrade

In the case of Structure II (Pavement Type 10), the surface layer is a surface treated layer.

Figure 11. Pavement Structures.

StructureI with 4 in. asphalt concrete and 12 in. cement treated base is the strongest among the considered structures, while Structure II, which is comprised of a surface treatment placed over flexible base and lime treated subgrade, is the weakest structure. Structure III is stronger than II but weaker than I. Structures II and III represent pavement structures of city streets, county roads, or rural TxDOT coastal districts.

Given the low diffusivity of liquid water in the AC layers, it is widely accepted that flooding does not notably change AC stiffness, hence, AC rutting. Therefore, in this study, the rutting property of AC is assumed unchanged.[3] On the other hand, the subgrade layers are very susceptible to long term weakening due to moisture content. Researchers therefore adjusted the resilient modulus in the Texas Mechanistic-Empirical (TxME) pavement design software to simulate flooding of the base coarse. Stiffness and stress states of these layers change significantly as a function of saturation. Furthermore, based on a review of the soil properties in the TxDOT Houston District, researchers assumed that the soil in Houston District drains slowly (e.g., it will take approximately five months to recover and regain strength after flooding).

According to experimental and analytical studies reported in the literature, resilient modulus of unbound layers decreases immediately after flooding, resulting in an increase in the pavement deflection. As flood water recedes, unbound layers gain strength again and recover gradually in terms of stiffness. However, the flood-induced deformations do not return to zero, and unbound layers reach a new equilibrium stress-strain state. Flood-induced deformations contribute to the accumulated deformation of the pavement and can result in a service life reduction.

Finally, researchers simulated the impact of different traffic volumes on the selected structures. Traffic levels were categorized as low, medium, and high (see Table 2). To account for the impact of post flooding events, such as increased number of emergency and recovery (e.g., for debris removal) vehicles immediately after flooding, the percentage trucks for the low traffic category was increased from 2 percent to 17 percent, and the average daily traffic (ADT) was increased by 50 percent. The post-flood traffic increase was only applied to Pavement Structures II and III. During the initial analysis, these pavements only performed satisfactorily over a 20-year design life for the low traffic volume. Therefore, the evaluation of service life and the potential reduction in service life for Pavement Structures II and III assume the typical traffic loading is represented by the low traffic volume. For Structure I, the initial design is robust enough to endure high traffic volumes, and the assumption was made that post-flood traffic does not significantly increase the amount of traffic typically using a Structure I roadway.

[3] However, water inundation can lead to stripping of AC layers, creating the potholing affect often seen after heavy rain events. This phenomenon is not modeled in TxME and its occurrence is difficult to simulate.

Table 2. Traffic Volumes.

Traffic Volume	Beginning ADT (vehicles/day)	20-Year End ADT (vehicles/day)	Percent Truck (%)
High	25,000	50,000	25
Medium	7,500	15,000	17
Low	1,000	2,000	2

The required design/simulation inputs for the TxME were collected from TxDOT resources, online resources, and the literature. These input values included typical material properties for each layer, soil data, traffic data, and climate data (e.g., subsurface water table, precipitation, and temperature). Unflooded pavements were simulated using TxME to determine the service life of dry pavements without any flood events. The design/simulation parameters affected by flooding were then changed to simulate a flooding event(s). These parameters include resilient modulus and rutting parameters of unbound layers, traffic levels, and most importantly, subsurface water level. Different flood scenarios were simulated to explore the potential impact to different pavement structures. The outcome of the simulations is therefore dependent upon the inputs for each variable and the output should be considered specific to those inputs. However, the knowledge gained through simulations can be used to inform decisions about other scenarios where the inputs are different. Several flood event scenarios were defined. It was assumed that the pavements would be in service for at least 20 years. The following four flood event scenarios were used to assess the impact to existing pavements:

I. Flooding happens in year 1 after pavement construction.

II. Flooding happens in year 10 of the pavement's life.

III. Flooding happens in year 20 of the pavement's life.

IV. Flooding happens consecutively in year 15, 16, and 17 of the pavement's life.

For the simulations, flooding is defined as the complete inundation of the subgrade material. The depth of inundation is assumed to be enough and last long enough to saturate the subgrade completely. The simulations represent scenarios that can be used by network managers to assess impacts on their network. For example, Scenarios 1 through 3 can be used to consider the impacts of a single flood event at various stages throughout the life of a pavement. While the damage caused by flooding at these different pavement ages is not linear, it creates a perspective for network managers to understand the potential impact given their knowledge of the network's age. Scenario 4 provides results of consecutive floods that compound the amount of damage caused. Using the results of these simulations engineers have a better understanding of how consecutive events can impact their network.

The simulation was repeated with the modified input values to estimate reductions in the service life of the pavements for each of the flood events. Total rut depth of 0.5 in. was selected as the design limit, dictating the end life of flooded pavements. Figure 12 illustrates the simulation framework.

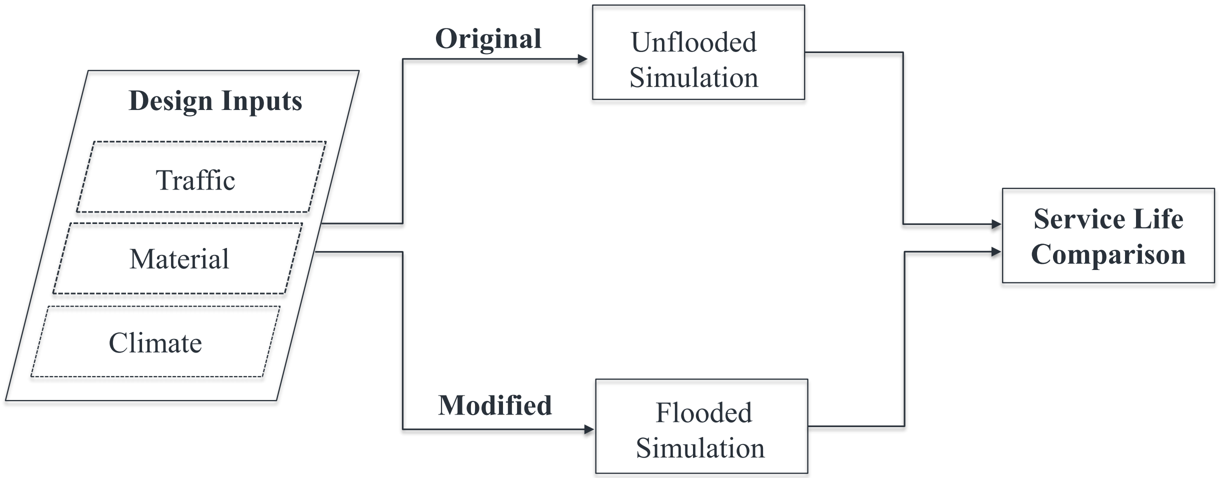


Figure 12. Simulation Framework.

Infrastructure Impacts

Structure I

Pavement Structure I is the strongest pavement structure and is designed for higher traffic levels. Pavement Structure I was therefore simulated using the high traffic level assumption. Figure 13 shows the rut-depth curve associated with each layer of Structure I when there is no flooding.

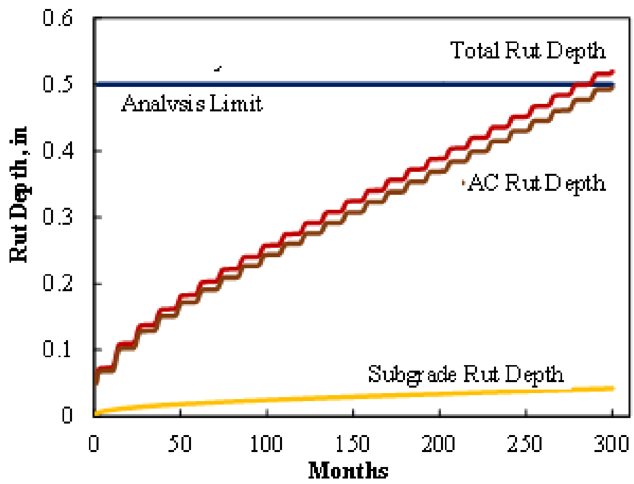
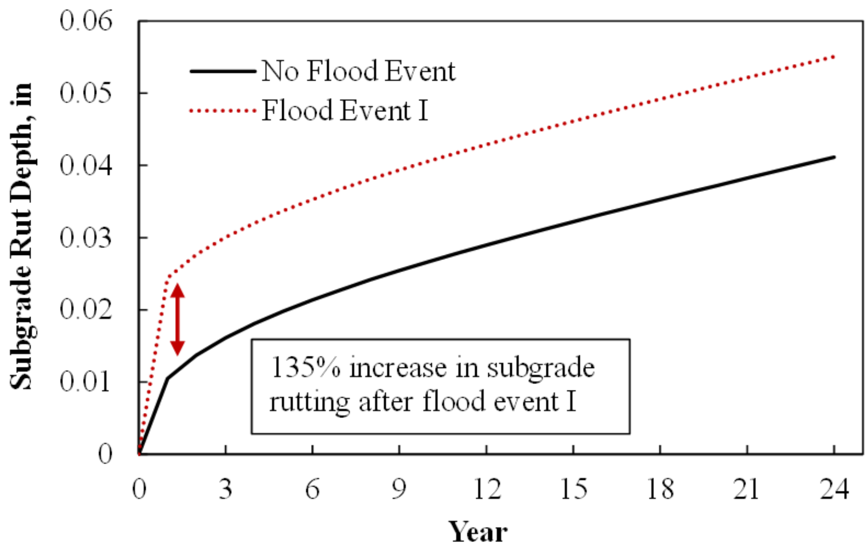
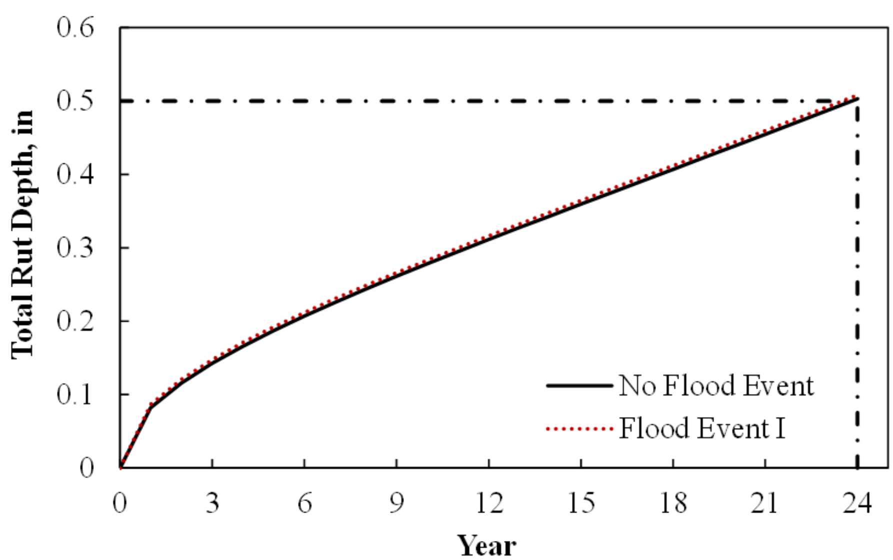


Figure 13. Development of Rutting in an Unflooded Pavement with Structure I.

The unflooded simulation results show that the contribution of subgrade rutting to total rutting is almost 8 percent; thus the rutting of this structure is dominated by rutting of the AC layer. Figure 14 shows that the service life of a pavement with Structure I is estimated to be 24 years (i.e., 288 months) in the absence of flooding events. The analysis results show that Flood Event Scenario I increase the subgrade rutting by more than 100 percent (Figure 14(a)). However, the impact on the total rutting is negligible given the small contribution of subgrade rutting to the total rut depth (Figure 14(b)).



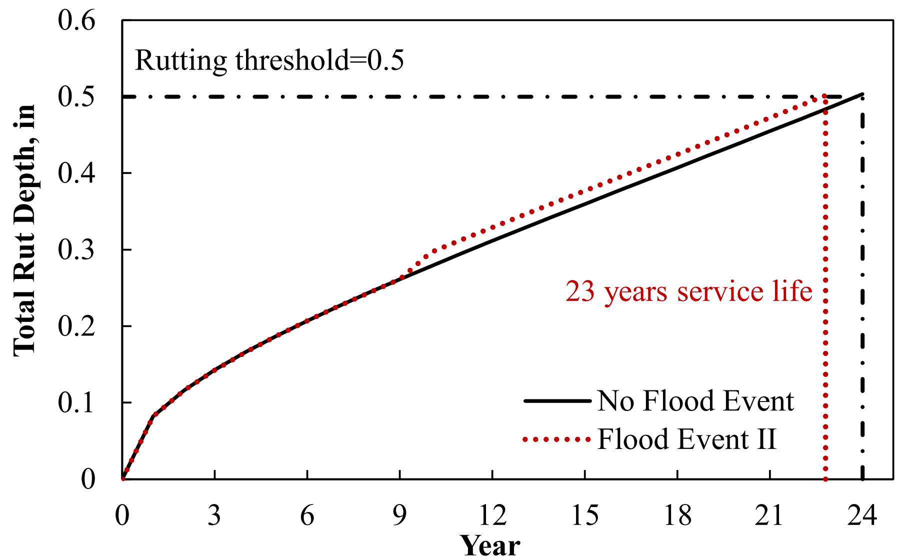
(a)



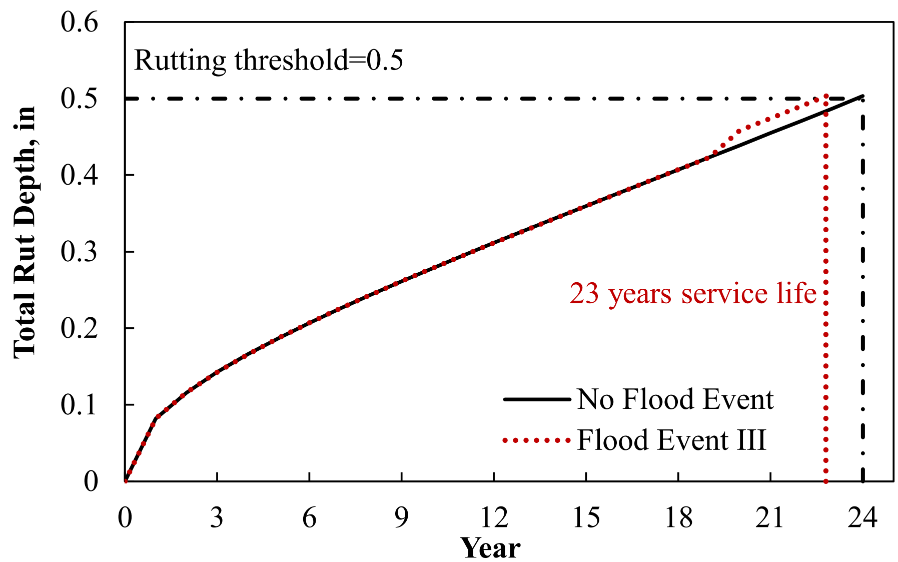
(b)

Figure 14. Structure I Given Flood Event I (a) Subgrade Rutting (b) Total Rutting.

The service life of this pavement given Flood Event I remained 24 years. Flood Event I therefore does not cause serious long-term damage to this structure. Flood Event I essentially assumes that a new road was flooded within the same year of construction. In reality, most of the network has been in service for several years when it experiences a flood event. Therefore, researchers also conducted simulations that varied the timing of flood events. Figure 15(a), (b), and (c) present the total rut depth of Structure I under the Flood Event II, III, and IV scenarios. Flood Event scenarios II, III, and IV increase the total rut by 6 percent, 6 percent, and 12 percent, respectively. The results are a reduction of the pavement service life by 1, 1, and 3 years, respectively. The use of treated base and treated subgrade mitigates the impact of flooding on this structure.



(a)



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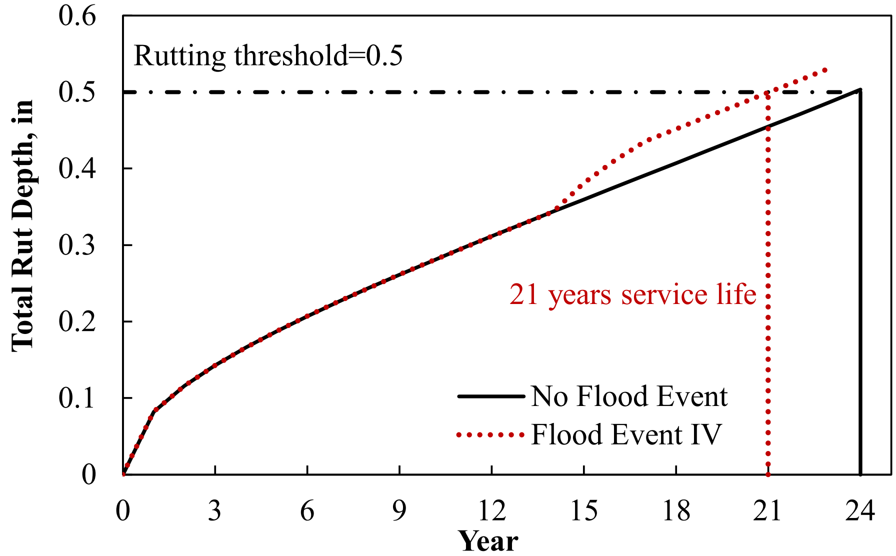


(c)

Figure 15. Service Life of Structure I Given Flood Events (a) I, (b) II, and (c) III.

Structure I is a robust pavement structure that is not prone to failure after flooding. Relatively new Structure I roads (i.e., less than 10 years) are not impacted by flooding in terms of a reduction in service life. Once Structure I roads have been in service for 10 or more years, each flood event reduces the structure's service life by one year. This is not to say that some Structure 1 roadways that have been in service for less than 10 years will not experience loss of life. Certainly, a Structure 1 roadway that has been in service for nine years is more likely to experience a loss of life than one that has been in service for only one year. As indicated before, the simulation results are specific to the set of inputs used. However, network managers can use these results and the knowledge of their network to assess the potential impact they will experience. For example, if a large network consists primarily of thicker pavement sections, similar to Structure I, the impact from flooding should not be extensive. However, using institutional knowledge of the age of the network, engineers might want to further investigate the older sections of the network or begin to consider programing work for those sections given consecutive flooding events.

Structure II

Pavement Structure II is not designed for medium or high traffic levels; it was simulated only under low traffic levels assuming no flood events. Figure 16 shows the rut depth developed in each layer of this structure in the absence of a flood event. The contribution of the flexible base rutting to total rutting is more than 95 percent. Rutting in this structure is therefore determined by the base rutting. The service life of this structure is 24 years given low traffic levels and no flood events.

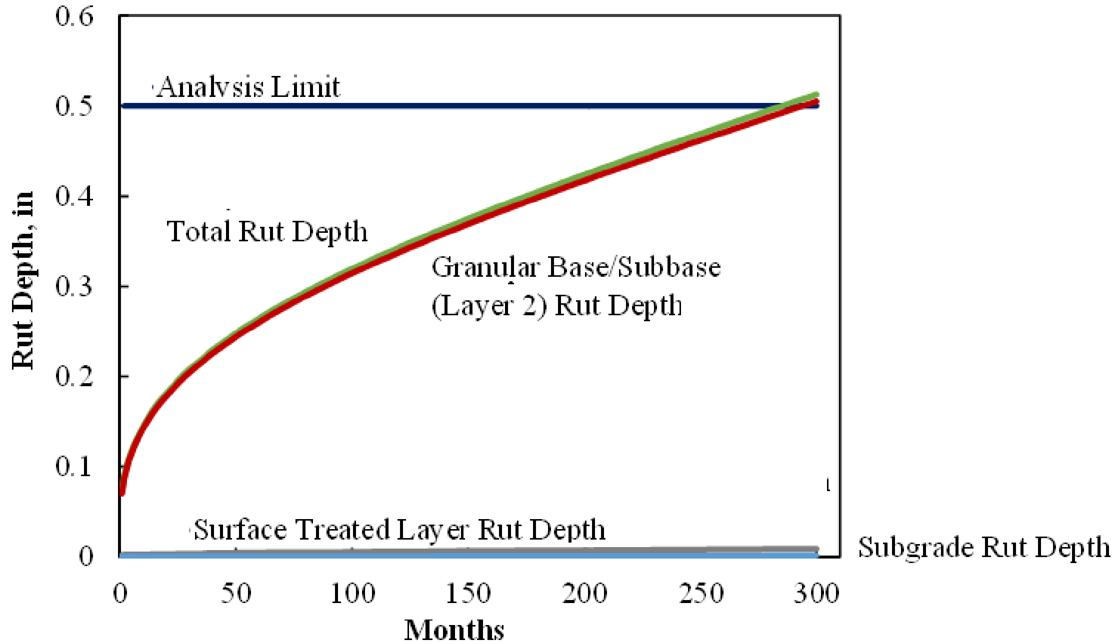
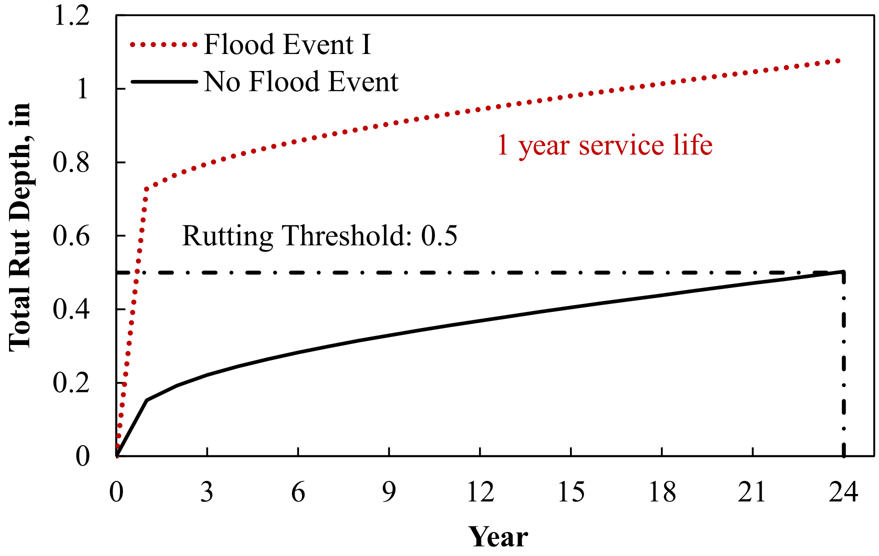


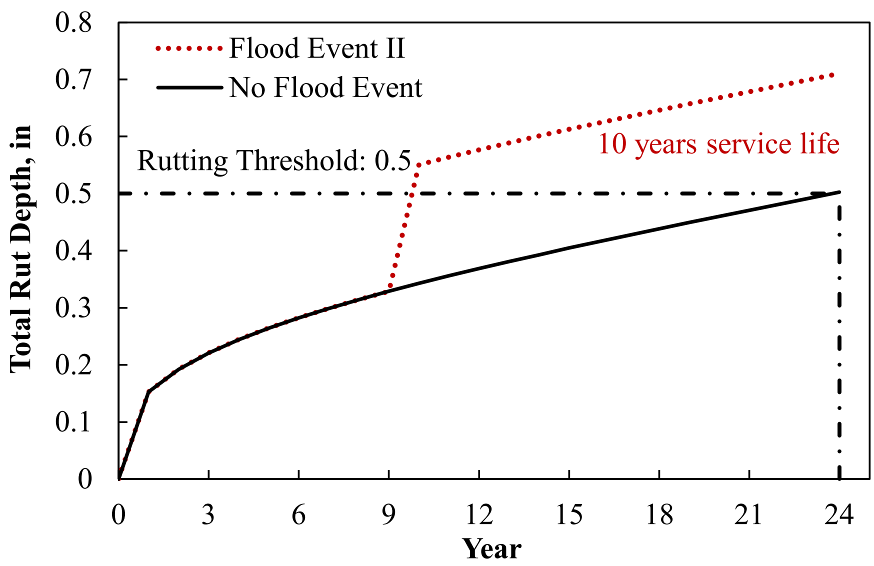
Figure 16. Development of Rutting in an Unflooded Pavement with Structure II.

Figure 17(a), (b), (c), and (d) illustrate the total rut depth of Structure II given Flood Event scenarios I, II, III, and IV, respectively. This structure is severely impacted by flooding, such that the total rutting exceeds the 0.5 in. threshold after one flooding event. This is attributable to the large increase in FB rutting after flooding. Since the FB rutting has a major impact on total rutting, an increase in base rut depth causes a notable increase in the total rut depth. The major factor in early rutting failure (i.e., pavement damage) comes from the increase in traffic immediately after the flood event. As previously described for Pavement Structure II, the typical low volume traffic used for pavement life analysis was increased by 50 percent and the volume of trucks was increased to 25 percent immediately after the flood event. This increase was used to capture traffic loadings associated with recovery efforts (e.g., debris removal and utility repair). In addition to the increase in traffic, base resilient modulus, and rutting parameters α, μ, attributable to a flooding event are the main causes of the flood-induced damage to Structure II.



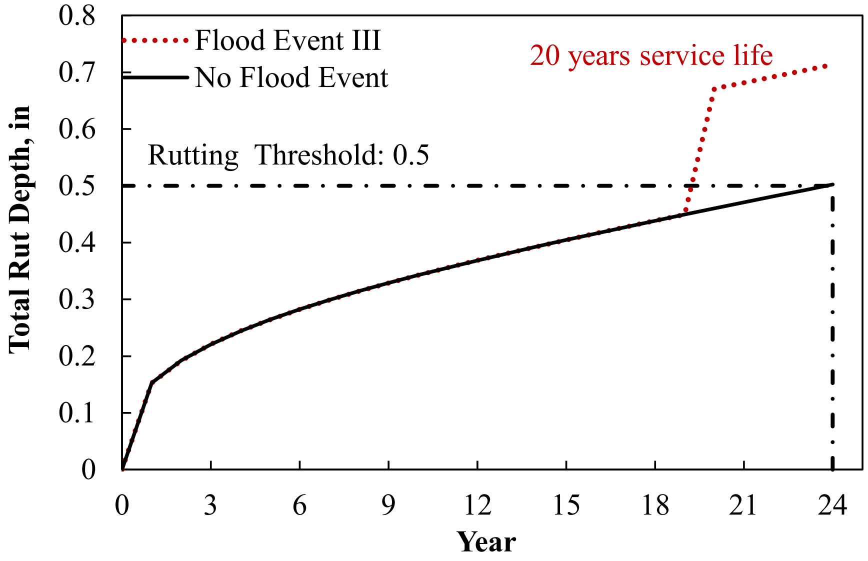
1.2
1
0.8
0.6
0.4
0.2
0
Flood Event I
No Flood Event
1 year service life
Rutting Threshold: 0.5
Total Rut Depth, in
0
3
6
9
12
15
18
21
24
Year

(a)

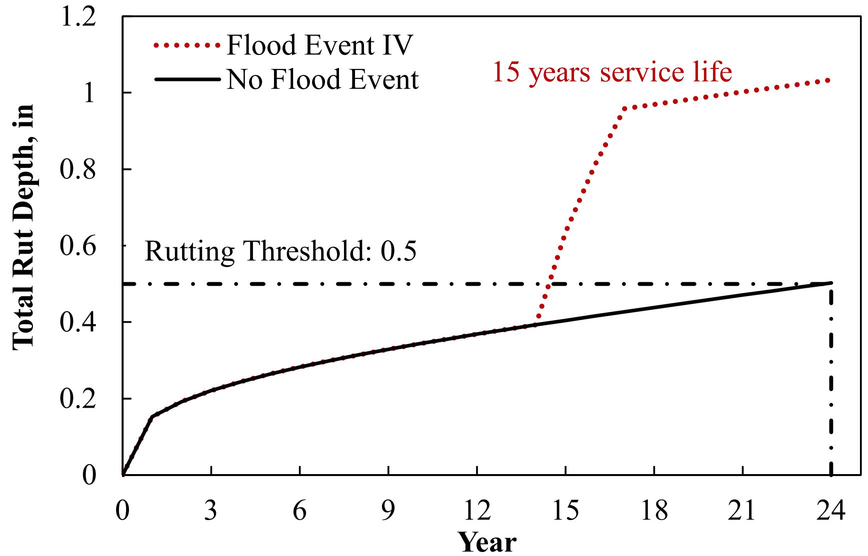


0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Flood Event II
No Flood Event
Rutting Threshold: 0.5
10 years service life
Total Rut Depth, in
0
3
6
9
12
15
18
21
24
Year

(b)



(c)



(d)

Figure 17. Service Life of Structure II Given Flood Event Scenarios (a) I, (b) II, (c) III, and (d) IV.

Figure 18 shows the service life reduction of Structure II under the various Flood Event scenarios under low traffic levels. Under low traffic levels, the service life of Structure II decreases by:

- 8 years if the flooding event happens in the first year of the roads construction (Flood Event scenario I).
- 5 years if the flooding event happens in year 10 of the road's service life (Flood Event scenario II).
- 4 years if the flooding event happens in year 15 of the road's service life (Flood Event scenario III).
- 8 years if flooding happens in year 15, 16, and 17 of the road's service life (Flood Event scenario IV).

Flood Event Scenario I and IV had the greatest impact on the pavement service life. It is generally agreed that rutting develops gradually. Equation (2) (Appendix B) shows that rutting follows a concave model in which the rate of increase in rutting declines with the number of load repetition. In other words, the rate of increase in accumulated rut depth is greater in the early stages of the pavement's life. Flooding events in the early years of the pavement life will therefore have a bigger impact on rutting, particularly for pavements where rutting is determined by the unbound layers. Figure 18 implies that the reduction of service life is mainly due to the changes of the resilient modulus and the rutting parameters of unbound layers.

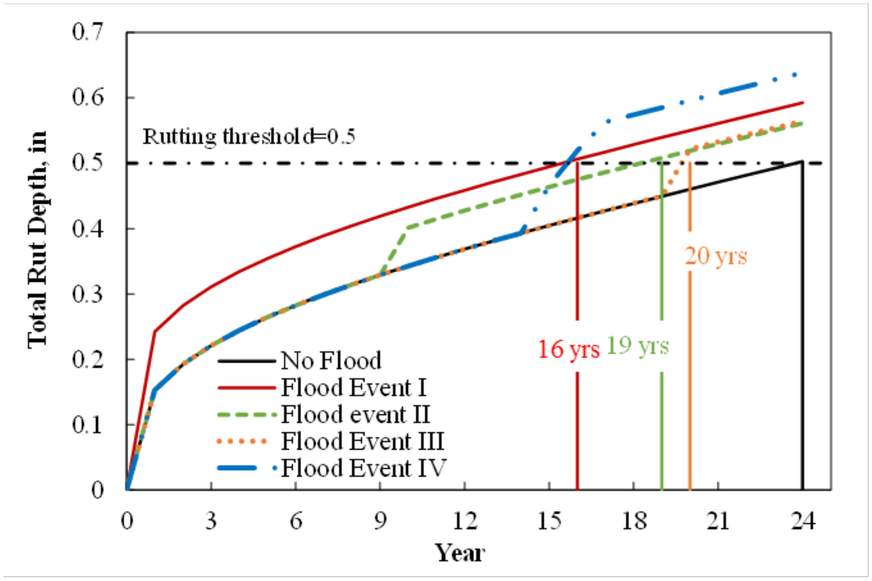
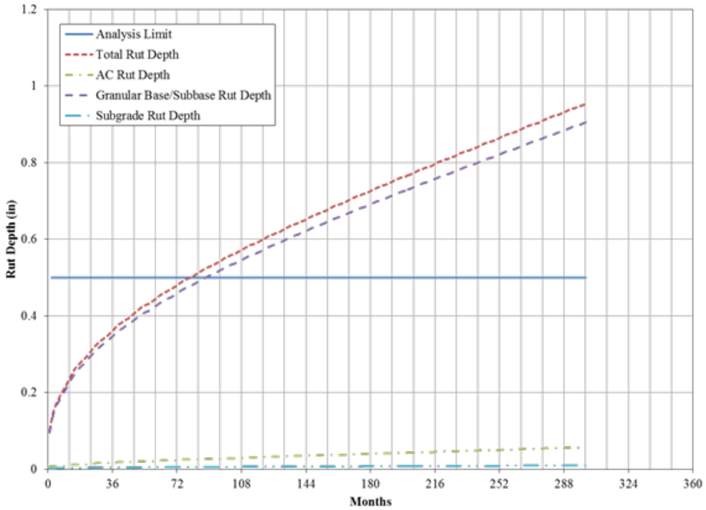


Figure 18. Service Life of Structure II Given Four Flood Event Scenarios Assuming Low Traffic Levels.

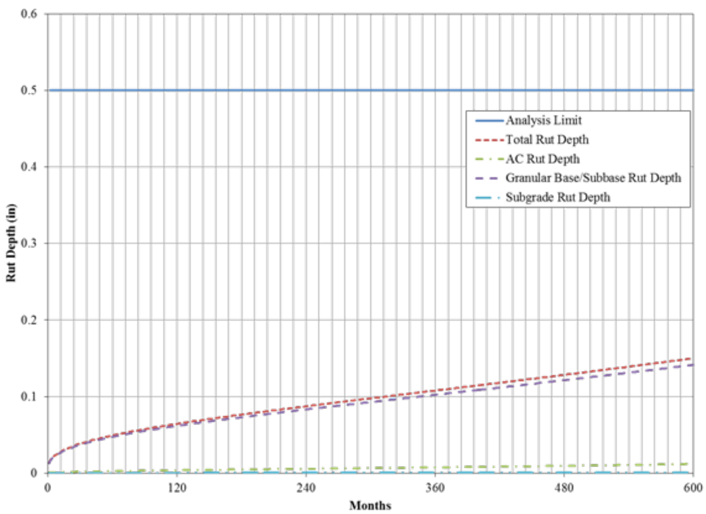
Unlike Structure I, where rutting is determined by the AC layer, rutting in Structure II is determined by the unbound layers, particularly the FB. The unbound layers sensitivity to moisture content leads to immediate failure following a flood event if traffic levels are increased.

Structure III

Similar to Structure II, total rutting in Structure III is determined by the base rutting. In the absence of flooding events, the service life of this structure is estimated to be only seven years under medium traffic levels. This is due to the untreated base. Under low traffic levels, the service life of Structure III is approximately 40 years. This type of pavement structure serves local municipalities well on low traffic volume roads when flooding does not occur. Figure 19 shows the rutting curves for Structure III under medium and low traffic volumes. Under low traffic volumes, the total rut depth of this structure is well below the threshold even after 600 months of service. Given that the service life of this pavement structure is shorter under medium traffic levels (i.e., seven years) than the timing assumptions of Flood Event Scenarios II, III, and IV, the impact of flooding on the serviceability of this structure was only simulated for low traffic levels.



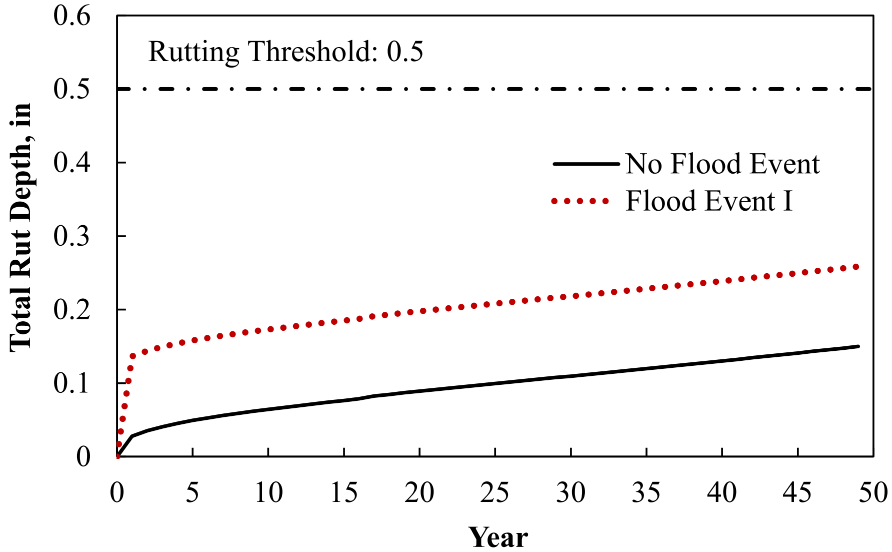
(a)



(b)

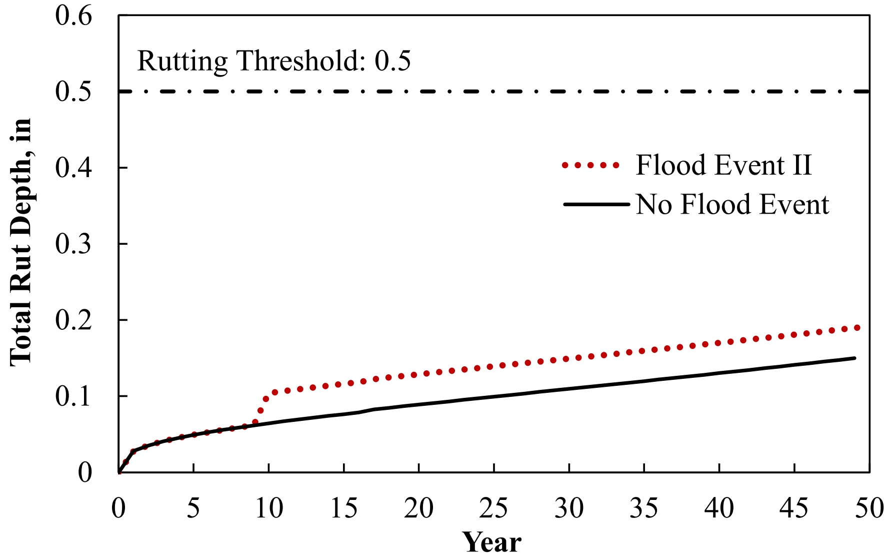
Figure 19. Development of Rutting in an Unflooded Pavement with Structure III under (a) Medium Traffic (b) Low Traffic.

Figure 20 presents the results of the flood event simulation on this structure. Figure 20 shows that flooding events increase rutting, but the total rut depth never reaches the failure threshold regardless of the Flood Event scenario (under low traffic levels). The 2-inch AC layer and decreased thickness of the FB by 6 inches relative to Structure II result in this structure experiencing less rutting. The FB is a major contributor to the flood damage incurred, hence decreasing the FB thickness, while adding a stronger surface layer can improve the rutting performance significantly.



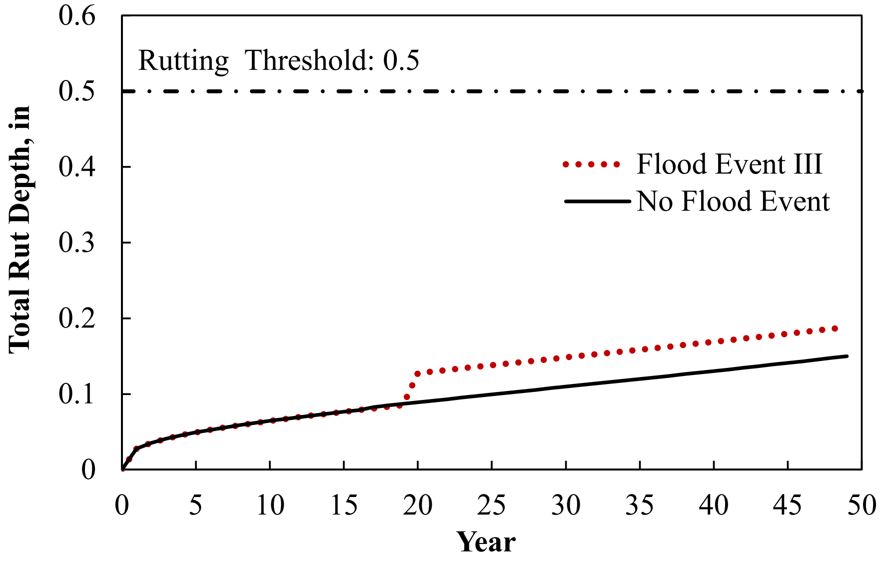
Rutting Threshold: 0.5
No Flood Event
Flood Event I
Total Rut Depth, in
Year
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
35
40
45
50

(a)

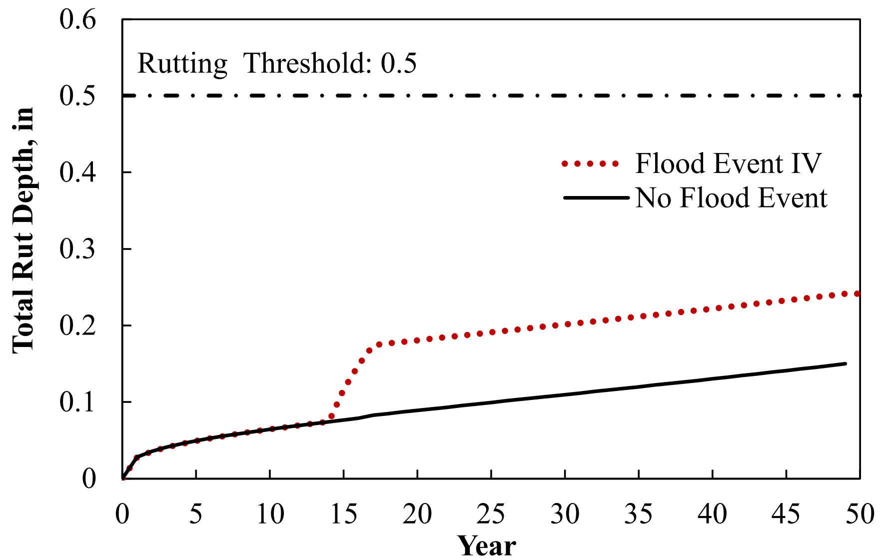


Rutting Threshold: 0.5
Flood Event II
No Flood Event
Total Rut Depth, in
Year
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
35
40
45
50

(b)



(c)



(d)

Figure 20. Service Life of Structure III under Flood Event Scenarios (a) I, (b) II, (c) III, and (d) IV (Low Traffic Levels).

Utility of Pavement Simulations for Asset Management

The data and methodologies outlined in this section of the report provide the agency with a framework to better assess the impacts of flooding on its state-maintained network. Although the pilot study was focused primarily on the Houston District, the methods can be used to assess the impacts of flooding events on the entire state's road network. The results of applying the methodologies can also be used to inform changes to TxDOT's pavement management system (Pavement Analyst), such as deterioration models and decision trees to select investment strategies in preparation for and in the aftermath of future flooding events.

The data and models outlined in the previous section of this report provide methods to determine: a) the likelihood of flood events occurring (flood depth and road elevation data); and b) the impacts of flood events on the longevity of pavements.

This section uses these data to provide a more *complete* risk assessment of flood impacts on TxDOT Houston District's road infrastructure (i.e., where risk is defined in this study as the product of the probability of an event occurring and the probability of the impact of that event (Equation 1).

This section of the report documents:

- An assessment of the risk of Houston's road infrastructure to flooding.
- Potential mitigation measures that can be implemented to ensure a more resilient state-maintained road system.
- The costs involved in implementing the identified mitigation measures. These costs can be used in future lifecycle planning efforts.
- Potential proxy indicators that the agency can track to anticipate the impacts of future flooding events.

Houston's Road Infrastructure Vulnerable to Inland Flooding

The data layers and methodologies outlined earlier allowed researchers to identify the state-maintained system vulnerable to:

- Pavement flooding and associated damage – Pavement Structures I (Pavement Type 5), II (Pavement Type 10), and III (Pavement Type 6).
- Disruptive impacts/road closures – Pavement sections that are impassable because of floodwater over the road.

The following two-tiered risk assessment approach was adopted:

- First, the FEMA floodplain boundaries were used to delineate flooding for the entire Houston District. To determine flood impacts, researchers overlaid these data with pavement data for the on-system TxDOT network, yielding estimates of the lane miles of each pavement type affected by regular flood events that occur within delineated floodways, 100-, or 500-year flood events.
- Researchers developed a refined risk assessment approach for Harris County. The refined approach overlaid flood depth and road elevation data of the state-maintained network to obtain the depth of road inundation). Overlaying these two layers also allowed the study team to estimate: a) the likelihood of roads becoming impassable during floods; b) sections most at risk to flooding because of pavement structure and the depth

of flood water (where flood water depth is assumed to be a proxy measurement for duration and frequency of inundation).

- In both risk assessment approaches, researchers used pavement structure information[4] for the Houston District's state-maintained network to determine vulnerable sections. As indicated previously, the pavement impact analysis conducted revealed that pavement structures II (Pavement Type 10) and III (Pavement Type 6) are prone to flood damage. The analysis also showed that relatively new Structure I roads (i.e., less than 10 years) are not impacted by flooding in terms of a reduction in service life. Once Structure I roads have, however, been in service for 10 or more years, each flood event reduces the structure's service life by one year. Researchers identified the locations of Pavement Types 5, 10, and 6 in Harris County and determined the sections vulnerable to pavement damage by overlaying the pavement structure layer with the flood and road elevation layers. These pavement structures may be affected by floodwater even if their surface is not completely inundated.

Figure 21 and Table 3 show the incidence of flood risk on segments of the state-maintained network in the Houston District. Specifically, Figure 21 shows the road segments that are not vulnerable to flooding (black lines), road segments in the floodplain (red lines), and segments that are within the 100-year (yellow lines) and 500-year (orange lines) flood zones.[5].

[4] Included in Pavement Analyst

[5] There are currently no official flood maps for Brazoria and Galveston Counties. Unofficial FEMA flood maps were therefore used for these counties.

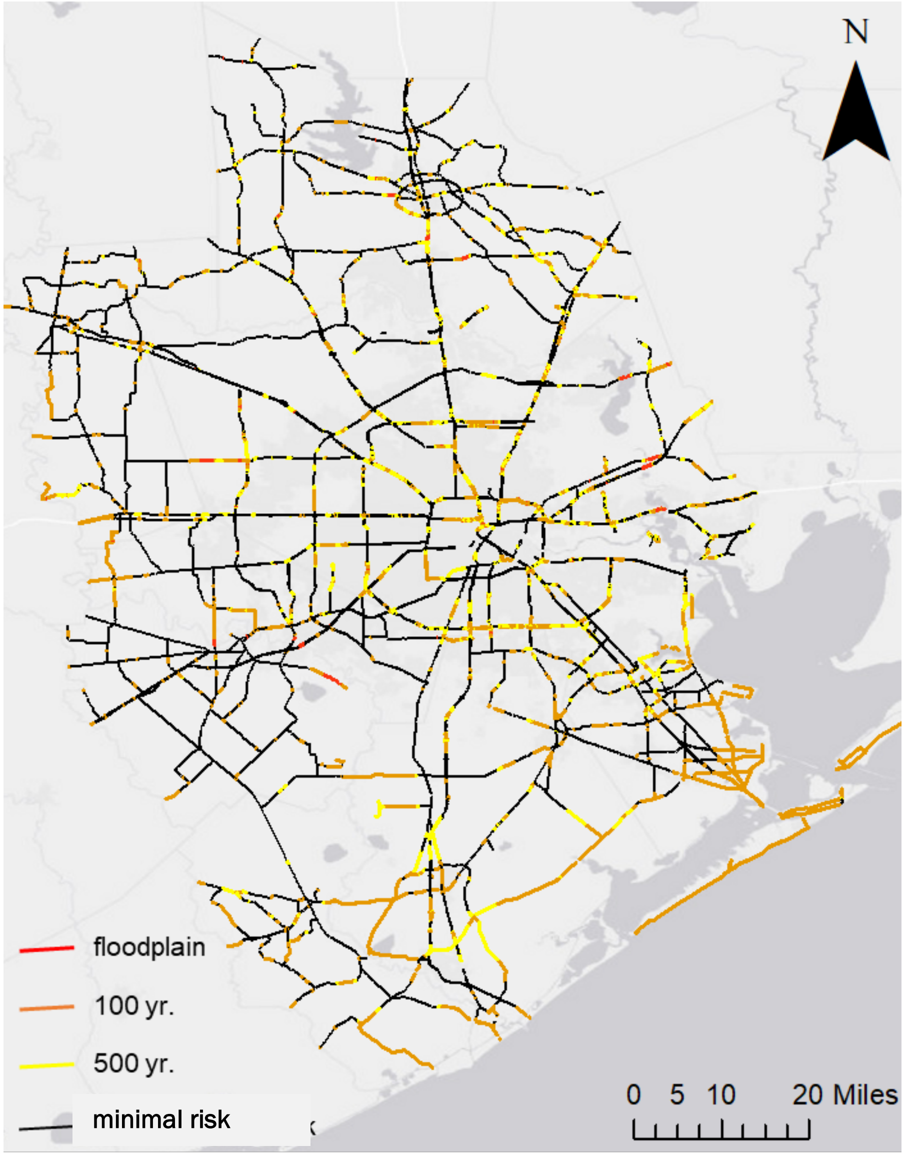


Figure 21. Houston District Road Network Color Coded by FEMA Flood Risk Zone.

Table 3 shows the pavement lane-miles by pavement type at risk of flooding in TxDOT's Houston District. From Table 3, it is evident that almost 75 percent of the state-maintained lane miles in the Houston District are at minimal risk of flooding. Moreover, of the vulnerable pavement types (Pavement Types 6 and 10), almost 50 percent of the lane-miles are at minimal risk of flooding.

*Table 3. Summary of Pavement Lane Miles versus Flood Risk for TxDOT's Houston District.**

Pavement Type	Minimal Flood Risk	Flood Plain	100-Year Risk	500-Year Risk	Total
1	3,782.4	116.2	517.5	422.8	4,839
2	128.3	2.1	35.6	29.1	195
3	49.0	4.0	20.0	11.4	84
4	1.7	0.0	0.0	0.0	2
5	**2,042.3**	**42.2**	**518.7**	**142.4**	**2,746**
6	**0.9**	**0.1**	**7.6**	**0.3**	**9**
7	264.5	2.9	86.6	33.5	388
8	304.6	5.1	114.0	65.8	489
9	442.9	1.3	159.2	56.0	659
10	**51.9**	**0.0**	**40.8**	**8.4**	**101**
Total	7,069	174	1500	770	9,512**

* The categories are exclusive, i.e., a road section measured in a 500-year zone is not counted in a 100-year zone.

** There are 10,077 lane miles in Houston, but not all have up to date pavement information.

Researchers overlaid the flooding data layers (spatial extent and flood depth) with the road elevation data layer for the TxDOT state-maintained network in Harris County to determine whether a road pavement will be inundated by flood water. Figure 22 shows the different levels of inundation (maximum floodwater depth) on the state-maintained network based on estimated local flood water depth, road elevation, and the 100-year FEMA flood maps. The time it takes the subgrade to dry dictates the amount of pavement damage. While depth of inundation provides a proxy indicator for how long the pavement might remain under water, this timeframe is typically relatively short in relation to how long the subgrade takes to dry. For example, if the subgrade takes 90 days to "dry back," the difference between the roadway being underwater for three days or six days will have little impact on the overall damage. However, the higher the level of inundation the higher the risk of pavement damage to the network (because of more pavements potentially going under water, thus impacting more of the system. There are also disruptive impacts through road closures.

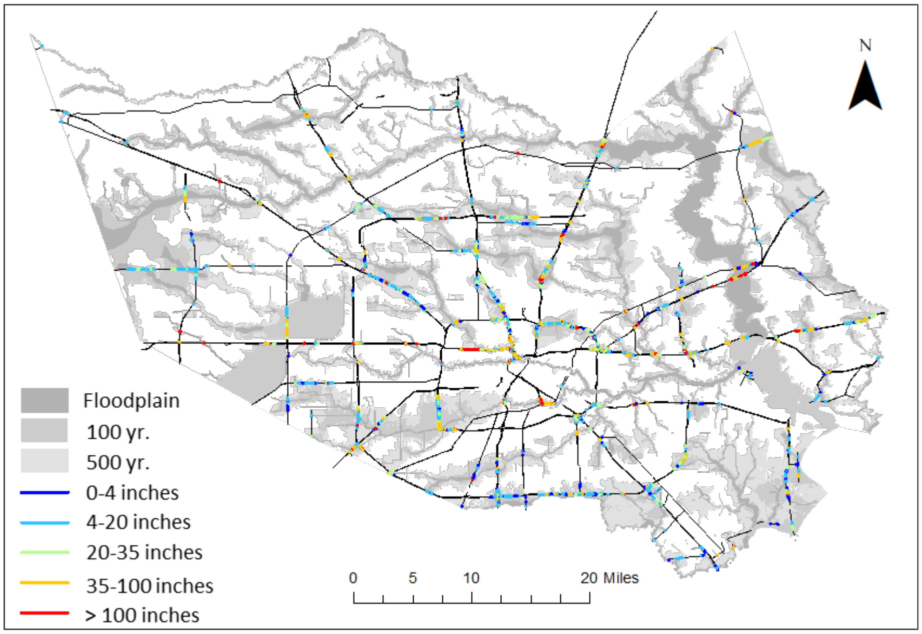


Figure 22. Estimated 100-Year Water Inundation Levels of TxDOT State-Maintained Network in Harris County.

Figure 23 shows the different levels of inundation (maximum flood water depth) on the state-maintained network based on estimated local flood water depth, road elevation, and the 500-year FEMA flood maps.

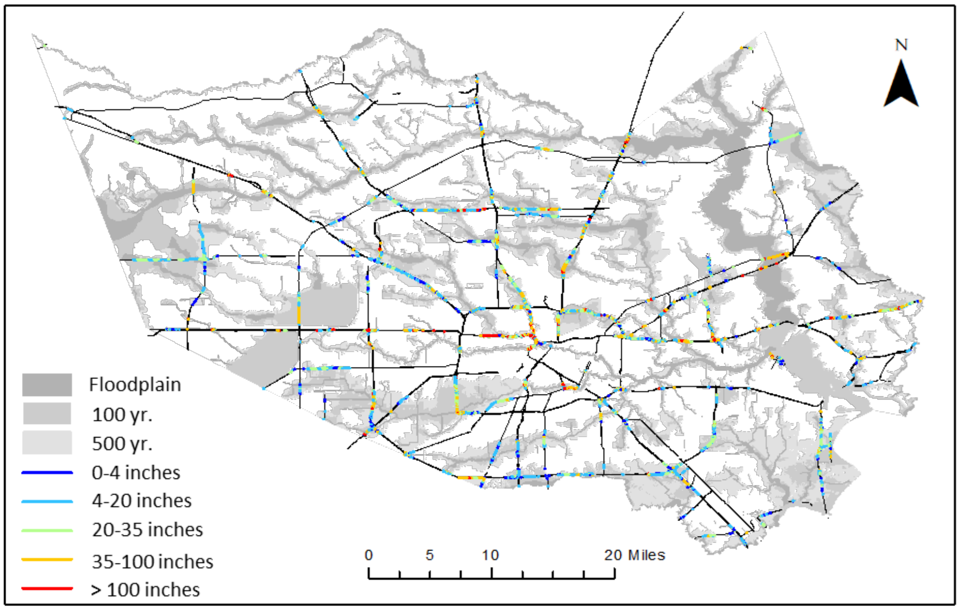


Figure 23. Estimated 500-Year Water Inundation Levels of TxDOT State Maintained Network in Harris County.

Table 4, Table 5, and Table 6 provide the estimated inundation depths for the TxDOT state-maintained network by pavement type (expressed in lane-miles) in Harris County for events delimited by the floodplain, the 100-year FEMA flood zone, and the 500-year FEMA flood zone. Table 4 shows that almost 97 percent of the state-maintained lane-miles in the floodplain in Harris County is not at risk of flooding.

Table 4. Estimated Inundation Depths of Roads in Harris County for ***Regular*** *Flood Events (i.e., Events Delimited by the Floodplain).*

Pavement Type	Not Flooded	> 0–4 inches	4–20 inches	20–36 inches	36–100 inches	>100 inches	Total
1	3,192.7	91.2	8.8	2.7	5.7	0.5	3,302
2	159.4	7.2	0.2	0.1	0.0	0.0	167
3	67.1	0.6	0.1	0.2	0.3	0.0	68
4	1.7	0.0	0.0	0.0	0.0	0.0	2
5	**794.4**	**18.8**	**6.8**	**3.5**	**0.3**	**0.4**	**824**
6	**3.9**	**0.0**	**0.0**	**0.0**	**0.1**	**0.0**	**4**
7	76.8	0.0	0.4	0.3	0.2	0.0	78
8	319.6	0.4	0.1	0.0	0.2	0.0	320
9	54.7	0.0	0.0	0.0	0.0	0.0	55
10	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0**
Total	4,670	118	16	7	7	1	4,820

Table 5 shows that almost 12 percent of the state-maintained lane-miles in Harris County is at risk of flooding in the case of 100-year events. Table 5 also shows that most of the impacts will be disruptive as compared to damage to the pavement structure since very few lane-miles in Harris County comprise Pavement Types 6 and 10. However, managers with thin pavement structures should be more concerned about flooding impacts and should consider the results of the simulations in light of the age of the network they manage. Slightly more than 5 percent or 254 of the lane-miles in Harris County will be inundated with 20 or more inches of water in a 100-year flood event. Road closures of the state-maintained network can, however, potentially result in damage to the county and city network if traffic is diverted to roads with weaker pavement structures.

Table 5. Estimated Inundation Depth of TxDOT Roads in Harris County for 100-Year Flood Events.

Pavement Type	Not Flooded	> 0–4 inches	4–20 inches	20–36 inches	36–100 inches	>100 inches	Total
1	2,932.7	112.6	94.5	55.4	67.3	39.0	3,302
2	130.5	13.6	12.4	7.0	3.3	0.1	167
3	52.4	0.6	4.9	5.2	4.2	0.9	68
4	1.7	0.0	0.0	0.0	0.0	0.0	2
5	**752.3**	**20.5**	**21.7**	**10.9**	**12.7**	**6.1**	**824**
6	**1.8**	**0.3**	**1.7**	**0.2**	**0.0**	**0.0**	**4**
7	72.7	0.6	1.0	1.1	2.0	0.5	78
8	258.8	4.5	19.5	15.7	18.1	3.8	320
9	53.8	0.2	0.7	0.1	0.0	0.0	55
10	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Total	4,257	153	156	96	108	50	4,820

Table 6 shows that almost 18 percent of the state-maintained lane-miles in Harris County are at risk of flooding in the case of 500-year events. Similar to the 100-year events, Table 6 also shows that most of the impacts will be disruptive as compared to damage to the pavement structure since very few lane-miles in Harris County comprise Pavement Types 6 and 10. Almost 9 percent or 411 of the lane-miles in Harris County will be inundated with 20 or more inches of water in a 500-year flood event.

Table 6. Estimated Inundation Depth of TxDOT Roads in Harris County for 500-Year Flood Events.

Pavement Type	Not Flooded	> 0–4 inches	4–20 inches	20–36 inches	36–100 inches	>100 inches	Total
1	2,762.9	120.6	170.8	80.1	110.1	56.9	3,302
2	112.8	10.0	17.3	18.1	8.2	0.5	167
3	46.0	1.5	5.9	7.1	6.6	1.1	68
4	1.7	0.0	0.0	0.0	0.0	0.0	2
5	**707.7**	**24.5**	**39.0**	**24.9**	**18.0**	**10.2**	**824**
6	**3.1**	**0.3**	**0.5**	**0.0**	**0.0**	**0.0**	**4**
7	67.5	1.3	3.5	1.8	3.1	0.7	78
8	220.9	4.9	32.7	28.8	24.8	8.3	320
9	51.3	0.7	2.1	0.7	0.0	0.0	55
10	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Total	3,974	164	272	162	171	78	4,820

Potential Mitigation Measures

Pavement Damage

According to researchers' analysis, there are nine lane-miles of Pavement Type 6 in the Houston District and 101 lane-miles of Pavement Type 10 (see Table 3). Figure 24 shows a map showing the locations of these roadways.

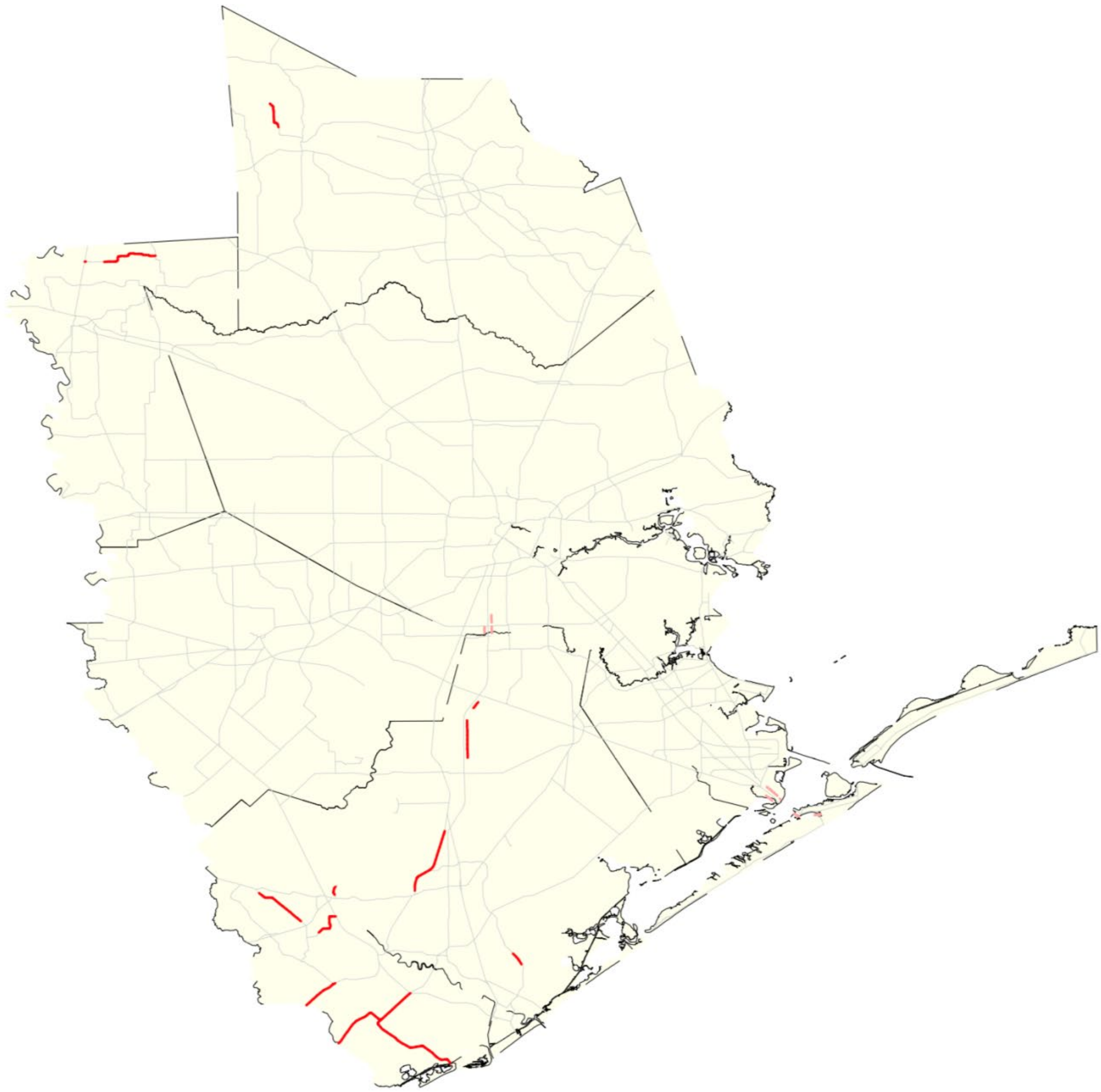


Figure 24. Locations of Pavement Types 6 and 10 Roadways in the Houston District.

The pavement impact analysis documented earlier showed that the base course, subgrade type, and pavement structure have the most influence on the rutting performance of the flooded pavement. The use of treated base and treated subgrade mitigated the flood impact significantly. In addition, unbound base layers contributed to flood damage.

The simulation results showed that the service lives of the weak pavement structures (i.e., the structures designed for low traffic):

- Are unaffected by flood events assuming the design level of traffic after the event (Pavement Type 6).
- Loses structural capacity equivalent to four to eight years of service life (depending on when the flood event happens in the design life of the pavement and the frequency of flooding events) (Pavement Type 10).

Since it is anticipated that traffic volumes (specifically truck volumes) increase during the recovery phase of an extreme flooding event,[17] researchers conducted the simulation analysis assuming higher traffic volumes on Pavement Types 10 and 6. Although these facilities may not serve a significant amount of traffic during normal operations, they could become critical during extreme weather events to provide safe routes for motorists. The simulation results showed that the weak pavement structures are extremely vulnerable to an increase in the number of post-flooding heavy vehicles and fail immediately.

"As of October 2017, TxDOT collected at least an estimated 12 million cubic feet of debris, which if spread out would cover the equivalent of about 222 football fields. Debris removal remained ongoing for several more months .... As of early October 2017, TxDOT faced costs of over $150 million that included damage repair, equipment and facility costs, and the costs of mobilizing TxDOT staff and crews."[15]

Figure 25 provides a snapshot of some of the simulation results. First, Structure I has a typical service life of 24 years under heavy traffic loading when there is no flood event. Event I represents a flood event immediately after pavement construction. This event has no impact on the service life of the pavement, so the service life remains 24 years in Event I. However, as the pavement remains in service for 10 or more years and gets flooded, the service life begins to shorten. The service life is essentially shortened by one year per event for pavements older than 10 years. For Event IV, when floods occur in three consecutive years, the service life is reduced from 24 years to 21 years. The results shown for Pavement Structure II in Figure 25 display the failure that can occur for this structure immediately after flooding when the roadway is heavily trafficked. The typical service life of Structure II is 24 years under low traffic volume, but when the roadway is flooded and traffic increases significantly in the year immediately after flooding, failure occurs almost immediately. In summary, if a large recovery effort is required on roadways with a similar structure to Pavement Structure II, the managing agency should plan for immediate rehabilitation projects.

The results for Pavement Structure III show that under consistent low traffic volume (i.e., a recovery effort that does not include a major increase in traffic) the service life of the pavement remains unchanged regardless of the flood events. This type of structure can be a resilient structure for roadways that are trafficked predominantly by vehicular traffic (e.g., a neighborhood street). However, similar to Pavement Structure II, Pavement Structure III will fail quickly under heavy traffic loading.

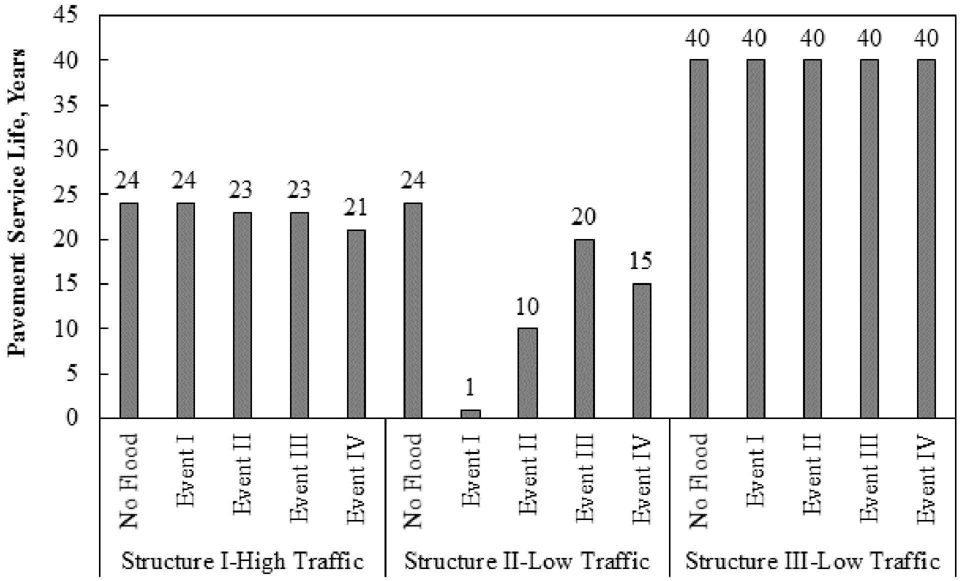


Figure 25. Summary of the Simulation Results for the Three Studied Structures.

In the case of both Pavement Types 10 and 6, the roadways at risk of flooding may need to be reconstructed to the specifications of Pavement Type 5 (i.e., AC surfaced pavement structure) to withstand future flooding events. Only 57.1 lane-miles of Pavement Type 6 and 10 are vulnerable to flooding in TxDOT's Houston District (see Table 3). It will cost the agency $17.2 million to reconstruct these pavements to the specifications of Pavement Type 5. It is, however, recommended that TxDOT conduct a project level analysis to determine if these roadways need reconstruction. The criticality of these roads also needs to be considered.

Normally reconstruction involves the use of new materials, but full depth reclamation (FDR) may be an option for these roadways (see Figure 26). This process involves pulverizing and stabilizing the existing pavement in place with cement, asphalt emulsion, or other stabilizers. The stabilized layer becomes either the base or subbase of the new pavement structure. This process has been used widely for over 20 years in Texas to strengthen and widen structurally inadequate pavement sections.[6] This can also be a cost-effective option for city and county roadways that are impacted by flooding.

Two additional options exist. TxDOT can also abandon the infrastructure or restrict the number of trucks using these roadway segments after a flooding event, but these options may not be politically feasible.

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6 TTI Research Project 0-6271 developed guidelines on successful FDR practices, developed training materials, and identified areas where improvements to current practices are required. These guidelines were adopted by TxDOT and incorporated into their pavement design and construction practices. In particular, field and laboratory testing need to be conducted on the existing pavement to determine if it would be a candidate for FDR. Generally, pavements that have been contaminated with clay soils would not be candidates for FDR. However, the FDR process can be considerably lower in cost than reconstructing with new materials.

Figure 26. Full-Depth Reclamation (FDR): Recycle Old Roads into Smooth Roadways

Road Closures

The researchers' analysis showed that slightly more than 5 percent or 254 of the lane-miles in Harris County will be inundated with 20 or more inches of water in a 100-year flood event. Similarly, almost 9 percent or 411 of the lane-miles in Harris County will be inundated with 20 or more inches of water in a 500-year flood event. These roads vary in terms of functional classification and therefore pavement design.

The costs of reconstructing these at-risk highways considering more conservative flood frequency events (i.e., 200-year flood occurrences or greater) would be site specific. Constructing to more conservative flood frequency events could result in these roadways and bridges having higher than usual profiles, more substantial drainage systems, and possibly longer bridge lengths to withstand severe flooding events. Table 7 lists potential projects identified by TxDOT's Houston District that were impacted by past flood events and the estimated cost of elevating these pavements.

Table 7. Potential Resiliency Projects Identified by TxDOT for the Houston District.

County	Road	Limits	Estimates ($ million)	Description	Flood Frequency
Fort Bend	Spur 10	SH 36 to Cottonwood School	60	Elevate pavement	Harvey 2017
Fort Bend	US 90A	FM 359 to SH 99	50	Elevate pavement and replace bridges	Memorial 2016, Harvey 2017
Fort Bend	FM 723	Brazos River to FM 359	100	Elevate pavement	Memorial 2016, Harvey 2017
Fort Bend	SH 6	Fort Bend County Line to FM 1092	250	Elevate pavement and replace bridges	Harvey 2017
Fort Bend	FM 1093	Brazos River to FM 1489	75	Elevate pavement	Tax Day 2016, Memorial 2016, Harvey 2017
Brazoria	SH 6	SH 35 to Fort Bend County Line	450	Elevate pavement and replace bridges	
Harris	SH 6	Addicks Dam to Clay Road	200	Bridge roadway through revisore	Memorial 2015, Tax Day 2016, Memorial 2016, Harvey 2017
Harris	I 45N	Cypresswood to Parramatta	250	Elevating pavement and rebuild two intersections	Memorial 2015 Frontage Road, Tax Day 2016 Frontage Road, Memorial 2016 Frontage

County	Road	Limits	Estimates ($ million)	Description	Flood Frequency
					Road, Harvey 2017 Frontage Road and Main lanes
Harris	US 290	Skinner Road to Telge Road	200	Elevating pavement and rebuild two intersections	Tax Day 2016, Harvey 2017
Harris	I 10 E	Monmoth to Spur 330	2	Elevate pavement and replace bridges	Harvey 2017
Waller	I 10	1000'East and West of Petterson Road	75	Replace and build urban intersection	Harvey 2017

The cost of road elevation needs to be traded off against the cost imposed by the risk of future flooding events (i.e., frequency and anticipated impact in terms of number of days the roads are closed), and the associated disruptive costs to the users of the system (e.g., economic implications of lost trips, increased travel times, etc.). Also, as stated earlier, road closures of the state-maintained network can also impose a cost to the local road system if these road closures result in damage to the county and city network from diverted traffic onto roads with weaker pavement structures.

In addition to road elevation, several studies have been conducted to prepare infrastructure for or recover from extreme weather events. Some of the measures listed for mitigation flood events include:

- **Hard engineering solutions,** such as flood defenses, higher flood walls, levees, surge barriers, and adding pumping stations. [18]
- **Soft engineering solutions**, such as the creation of wetlands and marsh rehabilitation.[18]
- **Green infrastructure** to deal with rainfall events and to capture storm water.[18]

Lifecycle Planning Analysis

Lifecycle cost analysis at the project level and lifecycle planning analysis at the network level typically calculates the discounted implementation cost (e.g., initial construction or retrofitting costs) of a proposed measure relative to the measure's impact on the service life of the asset and where applicable the discounted reduced maintenance costs over the life of the asset. A comparison of the calculated present value of the discounted lifecycle costs of different measures allows an agency to identify the most desirable or preferred measure. Lifecycle planning analysis at the network level typically allows for the evaluation of:

> Lifecycle Planning (LCP) is defined by the FHWA "as a process to estimate the cost of managing an asset class, or asset subgroup over its whole life with consideration for minimizing cost while preserving or improving the condition."

- Different measures to ensure the best condition of the assets for a given funding scenario.
- The funding needed to ensure a given asset condition (e.g., 90 percent of the lane-miles in good condition).
- The effect of different funding scenarios on the condition of the assets.

TxDOT's new pavement management system (i.e., Pavement Analyst)) has the capability to conduct lifecycle planning analysis at the network level for the state, individual districts, area offices, and specific maintenance sections. Pavement Analyst evaluates different maintenance and rehabilitation measures and predicts the performance of the network using performance models. For the specified analysis period, the performance models predict several distresses[7]—of which rutting is one—and ride scores for each pavement section for each year. Once the level of distress for each distress type and the ride quality are estimated, the combined distress, ride, and overall condition scores are calculated. Finally, the optimization model allocates the resources to the network given the constraints specified (e.g., best condition for given funding, funding needed for given asset condition, or the impact of different funding scenarios on the asset condition), the costs of the measures, and the lifecycle of the measures. To reduce the run time for large networks with many pavement sections, TxDOT has developed decision trees to identify measures for given pavement conditions and sections. However, the final selection of treatments is determined by the optimization model and the constraints specified. The decision trees are based on engineering experience.

The findings of this pilot study provided insight into the long-term impact of flooding on the service life of inundated flexible pavements, historically the vulnerable components of the Houston network. The analysis results showed that both Pavement Types 6 and 10 are vulnerable to flood damage (specifically rutting) and may need to be reconstructed to the

7 Other distresses for asphalt pavements include: alligator cracking, transverse cracking, and longitudinal cracking.

specifications of Pavement Type 5 (i.e., AC surfaced pavement structure) to withstand future flooding events. The other two options (abandoning the infrastructure and restricting heavy vehicles) are largely seen as not feasible. Since these Pavement Types represent a relatively small percentage of the Houston state-maintained network, hardening all the pavement sections, will cost the agency $17.2 million. The simulation analysis also found that relatively new Pavement Type 5 roads (i.e., less than 10 years) are not impacted by flooding in terms of a reduction in service life. Once these roads have, however, been in service for 10 or more years, each flood event reduces the structure's service life by one year. It is difficult to quantify this loss of life in terms of dollars. Managing agencies typically work on constrained budgets that lead to deferred maintenance without a flood event. Introducing a flood event that reduces pavement life further exacerbates the situation. Nonetheless, TxDOT indicated that the cost to reconstruct a roadway to the more resilient thicker pavement structure would cost $0.5 million/lane-mile. From Table 3, 704 lane miles of Pavement Type 5 are at potential risk of flooding. Using a 20-year design life and a cost of $0.5 million/lane-mile, a basic annual cost per lane mile is $25,000. With a flood event that leads to a loss of one year of pavement life, the annual cost per lane mile increases to $26,316. When three years of life are lost, the annual cost per lane mile increases to $29,412. Therefore, with 704 lanes at risk of loss of life during a flood event, the cost impact varies between $926,464 (for one year lost in service life) and $3,106,048 (for three years lost in service life)[8]. These costs merely reflect the loss of life of the 704 miles. In practice, it would cost significantly more to upgrade 704 lane miles, but in reality, not all 704 lane miles require upgrading. Furthermore, the actual costs to the network will include deferred maintenance and other maintenance required on flooded roadways (e.g., pothole repair) before reconstruction takes place.

This pilot study evaluated the impact of flooding on pavement structures in terms of rutting. Simulations were performed that provide a better understanding of the potential pavement impacts to various pavement structures at different points in the pavement's life. These simulations are limited to the specific scenarios and inputs used, thus requiring engineers to use engineering judgement to infer the results of other scenarios. DOTs and other managing agencies should evaluate the creation of more robust models to help evaluate the impact of flooding on other distresses and the evaluation of alternative measures (more frequent maintenance of culverts, improved drainage, adding shoulders, roadside vegetation/stabilization) on the pavement service life given a flooding event. The development of more robust models will assist DOTs in better understanding the pavement and financial impacts caused by flooding.

The findings of the pilot project also highlighted the potential disruptive effects of flooding and the significant cost in elevating impacted roads. Lifecycle planning analysis typically

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[8] These estimates do not account for any future reduction in service life of Pavement Type 6 and 10 if upgraded to Pavement Type 5. As stated before, the simulation analysis found that relatively new Pavement Type 5 roads (i.e., less than 10 years) are not impacted by flooding in terms of a reduction in service life. Once these roads have, however, been in service for 10 or more years, each flood event reduces the structure's service life by one year.

does not consider the cost and disruption of road closures. The impact of road closures due to flooding is therefore not considered in the lifecycle planning analysis of an agency's pavement management system. Furthermore, there are no tools currently to conduct a robust analysis of the inundation impacts of measures to increase the resiliency of pavements to flooding: flood defenses, higher flood walls, levees, and adding pumping stations, the creation of wetlands and marsh rehabilitation, and green infrastructure to deal with rainfall events and to capture storm water. Also, as noted previously, road closures of the state-maintained network can impose a cost to the local road system if these road closures result in damage to the county and city network from diverted traffic onto roads with weaker pavement structures. These costs were not considered in this pilot study.

The findings of this pilot study can be used to flag roads susceptible to flooding damage in TxDOT's pavement management system and can be used to inform changes to the embedded decision trees. Finally, the analysis conducted in this pilot project may inform future lifecycle planning efforts of major rehabilitation projects aimed at improving the resiliency of the system to flooding (both pavement damage and road closures), as well as in the lifecycle cost analyses and resilience assessment of pavement networks to extreme weather events in the update of the TAMP.

Proxy Indicators

For the purposes of this study, a proxy indicator is an indirect measure of a phenomenon that approximates a direct measure of the phenomenon. In this way, proxy measurements are useful whenever a direct measurement of a phenomenon is difficult or even impossible to obtain; and a good proxy indicator is a practically useful substitute for a direct measurement or observation.

Figure 27 illustrates the concept of proxy indicators for the purposes of this study. Figure 27 illustrates a simplified, conceptual view of the processes and phenomenon involved in flooding, and its impacts on transportation. Flooding is the principal driver of risk to pavement structure life, to system mobility, and safety. However, flooding occurs because of a complex sequence of spatially and temporally defined events and processes. The first of these is the intensity, duration, and spatial extent of rainfall, categorized as an external driver or disturbance because transportation engineers have very little control over such events. However, other factors also determine whether flooding will occur following or during a rainfall event, many of which provide options for mitigating floods. For example, land use influences processes such as storage and runoff,[9] while natural (streams) and artificial (culverts, storage ponds) hydraulic structures also play a large role in determining the extent, severity, and duration of floods. The location and design of transportation structures (e.g., whether roads are elevated) determines the amount of network impacted by floods. Finally, the impacts of flood events are driven by the extent, depth, and duration of flooding

[9] It could be argued that many of these geographic entities and processes are an external factor that cannot be controlled directly by transportation engineers.

and another external factor—the demand for travel across the network. This study addresses two impacts of flooding: short-term disruptive impacts (road closures), and longer-term maintenance and asset management costs.[10]

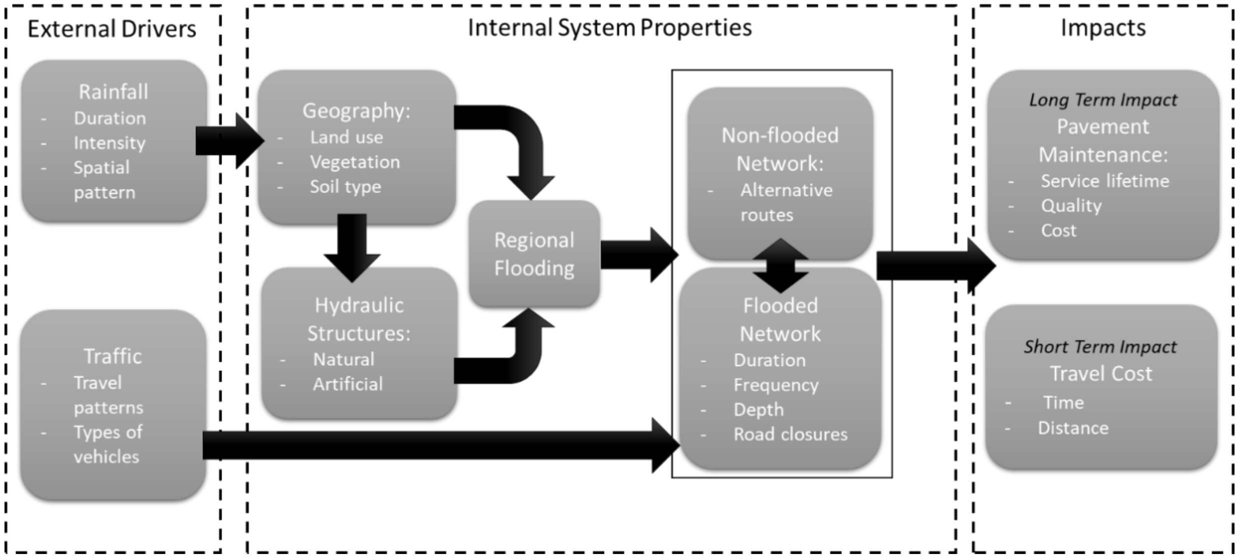


Figure 27. Conceptual View of Flooding and the Impacts on Transportation.

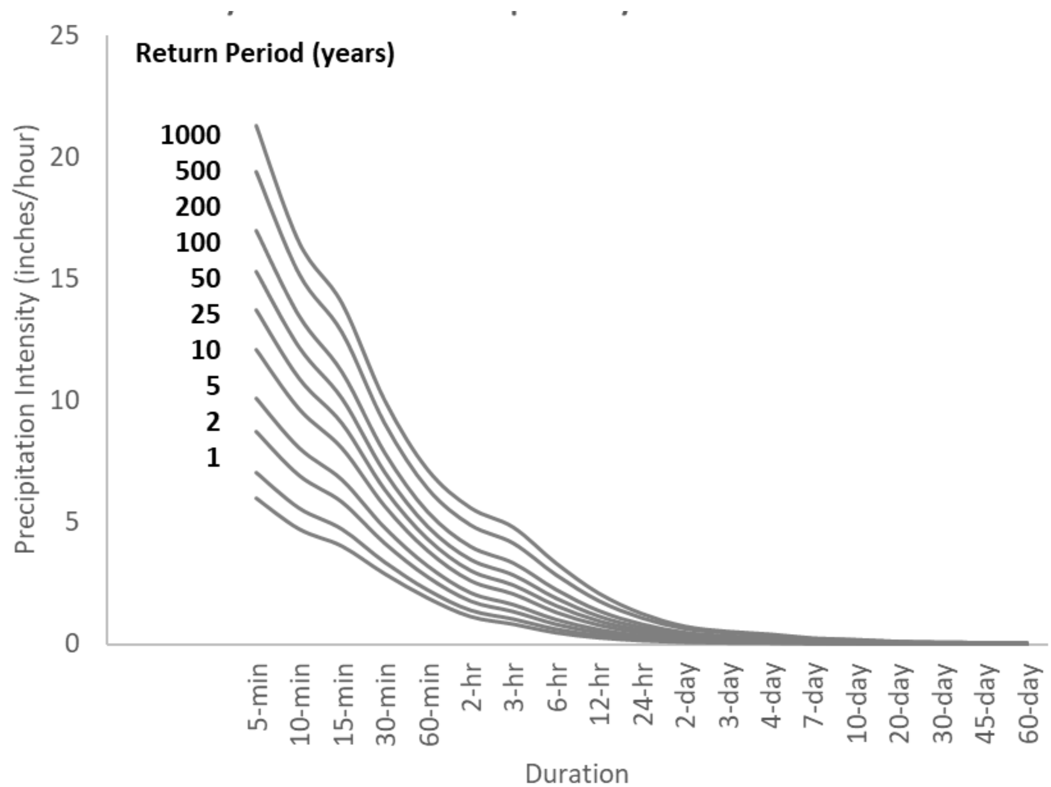
Figure 27 offers a greatly simplified view of the causality, potential for mitigation, and impacts of flood events to the transportation network. However, even this simplistic representation hints at the challenges in managing flood events to reduce system impacts. In the absence of a complete understanding of the processes that lead to flooding, transportation engineers require effective proxy indicators that can be used to a) predict the frequency, intensity, location, and duration of floods; and b) assess their impacts to the transportation system. The work performed during this study provides the following insight into the utility of proxy indicators:

- FEMA floodplains, LIDAR data, and pavement deterioration simulations used in this study are all examples of proxy indicators useful for estimating flood risk. They are routinely available, indirect measurements of the system, which when integrated using simple models provide insight into the location, frequency, and severity of future flood events; or in the case of the pavement simulations provide insight into the likely impacts of flood events.
- The risk assessment framework used in this study effectively partitions risk into causes and effects. Each of these (including relevant proxy indicators) can be refined relatively independently of each other.
- The causes of flooding are complex, but proxy indicators such as rainfall intensity/duration curves (Figure 28) linked to historical patterns of flooding may provide useful refinements for predicting and mitigating floods. Such data are widely available

10 Other impacts are also relevant including safety costs, acute damage to roads, and environmental costs.

across the United States (e.g., NOAA Atlas 14 data). Flood hydrographs (plots of water level and flow in drainage structures) may provide even better proxy indicators of floods. These measurements and data are already available for rivers and streams in many areas, including Houston. Further refinement may be accomplished by measuring flow and water levels in artificial structures (culverts, storage ponds) adjacent to or part of the transportation system.

- Travel cost impacts could be assessed (by proxy) using anonymous cell phone collected GPS data sets (such as, INRIX data). These data could be leveraged to estimate changes in travel patterns, such as diversions or changes in traffic volumes. These indicators could both identify flooded areas or to directly measure the disruptive impacts of floods.
- Maintenance costs associated with flooding are difficult to measure for three reasons. First, damage occurs in the substructure of pavements and is therefore difficult to measure directly. Second, damage is most likely to occur because of repeated exposure to flooding, which is an inherently long-term process. Third, damage also occurs through changes in the types and volumes of vehicles using pavement sections. In addition to the simulation approaches adopted in this study, useful proxy indicators could be developed by linking easily measurable surface characterization of pavement condition to subsurface structures or by developing sampling methods that use subsurface measurements (e.g., ground penetration radar) to infer pavement performance over the entire network.



Source: NOAA Atlas 14 data

Figure 28. Intensity, Duration, Frequency Curve for Houston.

Transferable Successes

Researchers adopted a pragmatic approach to risk assessment in line with the probabilistic and uncertain nature of risk. The goal was to provide the best estimates of risk given current available data and knowledge. The methods, data, and analyses adopted in this study therefore used publicly available data and readily available software and analysis. The outputs of the study and the methods to derive these outputs can be easily modified and improved as new data or knowledge becomes available.

Furthermore, the partitioning of risk into components provided a flexible risk assessment framework, where risk can be updated and refined as new information or technology becomes available. Refinement can occur in several ways, for example through:

- More accurate characterization of the probability of adverse events occurring. This may occur because of the availability of more or improved data, or improved analyses.
- More useful information or variables associated with adverse events.
- Better models to translate the impacts of adverse events into estimates of damage.

The Texas TAMP is governed by TxDOT Administration and implemented by a steering committee with members from the Administration, divisions (Bridge, Construction, Financial Management, Maintenance, Transportation Planning and Programming), and district representatives.

These refinements usually occur iteratively. For example, improving the characterization of flood events should inform improved methods for estimating damage impacts. Similarly, improved models of pavement damage should inform improvements in methods used to characterize flood events and report flood variables that are more useful to the risk assessment process.

Finally, the results of this study add to the understanding of the long-term impacts of flooding events on serviceability of flexible pavements and can be employed in lifecycle cost analysis and resilience assessment of pavement networks.

Other Accomplishments

The pilot project built and continued the dialogue among various TxDOT divisions and districts that started with the development of the TAMP. For example, researchers presented the initial pilot findings to representatives from TxDOT's Environmental Affairs, Bridge, and Transportation Planning and Programming Divisions. Researchers also made several presentations to the FHWA Texas Division. The pilot project therefore provided an additional opportunity to enhance the awareness of extreme weather events and the potential impacts to the transportation system. The outcome of this pilot project will therefore inform and be considered in future agency actions, such as the development of the agency's statewide long-range transportation plan.

Challenges, Lessons Learned, and Next Steps

The International Transport Forum in a report entitled *Adapting Transport to Climate Change and Extreme Weather* reported the following policy insights:[9]

- Asset managers need to prepare for more frequent failure of transportation infrastructure.
- Asset managers need to plan for transportation infrastructure not being available for periods of time.
- Asset managers need to focus on a resilient transportation system that accepts asset failure as an unavoidable consequence of an extreme weather event at times.
- Asset managers need to consider implementing redundancy in the transportation system.
- Asset managers need to develop new decision-support tools that consider significant uncertainty in asset appraisal.

In this pilot project, TTI researchers developed a framework to allow TxDOT's asset managers to assess the vulnerability of its state-maintained network to flooding events in Houston, as well as understand the potential damage and disruptive impacts of such events. This framework—although developed for Houston— can be used and replicated for other TxDOT Districts and by counties and cities. This section documents:

- Some of the challenges encountered and actions taken to address the challenges.
- Lessons learned.
- Specific benefits of the pilot project to TxDOT.
- Recommendations for future work.

Challenges Encountered

TTI researchers identified more than 40 data sets, interactive viewers, and websites that contained data pertaining to the pilot study topic (see Appendix D). Evaluating and determining the robustness and usefulness of the data can be overwhelming and time consuming. The challenge was overcome by consulting with and obtaining input from stakeholders during the Houston Stakeholder workshop as to where researchers should focus on during the pilot project. On the other hand, critical data sources for the risk assessment (e.g., official FEMA flood maps for Brazoria and Galveston Counties) were unavailable or difficult to standardize. The study indicated the importance of cross-disciplinary collaboration for understanding and predicting flood events. For example, the FEMA flood maps used in this study are the product of considerable and long-term efforts by flood control districts. Although useful, they represent a relatively indirect and coarse picture of flood risk. Researchers recommend that more direct and explicit involvement of such agencies may lead to data sets and models useful for refining risk.

Pavement damage attributable to flooding is a function of both flood depth and the elevation of pavement surfaces. Although GIS layers depicting the two-dimensional location of roads are common, these layers usually do not contain information on the elevation of pavement surfaces or other infrastructure relevant to the design or functioning of the pavement (e.g., embankments, ramps, drainage ditches). TTI researchers conducted an analysis that uses aerial LIDAR data to estimate the elevation of road surfaces and surrounding infrastructure within Harris County.

It is difficult to simulate damage that occurs in asphalt concrete pavement surfaces. The pavement simulations determined loss of service life based on rutting impacts, but it is known that pavement surfaces can experience delamination and stripping after being inundated with water. Researchers simulated the impact of flooding on the structural capacity of selected pavement structures (i.e., rutting) using pavement design software (i.e., TxME). In simulating the impact, TxME does not allow changing the design inputs in different years. In other words, if a design input is defined for the first year of simulation, it remains the same throughout the entire design period. To overcome this limitation, the simulation period was divided into three periods: before flooding, during flooding, and after flooding. Each period was simulated using its corresponding properties. The pavement condition at the end of each period was entered as the pavement condition at the beginning of the next period. At the end, rut depths developed during each period were summed to generate the total rut depth of the pavements over the service years. More complex and detailed simulations were beyond the scope of this study. However, the basic methodology could be extended to achieve better indicators of pavement damage, which could prove invaluable for developing more refined impacts. Used in conjunction with field samples of easily measurable surface indicators of pavement damage, and/or other more detailed measurements of subsurface condition, these techniques could provide valuable and currently poorly understood knowledge of the relationship between repeated flooding, traffic loads, and pavement life.

Lessons Learned

The methods and analyses adopted in this study use publicly available data and readily available software and analysis. The outputs of the study and the methods to derive these outputs can be easily modified and improved. Crucially, researchers have learned that the direct engagement of other agencies and of other domain expertise within transportation are essential for developing vulnerability assessments. Many of the data, models, and expertise required to refine and mitigate flood risk already exist. As such, one of the challenges for transportation professionals is to incentivize experts in other fields to share data, models, and knowledge, in other words to develop a system level approach to predict, assess the impact of, and mitigate flood risk. To this end, the stakeholder meeting conducted at the beginning of this project identified key reciprocal interactions that could benefit all agencies involved in predicting and mitigating floods. For example, hydrologists charged with predicting flood events highlighted the importance of engaging with transportation engineers to better understand the influence of transportation infrastructure on flood risk. Other stakeholders noted that useful constraints on travel require effective collaboration among transportation stakeholders and entities such as school districts or major industries. Even within the transportation domain, much work is required to operationalize models and data capable of predicting alternative travel patterns and assess routing alternatives to enable a more refined understanding of flood risk and the impacts of flooding events on the transportation system.

In addition to adopting a system approach to understanding and mitigating flood risk, specific findings of the study are as follows:

- The LIDAR data and analyses could be modified to more accurately determine the profile of selected road infrastructure. The road topography layer can be further analyzed to explore the impacts of local topographic features on flood risk. FEMA flood maps can be re-analyzed in line with the regular changes in the flood risk maps. Similarly, the LIDAR data used in this analysis was collected in 2001, and new data are now available for purchase. The exploration and further improvements to the analyses presented in this study may be useful for transportation engineers to formulate hypotheses about the relationships between topography, roads, and flooding. This may result in ideas on how to further refine road flooding risk assessments, as well as improve collaboration among climatologists, hydrologists, pavement engineers, and other transportation domain specialists.
- The road topography data generated using LIDAR could be useful for extending the flood risk assessment methodology. Combined with routing information and traffic volumes, it could be used to explore interactions among traffic volumes using the roads following flooding and pavement damage. For example, it is possible that roads closed because of complete floodwater inundation are subject to less damage than those whose substructures become saturated, but remain open, and therefore experience normal traffic volumes, or increased traffic volumes as vehicles re-route due to other road closures. Similarly, the data may be useful to identify routes that are largely unaffected by inundation, but which contain sections of roads that flood rapidly. Such routes may present a safety concern or at least an inconvenience for travelers using those roads.
- The methods and data sets generated through this study provide pavement engineers with the potential to analyze the interactions between floodwater depth and pavement damage. The next step of the risk assessment process is to provide the road links and flood depth information to pavement engineers in a format useful for refining damage assessment models.
- Pavement engineers provided additional information on the design characteristics of each link to explore the impacts of different levels of floodwater on pavement damage. These methodologies could be extended by estimating the rate at which floodwater levels recede following flooding and exploring how different levels of flood inundation (i.e., interpolating and extrapolating beyond 100- and 500-year flood levels) may impact road infrastructure.

Benefits to the Pilot Agency

Researchers translated FEMA flood maps describing the extent of 100- and 500-year floods into maps estimating local flood water levels/heights. Researchers also developed a novel data set describing the elevation of road infrastructure relative to sea level. Used together, the data were used to assess inundation of road infrastructure during floods and to refine estimates of the risk of floods on road infrastructure. Furthermore, the results of this study added to the understanding of the long-term impacts of flooding events on serviceability of flexible pavements and can be employed in lifecycle cost analysis and resilience assessment of pavement networks. However, in line with the overall risk assessment methodology adopted for the study, the flood water height and road elevation GIS layers correspond to one necessary component of a flood-road infrastructure risk assessment. The data will be useful to pavement engineers in developing novel and more accurate assessments of pavement damage based on inundation levels of road structures/material characteristics.

Recommendations for Future Work

The following are recommendations and opportunities for future work:

- Flood risk mapping is a specialized area involving complex models with both temporal and spatial dimensions. Although the analysis presented in this study reproduces the spatial extent of FEMA predicted flooding fairly accurately, improved results could be obtained by working with the original hydrological models, which explicitly translate rainfall frequencies and intensities into flood depth maps. Such an approach could also refine risk assessments by incorporating additional spatial and temporal dimensions into the analysis. For example, it is likely that floodwater dissipates more rapidly from some areas than others due to underlying topography and drainage structures. Similarly, the FEMA flood maps provide estimates of flood extent over long time-periods. It is probable that individual flood events result in different spatial patterns of flooding within Houston depending on the spatial and temporal pattern of rainfall in the area, and other factors such as active flood control strategies (e.g., the release of water from flood control reservoirs). The data and methods outlined in this study may help promote useful dialogue between transportation engineers and hydrologists.
- The characterization of floodwater heights and road elevations investigated in this study also illustrate another important relationship between flooding and road infrastructure. While transportation engineers may be predominately concerned about the impacts of flooding on roads, road surfaces also alter the topography of an area and play an important role in determining the nature of surface water flow. Increased collaboration between transportation engineers and hydrologists to understand the relationship between flooding and road infrastructure can therefore inform efforts to incorporate resiliency into asset management.
- This pilot study evaluated the impact of flooding on pavement structures in terms of rutting. Further work is needed to convert the rutting impact into the distress and condition scores used in TxDOT's Pavement Analyst, because the condition score is the

performance measure used by the agency in evaluating maintenance measures and managing its assets. Furthermore, besides rutting, water inundation can also lead to stripping of AC layers, creating the potholing affect often seen after heavy rain events. This phenomenon is not modeled in TxME, and its occurrence is difficult to simulate. More robust tools are needed to simulate this impact. A lack of robust models also prevented the evaluation of alternative measures (more frequent maintenance of culverts, improved drainage and hydrological solutions, adding shoulders, roadside vegetation/stabilization) on the pavement service life given a flooding event.

- The findings of the pilot project also highlighted the potential disruptive effects of flooding and the significant cost in elevating impacted roads. Lifecycle planning analysis typically does not consider the cost and disruption of road closures. There are no tools currently to conduct a robust analysis of the inundation impacts of measures to increase the resiliency of pavements to flooding: flood defences, higher flood walls, levees, and adding pumping stations, the creation of wetlands and marsh rehabilitation, and green infrastructure to deal with rainfall events and to capture storm water. Additional work is also needed to understand the routing decisions and the impact of road closures of the state-maintained network that result in the diversion of traffic onto roads with weaker pavement structures in cities and counties.
- Identification of vulnerable roads to flooding and implementing the obtained results on the network level to adjust managerial decision trees for the impact of flooding events.
- The framework developed in this pilot study provides a repeatable process for risk assessment of the extreme weather event threats to the agency’s assets. It is recommended that the work be extended to develop a resilience index for the state-maintained system in terms of both potential infrastructure damage and disruptive impacts. Such a resilience index can be ultimately used to inform and prioritize investment decisions.

Appendix A—Asset Management, Extreme Weather, and Proxy Indicators Workshop Participants

Workshop Participants

Table 8 provides the names of the workshop participants and the agency/company that they represented.

Table 8. Forum Participants by Agency/Company.

Participant Name	Agency/Company
Mark Wooldridge, PE	TxDOT, Houston District
Sarah Benavides	City of Pasadena
Gary Trietsche, P.E.	Harris County Toll Road Authority
Eric Gayetsky	H-GAC
Al Durel	Port Freeport
Hugh McCulley	Crady, Jewett & McCulley, LLP
Melissa Huffman	National Weather Service
Mr. Paul Reitz, P.E.	TxDOT, Yoakum District
Derek Feil	TxDOT
Barbara Koslov	Harris County, Judge Ed Emmett
Pramod Sambidi	H-GAC
Leilany Lugo-Reyes	Harris County Toll Road Authority
Michael Shannon	Galveston County
Patrick Mandapaka	H-GAC
David Fink	H-GAC
Nader Mirjamali	Houston METRO
Anne Dunning	Port Houston
Georgios Balomenos	Rice University
John Bilyeu, P.E.	TxDOT
Jason Lambert	TxDOT, Corpus Christi District
Loyd Smith	Harris County
Eddie Garza	City of Pasadena
Rep for Amanda Edwards	City of Houston

Participant Name	Agency/Company
Tanu Hiremath	City of Houston
Stephen Gage	H-GAC
James Hoss	Fort Bend County Public Transportation
CAPT Steven Nerheim, USN (Ret.)	Coast Guard Vessel Traffic Service Houston-Galveston
Dan Reilly	National Weather Service
Qun Zhao	Texas Southern University
Idalid Navarro	Houston City Council

Small Group Discussions

Climate Factors/Extreme Weather Events of Concern

Workshop participants were provided a handout that lists various climate factors relevant to TxDOT's Houston District and illustrative impacts on the transportation sector (see Table 9). Participants were asked to discuss and reach consensus on the three events that Houston is most at risk of. Participants were also asked to discuss the dimensions that define an extreme event. Examples that were offered included:

Risk was defined as the probability of an event occurring and the impact of the event (in terms of cost, how many people died or livelihoods impacted, etc.)

- Hurricanes – Category 4 and 5 storms.
- Heat/Drought – Number of days exceeding 100°.
- Heavy Precipitation Events – One measure of a heavy precipitation event is a 2-day precipitation total that is exceeded on average only once in a five-year period, also known as a once-in-five-year event. Another measure is 1 inch/hour of rain.

Table 9. Climate Factors (Relevant to TxDOT's Houston District) and Illustrative Impacts on Transportation.

Climate Factors	Examples of Impacts on Transportation Infrastructure and Operations
Increases in very hot days and heat waves	• Thermal expansion on bridge expansion joints and paved surfaces • Concerns on pavement integrity, traffic-related rutting, migration of liquid asphalt • Rail-track deformities • Limits on periods of construction activity due to health and safety concerns
Sea level rise combined with storm surges	• Inundation of roads, rail lines, and airport runways in coastal areas • Erosion of road base and bridge supports • Reduced clearance under bridges, changes in harbor and port facilities to accommodate higher tides and storm surges • More frequent interruptions to coastal and low-lying roadway travel and rail service due to storm surges • More severe storm surges, requiring evacuation
Increases in intense precipitation events	• Increases in weather-related delays and traffic disruptions • Increased flooding of evacuation routes • Increases in road washout, damages to rail-bed support structures, and landslides and mudslides that damage roadways and tracks • Increases in scouring of pipeline roadbeds and damage to pipelines
Increase in frequency of intense hurricanes	• Greater probability of infrastructure failures • Increased threat to stability of bridge decks • Impacts on harbor infrastructure from wave damage and storm surges

Group 1 (Moderator – Bob Huch, Notes – Sarah Overmyer)

Group 1 identified the following events that Houston is most at risk of:

- Water – whether tropical storms of hurricanes,[11] a high rainfall event, storm surge, coastal flooding caused by high tides not associated with a tropical event.
- Inland flooding.
- Ice.
- Drought (that affects pavement).
- Wind – attributable to hurricanes or tropical storms.
- Tornados – although not very common, can be very destructive and can be a result of a hurricane).
- Fog (smaller factor).

The weather events that Group 1 agreed that Houston is most at risk of were hurricanes, inland flooding, and wind (attributable to hurricanes or tropical storms).

Group 2 (Moderator – Jolanda Prozzi, Notes – Sandra Rodrigues)

Group 2 identified several extreme weather events that Houston is at risk of:

- Hurricanes (wind, flooding, rain).
- Flooding/drainage of watersheds/inland flooding.
- Drought.
- Ice storms, ice.
- Local precipitation.
- Erosion.
- Wind.

Participants noted that when a tropical storm and or hurricane hit Houston, the area will experience an ice storm the same year. It was less known, but participants stated that Houston experiences ice storms every six to seven years.

The weather events that Group 1 agreed that Houston is most at risk of were hurricanes/flooding and drought.

Defining the dimensions of an extreme weather event proved more challenging for participants to agree upon. Participants pointed out that the location of the event largely determines the impacts. Often it is a matter of local perspective. A Category 3 hurricane that moves slowly can more be devastating for a community than a Category 5 hurricane that moves quickly. The Port Houston representative pointed out that it is not only the volume of water, but also the speed of the water flow that is important. The speed of the water flow is largely a function of land use, specifically impermeable cover. Port Houston experienced erosion damage with Hurricane Harvey. The Galveston County Engineer pointed out that the

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11 The Port of Freeport is the most concerned (top concern) about hurricanes.

coastal areas are less concerned about flooding, but more concerned about storm surge and roads that are washed out. Houston can also be impacted by weather events inland. Heavy precipitation inland can cause flooding in Houston several days later because of the watershed.

Group 3 (Moderator – Andrew Birt, Notes – Andrew Wimsatt)

Group 3 identified the following weather events of concern in Houston:

- Flooding.
- Wind.
- Tornados.
- Storm surge.
- Rainfall.

Participants also mentioned that fog affects the operation of the Houston ship channel.[12] After a hurricane, problems with fog appear to occur more frequently.

Houston is most at risk of flooding and storm surge. Galveston is very vulnerable to storm surge. Rainfall rates were also discussed as it impacts urban flooding. During Hurricane Harvey, the rainfall rate was between 4 and 5 inches an hour (20 inches in one night). The effect of the rainfall is a function of the speed of the motion.

Hurricane Harvey is seen as an exceptional event. Not only was Houston impacted by the rain from Hurricane Harvey, but also by rain that fell inland. For example, Brenham saw 20 inches of rain in 24 hours. Fort Bend County (Rosenberg) was affected by the inland flooding in Brenham. Participants also pointed out that river and flash flooding have different impacts. Ground saturation (i.e., how wet the soil was) before a weather event is another important factor.

Participants pointed out that every extreme weather event is different. Participants referenced the Tax Day Storm (2016) and Allison (2001), which resulted in 30 inches of rain, but has more localized impacts. Carla (1961) was a Category 4 storm that moved down the coast from Houston. A storm moving up from SH 36 from Galveston would be devastating (similar to the 1900 Galveston Hurricane).

Transportation Challenges and Issues of Concern

Workshop participants were asked about the challenges extreme weather events present, as well as the impact during, in the aftermath, and after an extreme weather event.

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12 Participants mentioned discussions to redesign the Houston ship channel (i.e., placing tanks on the south side of the channel and containers on the north side to eliminate trucks from crossing the ship channel bridge).

Group 1

Group 1 discussed several challenges during a hurricane. Specifically, evacuation challenges, included:

- When to evacuate and the procedure for evacuating, the capacity of roads to evacuate, need for maps (H-GAC maps "Together Against the Weather").
- Identifying and arranging for shelter.
- Barricading of roads that have flooded or will potentially flood, including people management as people often ignore barricades and travel around them.
- Emergency response, specifically how to mobilize help and communicate clearly as individuals who do not usually engage in these roles may be involved.[13]
- Activating emergency protocols (Transtar Emergency Management in Houston).
- Ensuring consistent public information and a consistent message.[14]

Group 1 also discussed challenges in the immediate aftermath of a hurricane. The identified challenges mostly related to managing damage to infrastructure and transportation systems and ensuring that people have access to goods and services. More specifically, the challenges identified were:

- Wind damage.
- Traffic signals not working/traffic control.
- Power cables/utilities down.
- Debris clearing (especially when blocking roadways).
- Port closures (strong currents at port).
- Safe drinking water.
- Power outages.
- Assessing road closures/road safety and removing barricades (determining where is it safe to drive).
- School closures.[15]
- Access to food (groceries).
- Access to hospitals and medical services.
- Access to fuel.

Over the long term, participants highlighted the following concerns after a hurricane:

- Home damage.
- Reinstating waste water plants.
- FEMA reimbursements, specifically FEMA does not reimburse for lost revenue.

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[13] The City of Pasadena staff, for example, had to close roads.

[14] Participants mentioned, as an example, Governor Abbot, stating that he would have evacuated Houston even though mayors and others stated that they would not.

[15] People need to stay home to take care of children, so there is a need to open schools.

- Rebuilding of roads, utilities, ports (specifically, dredging the ship channel), and airports.
- Delays in construction.

Group 2

Group 2 discussed the concerns and impacts related to hurricanes specifically. Group 2 pointed to the need for an asset management system to assess damage incurred and to facilitate recovery after the event. The Houston METRO representative mentioned that the transit agency's bus parking facility is in a flood prone area. During Hurricane Harvey, buses were moved and parked on higher elevation managed lanes in the city to protect the bus fleet.

The Port Houston representative reported that ships were moved out into the sea prior to Hurricane Harvey, but a decision was made to shelter barges in place. Some barges, however, got loose. Furthermore, the flood water washed tons of silt and sediment into the Houston ship channel that will require dredging of the channel.

In terms of the transportation system, the port was shut down for several days, the rail was shut down, and many of the areas north/south highway corridors were flooded, which resulted in long detours to move around in the area. Participants pointed out that many of the road underpasses flooded. One of the issues that were pointed out is that the flooding alerts do not result in the automatic closure of underpasses. Gates are still manually closed in the event of flooding. Finally, participants pointed out that road bases were comprised, specifically those of the older road system.

Group 3

Group 3 discussed the issue of land management. Some participants felt that better land use controls could help reduce flooding and water damage. Hurricane Harvey was seen as a different type of Gulf storm as it tracked along the coast.

The Barker and Addicks reservoirs were built in the 1950s to mitigate flooding. Several subdivisions have since been built in or near the reservoirs. The coastal plains have seen a lot of development (sometimes in the wrong areas) resulting in increased impermeable cover. One participant commented that 25 percent of Houston's housing has been built since 2000.

A TxDOT participant mentioned that Hurricane Harvey had the largest recorded impact (including debris removal) on the TxDOT maintenance budget.

Participants pointed out that Hurricane Ike did much more damage to the private sector facilities than to public sector assets. The transportation system is much more resilient than privately owned facilities. Although the roadways flooded, most were opened to traffic after flooding subsided.

Houston's Critical Transportation Infrastructure

Participants were asked to reach consensus on the critical commerce and commuter corridors in the Houston region.

Group 1

Group participants stated that Houston has greater freight mobility going east-west than north-south. Specific highways that are critical to freight movements in the Houston region are:

- 610 W Loop.
- Highway 6.
- State highway (SH) 225.
- I-10,[16] I-45, and I-59, all of which connect to other states.

In addition to the specific highways mentioned above, Group 1 also mentioned the importance of city streets, roads accessing airports, and ports. Ports and airports are considered critical to the economy. Railroad infrastructure, bridges, and railroad signaling systems are also vulnerable to extreme weather events. Furthermore, participants felt that all the major highways in Houston are critical commuter corridors.

Group 2

Group 2 identified the following roads as critical to commuters and commerce:

- Interstate highways (e.g., I-10 and I-45).
- US 59.
- SH 6.
- SH 225 and SH 146 (which provide access to Port Houston).
- Beltway 8.

Group 2 felt that the interstate system is the most critical to the Houston area and since the interstate system is already built to higher design standards it would be more effective and cost-effective to invest in a resilient interstate system in Houston. A second tier of roads that can be hardened and made more resilient are the Hurricane Evacuation Routes. These roads are designated as evacuation routes because of their capacity (i.e., not elevation) to move people away from the coast before a hurricane. Finally, the Group discussed the need for redundancy in the system. Specifically, the need to designate a detour network (for people and trucks) if elements of the critical network is washed out.

Mitigation Measures

Participants were asked about measures that can be taken during the event and in the aftermath to recover and repair the infrastructure, as well as measures that can prepare the

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16 Participants pointed out that if I-10 in Houston close, trucking companies start to divert traffic in El Paso. The closure of these highways therefore can affect a much larger region.

road network better for future extreme weather events. Examples that were offered to stimulate the discussion included:

- Improve design standards to respond to future events.
- Moisture resistant pavement layers.
- Imposing truck restrictions.
- Raising road profiles.

Group 1

Group 1 agreed that during an extreme weather event an assessment needs to be made as to whether to evacuate. TxDOT, for example, widened the shoulders of some bridges to use as lanes during evacuations. Contraflow (lanes in both directions are used to evacuate) is more resource intensive, because all ramps need to be manned and commerce is practically shut down.

Group 1 also commented that lessons learned should be documented and reviewed to mitigate the impacts of future extreme weather events. Some of these lessons include understanding extreme weather events from an engineering perspective (where runoff goes) and using this information in the planning and building of roads (i.e., make sure roads are not build in the flood prone areas and that water can drain).

Group 2

Group 2 discussed several measures that can be broadly categorized as infrastructure, operational, and funding to mitigate the impacts of extreme weather events.

Proposed infrastructure measures included building and maintaining levees and drainage improvements (e.g., cleaning bayous and investing in detention ponds). A concern was raised about the Army Corps of Engineers' policy to build levees and then handing the levees over to the counties to maintain. Most of the measures proposed related to operational improvements as follows:

- Designating context sensitive detours for trucks. In other words, designating detours that ensure trucks can access establishments where freight originate or is destined for.
- Proactive inspection of bridges to ensure bridge infrastructure can handle an extreme weather event.
- Development of asset management systems.
- Designating resilient networks that include bridges.
- Fostering of public partnerships to ensure effective coordination and response to extreme weather events.
- Movement of rolling stock (buses) to higher elevations for protection against flooding.
- Protecting communication infrastructure (e.g., cell towers).
- Operational improvements to underpass gates and installing flashing lights to warn against flooded underpasses.
- Pump station maintenance.

Workshop participants also pointed out that FEMA/FHWA reimbursements for flood damage can be challenging because of classification requirements, evidence needed (usually photos), and the timeframe to submit applications. Reimbursements are 90 percent federally funded and 10 percent state funded. Participants pointed out that FEMA/FHWA will provide funding to get the road or bridge to the state/condition prior to the weather event and not for any improvements to make the road or bridge more resilient to future weather events.

Group 3

Group 3 participants recommended researchers look at US 90 (Rosenberg) as a case study. This section of US 90 was raised, but the road was affected by flooding from the Brazos River during construction.

Fort Bend County will be implementing Levy Districts. Levy Districts will look at detention pond requirements and subdivisions may be required to adhere to more stringent detention pond requirements. It is expected that regulations will continue to change. Floodplain risk maps were first developed in the 1970s and 1980s. Prior to the 1980s, the frequency of storm events was low, and there were essentially no regulations. A high percentage of houses that were flooded during Hurricane Harvey were built before the 1990s. Also, some of these areas were affected by upstream development.

Harris County has implemented more stringent storm water detention/retention requirements in the 500-year FEMA floodplain risk locations. Project specific detention/retention requirements call for a zero impact from the project (i.e., project cannot make flooding worse), but downstream impacts on neighborhoods are not accounted for. It was pointed out that no agency looks at the whole system. Requirements are specific to individual projects, but there is no look at the cumulative impact of individual projects. A systems analysis of development (projects) would be frowned upon by business people and elected officials as it would be seen to slow development down. Planning for development will take time because the entire burden for flooding control cannot be placed on the last developer. Participants proposed a water suitability assessment, which will determine to what extent development should be curtailed or redirected. Apart from the size of detention ponds and the number of detention ponds (consider building one detention pond that costs less than building two detention ponds), the location of detention/retention ponds is also important. In terms of roadways, it was recommended that transportation agencies look at the drainage requirements for three concurrent roadway projects (rather than the individual requirements for each project). Jurisdictional cooperation can be problematic.

Given budget constraints, there are discussions about road bonds and flood control bonds to fund investments in detention/retention ponds.

The group also discussed the need for redundancy in the system, specifically as it pertains to arterials. For example, when investing in a parallel facility (i.e., adding lanes/capacity to an existing facility), the facility should be elevated so that it will not flood as frequently in the future. Some roadways, such as US 90 (Fort Bend County), also need to stay open during flooding for evacuation purposes and to facilitate emergency services. Participants discussed a tiered approach when making infrastructure more resilient. The following question should be asked when designating the tiers:

- Which assets are more critical?
- What level of service is needed?
- How much inconvenience can people tolerate?
- What is the threshold for disruption pain?[17]

A mitigation measure, for example, is to discourage people from traveling for seven days after an extreme weather event. It was noted that "civilization will last 72 hours" after the power fails. The strategic question is what is the tolerance for disruption? Or put differently, how much money should be spent to reduce the disruption by three days (for example)? The window for extreme weather events (specifically hurricanes) is from June to November, but for the Houston area, the hurricane risk is high in August and September. Participants pointed to the challenges associated with evacuation. With Hurricane Rita, more people died from the evacuation than from the hurricane. Respondents agreed that development should occur where evacuation would not be necessary. Development of the Bolivar Peninsula is subject to storm surge concerns. The issue is that unincorporated areas may not have land use requirements.

Respondents also mentioned that agencies should do better to warn people in advance of severe flooding events, add remote controlled gates for roadways in flood prone areas, and add cameras in the areas that are prone to flooding that can be monitored by Transtar.

Finally, participants pointed to the need for regular meetings of the 26 constituencies that are involved to discuss hypothetical events and the actions that should be taken during such events.

Available Data/Information and Gaps

The final topic discussed was data available and needed before an extreme weather event, during the event, to understand the impact, and to recover and design mitigation measures.

Group 1

Group 1 participants' discussion of data needed before the event centered on weather information/predictions, specifically, wind speeds, water levels, and surge forecast. Participants pointed out that 39 mph is used as the threshold to indicate the onset of tropical storm force winds. Many ports and facilities use this as the threshold for shutting down. Some counties do not allow trucks (or in some cases emergency vehicles) on the

[17] For example, focus on hardening infrastructure to ensure a maximum disruption time of 96 hours.

roads during wind speeds of 39 mph or higher. Also, some bridges are closed when wind speeds reach 39 mph.

During the event, participants indicated that access is needed to:

- Bridge inspection information.
- Storm direction and forward speed.[18]
- Corridors blocked by floodwaters to provide to emergency responders.
- Rain gauges that measure rainfall per hour to inform resource distribution.
- Wind speeds.
- Flood elevations.
- Status of reservoirs and bayous.
- Estimates of debris.

Finally, participants mentioned that specific evacuation instructions are needed for private citizens. For example, you need to evacuate in a reliable vehicle, because there will not be service available if you break down.

To tell the story of the impacts of an event, Group 1 agreed that the following information will be useful:

- Pictures/graphics – providing information on the rainfall totals (e.g., 50 inches of rain) is meaningless to people.
- Number of homes lost.
- Number of lives lost.
- Compare the event to other events or indicate the disaster level.
- Water depth and movement.
- Economic impact in terms of the cost of the damage[19] or the amount of money received from charitable contributions.
- Number of people that left the area and did not return.

- The number of people rescued.

Group 2

Group 2 participants use the following sources of data leading up to an extreme weather event, during the event, and to understand the impacts in the aftermath of an extreme weather event:

- Department of Homeland Security.
- FEMA.

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18 Participants pointed out that accurate information about a storm surge is only available 48 hours before the storm, whereas evacuation orders need to be called 100 hours beforehand. Only the setting up of contraflow takes several days.

19 The cost of the damage incurred determines qualification for federal assistance and state or federal emergency/disaster declaration.

- NOAA.
- National Weather Service.
- Social Media (Facebook, Twitter, Gasbuddy, Nextdoor).
- Google.
- TxDOT.
- Houston Transtar.
- American Trucking Research Institute (ATRI).

Specific data used leading up, during, and in the aftermath of an extreme weather event are:

- Flood gauge bridge data.
- Flood insurance rate maps.
- Elevation maps, stream gauges (high water marks), and historical data.
- Meteorological data.
- National Weather Service models.
- Road closure maps.
- Google Satellite images.
- Social media information.
- Google driving directions.
- TxDOT Drive Texas.
- Houston Transtar traffic/driving conditions.
- General structural data for bridges.
- Overhead imagery (satellites).
- ATRI's truck maps showing trucks impacted by extreme weather event.
- Rail data.

The participants also pointed out that:

- FEMA has not updated the flood plain maps in recent years (specifically for Brazoria and Galveston Counties in the Houston region).
- Inundation data given precipitation levels are not readily available, and the structural data for ports and bridges are not available electronically.

The participants proposed implementing an archive system to capture data on extreme weather events. A framework is needed to record and capture data and information on extreme weather events. The framework needs to provide guidance on what and how to record data but needs to be flexible enough to accommodate future technologies.

Group 3

Group 3 discussed the need for wider knowledge of the locations of flood prone areas and to characterize disturbances. One participant mentioned that storm surge inundation maps are available and can be used to determine evacuation areas and routes. Rice University also completed a predictive flooding study. The Medical Center uses equipment installed by Rice University to close gates during flooding events.

Input on Study Approach

Group 1

Group 1 participants stated that researchers should keep in mind that if one link in the transportation system is impacted, many other links are also impacted. The group also recommended that the draft report be reviewed by a TxDOT Houston District employee. Finally, the group pointed to the private sector's response after an extreme weather event. The participants felt that the private sector (specifically utilities) have come to coordinate better in their response to disasters.

Group 3

There was general consensus in the group that a systems approach is needed to mitigate extreme weather events.

Appendix B—Impact of Flooding on Pavements

Literature Review

Much work has been done to study the short-term effect of flooding on the stiffness and capacity of pavements. Zhang et al.[19] conducted a damage assessment on flooded pavements in New Orleans after Hurricane Katrina by performing a full-scale pavement testing survey. The tests performed included falling weight deflectometer, ground penetrating radar (GPR), and dynamic cone penetrometer. Flooded pavements were tested within two months of Katrina, and a comparison was made between the structural capacity of flooded and unflooded pavements. Results of the field data suggested that flooded pavements had higher deflection, lower structural number, and lower subgrade resilient modulus compared to unflooded ones. Thinner pavements were damaged more severely than thicker pavements. In another study conducted by White et al.,[20] the impact of the 2011 Missouri River flooding on geo-infrastructure systems, including paved and unpaved roadways in western Iowa, was evaluated. Researchers conducted in situ testing and field investigation on flooded and non-flooded roadways shortly after flooding, and 6–8 months after flood water receded. They reported 20–30 percent reduction in subgrade modulus 6–8 months after flooding.

Field evaluations and in situ testing of flooded pavements are believed to be valuable means to evaluate the detrimental effects of flooding. The costliness of field testing has led some researchers to supplement analyses by mechanistic-based analytical approaches. Elshaer et al.[21] performed a parametric analytical analysis on saturated and unsaturated pavements to simulate the effect of floodwater recession on the performance of pavements. The authors suggested an influence depth for subsurface water level based on the soil type and pavement structure. The influence depth is the depth at which the pavement can withstand the traffic with minimum deterioration. In another study, Mallick et al.[22] developed a system dynamic-based methodology to determine the critical time for full saturation of the unbound layer and failure of the pavements. The methodology was embedded in a web-based simulation tool, which can be used to identify potentially vulnerable pavements before flooding happens and take action to improve them.

Previous studies mainly focused on the short-term impact of flooding on the structural capacity of pavements. According to the experimental and analytical studies reported in the literature, resilient modulus of unbound layers decreases immediately after flooding, resulting in an increase in the pavement deflection. As flood water recedes, unbound layers gain strength again and recover gradually in terms of stiffness. However, the flood-induced deformations do not return to zero, and unbound layers reach a new equilibrium stress-strain state. Flood-induced deformations contribute to the accumulated deformation of the pavement and can result in a service life reduction.

TxME Pavement Design Software

TxME pavement design software, version 1.0, was used in this study for the simulation. Granular base/subgrade rutting is the main factor affected by flooding given moisture content sensitivity. Stiffness and stress states of these layers change significantly as a function of saturation. The VESYS5 layer rutting model, presented in Equations (2)-(3), is implemented in TxME to predict the unbound layer rutting:[23]

$$RD_{granularbase} = \sum_{i=1}^{M} k_{granularbase} \int (U_i^+ - U_i^-) \mu_i N^{-\alpha_i} \quad (2)$$

$$RD_{subgrade} = k_{subgrade} \int (U_i^+ - U_i^-) \mu_{subgrade} N^{-\alpha_{subgrade}} \quad (3)$$

where,

$RD_{granularbase}$ & $RD_{subgrade}$ = granular base and subgrade rut depth, respectively;

$k_{granularbase}$ & $k_{subgrade}$ = calibration factor;

U_i^+ & U_i^- = deflection at top and bottom of layer i due to axle group;

M = total number of granular base layers;

$\mu_{subgrade}, \alpha_{subgrade}$ = permanent deformation parameters of subgrade;

μ_i, α_i = permanent deformation parameters of layer i.

μ_i, α_i are dependent upon the temperature, moisture content, and stress levels applied to the materials. U_i^+ and U_i^- are determined by the Multi-Layer Elastic Theory solutions embedded in TxME. Material properties of each layer (such as resilient modulus of unbound layers and Poisson’s ratio), traffic inputs, and pavement geometry are inputs of Multi-Layer Elastic Theory to calculate the values of U_i^+ and U_i^-.

Effects of moisture content on the modulus of granular base layers are considered in TxME through a moisture impact model. The model modifies the initial resilient modulus based on the moisture content estimated by the Enhance Integrated Climate Model (EICM). EICM is incorporated in TxME to predict temperature profiles and moisture contents in pavement layers based on the user inputs, such as groundwater table depth, weather-related data, pavement structure materials, drainage, and surface properties. The moisture impact model is presented in (4):

$$\log\frac{M_r}{M_{ropt}} = a + \frac{b-a}{1+e^{(\ln\frac{-b}{a}+K_s(S-S_{opt}))}} \tag{4}$$

where,

M_r = representative resilient modulus at a degree of saturation;

M_{ropt} = representative resilient modulus at the optimum moisture content;

S = degree of saturation;

S_{opt} = degree of saturation at the optimum moisture content,

a, b, and k_s = regression parameters.

Note that M_{ropt} is a user input, and S_{opt} is a material property calculated internally in the software using Equation (5) from several user inputs, including optimum gravimetric moisture content (w_{opt}), maximum dry density of the unbound material ($\gamma_{d\max}$), and specific gravity of the unbound material (G_s).

$$S_{opt} = \frac{\frac{w_{opt}\gamma_{d\max}}{\gamma_{water}}}{1-\frac{\gamma_{d\max}}{\gamma_{water}G_s}} \tag{5}$$

S is the only unknown in Equation (4), which is the function of volumetric moisture content, θ, as shown in Equation (6). As stated earlier, θ is determined internally by EICM:

$$S = \frac{\theta}{w_{opt}}\frac{\gamma_{water}}{\gamma_{d\max}}S_{opt} \tag{6}$$

In the current version of TxME, automatically adjusting modulus is only available for granular base layers, and not subgrade. This option is employed in this study to adjust M_r of granular base layers after flooding. However, for subgrade layers, monthly M_r values are estimated manually based on the Houston District soil data and online resources, and inputted directly in TxME.

Simulation Approach

The first step in the simulation was to identify the potential pavement structures in TxDOT's Houston District and thinner sections potentially used by local municipalities. The required design/simulation inputs were collected from TxDOT resources, online resources, and the literature. These inputs include typical material properties for each layer, soil data, traffic data, and climate data, such as subsurface water table, precipitation, temperature, and so on. Unflooded pavements were simulated using TxME to determine the service life of dry pavements without any flood events. Next, the design/simulation parameters affected by flooding were selected, and their corresponding values after flooding were estimated. These parameters include resilient modulus and rutting parameters of unbound layers, traffic levels, and most importantly, subsurface water level. Several flood event scenarios were defined based on the flooding years. It was assumed that the pavements would be in service for at least 20 years. The following four flood event scenarios were defined to assess the impact to existing pavements:

I. Flooding happens in year 1.
II. Flooding happens in year 10.
III. Flooding happens in year 20.
IV. Flooding happens consecutively in year 15, 16, and 17.

The simulation was repeated with the modified input values to estimate reductions in the service life of the pavements for each of the flood events. TxME does not allow changing the design inputs in different years. In other word, if a design input is defined for the first year of simulation, it remains the same throughout the entire design period. To overcome this limitation, the simulation period was divided into three periods: before flooding, during flooding, and after flooding. Each period was simulated using its corresponding properties. The pavement condition at the end of each period was inputted as the pavement condition at the beginning of the next period. At the end, rut depths developed during each period were summed up to generate the total rut depth of the pavements over the service years. Total rut depth of 0.5 in. was selected as the design limit, dictating the end life of flooded pavements. Figure 29 illustrates the simulation framework.

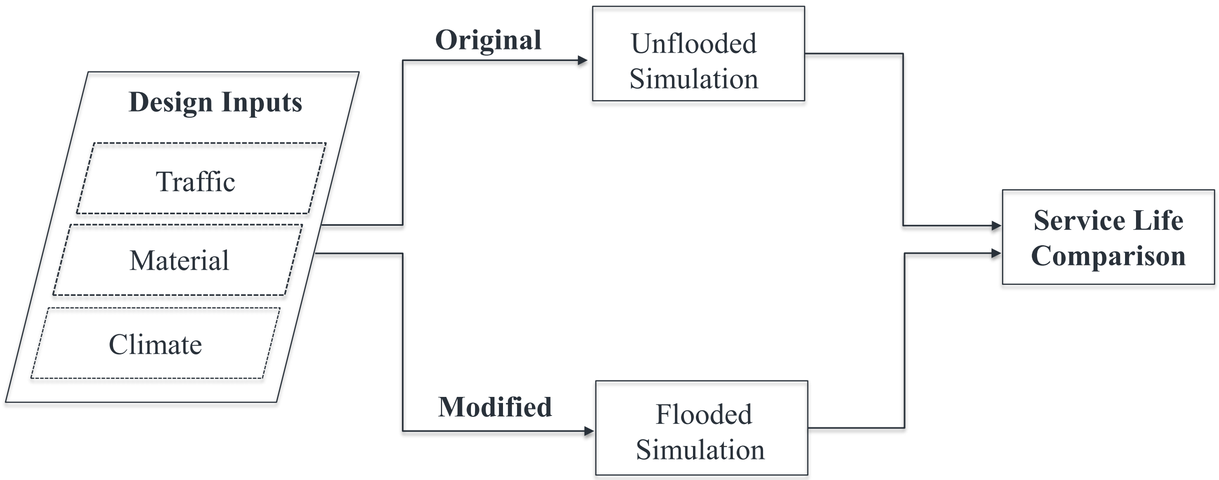

Figure 29. Simulation Framework.

Data Collection

Three pavement structures are considered in this study, shown in Figure 30.

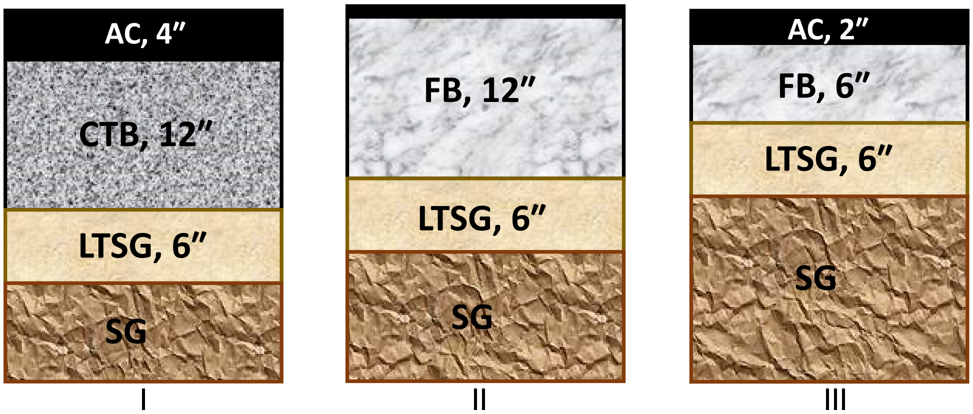

Figure 30. Pavement Structures.

Structure I with 4 in. AC and 12 in. CTB is recognized as the strongest among the considered structures, while Structure II, which is comprised of a surface treatment placed over FB and LTSG, is identified as the weakest structure. Structure III is stronger than II but weaker than I, and is composed of AC, FB, and LTSG. Structure I represents the minimum desired pavement structure for all on-system roadways in the Houston District. Structures II and III represent pavement structures more indicative of city streets, count roads, or rural TxDOT coastal districts. Typical properties of AC layers including dynamic modulus, rutting parameters (i.e., α and μ), Poisson ratio, etc., were obtained from TxDOT resources and literature. Considering the low diffusivity of liquid water in AC, it is widely accepted that flooding does not make notable changes to AC stiffness, hence, AC rutting. Therefore, in this study, the rutting property of AC is assumed unchanged throughout the simulation process. However, researchers note that water inundation can lead to striping of AC layers, creating the potholing effect often seen after heavy rain events. This phenomenon is not modeled in TxME and its occurrence is difficult to simulate.

The resilient modulus of FB is sensitive to the moisture content. As stated earlier, TxME adjusts the resilient modulus based on the water content, calculated by EICM. One of the user-defined inputs required for this adjustment is the subsurface water level. According to the data explored from the Texas Water Development Board website,[24] it was assumed that the subsurface water level rises from 18 ft below the pavement surface to the top of the base coarse once flooding occurs. The properties G_s, ω_{opt}, γ_{dmax}, and M_{opt} involved in Equation (4), (5), and (6) for the moisture adjustment were extracted from LTPP data.

Typical values of rutting parameters α and μ for dry base/subbase layers were obtained from the literature for each traffic volume.[25] But, unfortunately, no value for these parameters is reported in the literature for wet materials (i.e., corresponding to after-flood condition of the pavement). The best estimates of the corresponding wet values can be determined by the Repeated Load Permanent Deformation (RLPD) test. For the scope of this study, a rough estimate of these values was used based on the assumption that the impact of moisture content on rutting is positively correlated with that of load. The trend of change in α and μ with respect to the load is available in the literature.[25] The same trend was applied to account for the effect of moisture.

Strength and drainage characteristics of the subgrade are two important factors affecting the flood damage in flexible pavements. A comprehensive literature review was conducted to study the soil properties in the TxDOT Houston District. Based on the survey conducted by Natural Resources Conservation Service (NRCS)[26] of the United States Department of Agriculture, the soil in Houston District is mostly composed of silt-clay materials, which are categorized as A-4, A-6, and A-7-6 according to the AASHTO classification.[27] The strength and drainage characteristics of A-4, A-6, and A-7-6 are poor.[28] In most areas in Houston, soils have a very slow infiltration rate when thoroughly wet. Infiltration rate is usually defined by a property known as Saturated Hydraulic Conductivity (SHC), which describes water movement through saturated media. In most regions in Houston, the SHC of soil is approximately 10^{-5} to 10^{-3} cm/sec, which implies poor drainage quality. To observe this, notice that the time to reach 20 percent saturation for SHC = 10^{-3}cm/sec is 100 hours, while for SHC = 10^{-5} cm/sec it is 2000 hours.

Researchers have noted that the saturation degree of soil plays a major role in its elastic response to loading.[29] An increase in the saturation degree, caused by seasonal changes or flooding, can bring about a significant decrease in the soil's resilient modulus. Based on the collected data, researchers assumed that the soil in Houston District drains slowly such that it approximately takes five months to recover and regain strength after flooding. Figure 31 shows the trend of resilient modulus change over time for a flood event occurring in August, a common month for hurricanes in the Gulf of Mexico.

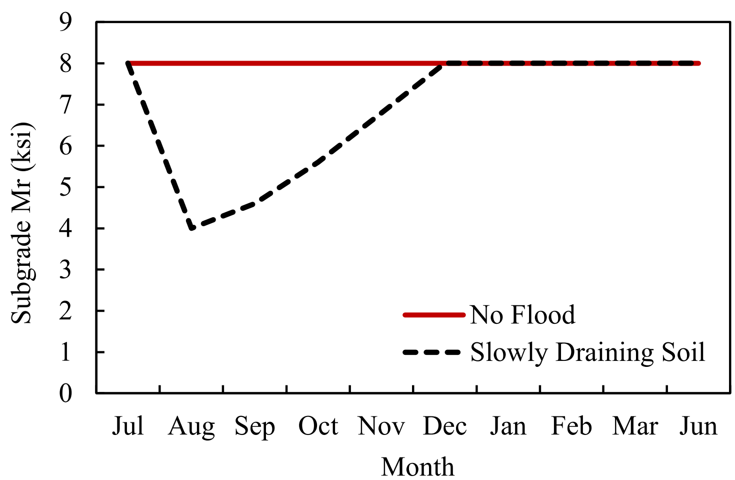

Figure 31. Change of Resilient Modulus after Flooding.

As a part of the simulation scenarios, traffic levels on each selected structure were estimated. These levels, characterized in Table 10, are categorized as low, medium, and high. To account for the impact of post flooding events, such as increased number of emergency and recovery (e.g., construction traffic) vehicles immediately after flooding, the percent truck for the low traffic category was increased from 2 percent to 17 percent, and the ADT was increased by 50 percent. The change of traffic was only applied to pavement Structure II and Structure III, initially designed for the low traffic. For Structure I, the initial design is robust enough to endure high traffic volume and the assumption was made that post-flood traffic does not significantly increase the amount of traffic typically using a Structure I roadway. The increase in traffic to thinner or weaker pavement sections simulates the impact that can occur on local municipality roadways or other rural TxDOT districts.

Table 10. Traffic Volumes.

Traffic Volume	Beginning ADT[1] (veh./day)	20-Year End ADT (veh./day)	Percent Truck (%)
High	25000	50000	25
Medium	7500	15000	17
Low	1000	2000	2

Appendix C—Pavement Structure Recommendations

Based on the observed performance of pavement structures in the Houston District after Hurricane Harvey, the pavement structures currently used by the Houston District for reconstructing roadways perform well after extreme weather events. These pavement structures are:

- Asphalt Concrete Pavement (ACP) Structure:
  - 4 in. Asphalt Concrete Pavement.
  - 12 in. Cement Treated Base.
  - 6 in. Lime Treated Subgrade.
- Continuously Reinforced Concrete Pavement (CRCP) Structure:
  - 9 in. to 15 in. Continuously Reinforced Concrete Layer.
  - 1 in. Asphalt Concrete Layer.
  - 6 in. Cement Treated Base.
  - 6 in. Lime Treated Subgrade.

The Houston District has used the ACP structure for reconstructing most of the roadways on their Farm to Market Road system and some roadways on their State Highway System, and the CRCP structure for reconstructing roadways on other higher volume road systems (Interstate Highway and US Highway systems). In the ACP study, using the Texas Triaxial Design Check procedure used by TxDOT, the pavement structure is adequate for a design wheel load of 15,000 lb and a Texas Triaxial Class Value of 6.5 for a subgrade soil (a very weak soil). This procedure is used to check that the pavement structure can withstand a limited number of heavy wheel loads without suffering significant damage.

Although the CRCP surface pavement structure was not analyzed under this study, visual observations and analysis of GPR data obtained by TTI after Hurricane Harvey on I-10 (between I-610 West and I-45) and SH 288 (from downtown Houston to I-610) showed that both pavement structures suffered minimal damage due to moisture intrusion. Sections of both roadways were underwater for an extended period during Harvey and previous events. Figure 32 shows a representative GPR data sample on I-10; Figure 33 shows a representative GPR data sample on SH 288. In both cases, the pavement structure is structurally sound according to the GPR data.

Figure 32. GPR Data Analysis on a Section of I-10.

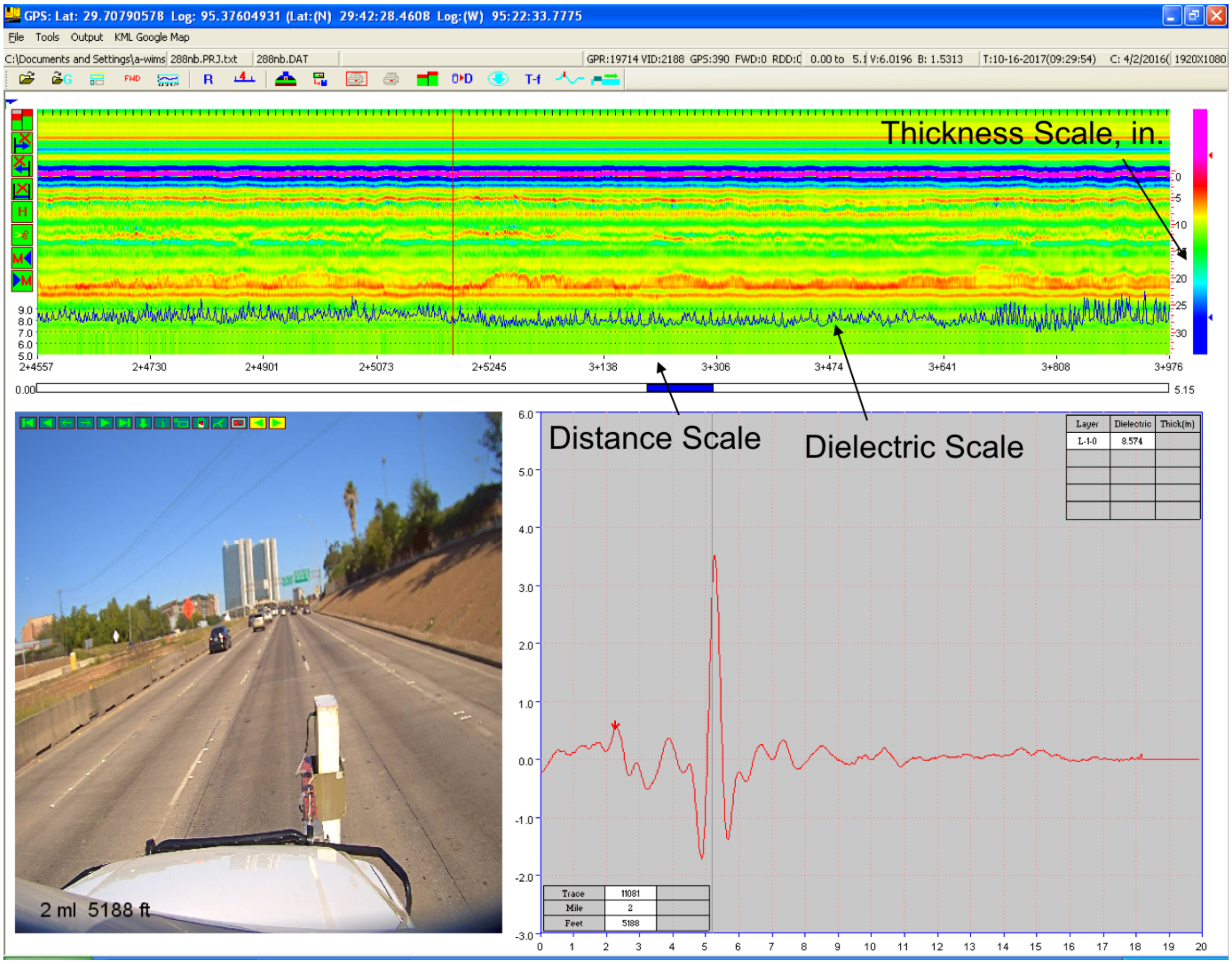

Figure 33. GPR Data Analysis on a Section of SH 288.

In addition, the Houston District has also overlaid existing concrete pavements (both CRCP and Jointed Concrete Pavement) with ACP. In general, these overlays performed well after Hurricane Harvey, but there were a few isolated cases where the overlays had not bonded well to the existing pavement, which resulted in those overlays being washed away by floodwaters. TxDOT does have sufficient specifications and practices for ensuring proper bond between overlays and existing pavements. It may be desirable for the Department to offer training courses for construction inspectors on proper material selection and construction practices to ensure bonding.

Appendix D—Identified Data Sets and Information

TTI researchers conducted a review of geospatial data potentially useful for understanding and modeling extreme weather events. The review focused on Houston and surrounding areas. Researchers used file types and extreme weather event keywords to perform the searches, along with key file types used to store geospatial data, for example:

- Shape files.
- KMZ or KML files.
- PDF and other photo-based maps.
- Online interactive maps and viewers.
- Informational websites and pages.

Typically, geospatial data sets were located within a GIS data portal or interactive map or viewer. These sites provided information on many other related and potentially useful data sets.

Each data set was evaluated by exploring its meta data and by mapping the data in GIS software. The data sets were catalogued by coverage, data source, attributes, resolution, last update, or revision.

Data files of interest were found within data portals developed by the following organizations:

- City of Houston (COH).
- Dartmouth Flood Observatory (DFO).
- Department of Homeland Security's (DHS) Homeland Infrastructure Foundation-Level Data.
- ESRI.
- FEMA.
- Fort Bend County Office of Emergency Management (FBCOEM).
- Google.
- Harris County Appraisal District (HCAD).
- Harris County Flood Control District (HCFCD).
- Houston Community Data Connection (HCDC).
- Houston-Galveston Area Council (H-GAC).
- National Hurricane Center (NHC).
- NOAA.
- NRCS.
- Prism Climate Group (PRISM) at Oregon State University.
- TxDOT.
- Texas Natural Resources Information System (TNRIS).

- United States Army Corp of Engineers (USACE).
- USGS.

GIS Data Sets

Following the discovery of relevant data sets, they were mapped and explored to identify potentially useful combinations of data. Several data sets and combinations of data sets were used during the Extreme Weather Workshop (see next section) as a tool to assist in the workshop discussions. For example, Figure 34 shows FEMA floodplain data and crowd-sourced road closure data obtained from Google. Figure 35 shows DFO maximum flooding data set and crowd-sourced road closures due to Hurricane Harvey.

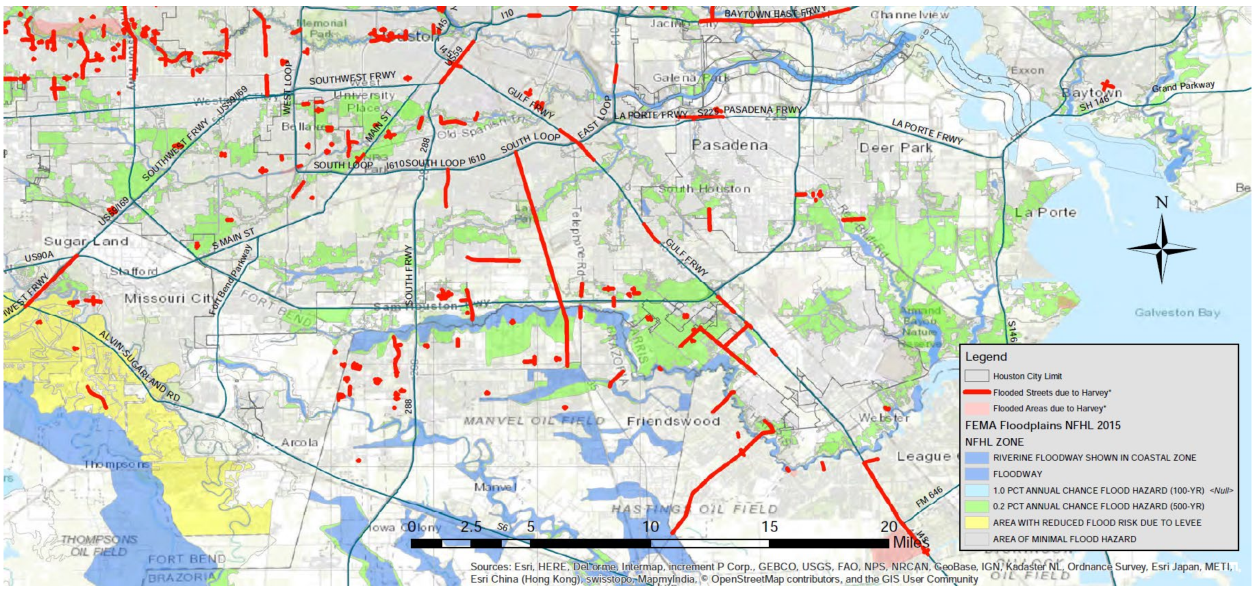

Figure 34. Example Data Set Combination of FEMA Floodplains National Flood Hazard Level 2015 and Harvey Road Closures.

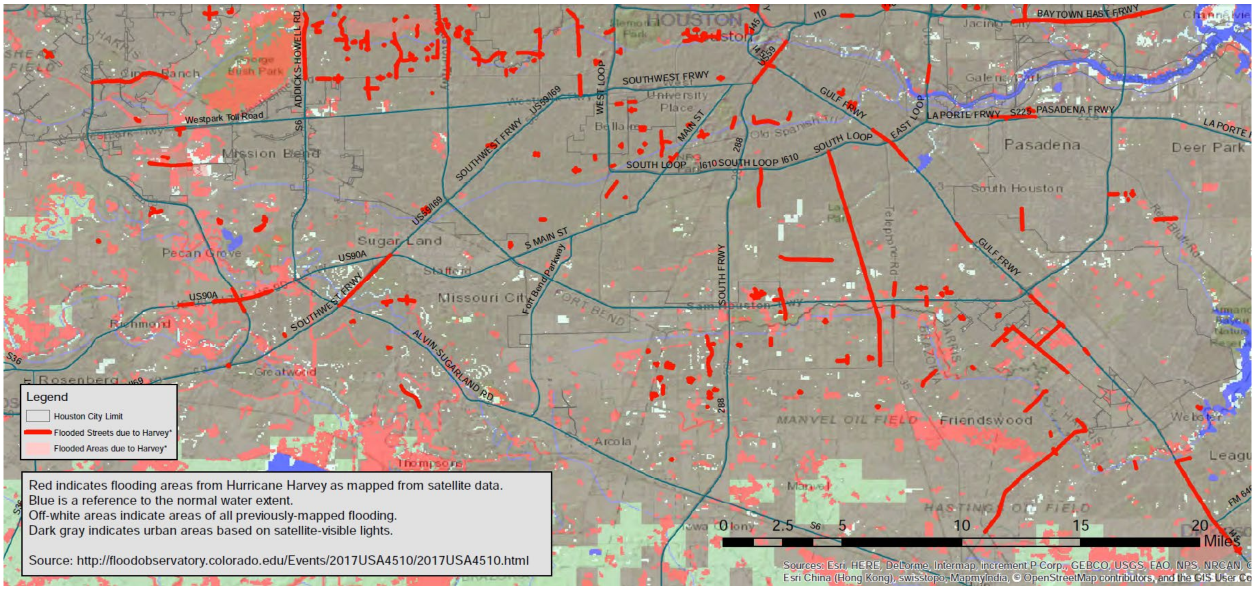

Figure 35. Example Data Set Combination with DFO Maximum Flooding and Street Closures due to Hurricane Harvey.

Table 11 summarizes data sets, interactive viewers, and websites identified as potentially useful for subsequent analysis.

Table 11. Identified Data Sets, Interactive Viewers, and Websites.

Source	Site/File Name	Data Type	Description	File Location	Data Content
COH	City of Houston GIS Open Data Portal	Interactive Web Application CSV, KML Shapefile	City of Houston GIS Open Data Portal	http://cohgis-mycity.opendata.arcgis.com/	Various data sets including boundaries and transportation data
DFO	North America Flood Information Viewer	Interactive map	DFO Interactive maps	https://diluvium.colorado.edu/arcgis/apps/Viewer/index.html?appid=52335a2e48e342fc82b56f8a018dd77d	Displays various event layers that include Hurricane Harvey
DFO	Overview: Maximum Observed Flooding Viewer	interactive map	DFO Flood Event 4510, Hurricane Harvey, Texas and Louisiana	http://floodobservatory.colorado.edu/Events/2017USA4510/2017USA4510.html	Overview: Maximum Observed Flooding
DHS	Hurricane Ready Information Site	Information	Explains what actions to take when you receive a hurricane watch or warning alert from the NOAA for your local area	https://www.ready.gov/hurricanes	Provides tips on what to do before, during, and after a hurricane
ESRI	Imagery Collection of Inundation Areas from European Space Agency's Copernicus Satellite	Interactive viewer	Imagery Collection of Inundation Areas from Copernicus	https://www.arcgis.com/home/webmap/viewer.html?webmap=087d1d9fc5e24f0ebf29a838add77a67	ESRI

Source	Site/File Name	Data Type	Description	File Location	Data Content
ESRI	Addicks Reservoir inundation model	Interactive viewer	Addicks Reservoir inundation model	http://www.arcgis.com/home/webmap/viewer.html?url=https://services7.arcgis.com/n1YM8pTrFmm7L4hs/ArcGIS/rest/services/addicks_inundation_model/FeatureServer/0&source=sd	ESRI
FBCOEM	Brazos River Inundation Map	Interactive viewer	Brazos River Inundation Map	http://arcg.is/ziPTT	Fort Bend County Office of Emergency Management
FEMA	S_FLD_HAZ_AR.zip	shapefiles	FEMA's National Flood Hazard Layer (Official)	https://fema.maps.arcgis.com/home/webmap/viewer.html?webmap=cbe088e7c8704464aa0fc34eb99e7f30	Official source for flood hazard layer. Summary of Discharges with location, drain area, event type (by 0.2, 1, 2, 4, 10% chance)
FEMA	FEMA's National Flood Hazard Layer Viewer	Interactive viewer	FEMA's National Flood Hazard Layer Viewer	https://hazards-fema.maps.arcgis.com/apps/webappviewer/index.html?id=8b0adb51996444d4879338b5529aa9cd	National level
FEMA	Hurricane Incident Journal website	Interactive viewer	National-level Hurricane Incident Journal	https://fema.maps.arcgis.com/apps/MapJournal/index.html?appid=97f53eb1c8724609ac6a0b1ae861f9b5	Provides live stream gauges and "NOAA nowCOAST Storm Track"
FEMA	Index of Hurricane Harvey Data	Various files for DL	Index of National Disaster/Hurricane Harvey/ Data	https://data.femadata.com/NationalDisasters/HurricaneHarvey/Data/	Buildings, Damage Assessment, Depth Grid, Remote Sensing
Google	Flooded Streets due to Harvey	KML	Flooded Streets due to Harvey	https://www.google.com/maps/d/viewer?mid=1Nzjiw9FHdJPHgNJiVMSHWhBQQd0&hl=en&ll=29.827383837787476%2C-95.27925249999998&z=9	Hurricane Harvey Road Closures
HCAD	GIS_Public.exe	Shapefiles	Exe file containing compressed (zipped) shapefiles	http://pdata.hcad.org/GIS/index.html	abstract, college, county, easement, easement name, emergency, facet, fire, hwy, parcels, row_anno, row Line, school, special, sub_poly, TIRZ, utility, water district

Source	Site/File Name	Data Type	Description	File Location	Data Content
HCDC	HCDC Dashboard (beta)	Interactive viewer	HCDC Dashboard (beta), Estimated Number of Harvey-Flooded Homes	http://www.datahouston.org/Map.html	Estimated Number of Harvey-Flooded Homes
HCFCD	Hurricane Harvey Storm Impact and Recovery website	Information and PDF maps	Harris County Flood Control District	https://www.hcfcd.org/	Provides various PDF reports, tables, and maps for hurricanes and reservoirs
H-GAC	Eco Logical GIS – H-GAC	Interactive Web Application	Eco Logical GIS – H-GAC	http://arcgis02.h-gac.com/EcologicalGIS/	GIS, Imagery, & Online Mapping Tools
H-GAC	Regional Flood Information – H-GAC	Interactive Web Application	Regional Flood Information – H-GAC	http://arcgis02.h-gac.com/flood/	Eco Logical GIS – H-GAC
H-GAC	Contours_2_Feet.zip	GDB Files	2-ft Elevation Contours - polygons	http://www.h-gac.com/rds/gis-data/gis-datasets.aspx	Two-foot elevation contours
H-GAC	Contours_5_Feet.zip	GDB Files	5-ft Elevation Contours - polygons	http://www.h-gac.com/rds/gis-data/gis-datasets.aspx	Five-foot elevation contours
H-GAC	NLCD_Imperviousness_2011.zip	GDB Files	2011 Imperviousness	http://www.h-gac.com/rds/gis-data/gis-datasets.aspx	100 ft x 100 ft raster area colormap classified at 1% intervals
H-GAC	NOAA_Land_Cover_2011_22_Class.zip	GDB Files	NOAA Land Cover 2011 [22 classes]	http://www.h-gac.com/rds/gis-data/gis-datasets.aspx	NOAA Land Cover Classes (22 classes)
H-GAC	FEMA_Floodplains_NFHL_2015	GDB Files	FEMA National Flood Hazard Layer	http://www.h-gac.com/rds/gis-data/gis-datasets.aspx	Many various data sources are provided at this location
NOAA	Flooding in Texas website	Information	Information on typical types of flooding in Texas	http://www.floodsafety.noaa.gov/states/tx-flood.shtml	Provides information on significant flooding events
NOAA	National Storm Surge Hazard Maps	Interactive map	National Storm Surge Hazard Maps for Texas to Maine and Puerto Rico	http://noaa.maps.arcgis.com/apps/MapSeries/index.html?appid=d9ed7904dbec441a9c4dd7b277935fad	Illustrates storm surge hazard areas based on storm categories 1 through 5.
NOAA	National Hurricane Center Data in GIS Formats	Interactive map shapefiles, kmz, kml (not all types available for all information)	National Hurricane Center, NHC Data in GIS Formats	https://www.nhc.noaa.gov/gis/	Available Data: Advisory Forecasts for Track, cone of uncertainty, watches/warnings, wind field, wind speed probability, storm surge probability, and potential storm surge flooding /inundation.

Source	Site/File Name	Data Type	Description	File Location	Data Content
NOAA	Spatial Data Products for Geographical Information Systems	Geostationary Satellites (GOES) Imagery	NOAA Office of Satellite and Products Operations, Spatial Data Products for GIS	http://www.ospo.noaa.gov/Products/imagery/gis.html	FTP sites for GOES East Data, GOES West data, Advanced Very High Resolution Radiometer (AVHRR) data, GOES Winds data, Sea Surface Temperature (SST) data, and Surface data
NOAA	Measured Storm Effects	PDF reports	Office for Coastal Management, Measured Storm Effects	https://coast.noaa.gov/hes/stormEffects.html	Hurricane reports that provide information on measured storm effects.
NOAA	US_SLOSH_MOM_Inundation.zip	Shapefiles	NOAA National Hurricane Center, National Storm Surge Hazard Maps, - Version 2	https://www.nhc.noaa.gov/nationalsurge/#data	GeoTIFF Storm surge hazard maps for Texas to Maine for GIS Systems
NOAA	Climate Data Tools. 1981-2010 Normals	Weather Information	Provides the 1981-2010 Climate Normals	https://www.ncdc.noaa.gov/cdo-web/datatools/normals	Provides three-decade averages of climatological variables, including temperature and precipitation
NRCS	Web Soil Survey	Interactive Map	Web Soil Survey	https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm	Provides soil data and information produced by the National Cooperative Soil Survey.
PRISM	PRISM_tmean_30yr_normal_800mM2_01_asc.zip PRISM_tmean_30yr_normal_4kmM2_01_asc.zip	.BIL (raster) or .ASC (ARC/INFO ASCII grid) formats, PNG images, metadata	PRISM Climate Group - Northwest Alliance for Computation Science and Engineering	http://www.prism.oregonstate.edu/normals/	Baseline data sets describing average monthly and annual conditions over the most recent three full decades (1981–2010).
TNRIS	nlcd11.tx.zip	Shapefiles, GDB Files	National Land Cover Dataset 2011	https://tnris.org/data-download/#!/statewide	Web page provides various GIS and imagery data sets available at state, county, quadrangle, and quarter-quadrangle levels.

Source	Site/File Name	Data Type	Description	File Location	Data Content
TNRIS	nrcs-soils_tx.zip	Shapefiles	TNRIS NRCS Soils Simplified	https://tnris.org/data-download/#!/statewide	Web page provides various GIS and imagery data sets available at state, county, quadrangle, and quarter-quadrangle levels.
TNRIS	fema-nfhl_tx.zip	GDB Files	FEMA National Flood Hazard Layer	https://tnris.org/data-download/#!/statewide	Web page provides various GIS and imagery data sets available at state, county, quadrangle, and quarter-quadrangle levels.
TNRIS	tnris-hwm_tx.zip	Shapefiles	Texas High Water Marks	https://tnris.org/data-download/#!/statewide	Web page provides various GIS and imagery data sets available at state, county, quadrangle, and quarter-quadrangle levels.
TxDOT	TxDOT District Areas	Shapefiles CSV	Provides TxDOT's 25 District geographic subdivisions of the state.	http://gis-txdot.opendata.arcgis.com/	Web page provides 18 GIS Data Categories*
TxDOT	TxDOT Texas Highway Freight Network	Shapefiles CSV	The Primary Freight Network comprises nearly 6,400 miles of highways and includes connections to major freight generators, gateways and ports-of-entry.	http://gis-txdot.opendata.arcgis.com/	Web page provides 18 GIS Data Categories*
TxDOT	TxDOT National Highway System	Shapefiles CSV	The National Highway System (NHS) consists of roadways important to the nation's economy, defense, and mobility.	http://gis-txdot.opendata.arcgis.com/	Web page provides 18 GIS Data Categories*
TxDOT	TxDOT Seaports	Shapefiles CSV	TxDOT's point layer of general seaport locations in the state of Texas. Locations are based off aerial imagery.	http://gis-txdot.opendata.arcgis.com/	Web page provides 18 GIS Data Categories*
TxDOT	TxDOT AADT	Point Shapefiles, CSV	Contains combined traffic counts from roadbeds and frontage roads into one station displayed on the centerline of the roadway.	http://gis-txdot.opendata.arcgis.com/	Web page provides 18 GIS Data Categories*

Source	Site/File Name	Data Type	Description	File Location	Data Content
TxDOT	TxDOT Top 100 Congested Roadways	Shapefiles CSV	Each year, TxDOT identifies and ranks the most congested roadways in the state. The top 100 are ranked and included in this data set	http://gis-txdot.opendata.arcgis.com/	Web page provides 18 GIS Data Categories*
TxDOT	TxDOT Evacuation Routes	Shapefiles CSV	Routes to be taken away from the Texas coast during an emergency	http://gis-txdot.opendata.arcgis.com/	Web page provides 18 GIS Data Categories
USACE	Potential Flood Maps, Buffalo Bayou Inundation Map	PDF	USACE Potential flood maps, Buffalo Bayou Inundation Map	http://www.swg.usace.army.mil/Missions/Dam-Safety-Program/About-The-Reservoirs/Addicks-and-Barker-Potential-Flood-Maps/	Depict modeling projected early Aug. 29, 2017, before releases were increased to 7,000 and 6,000 at Addicks and Barker Dams.
USGS	Hurricane Harvey Flood Event Viewer FilteredHWMs.csv FilteredPeaks.csv	Interactive viewer with CSV and JSON file downloads	USGS Flood Event Viewer - Harvey	https://stn.wim.usgs.gov/fev/#HarveyAug2017	Provides point data for real-time, observed, and interpreted data for storm tide, wave height and high water marks.

* TxDOT's GIS Data Categories include Boundaries, Environmental, Geographical, Highway Performance, Highway Referencing Systems, Locations, Pavement, Planning, Political, Projects, Reports, Right of Way, Safety, Society, Structures, Traffic, Transportation, and TxDOT Infrastructure.

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