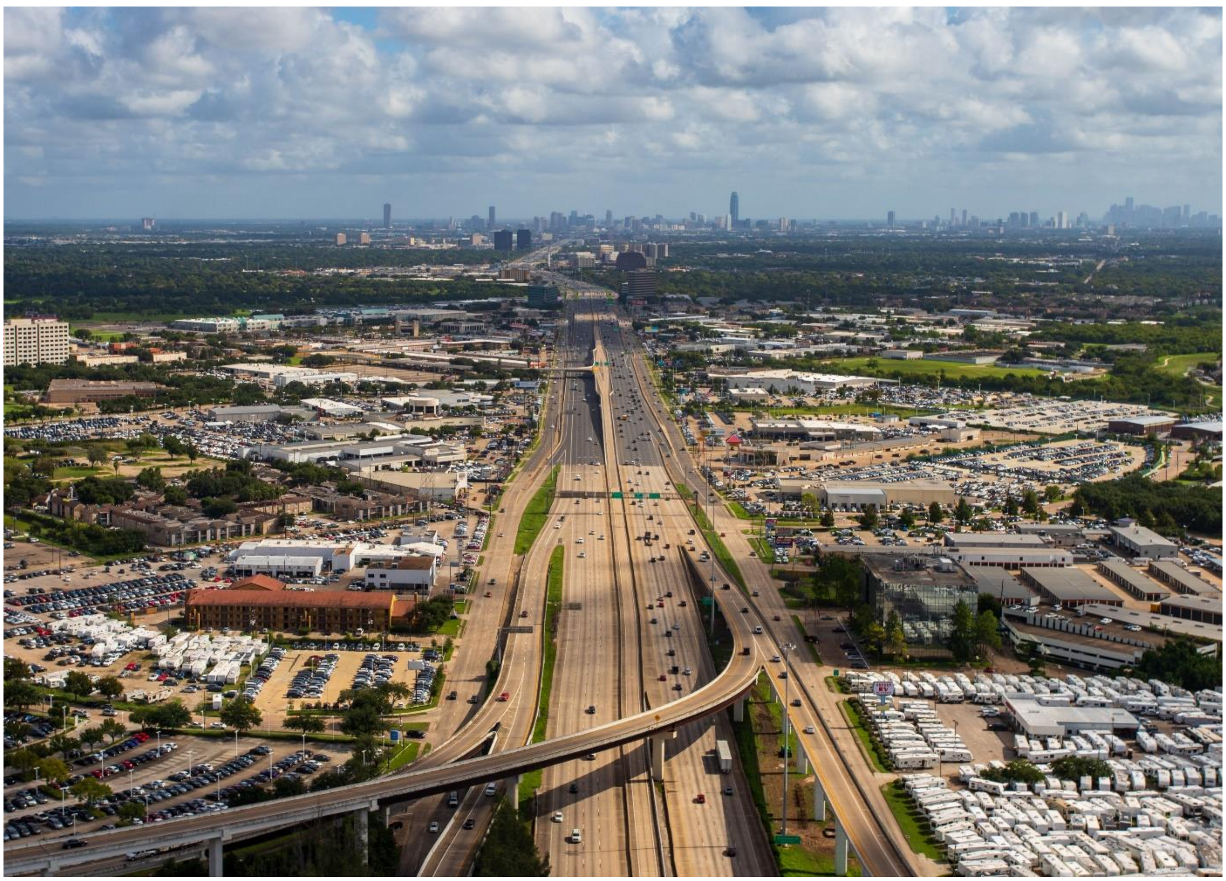
METROPOLITAN HOUSTON REGIONAL WATERSHED ASSESSMENT

DRAFT

JUNE 2021



US Army Corps of Engineers®
Galveston District

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Disclaimer: The information presented in this report is to provide a strategic framework of potential options to address problems within the Metropolitan Houston Region and the 22 Watersheds within Harris County. Options identified will follow normal authorization and budgetary processes of the appropriate agencies. Any costs presented are rough order magnitude estimates used for screening purposes only.

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1. INTRODUCTION

The Houston Metropolitan Region experienced catastrophic flooding as a result of record-breaking rainfall from Hurricane Harvey in August of 2017. Harvey made landfall on August 25th about 30 miles northeast of Corpus Christi near the communities of Rockport and Fulton. The Category 4 hurricane caused extensive damage as it moved north toward San Antonio and then veered sharply east towards Houston and Louisiana. After stalling, Harvey dropped record rainfall volumes in southeast Texas causing widespread flooding in the region.

The U.S. Army Corps of Engineers (USACE) is completing a Watershed Assessment (Assessment) with specific focus on flood risk management (FRM) efforts within the Metropolitan Houston Region. This draft assessment documents initial analyses conducted by the project delivery team (PDT) and presents preliminary conclusions and recommendations to achieve greater risk reduction and resiliency through agency coordination and strategic actions. The final assessment will incorporate public, agency and technical comment to provide final recommendations.

1.1. NON-FEDERAL SPONSOR

The Assessment is a collaborative effort between the USACE and Harris County Flood Control District (HCFCD), as the non-federal sponsor (NFS). HCFCD is a special purpose district created by the Texas Legislature in 1937 and governed by Harris County Commissioners Court. HCFCD is described in greater detail in Section 8.2.

Primary content preparation is undertaken by the USACE and coordinated with HCFCD for consistency and accuracy. The Assessment reflects the HCFCD's ongoing planning efforts and leverages, as appropriate, state agencies' planning and investigation capabilities to ensure the assessment is a broad analysis of current FRM resources. The NFS has created hydrologic and hydraulic (H&H) models to support their efforts to assess and address flood risk in their jurisdiction. These models are currently being updated through the MAAPnext program. The MAAPnext program will update the existing hydrologic methodology to use a basin development factor (BDF) and to use both one-dimensional and two-dimensional hydraulic models to better resolve complicated hydraulic conditions. The updates will also include updated rainfall depths, and the latest topographic data. MAAPnext will improve model accuracy and would render any major modeling effort in this project duplicative. The existing models are available for use but would provide information that will be outdated and inaccurate once the MAAPnext program is completed. available for use but would provide information that will be outdated and inaccurate once the MAAPnext program is completed.

1.2. PURPOSE

Section 729 of the Water Resources Development Act (WRDA) of 1986 (Public Law 99-662), as amended, allows the USACE to assess the water resources needs of entire river basins and watersheds of the United States, in consultation with appropriate federal, state and local agencies and stakeholders:

"The Secretary may assess the water resources needs of river basins and watersheds of the United States, including needs relating to ecosystem protection and restoration; flood damage reduction; navigation and ports; watershed protection; water supply; and drought preparedness."

The focus of this Assessment was restricted to FRM because of the funding source and the multiple regional investments in FRM improvements underway in response to Hurricane Harvey. The Assessment considered the allocative and technical efficiency of improvements, investments, and programs to reduce risk from flooding within the region. Broader objectives such as environmental impacts, habitat, water quality, access and socioeconomic considerations were evaluated where appropriate in FRM decision making and policy considerations. The Vertical Team also specifically named this effort a watershed assessment, rather than a watershed study.

The purpose of a watershed study is to develop a meaningful report to inform multiple audiences and decision makers at all levels of government, local, state, federal, USACE, Assistant Secretary of the Army, Civil Works (ASA/CW) and Congress. This Assessment identifies the problems, opportunities, goals and constraints facing agencies with FRM responsibility in the region and to develop a strategic roadmap acknowledging risk and uncertainty and identifies recommended phases of implementation for greatest success to inform future investment decisions by multiple agencies.

2. WATERSHED PLANNING GUIDANCE

The USACE guidance for watershed planning is Planning Bulletin No. PB 2019 -01 and Engineering Circular 1105-2-411. Figure 1 presents the typical Watershed Study process.

Watershed studies are not project implementation documents. The level of detail is adequate for making watershed-level resource assessments and recommendations. If specific projects are identified for potential implementation under existing USACE authorities, separate feasibility studies would be required to conduct detailed engineering and National Environmental Policy Act (NEPA) documentation.

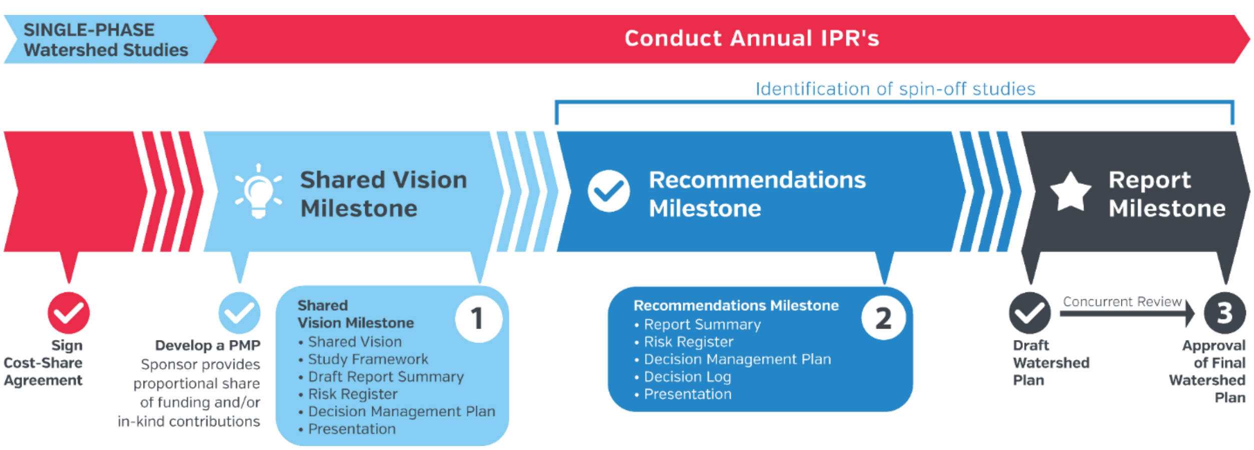


Figure 1 - Watershed Assessment process and milestones

2.1. WATERSHED PLANNING APPROACH

This Assessment presents findings and recommendations for future efforts, including potential future projects and studies in which the USACE could partner with the State of Texas, City of Houston, HCFCD, partner agencies, or other non-federal entities.

The assessment developed the findings and recommendations following an inventory of current conditions of land and water resources in the watershed. Essential steps included:

- Identify problems and opportunities within the watershed through continued stakeholder engagement and agency collaboration
- Inventory and forecast existing conditions related to identified water resource issues
- Evaluate and compare alternative approaches to address the problems and opportunities; and
- Select strategies and/or broad level plans for recommendation, based on the shared vision of the sponsor and project stakeholders which may address water resource issues in the basin.

The Assessment process complied with Planning Bulletin 2019-01 within the narrowed focus of FRM. The PDT conducted an inventory of current activities and involved agencies, authorities, jurisdictions and available tools and technologies to provide FRM in the region. The PDT identified successes and missed opportunities or limitations to implementation of cost effective FRM interventions across the region.

A stakeholder group was convened to support problem identification and to develop a Shared Vision Statement to guide the development of objectives for the watershed. Recommendations were developed for phased actions to overcome institutional barriers and solve technical problems. A decision framework was developed to assess the potential recommendations and identify priority actions that warrant federal participation and are appropriate for multi-agency action.

The inventory ongoing efforts considered several prior reports and recommendations for FRM in the region, and they have been incorporated into the recommendations.

2.1.1. PLANNING GOALS:

- Reduce the risk to public safety from flooding in the watershed
- Communicate risk to community members, elected and government leaders, business, and industry
- Reduce the risk of damages from flooding to residential, agricultural, commercial/industrial areas, utilities, and to roads and other critical infrastructure
- Characterize the generational community losses from persistent flooding, both in terms of wealth and cultural resources
- Maximize the effectiveness of FRM investments through efficient application of modeling, measurements and coordination

- Broaden the recognition FRM measures and their appropriate application – the scale of vulnerability will not be addressed without consideration of tradeoffs of space, funds, aesthetics, environmental flows, and access.

The Assessment investigated an integrated approach to evaluate FRM efforts considering allocative decisions and priorities, and the related impacts and tradeoffs, that may warrant further analysis in the pursuit of engineered FRM solutions. The specific goal of this Assessment is to support the development of a broad management plan that will:

- Incorporate stakeholder input and involvement
- Assess existing watershed characteristics and conditions
- Identify watershed issues and concerns
- Develop, evaluate, and prioritize actions that could advance watershed goals and objectives
- Identify potential "spin-off" and "off-shoot" projects that may fall under appropriate Federal, State, and/or local authorities, and
- Identify potential regionally- or locally funded projects.

3. PROBLEMS, OBJECTIVES AND CONSTRAINTS

Flooding is a recurring challenge in Metropolitan Houston and has damaged or impacted billions of dollars of private property and businesses, as well as public and critical infrastructure such as roadways and hospitals. The Assessment considered the problems, objectives and constraints for FRM efforts in the region to inform potential recommendations. Figure 2 presents a timeline of past flood events and corresponding interventions in the region. The flood events are represented as purple rectangles, regulatory responses are shown in yellow, and large infrastructure projects are shown in green. Greater detail on the specific FRM interventions is provided in Section 8 where specific agency efforts are described.

3.1. PROBLEMS

The Houston area is vulnerable to rainfall-related flooding and coastal surge flooding associated with the landfall of tropical storms or hurricanes. This Assessment will focus on rainfall-related flooding, with some consideration of the intersection with sea level change and climate change impacts.

The primary problems are summarized below.

- Infrastructure upgrade needs exceed available agency resources
- Frequent flooding impacts communities with limited resources to rebuild, restart, repurpose and drives loss of green space in the pursuit of solutions
- Habitat is lost as a result of new development

- The adjacent or intertwined authorities of several agencies, in combination with the economic incentive to minimize current expenditures for current developments create a patchwork of regulations and therefore system quality

3.2. Objectives and Constraints

The goals and objectives for the Assessment recognize that local agencies are familiar with flooding issues, and have a good understanding of impacts, and structural interventions. The goal is to address flood solutions as part of a larger effort to be cost effective, to jointly consider impacts, opportunities to reduce risk and the impacts on the larger economy and community.

Planning objectives include:

1. Supporting community resilience and recovery.
2. Reducing impacts to families, transit, government budgets, business investment, and future resource availability for community needs
3. Increasing efficiency of FRM expenditures across agencies and waterways in the region
4. Increasing awareness of the scale of flood vulnerability and the necessary tradeoffs to achieve risk reduction on an impactful scale.

Planning constraints include:

1. The built environment impedes some structural solutions
2. Physical conditions require different solutions where the water collects and flows, so multiple interventions are required across the region
3. The scale of flood risk requires resources to retrofit or address, and funds are not unlimited
4. Data analysis tool updates will not be completed until after the completion deadline for the Assessment.

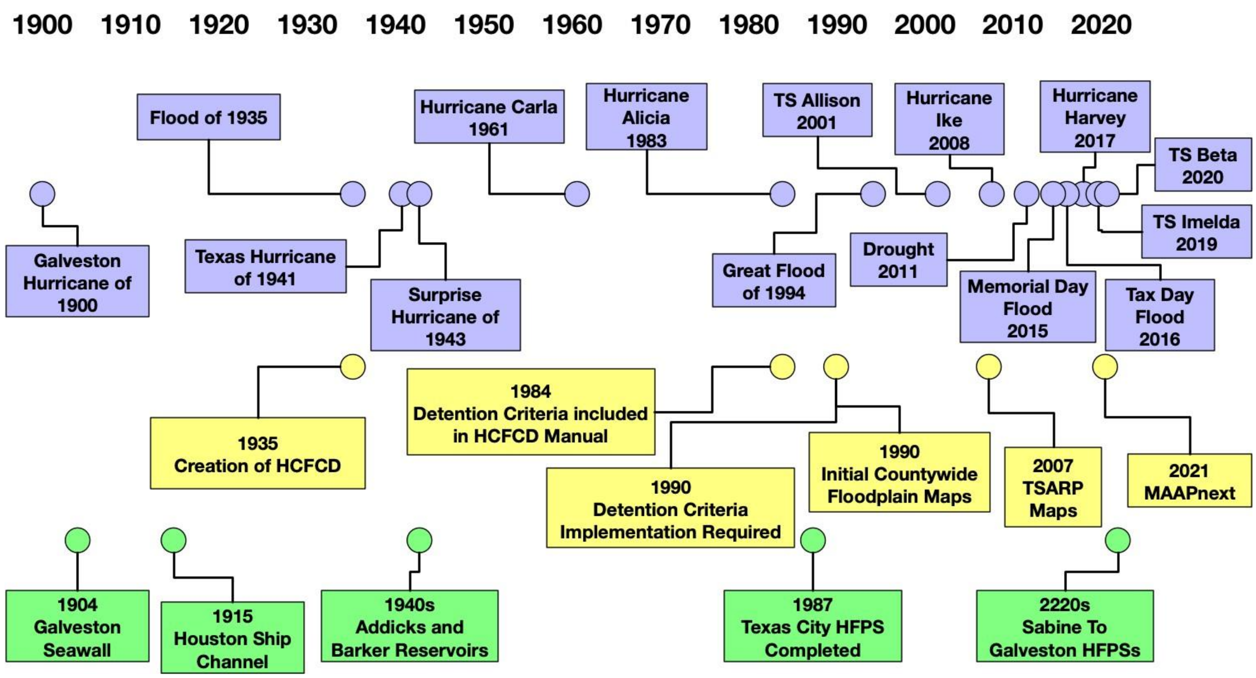


Figure 2 - Timeline of major weather events, regulatory or authority changes, and infrastructure projects

3.3. Report Organization

The Main Report characterizes the flood vulnerability in the region, reviews the current FRM efforts underway, presents broad findings and opportunities and concludes with recommended future actions to achieve greater efficiency in the implementation of flood risk reduction.

Appendices provide greater detail of the available tools and authorities to provide additional context for the findings and recommendations within the Main Report.

Appendix A: FRM Measures in Context

> Reviews typical FRM features and their relative effectiveness across multiple flood events and community types,

Appendix B: Climate Change Considerations in FRM

> Reviews the necessary considerations of climate change in the design and application of FRM solutions in the region.

Appendix C: Cultural Resource Considerations in FRM

> Reviews the potential impacts to cultural resources from flood events in the region, the typical process to assess those impacts as structural solutions have been selected as the recommended plan and assess alternative approaches to cultural resource benefits and impact tradeoffs.

4. Shared Vision Milestone and Coordination and Priorities/Roles

A Shared Vision Milestone was an initial decision point where the PDT to communicate the regional priorities, areas of interest and a future vision for efficient water and related resources within watershed to the USACE Vertical Team. The Shared Vision Statement (SVS) was developed collaboratively with the non-federal Sponsor, stakeholders, and Galveston District leadership. It also provided a preliminary opportunity to identify issues and opportunities, goals, objectives, and constraints that were confirmed through stakeholder outreach including two in person workshops.

While most watershed studies consider a broad range of water resource problems in the region, the Metro Houston Regional Watershed Assessment was focused on FRM efforts. This limited focus, and the severity of the flood risk in the region generated a SVS that is more specific than a typical SVS. The Metro Houston SVS stipulated more about “how” we get to the ideal future condition, not just an expression of what the ideal condition is. The stakeholders also felt that specific terms should be defined in a glossary for the SVS, to ensure that the values and intent of the statement was no misinterpreted.

The SVS for this assessment is more specific than a typical SVS, it stipulates more about “how” we get to their ideal future condition, not just what the ideal condition is.

> *Growth and infrastructure investments in the region are equitable, risk informed, coordinated, and determined through evidence-based, forward looking data and modeling and a broad consideration of regional resources and community values. Design objectives incorporate livability, resiliency, quality of life and consider flood risk and mitigation needs for the life of the development, rather than standards based on historic risk.*

Shared Vision Statement Glossary:

“Infrastructure” means features of the FRM system that detain, convey, contain, transport or receive water, including undeveloped floodplains.

“Resources” include economic resources such as agency and household costs and assets; environmental and social resources include natural habitats, aesthetics, recreation, public access, habitats.

“Forward looking data” means output from planning tools or engineering models that reflect uncertainty and anticipate possible future events, conditions, etc.

“Equitable” means dealing fairly and equally with all concerned.

“Quality of Life” means the general well-being of individuals and societies, considering physical health, family, education, employment, wealth, safety, and the environment.

5. Study Area

The study area was identified as the Metropolitan Houston region, which contains dense urban areas, large suburban communities, and some relatively rural areas that are anticipated to transition to residential communities. Harris County has been delineated into 22 watersheds by HCFCD. Portions of these watersheds encompass Metropolitan Houston and adjacent communities within Montgomery, Waller, Fort Bend, Brazoria, Galveston, and Chambers Counties, as shown in Figures 3 and 4.

Two broad flood hazards are reflected in floodplain maps within the Metropolitan Houston area: rainfall runoff and storm surge. The threat of rising sea levels and storm surge should not be minimized; however, the focus of this assessment is on the rainfall runoff flood hazard.

Flooding has been a persistent issue in the region. The combination of the physical conditions in the area and high annual rainfall create frequent and severe flood events. The flood vulnerability in the region increases as climate change brings more intense precipitation, and economic conditions draw increasing population and construction of new communities to house them.

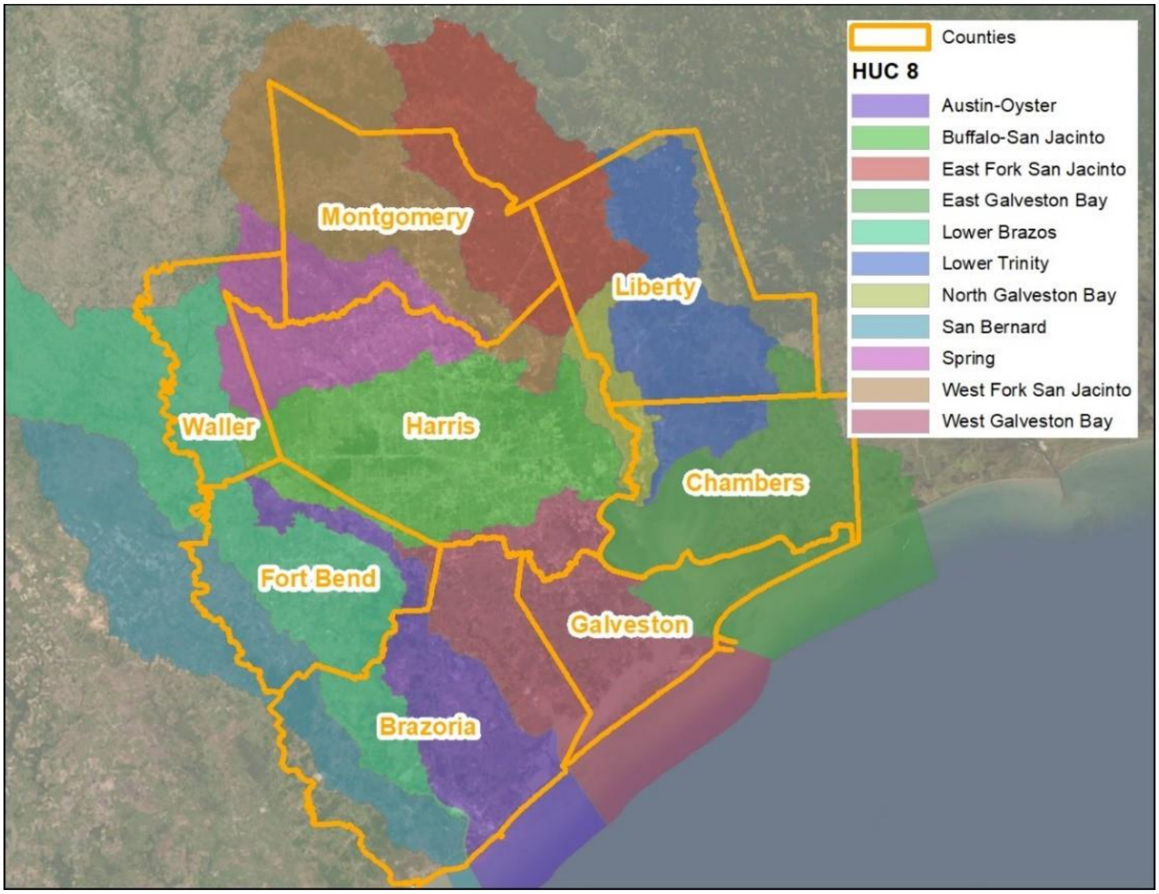


Figure 3 – Counties adjacent to Metropolitan Houston Region

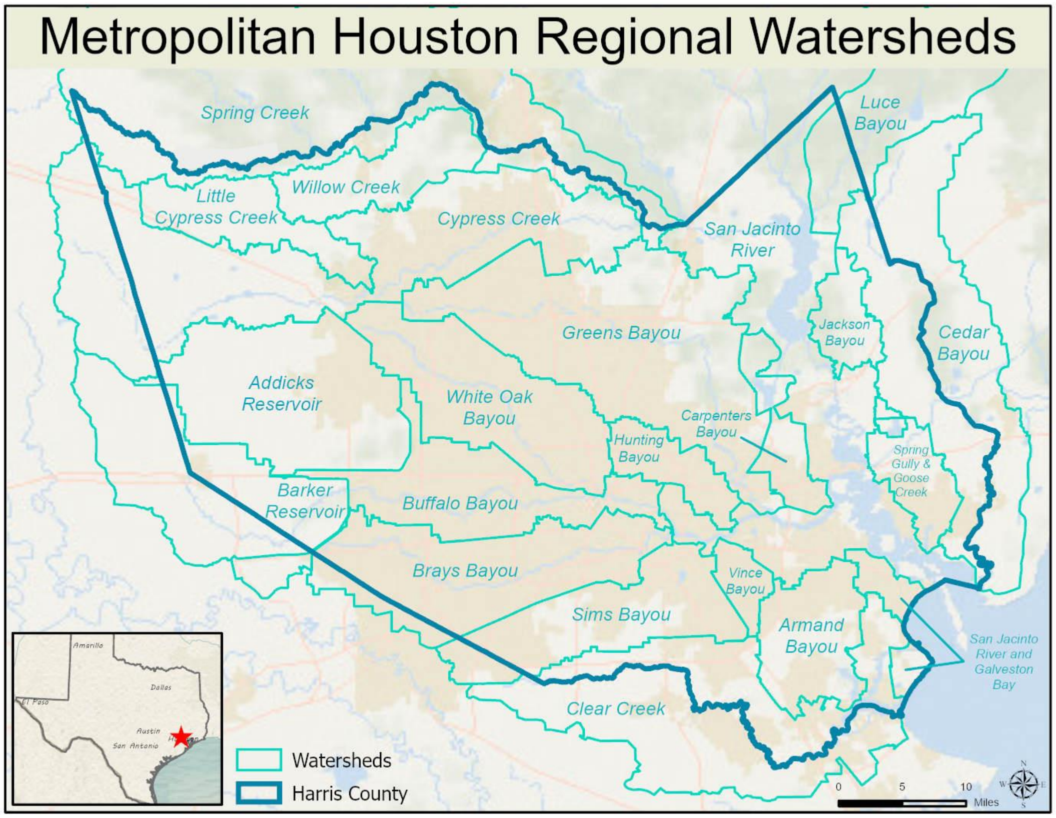


Figure 4 – Watersheds within Harris County

5.1. SUB-WATERSHEDS IN THE REGION

The region includes multiple waterbodies, large and small that collect stormwater and transports it downstream into Galveston Bay and the Gulf of Mexico. These Harris County watersheds, with the exception of the San Jacinto River and Galveston Bay, are not large, regional drainage systems. They are relatively small geographic areas and the water in these creeks and bayous can rise and fall relatively quickly, particularly in the developed core of Harris County and the city of Houston.

Each sub watershed varies in the primary land use, density of development and flood vulnerability. The most developed watersheds are highlighted here, as well as unique watersheds that factor into key recommendations of the assessment.

The Greater Houston Flood Mitigation Consortium (GHFMC), which is discussed in more detail in Section 9.1, produced a report in 2018 titled "Greater Houston Strategies for Flood Mitigation" (2018 GHFMC document) which focused on strategies for flood mitigation. The summaries of watersheds below include information from HCFCD and the 2018 GHFMC document.

5.1.1. ADDICKS RESERVOIR

The Addicks Reservoir watershed is located in western Harris County with a small portion crossing into eastern Waller County. Rainfall within the 138 square miles of the Addicks Reservoir watershed drains to the watershed's primary waterway, Langham Creek. The Addicks Reservoir watershed occasionally receives a significant amount of natural stormwater overflow from the Cypress Creek watershed during heavy rainfall events. Stormwater runoff from this watershed drains through the Addicks Reservoir and eventually into Buffalo Bayou. Rural and agricultural uses have historically dominated the upstream regions of the watershed, but residential and commercial developments are rapidly growing. There are 159 miles of open waterways in the Addicks Reservoir watershed, including Langham Creek and its major tributaries, such as South Mayde Creek, Bear Creek and Horsepen Creek. Based on the 2010 U.S. Census, the estimated population of the Harris County portion of the Addicks Reservoir watershed is 295,694. Together with Barker Reservoir, Addicks Reservoir was built in the 1940s as part of a federal project to reduce flooding risks along Buffalo Bayou, which runs west to east through downtown Houston. USACE completed construction of Addicks Dam and the outlet facility in 1948. USACE owns, operates, and maintains the reservoir, including leases or permits for some compatible recreational uses within the basin. Operation of the outlet facilities controls discharges from the reservoir into Langham Creek, then into Buffalo Bayou. Environmentally sensitive areas and a wide range of wildlife habitats exist within the reservoir boundaries and along the upper tributary reaches that extend into the Katy Prairie.

5.1.2. ARMAND BAYOU

Armand Bayou flows southward into Clear Lake, draining 60-square-miles, including portions of Pasadena, Deer Park and Houston and as of 2018 had a population of approximately 127,000. It has sizable, flat floodplains that make it susceptible to flooding as well as storm surge. Much of the watershed is developed, but considerable open space and natural habitat has been preserved toward the south end of the basin, most notably the 2,000-acre Armand Bayou Park and Nature Center.

5.1.3. BARKER RESERVOIR

The Barker Reservoir watershed encompasses the area that drains into Barker Reservoir. This reservoir, together with Addicks Reservoir, was created as part of a federal project to control flooding on Buffalo Bayou and protect downtown Houston. USACE completed construction of the Barker Dam and outlet facility in 1945 and continues to own, operate, and maintain the dam and outlet facilities. The watershed is located in west Harris County and extends into Fort Bend and Waller counties, encompassing portions of the cities of Houston and Katy. The Barker Reservoir watershed covers approximately 126 square miles and includes two primary streams: Mason Creek and Upper Buffalo Bayou. There are about 69 miles of open streams within the watershed, of which approximately 51 miles are within Harris County. The estimated population of the Barker Reservoir watershed is 169,000. The threat of flooding from high volumes of stormwater draining into the reservoir from its natural watershed is a concern. The need to control release rates from the reservoir during potential flood events causes concern for developments along the fringes of the reservoir boundary and for major thoroughfares. These concerns have prompted sub-regional planning on the major tributaries draining into the reservoir.

5.1.4. BRAYS BAYOU

The Brays Bayou watershed is located in southwest Harris County and portions of Ft. Bend County and drains parts of the cities of Houston, Missouri City, Stafford, Bellaire, West University Place, Southside Place, and Meadows Place. The bayou flows eastward from Fort Bend County to its confluence with the Houston Ship Channel. This heavily urbanized watershed covers approximately 127 square miles and includes three primary streams: Brays Bayou, Keegans Bayou, and Willow Waterhole Bayou. There are about 121 miles of open streams within the watershed, including the primary streams and tributary channels. Comprehensive planning for flood protection in the watershed and construction of flood damage reduction projects on and along Brays Bayou has occurred in the past and continues today. Severe flooding in the watershed has occurred on average at least once every decade. Because a majority of the urbanization occurred prior to the advent of floodplain regulations and prior to delineation of the 1% (100-year) floodplain, thousands of structures are now known to be in the currently mapped 1% (100-year) floodplain. Brays Bayou has had major flooding problems, and more than 23,000 homes were flooded in Hurricane Harvey. Channelization projects along Brays Bayou started in the 1950s and have continued since.

The 2018 GHFMC document describes Brays Bayou as one of Houston's most flood prone watersheds, which drains approximately 130 square miles of southwest Houston via 124 miles of natural and man-made channels. As of 2018, it was home to 800,000 people and is highly urbanized. Major tributaries include Keegans Bayou and Willow Waterhole Bayou. Brays Bayou was originally a natural, meandering waterway, but as urbanization extended upstream of Kirby Drive in the 1950s to 1960s, much of Brays Bayou was lined with concrete to address flooding as part of a joint federal-HCFCD project. After completion of this first federal project, urban growth continued, and, by the 1980s, over 95 percent of the watershed was developed. During the late 1970s through 1990s, flooding caused damage to more than 1,000 homes during Hurricane Alicia in 1983

5.1.5. BUFFALO BAYOU

The Buffalo Bayou watershed is primarily located in west-central Harris County with a small portion crossing into Fort Bend County. Rainfall within the 102 square miles of the Buffalo Bayou watershed drains to the watershed's primary waterway, Buffalo Bayou. Buffalo Bayou travels through heavily wooded residential areas and much of the bayou remains in a natural state. Near downtown Houston, White Oak Bayou flows into Buffalo Bayou. Just east of downtown Houston near the Turning Basin, Buffalo Bayou becomes the Houston Ship Channel. There are 106 miles of open waterways in the Buffalo Bayou watershed, including Buffalo Bayou and its major tributaries, such as Rummel Creek, Soldiers Creek, Spring Branch, and Turkey Creek. The 2010 U.S. Census estimated the population of the Harris County portion of the Buffalo Bayou watershed to be 444,602.

5.1.6. CARPENTERS BAYOU

The Carpenters Bayou watershed is located in east Harris County. Carpenters Bayou flows southward from its headwaters just west of Lake Houston into the Houston Ship Channel. The bayou parallels the East Sam Houston Tollway and passes through Channelview. The watershed covers approximately 25 square miles, with Carpenters Bayou being the single primary stream. There are about 44 miles of open streams within the watershed, including the primary stream and tributary channels. The 2010 U.S. Census estimated the population of the Carpenters Bayou watershed to be 57,249.

Under existing development conditions, the floodplain is not very extensive along Carpenters Bayou. The lower end of Carpenters Bayou is tidally influenced and therefore vulnerable to storm surge flooding.

5.1.7. Cedar Bayou

The Cedar Bayou watershed is the easternmost watershed in Harris County, and Cedar Bayou generally serves as the border for Harris County with Chambers and Liberty counties. The cities of Baytown and Mont Belvieu are located within the watershed, which encompasses nearly 200 square miles. Cedar Bayou flows in a southward direction from its headwaters in Liberty County to its mouth at Galveston Bay. There are about 128 miles of open streams within the watershed, including the primary stream and tributary channels. The main stem of Cedar Bayou is approximately 40 stream miles in length and directly impacts Harris County, Chambers County, Liberty County, and the City of Baytown. The 2010 Census data estimated the population within the watershed to be just over 59,000. Although a large floodplain exists in the upper and middle reaches of Cedar Bayou, this portion of the watershed is sparsely developed. Therefore, the flooding is more threatening to roads and agriculture than structures like houses and businesses. Flooding along the tributaries in the urbanized portions of the watershed is a concern.

5.1.8. Clear Creek

The Clear Creek watershed is located in southern Harris County. The watershed encompasses portions of Harris, Galveston, Brazoria, and Fort Bend counties; 16 cities including Houston, Brookside Village, Pearland, Friendswood, League City, Pasadena, the Clear Lake Area communities, and four drainage/flood control districts. Clear Creek flows from west to east through Clear Lake and into Galveston Bay. Armand Bayou is the largest tributary to Clear Creek, and its drainage area is considered a separate watershed. The Clear Creek watershed covers approximately 197 square miles and includes two primary streams: Clear Creek and Turkey Creek. There are about 154 miles of open streams within the watershed, including the primary streams and tributary channels. Based on the 2010 U.S. Census, the estimated population of the Harris County portion of the Clear Creek watershed was 164,172. Flooding occurs frequently along various reaches of the main channel and its tributaries. Storm surge has also caused flooding within the watershed and has the potential to extend upstream to I-45.

The lower parts of the watershed, which surround NASA's Johnson Space Center, were developed in the 1960s through 1980s. The upper end of the watershed was largely agricultural until the 2000s and has been rapidly developed since. However, significant undeveloped land remains. The lower portion of the channel, from the Galveston/Brazoria county line to Clear Lake, remains mostly natural.

5.1.9. Cypress Creek

The Cypress Creek watershed is located in northwest Harris County and extends into Waller County. Rainfall within the 267 square miles of the Cypress Creek watershed drains to the watershed's primary waterway, Cypress Creek. There are 250 miles of open waterways in the Cypress Creek watershed, including Cypress Creek and its major tributaries. By size, the watershed is one of the largest in Harris County. By population, it is the fifth largest of the county's 22 main watersheds, with an estimated population of approximately 347,000 (2010 U.S. Census). Like much of Harris County, the Cypress Creek watershed is flood prone. The downstream or eastern portion of the watershed was developed prior to our current understanding of floodplains and restrictions on building in the floodplains. The upstream or western portion of the floodplain was developed later, with more robust development regulations requiring stormwater detention to prevent downstream flooding impacts.

5.1.10. GREENS BAYOU

The Greens Bayou watershed is located in north Harris County and encompasses portions of the cities of Houston and Humble. The upper reach of Greens Bayou flows in an eastward direction and the lower reach flows southward into the Houston Ship Channel. The watershed covers about 212 square miles and includes four primary streams: Greens Bayou, Halls Bayou, Garners Bayou, and Reinhardt Bayou. There are about 308 miles of open streams, including the primary streams and tributary channels. Based on the 2010 U.S. Census, the estimated population of the Greens Bayou watershed is 528,720. Flooding of homes and businesses along Greens Bayou and its tributaries has occurred numerous times in the last two decades, with devastating flood levels throughout the watershed brought on by Tropical Storm Allison in 2001 and Hurricane Harvey in 2017. Significant floodplains and high-density development have combined to cause high damages during frequent flood events. Additionally, storm surges can influence flooding levels along the lower 10 miles of the watershed.

5.1.11. HALLS BAYOU

Halls Bayou is a tributary of Greens Bayou in north central Harris County. Flooding along Halls Bayou is a persistent hazard for area residents, businesses, and property owners, with flooding documented 14 times since 1989. Tropical Storm Allison in 2001 is the storm of record for the watershed, with more than 13,000 homes flooded. During Hurricane Harvey in 2017, an estimated 11,830 homes flooded along Halls Bayou. Reducing flooding risks in the Halls Bayou watershed is a priority for HCFCD. The Bond Program approved by voters in 2018 includes more than $110 million for the Halls Bayou watershed, which has the potential to leverage more than $346 million in total project value, depending on federal funding approval.

5.1.12. HUNTING BAYOU

The Hunting Bayou watershed is located in central Harris County within the city limits of Houston, Galena Park, and Jacinto City. Rainfall within the 31 square miles of the watershed drains to the primary waterway, Hunting Bayou. The bayou flows southeast from its headwaters just east of the Hardy Toll Road to its confluence with the Houston Ship Channel near the City of Galena Park. There are 45 miles of open waterways in the watershed, including Hunting Bayou and its major tributaries, such as Turkey Run Gully and Schramm Gully. The 2010 U.S. Census estimated the population of the Hunting Bayou watershed to be 75,908. The watershed is highly urbanized with a mixture of residential, commercial, and industrial developments. The largest open area is the City of Houston's Herman Brown Park, which covers approximately 550 acres in the Hunting Bayou watershed and provides recreational amenities and environmental habitat.

Hunting Bayou currently has a substantial floodplain in its upstream end, upstream of Liberty Road. This section is comprised primarily of single-family homes located in Kashmere Gardens and Trinity Gardens on either side of Loop 610 North and east of Interstate 69 North. There is more limited flooding along the immediate channel downstream of Liberty Road.

5.1.13. JACKSON BAYOU

The Jackson Bayou watershed is located in east Harris County, just east of Lake Houston, and serves the Crosby and Newport areas. The watershed covers about 25 square miles and flows into the San Jacinto River below Lake Houston via Jackson Bayou. There are about 36 miles of open streams within the watershed, including the primary stream and tributary channels. Gum Gully is the largest tributary in the watershed and drains about 17 square miles, which is close to 70% of the watershed. The 2010 U.S. Census estimated the population of the Jackson Bayou watershed to be 14,014.

Although erosion problems exist along most of the length of the Jackson Bayou and its tributaries, little or no regional planning has been done for Jackson Bayou due to the low incidence of structural flooding. Jackson Bayou is relatively deep with steep side slopes and the channel slope is relatively steep (for Harris County) which promotes rapid drainage of the watershed. Some flooding of a few structures has occurred in the last twenty years, although the mapped floodplain typically covers farmland and areas with scattered development. The floodplain in the lower portion of the watershed results from the San Jacinto River.

5.1.14. LITTLE CYPRESS CREEK

Little Cypress Creek is usually considered the "22nd Watershed" within Harris County, although it is actually a sub-watershed of the major Cypress Creek watershed. The Little Cypress Creek watershed encompasses a mostly rural, undeveloped area of northwest Harris County. The 2010 US Census estimated the population of the Little Cypress Creek watershed to be 28,879. Little Cypress Creek is not always delineated separately on HCFCD maps. Little Cypress Creek comprises more than 15% of the larger Cypress Creek watershed, with a drainage area of about 50 square miles.

5.1.15. SAN JACINTO RIVER

The San Jacinto River watershed is a very large watershed that originates well outside of Harris County. The San Jacinto River flows through much of eastern Harris County and joins with the Houston Ship Channel before flowing into Galveston Bay along the southeastern edge of the county. The watershed (within Harris County) extends through the cities of Houston, Galena Park, Pasadena, Deer Park, Baytown, Humble, La Porte, Morgans Point, Shoreacres, and Seabrook. The channels within the watershed drain all or part of Harris, Montgomery, Waller, Walker, Grimes, Liberty, and San Jacinto counties, for a total drainage area of approximately 4,500 square miles. In Harris County, the San Jacinto River watershed covers about 487 square miles and includes seven primary streams: The San Jacinto River, the Houston Ship Channel, Cotton Patch Bayou, East Fork San Jacinto River, Boggy Bayou, Patricks Bayou, and Panther Creek. There are about 310 miles of open streams within the watershed, including the primary streams and tributary channels. Based on the 2010 U.S. Census, the estimated population of the Harris County portion of the San Jacinto River watershed is 197,570. The San Jacinto River flows from its headwaters near Huntsville, through Lake Conroe and Lake Houston. Lake Houston was developed as a water supply reservoir and therefore does not provide significant storage during flood events. The Port of Houston Authority operates the Houston Ship Channel, which originates at the Turning Basin and follows the original alignment of Buffalo Bayou to the San Jacinto River. The Ship Channel continues through the San Jacinto River and San Jacinto Bay to Galveston Bay, which is the ultimate outfall for all drainage in Harris County. Structural flooding has occurred in low-lying areas adjacent to the water bodies. However, water surface elevations in the Houston Ship Channel, the San Jacinto River and Galveston Bay are not affected by the flow from any single watershed. These waterways are tidally influenced and can be affected by storm surge.

5.1.16. San Jacinto & Galveston Bay

The San Jacinto Galveston Bay watershed is located at the southeastern edge of Harris County. The watershed primarily drains the area that includes La Porte, Morgans Point and portions of Pasadena. However, Galveston Bay is the ultimate outfall for all drainage in Harris County. The Galveston Bay watershed covers about 20 square miles and includes two primary streams: Little Cedar Bayou and Pine Gully. There are about 24 miles of open streams within the watershed, including the primary streams and tributary channels. The 2010 U.S. Census estimated the population of the Harris County portion of the San Jacinto Galveston Bay watershed to be 14,952. Structural flooding has occurred in low-lying areas adjacent to the water bodies. However, water surface elevations in Galveston Bay are not affected by the flow from the bayou system. Water Surface elevations in Galveston Bay are tidally influenced and can be affected by storm surge. The watersheds that drain into the San Jacinto River have a population of over 1.2 million, with development occurring throughout the river basin, particularly in northern Harris County and Montgomery County.

5.1.17. Sims Bayou

The Sims Bayou watershed is located in southern Harris County. Most of the watershed is within the City of Houston. However, the upper reach of the watershed drains the City of Missouri City and the lower reach of the watershed drains the cities of South Houston and Pasadena. The Sims Bayou watershed covers about 94 square miles and includes two primary streams: Sims Bayou and Berry Bayou. There are about 121 miles of open streams within the watershed, including the primary streams and tributary channels. Based on the 2010 U.S. Census, the estimated population of the Harris County portion of the Sims Bayou watershed is 284,727. Structural flooding has occurred numerous times along Sims Bayou and its tributaries. The majority of the structures that are flood prone were built prior to the existence of detailed floodplain maps and prior to floodplain management regulations.

5.1.18. Spring Creek

The Spring Creek watershed is located across northern Harris County. Most of the watershed is located outside of Harris County. It extends across the southern area of Montgomery County and into Waller and Grimes counties. The watershed serves about half of the City of Tomball and the Woodlands/I-45 area in southern Montgomery County. It covers about 284 square miles, of which only about 60 square miles are within Harris County. Spring Creek, the watershed's single primary stream, forms the northern boundary of Harris County, west of its confluence with the West Fork San Jacinto River. There are about 111 miles of open streams within the watershed, including the primary stream and tributary channels. The 2010 U.S. Census estimated the population of the Harris County portion of the Spring Creek watershed to be 39,349.

Spring Creek is basically natural and therefore characterized by limited conveyance capacity in the channel and a larger natural floodplain. However, the lack of development in much of the watershed has kept flood damage to a minimum. The isolated incidents along the main channel are normally from structures built in naturally flood-prone areas. Most flooding cases in Harris County are adjacent to the tributaries in the Tomball area. A regional plan has not been developed for Spring Creek since most of the watershed is in other counties and the incidence of structural damage in Harris County is low.

5.1.19. Spring Gully and Goose Creek

The Spring Gully & Goose Creek watershed is located in east Harris County. Spring Gully flows southward from Highlands Reservoir to Burnett Bay, adjacent to the Houston Ship Channel. Goose Creek flows from the Highlands Reservoir through the City of Baytown and Goose Lake into Tabbs Bay on the Houston Ship Channel. A significant drainage area exists just north of the Highlands Reservoir that drains to Barbers Hill Road. At the northwest corner of the reservoir and Barbers Hill Road, the runoff splits. A portion of the runoff flows around the reservoir perimeter and into the upper end of Spring Gully, while the rest of the runoff flows into Bluff Gully, which is a small tributary that flows into the San Jacinto River.

The Spring Gully & Goose Creek watershed covers about 32 square miles and includes two primary streams: Spring Gully and Goose Creek. There are about 60 miles of open streams within the watershed, including the primary streams and tributary channels. The 2010 U.S. Census estimated population of the Spring Gully & Goose Creek watershed to be 52,386. Earlier flood damage reduction projects constructed by the District have significantly reduced the risk of flooding to area residents and latter phases of these projects are currently being implemented.

5.1.20. White Oak Bayou

The White Oak Bayou watershed stretches from central to northwest Harris County and includes the City of Jersey Village and portions of the City of Houston. Rainfall within the 111 square miles of the watershed drains to the primary waterway, White Oak Bayou. The bayou flows southeast from its headwaters northwest of FM 1960 to its confluence with Buffalo Bayou downtown Houston. There are 146 miles of open waterways in the watershed, including White Oak Bayou and its major tributaries, including Little White Oak Bayou, Brickhouse Gully, Cole Creek and Vogel Creek. Development in the White Oak Bayou watershed has progressed rapidly and is expected to continue. As of 2018, the watershed was estimated to be roughly 90 percent developed with a population of 433,250.

5.1.21. Willow Creek

The Willow Creek watershed is located in northwest Harris County and drains about half of the City of Tomball. Willow Creek is the single primary stream within the watershed and flows into Spring Creek just upstream of where Spring Creek crosses under I-45. The Willow Creek watershed covers about 54 square miles and has about 56 miles of open streams in the watershed, including the primary stream and tributary channels. The 2010 U.S. Census estimated the population of the Willow Creek watershed to be 45,890.

A large floodplain exists along Willow Creek that covers mostly undeveloped land. The downstream end of the watershed is within the floodplain of Spring Creek.

5.1.22. VINCE BAYOU

Vince Bayou watershed has a population of approximately 89,750 as 2018, draining 16 square miles through Little Vince Bayou and Vince Bayou. It is highly urbanized, being almost completely developed with channels that have been shaped by infrastructure and widened. This watershed sustained damage claims from Harvey at an estimated $5.5 million and does not have a significant budget or plan for flood infrastructure projects. In the Pasadena area, Vince Bayou has seen repeated flooding.

6. REGIONAL INVENTORY AND FINDINGS

There are multiple sources of flooding and levels at which their severity is categorized. Flooding can occur from rivers, drainage systems, sheet flow, tides or storm surge. Further, any individual or property can have exposure to multiple flood sources.

River flooding occurs when its flow can no longer be contained within its channel and the river overspills its banks. Flooding is a natural reality for many rivers and is instrumental in shaping and reshaping the water body and supporting ecosystems, such as wetlands and bottomland forests adapted to intermittent inundation. Anthropogenic changes, such as development in the floodplain, restrictions of the floodplain, channel modifications, or hydrologic changes, can alter the nature of flooding associated with rivers.

Drainage systems, in the context of FRM, consist of infrastructure such as inlets, storm sewers, ditches, pipe systems, small-scale detention basins and even the roadway as a means of short-term storage/conveyance. This network of infrastructure is intended to remove stormwater from areas such as streets and sidewalks and direct it to receiving waterbodies such as rivers or lakes. These systems can back up if the receiving body has reached its capacity or become overwhelmed by intense rainfall even when the receiving waterbody has not reached capacity if their level of service is insufficient for a given storm. This is also referred to as pluvial flood risk.

Storm surge is an abnormal rise of water generated by a hurricane or tropical storm that results in water levels above the predicted astronomical tides. This can result in extreme flooding in coastal areas especially when it aligns with the normal high tide. Storm surge is produced by water being pushed towards the shore by winds. It’s a complex phenomenon influenced by storm characteristics (e.g., wind speed, size, intensity), angle of approach to the coast, coastline characteristics and slope of the continental shelf.

6.1. REGIONAL FLOOD HAZARD

There are three primary sources of flood hazard in the Metro Houston area: (1) fluvial, (2) pluvial, and (3) storm surge. Storm surge is a coastal storm hazard related to tropical cyclones impacting land adjacent to the coast. Fluvial and pluvial flooding are related to rainfall runoff process, though the mode is different. A precipitation event poses flood hazard in that a portion of the precipitation is converted to runoff and must be managed by the drainage network. The drainage network can be delineated into two components: (1) the municipal drainage infrastructure and (2) the channel/bayou system.

It is important to understand that a deficiency in either of these systems can cause flooding.

Fluvial flooding, also known as river flooding, is inundation associated with flow escaping the banks of an open channel. This type of flooding occurs on channels of all size. This includes everything from small drainage channels servicing a neighborhood up to large rivers draining large parts of the continent. Flooding occurs when the flow exceeds the capacity of the channel. Figure 5 shows an example of this occurring in the Cypress Creek watershed during the Tax Day Flood on 2016.

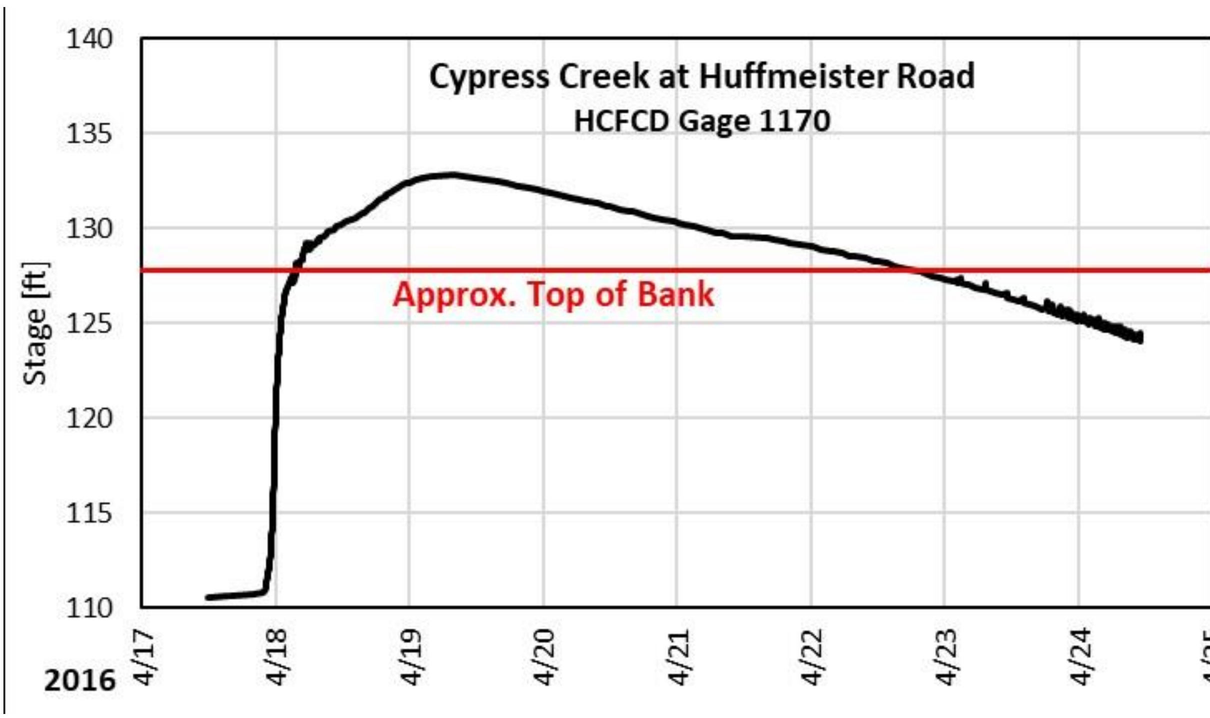


Figure 5 - Observed water-surface elevation during the period April 17-25, 2016 on Cypress Creek at Huffmeister Road (HCFCD Gage #1170)

Pluvial flooding is caused by rainfall not associated with an overflowing waterbody. This type of flooding is not represented in floodplain maps which only reflect fluvial and coastal flooding. A common misconception about flooding is that it only occurs near a waterbody. However, pluvial flooding is the counterexample in that anywhere rain falls is subject to possible flooding. Sixty-two percent of homes flooded in Harris County during Tropical Storm Imelda were outside the 1% floodplain (HCFCD Final Flood Report); 45 percent of Harris County homes flooded during

Hurricane Harvey were outside the 0.2% floodplain. Figure 6 shows the delineated floodplain extents presented with reported flooding complaints documented through the City of Houston 311 phone system to report non-emergency issues to the City. Many of the areas reporting flooding complaints were outside any mapped floodplain and/or not near a waterbody.

Bottom line – wherever it rains it can flood

The municipal drainage infrastructure typically consists of road-side ditches and enclosed storm sewers. These features convey local runoff to the outfall channels typically in conjunction with the roadway network. These are often designed such that higher frequency events are accommodated by the underground sewer network however a degree of ponding/conveyance is allowed in roadways for lower frequency rainfall.

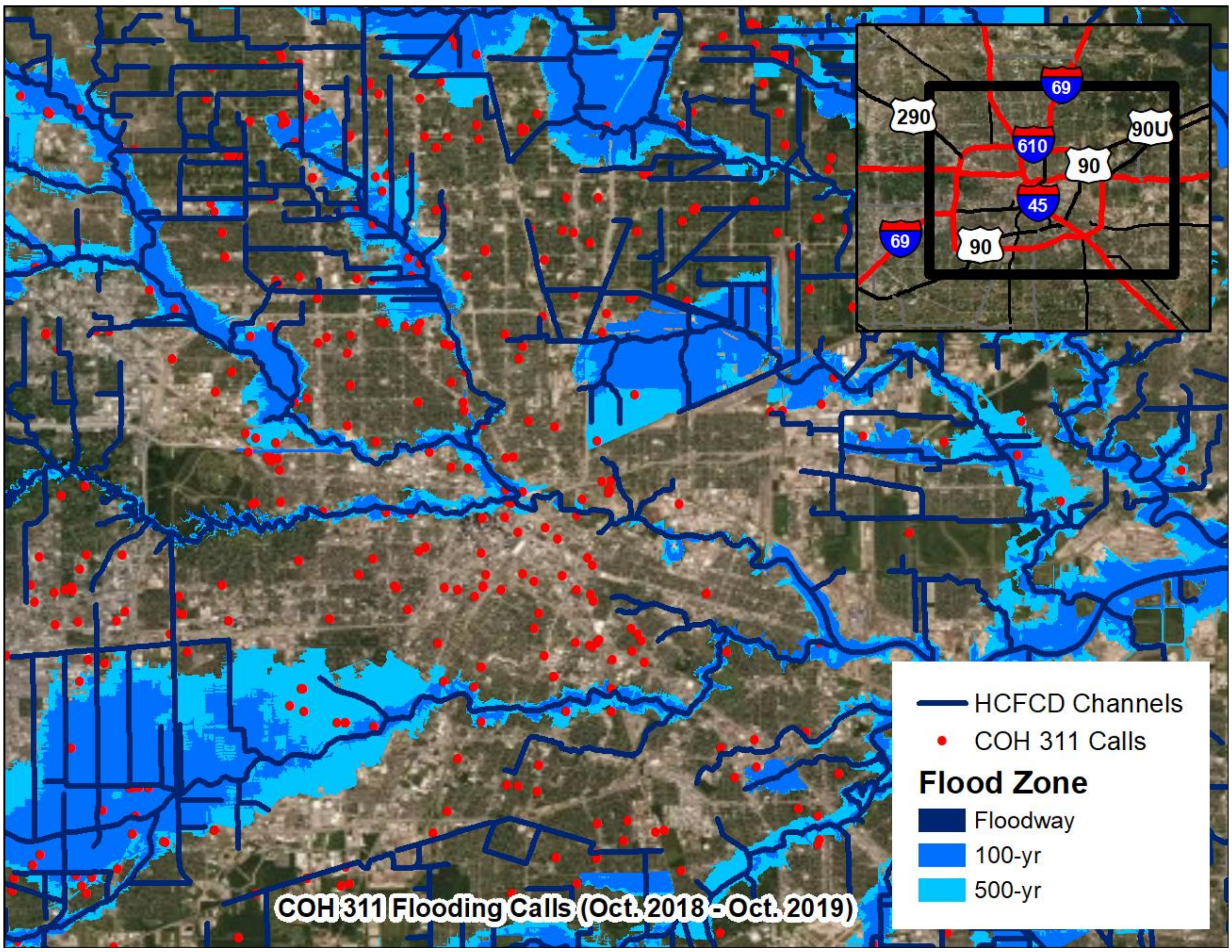


Figure 6 - Flood zones from the National Flood Hazard Layer (NFHL) and City of Houston 311 complaints for flooding during the period October 2018-October 2019

Storm surge is an abnormal increase of water-levels above the astronomical tide associated with a tropical cyclone. This occurs when high winds push water onshore and inundate typically dry areas. Figure 7 shows an example of this type of increase in water levels for Hurricane Ike at the NOAA Eagle Point gage (near San Leon). Coastal storms represent an important source of flood hazard in Metro Houston for watersheds adjacent to the Gulf of Mexico and Galveston Bay.

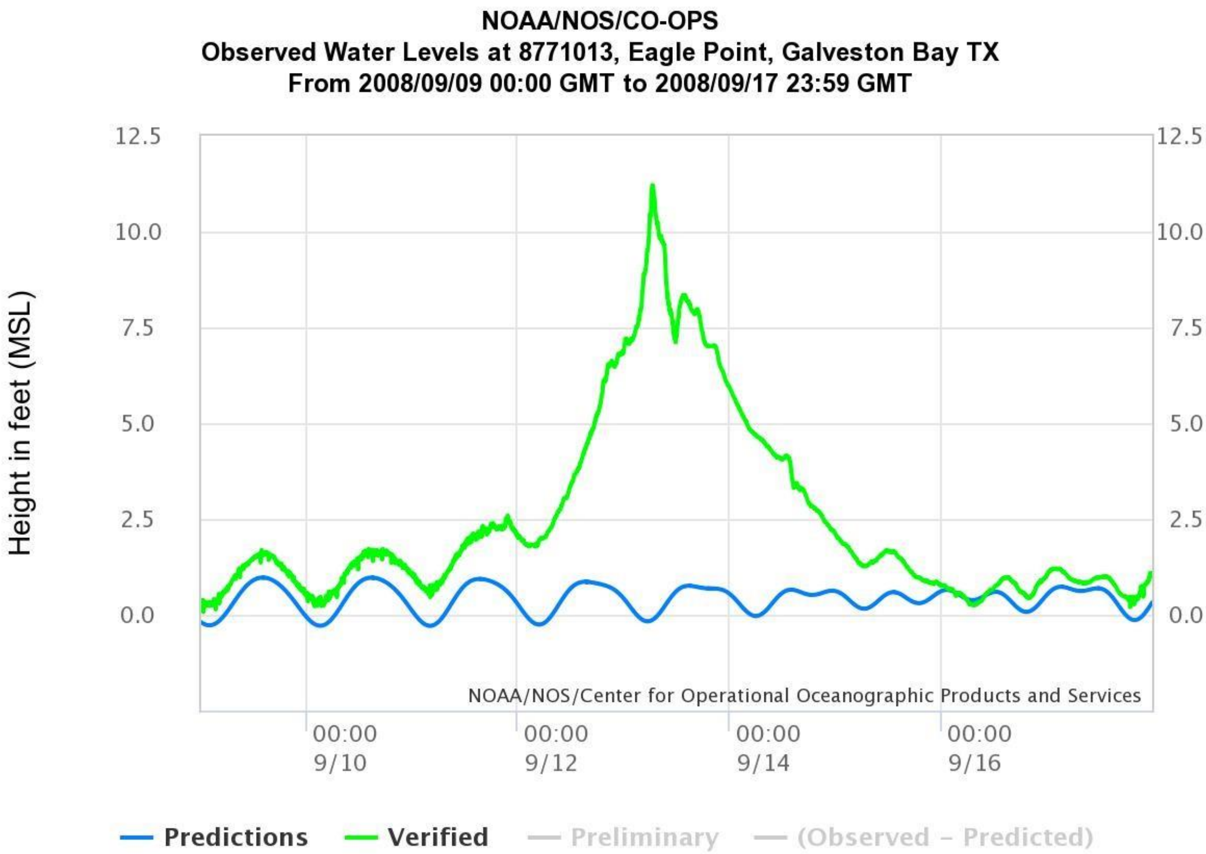


Figure 7 - Observed data for the period September 9-17, 2008 in Galveston Bay at the NOAA Eagle Point gage (#8771013)

6.2. FLOODPLAINS AND FLOOD HAZARD

Floodplain delineations on flood insurance rate maps (FIRMs) are a primary means of identifying and communicating flood hazard. However, the flood hazards represented on FIRMs are the coastal and fluvial hazards and do not include pluvial hazard. As noted previously, the number of structures that have flooded outside the floodplain indicates that this is an issue needing additional consideration in the Houston area. Also, there are areas that have exposure to multiple flood sources. Additionally, FIRMs are a useful tool, but are based on models with embedded assumptions. They present a single base flood elevation associated with the 1% ACE event, but there are a range of potential outcomes to a rainfall event. Flood inundation during a rainfall event is dependent of hydrologic and hydraulic conditions which can vary. Furthermore, most strategies are necessarily backward looking and ingest observed information. The duration of the observational record and nature of the observations impact the accuracy of the statistical rainfall or flow estimates.

Reality is often more complicated than can be represented in the modeling. This isn't to discount the importance of floodplain maps since they are important risk representation. Only that more risk may exist than is represented.

The HCFCD MAAPnext initiative is evaluating the pluvial flood hazard while also updating floodplain maps throughout the county.

A recent imitative by the First Street Foundation is a parcel-level description of flood risk available at floodfactor.com. Figure 8 shows a visual of Houston west of downtown from the Flood Factor website. Each parcel is assigned a "flood factor" score based on the modeled flood risk. The risk is based on a combination of the 30-year cumulative probability of inundation and the modeled depth of inundation. The floodplains as would be indicated on a FIRM are shown alongside the flood factor score. The flood factor methodology (First Street Foundation, 2020) takes into consideration all three flood hazard sources, pluvial, fluvial, and coastal. Areas with flood risk denoted that are outside the mapped floodplains, particularly those in the midtown and east downtown area where the open channel network is not present, can be inferred as those susceptible to pluvial flooding. These maps have not been confirmed by independent modeling, but they are relatively consistent with recent area analyses and are used here for illustration purposes.

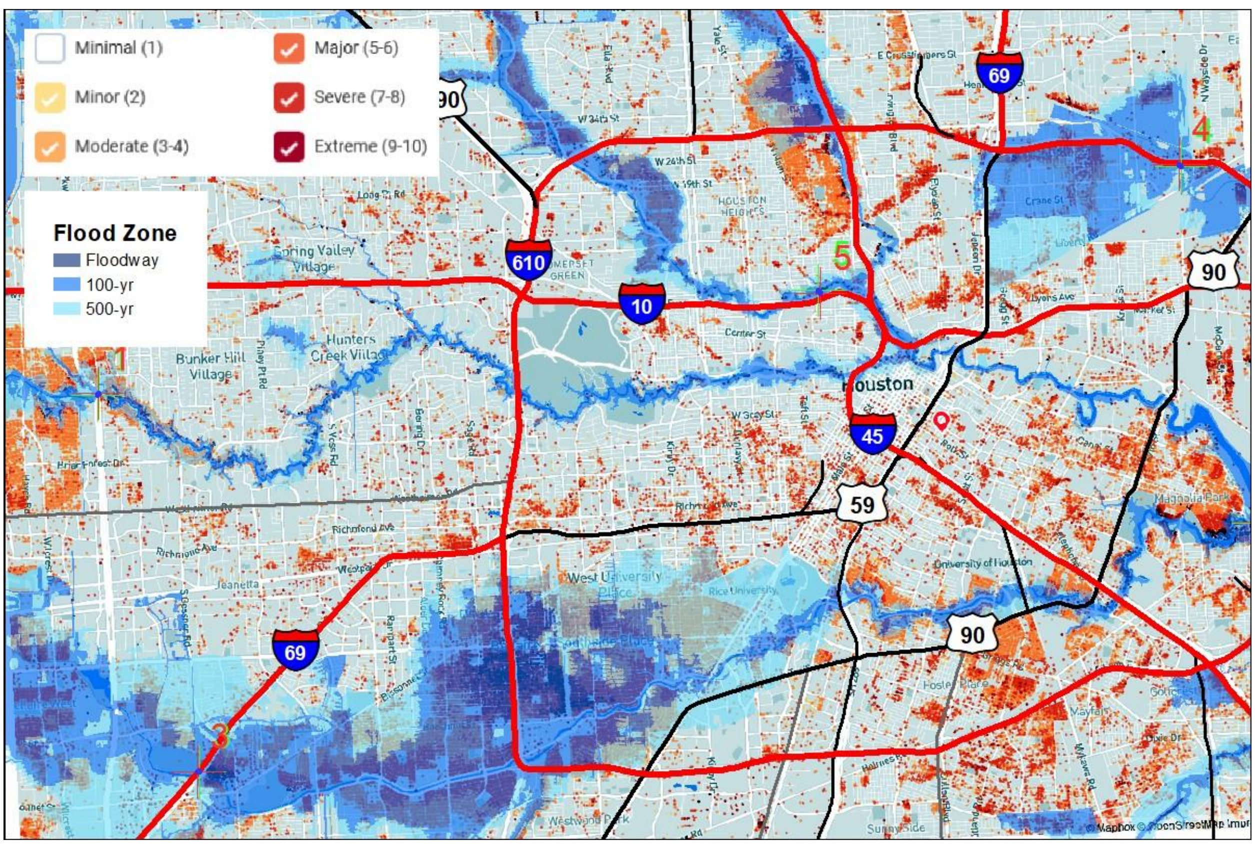


Figure 8 - Floodfactor.com scores on the west of downtown Houston (scores with minimal risk are omitted). The current floodplain extents are overlaid. The methodology and risk matrix for the flood score designation are available on the floodfactor.com website.

An additional consideration for coastal and estuarine communities is exposure to compound flooding. Compound flooding is when the cumulative water-surface elevation from coastal surge and inland flow exceed that of either hazard alone. The struggle associated with clearly delineated compound flood hazard is that statistical methods are predicated on historical observation of both independent hazards. Recent modeling studies have pursued a characterization of compound flooding in the Galveston Bay area. Valle-Levinson et al. (2020) simulated Hurricane Harvey using the Regional Ocean Modeling System (ROMS). As a test of the impact of each flooding source they ran several scenarios without some of the boundary conditions (fig. 9). The interaction of the significant environmental forcing, riverine runoff and surge is important to understanding the total anticipated water-surface elevation. It also highlights the importance of timing of the various forcing functions on the peak water-surface elevation. The effects of surge on water-surface elevations is primarily seen early in the event where the exclusion of atmospheric and ocean forcing leads to an underprediction (i.e., the coastal forces are important to predicating the water surface elevation). However, the exclusion of atmospheric and oceanic forcing was a lessor control on total water-surface elevation later in the simulation when surge would have receded during the event (i.e., the flow became the controlling factor on water surfaces). The overall impact of surge on peak water-surface elevation was generally muted during Hurricane Harvey only because of the phase lag between the low-level of surge and significant flow magnitude. A location like Houston, with exposure to both rainfall and surge, should consider the interaction of these forces during particular events

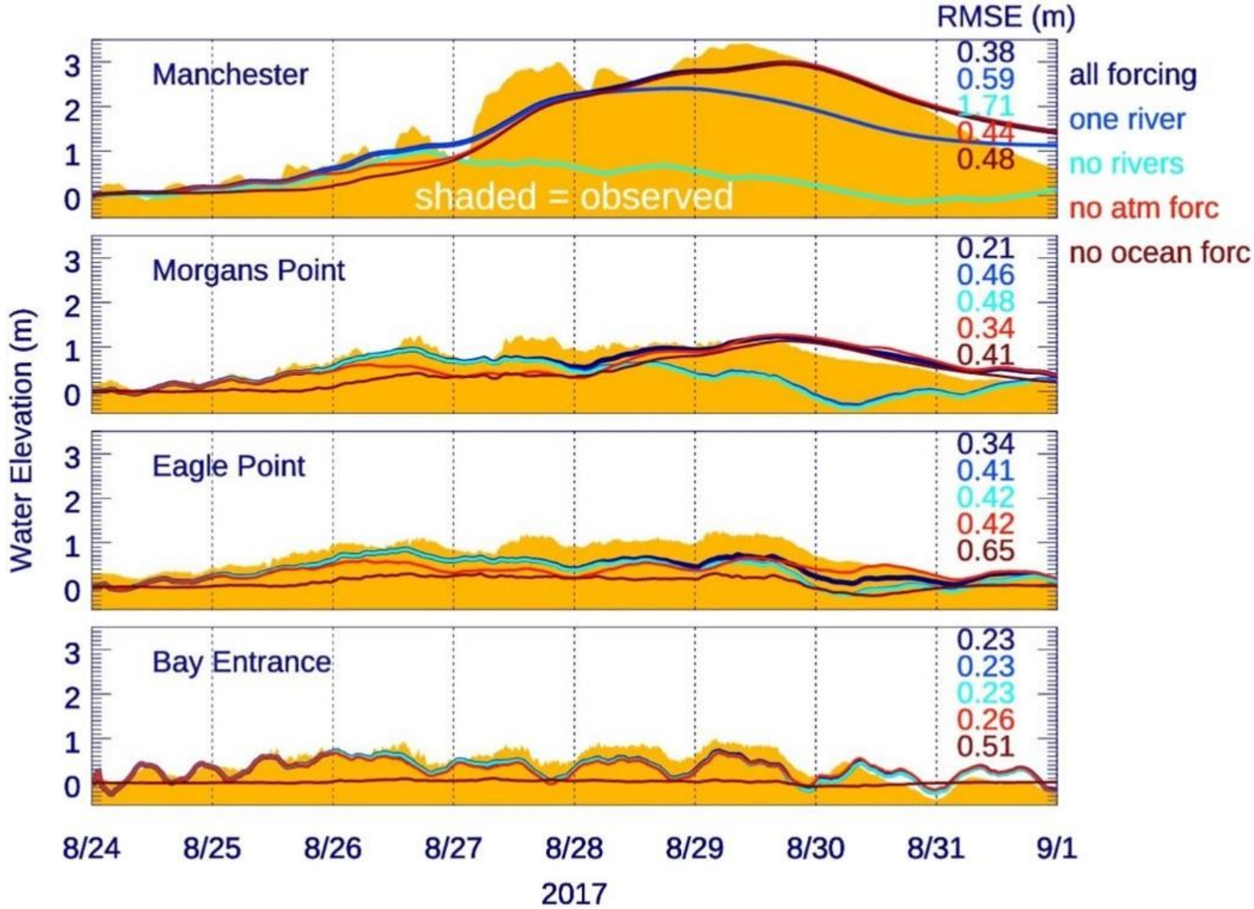


Figure 9 - Observed and modeled water-surface elevations in and around Galveston Bay for Hurricane Harvey (after Valle-Levinson et al., 2020)

6.3. FACTORS CONTRIBUTING TO FLOOD RISK

Physical conditions

Houston has generally low topography with a low gradient. Figure 10 shows the general topography in the Metro Houston area. The majority is low lying with some higher elevations to the northwest. The channel gradient is a substantial control on the ability of the channel system to convey runoff.

The Metro Houston area, and the Gulf of Mexico coast more broadly is a relatively wet portion of the United States in terms of annual precipitation (Figure 11). More importantly from an FRM perspective, in the Houston region is the amount of rainfall expected during events (Figure 12). The amount of rain expected in 24 hours for the 1% ACE is approximately 17 inches. By way of comparison, the equivalent precipitation depth is approximately 9” in Kansas City, MO, 8” in Minneapolis, MN, and 5” in Pittsburgh, PA.

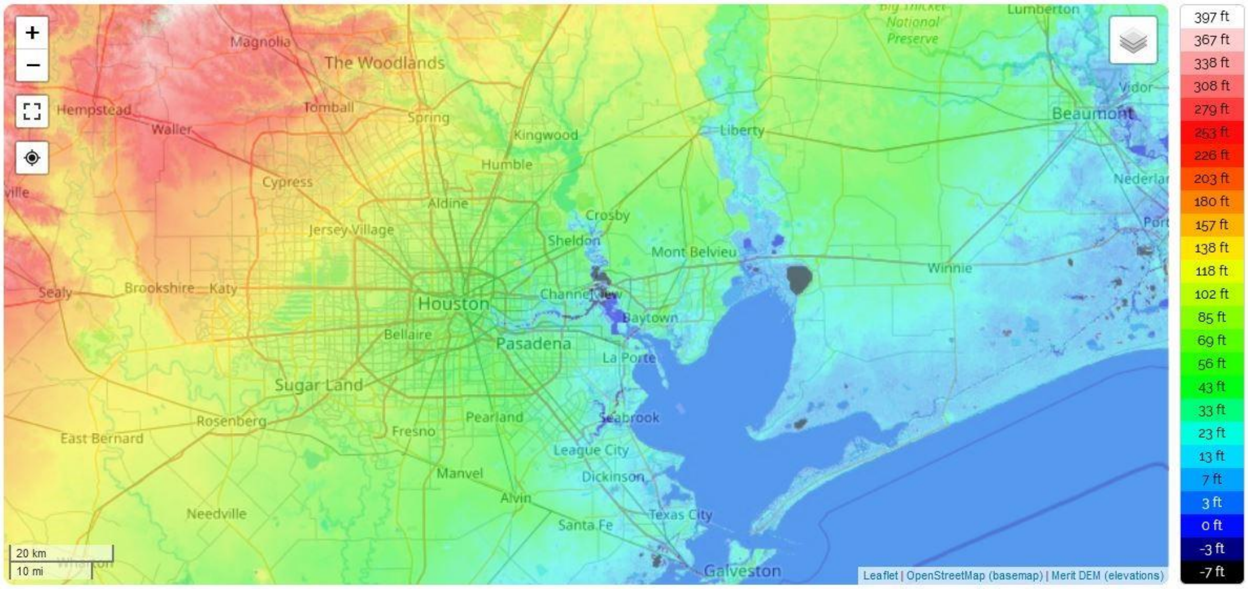


Figure 10 - General topography of Metro Houston area

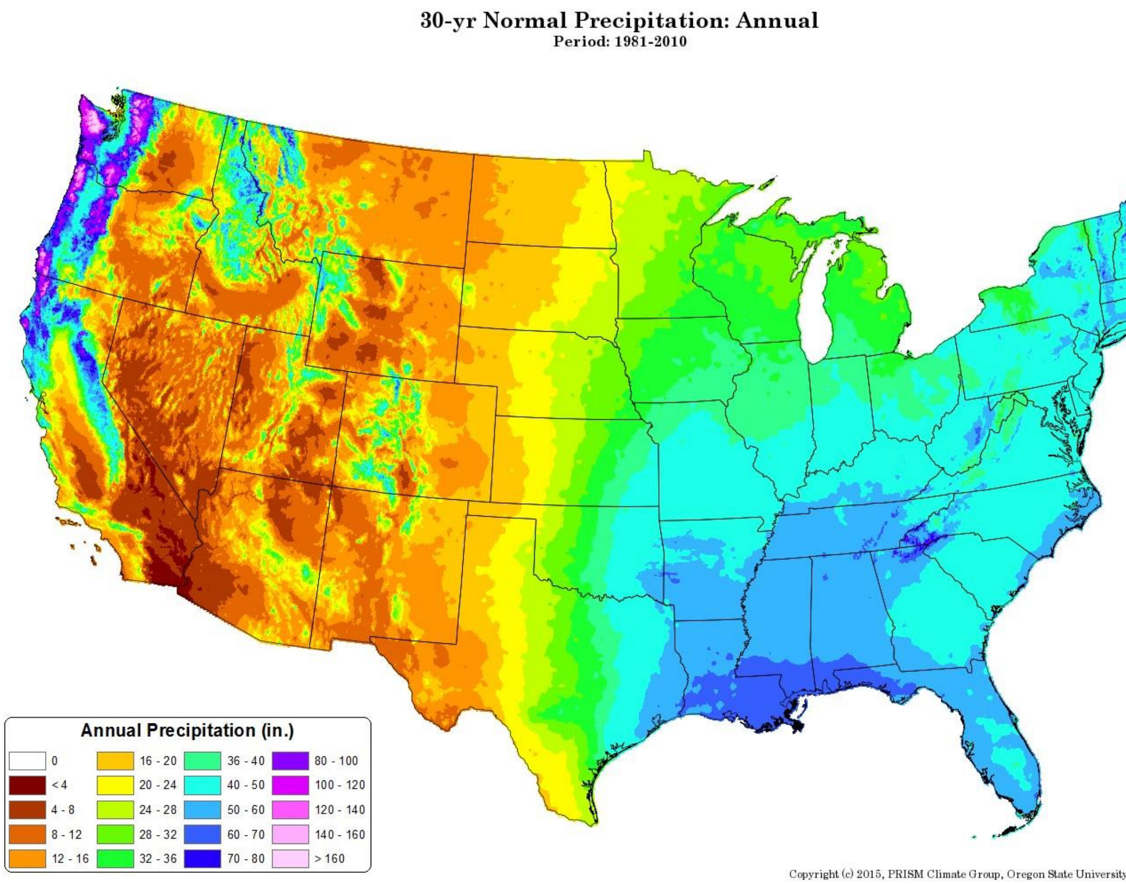


Figure 11 - 30-yr normal annual precipitation for continental US (PRISM)

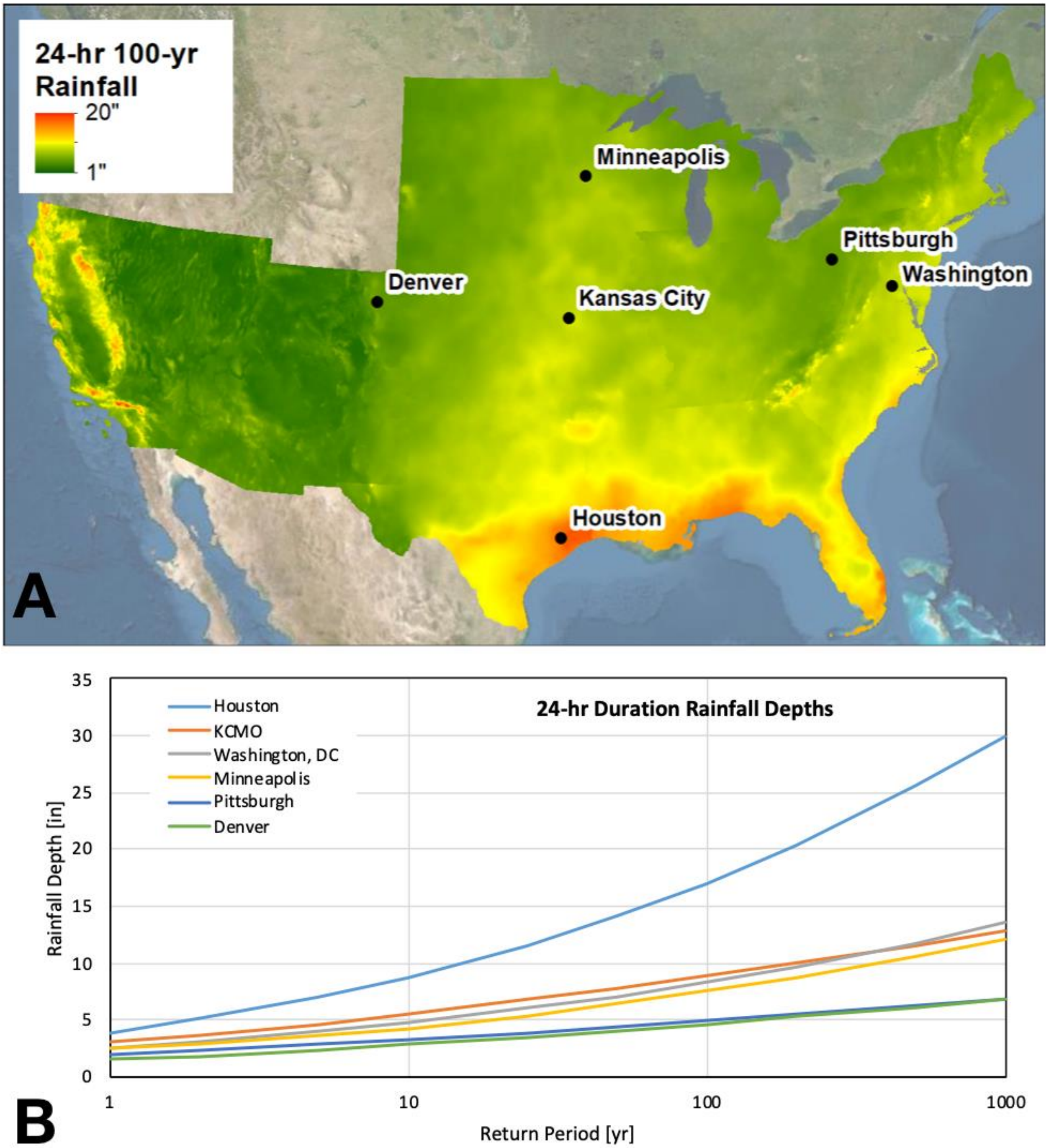


Figure 12 - Atlas 14 rainfall for (A) the 24-hr 100-yr event throughout the continental US where NOAA Atlas 14 data is available and (2) 24-hr rainfall depths as a function of average return period for specific locations.

Another physical property throughout the Houston area is generally poorly drained soils that limit infiltration compared to other soil types. Sandy soils can have infiltration rates upwards of 0.5 inches per hour whereas more clayey soils are often less than 0.2 inches per hour.

One chronic stressor that will act to increase water-surface elevations in general is relative sea-level change (RSLC). Figure 13 shows the RSLC projections in Galveston along the low, intermediate, and high curves from the USACE RSLC calculator. Increased water-surface elevation at the downstream boundary of the bayou network acts to reduce conveyance. These effects are most pronounced where the bayou meets the bay and become progressively less significant upstream. RSLC is a significant concern for the area because of the increase in coastal storm hazard, and the implications for inland runoff.

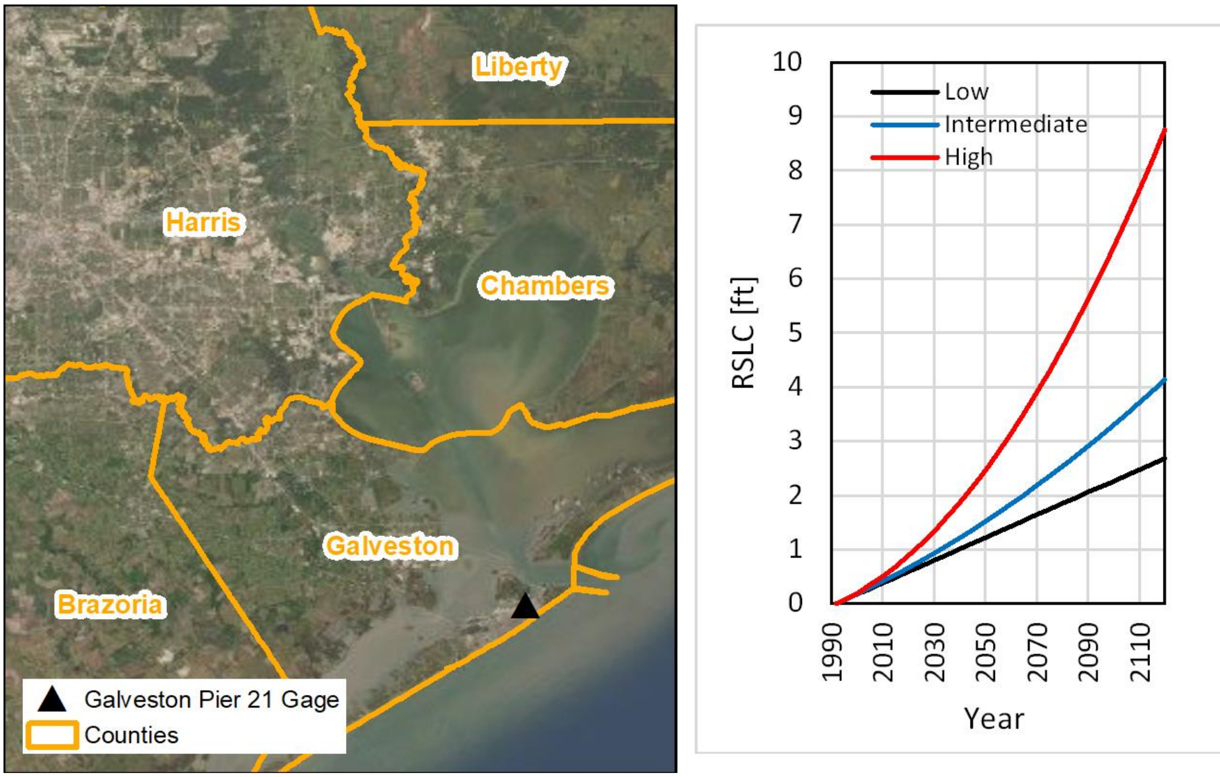


Figure 13 - RSLC curves for Galveston Pier 21 gage

Development

The very nature of a metropolitan area includes a variety of development including commercial and residential areas. Houston also includes substantial industrial development, largely near the Houston Ship Channel. Development replaces natural ground with a measure of altered topography and impervious surfaces. This alters the natural hydrology. Figure 14 shows a conceptual model of how progressive development impacts the runoff from a site. The numbers are not strictly correct but are indicative of relative values.

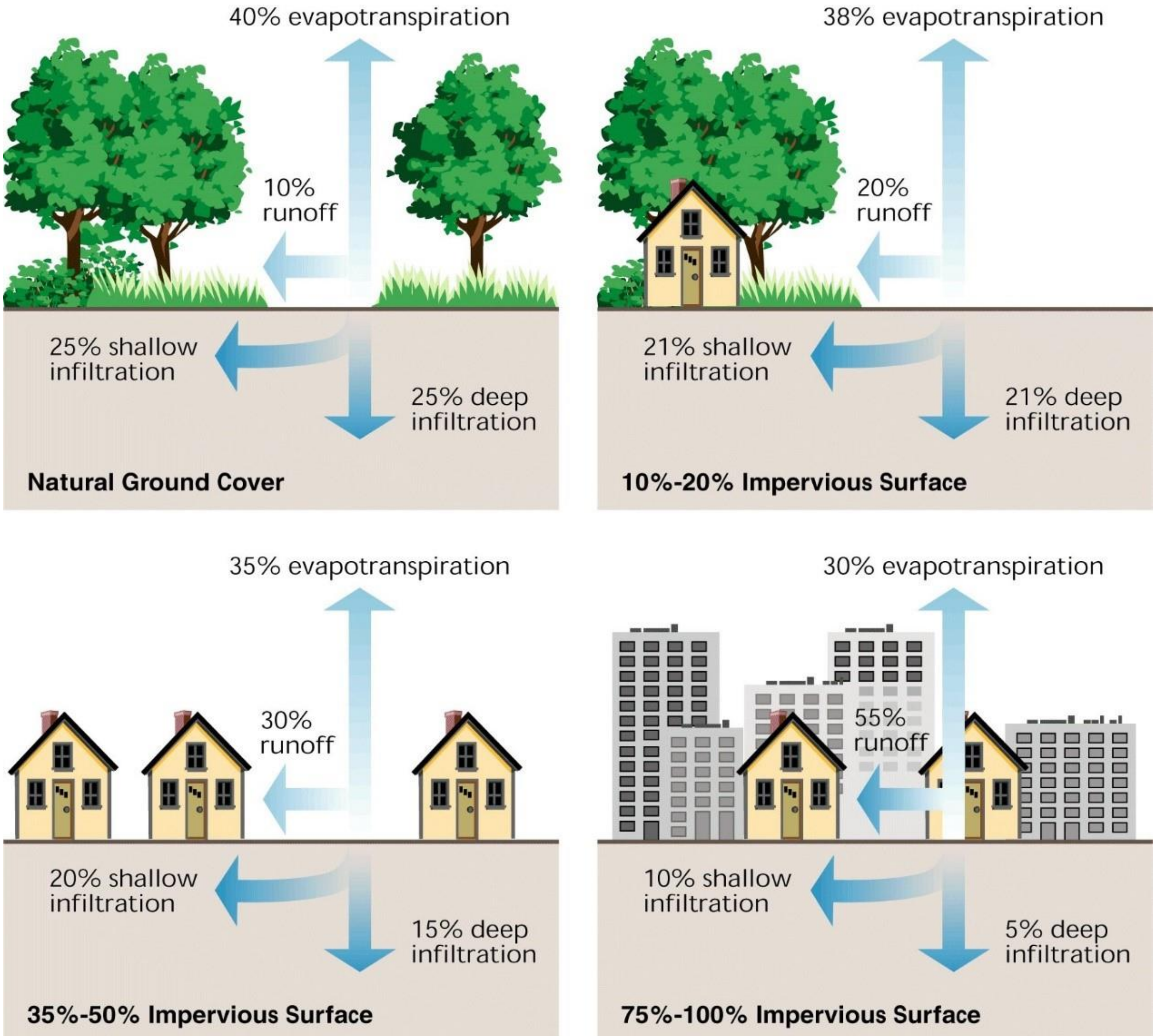


Figure 14 - Conceptualization of water balance based on level of development (after Federal Interagency Stream Restoration Working Group, 1998)

Error! Reference source not found.shows the parcels within the assessment area that have a structure. The colors correspond to the year the structure was built. This is generally indicative of the development age which is a helpful surrogate for the large scale. Development and drainage regulations have become progressively more rigorous over time to making the age of a development somewhat reflective of the potential for flood hazard.

Detention was recommended in 1980 to mitigate development-induced drainage impacts. Detention criteria was included in the 1984 HCFCD Flood Control Drainage Criteria Manual with required implementation after 1990.

The inclusion of detention with development is critically important since it is a tool intended to reduce developed peak flow from a site to the predevelopment condition. Figure 15 shows the conceptual utilization of detention to mitigate for peak flow impacts.

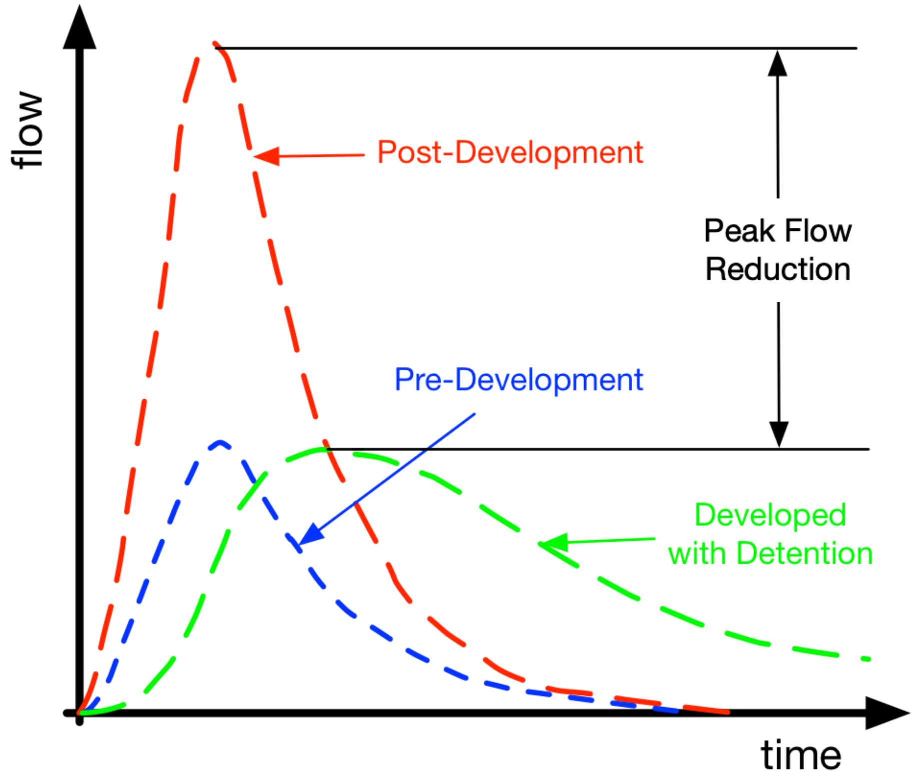


Figure 15 - Effects of detention on runoff when implemented with development

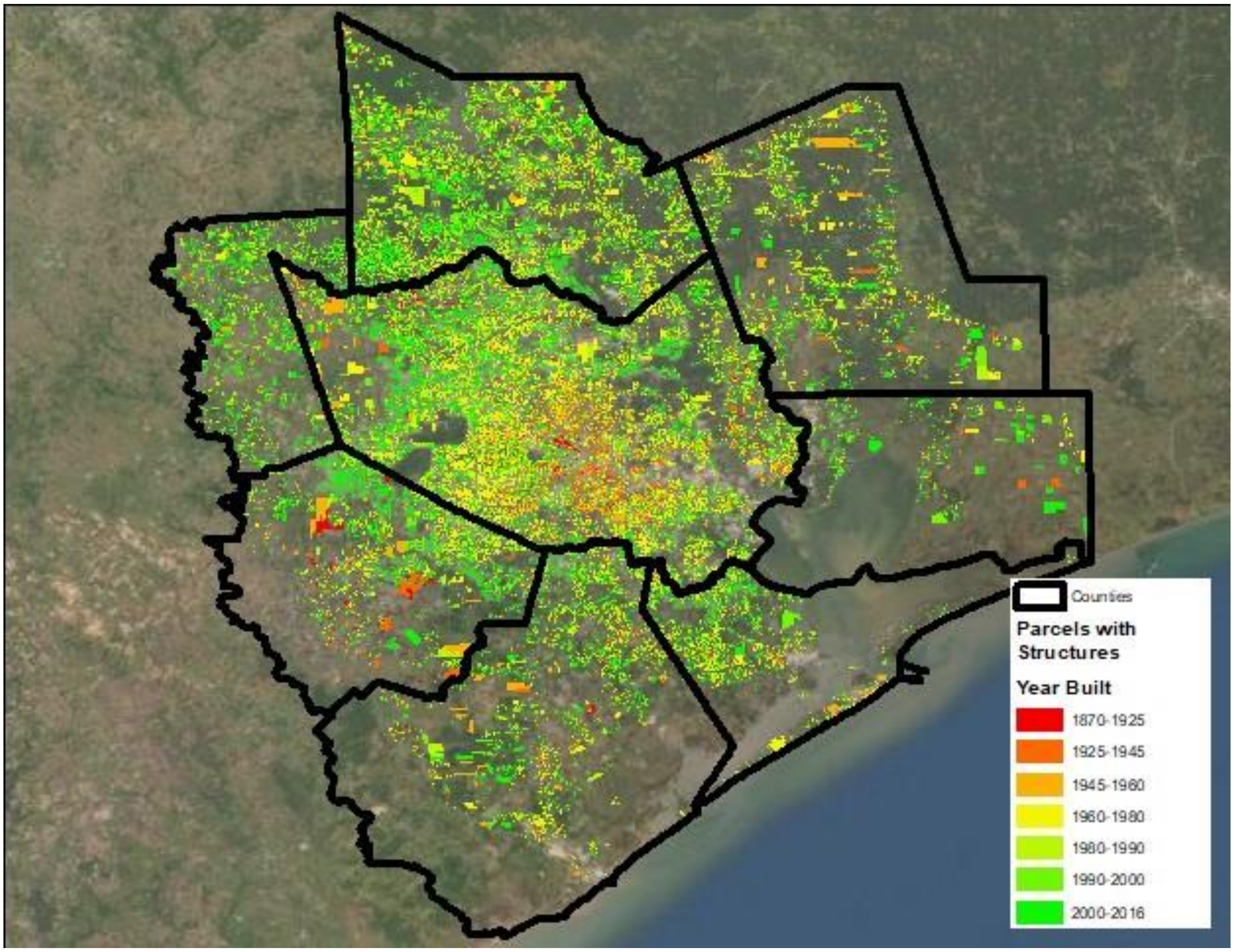


Figure 16 - Parcels with structures colored by year the structure was built

The Houston-Galveston Area Council (H-GAC) generates annual documentation of land use land cover (LULC) categories across the eight counties containing and neighboring the City of Houston (Harris, Montgomery, Liberty, Chambers, Galveston, Brazoria, Fort Bend, and Waller) and updates forecasts for that same region. Figure 16 shows the distribution of age of structures within the region. Figure 17 shows the existing land use and land cover for the region and Figure 18 shows the projected land use in 2045. Figure 19 shows the locations in the existing dataset that are vacant that are projected to become developed. Projected change is largely residential throughout.

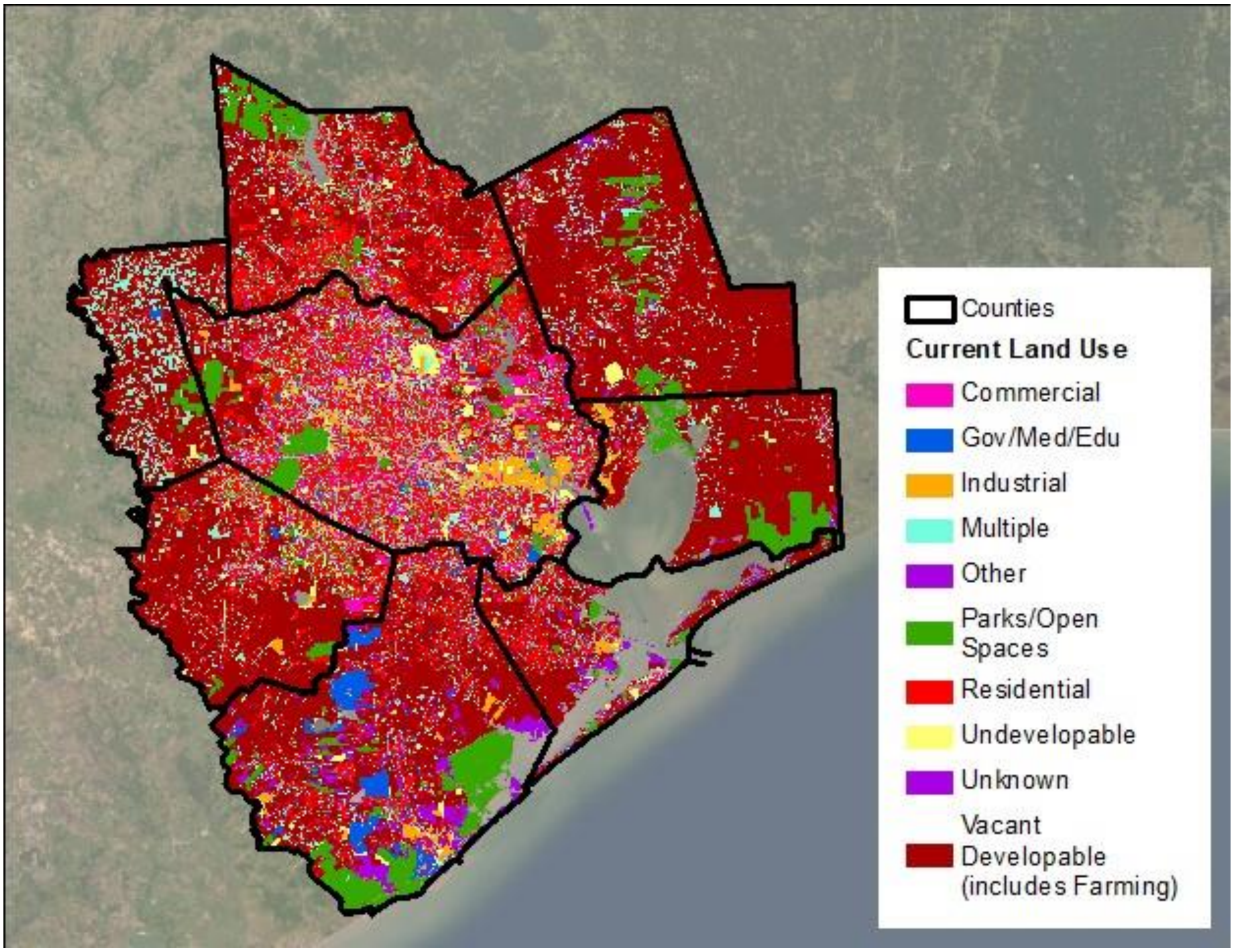


Figure 17 - Current (2015) land use (HGAC, 2019)

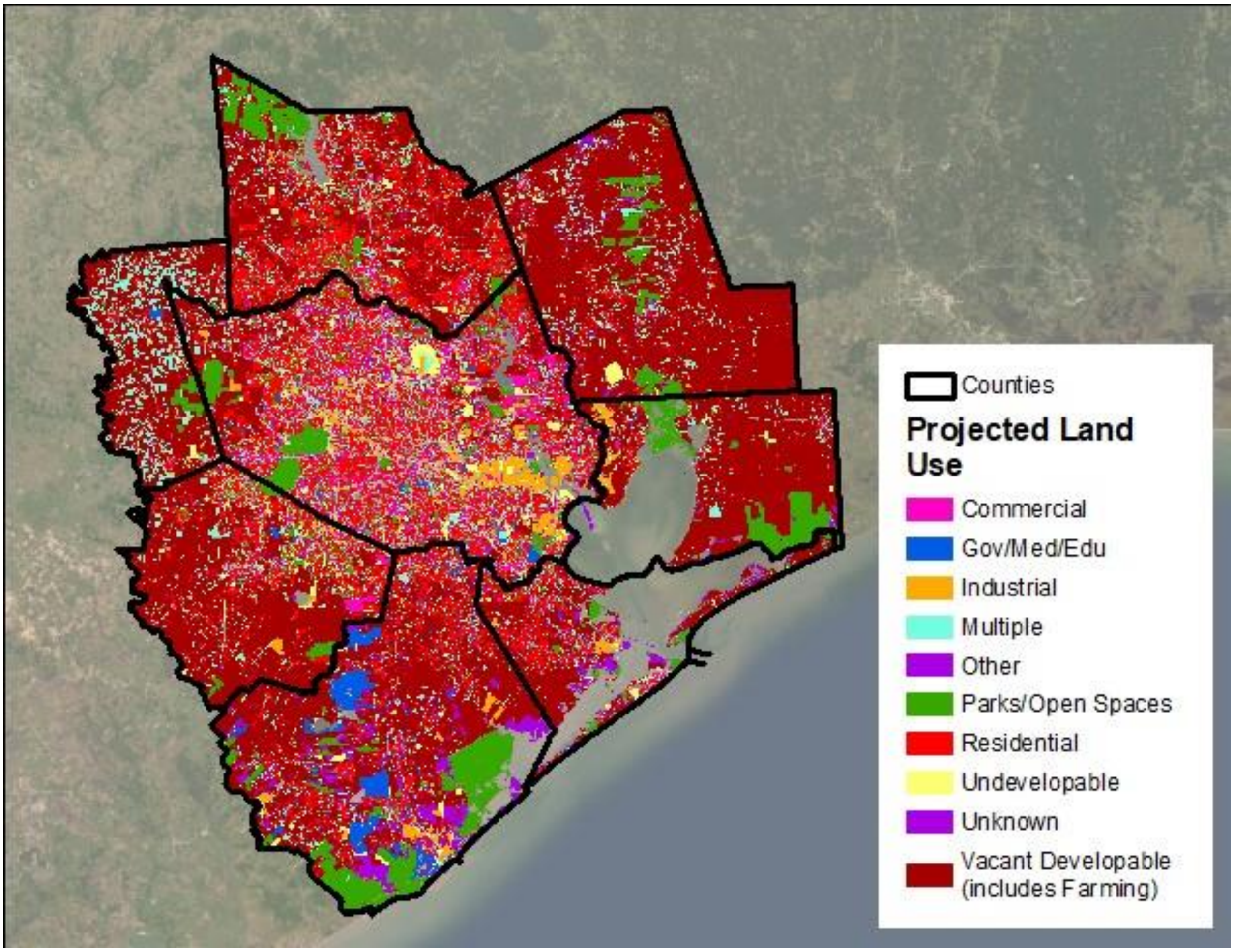


Figure 18 - Projected (2045) land use (HGAC, 2019)

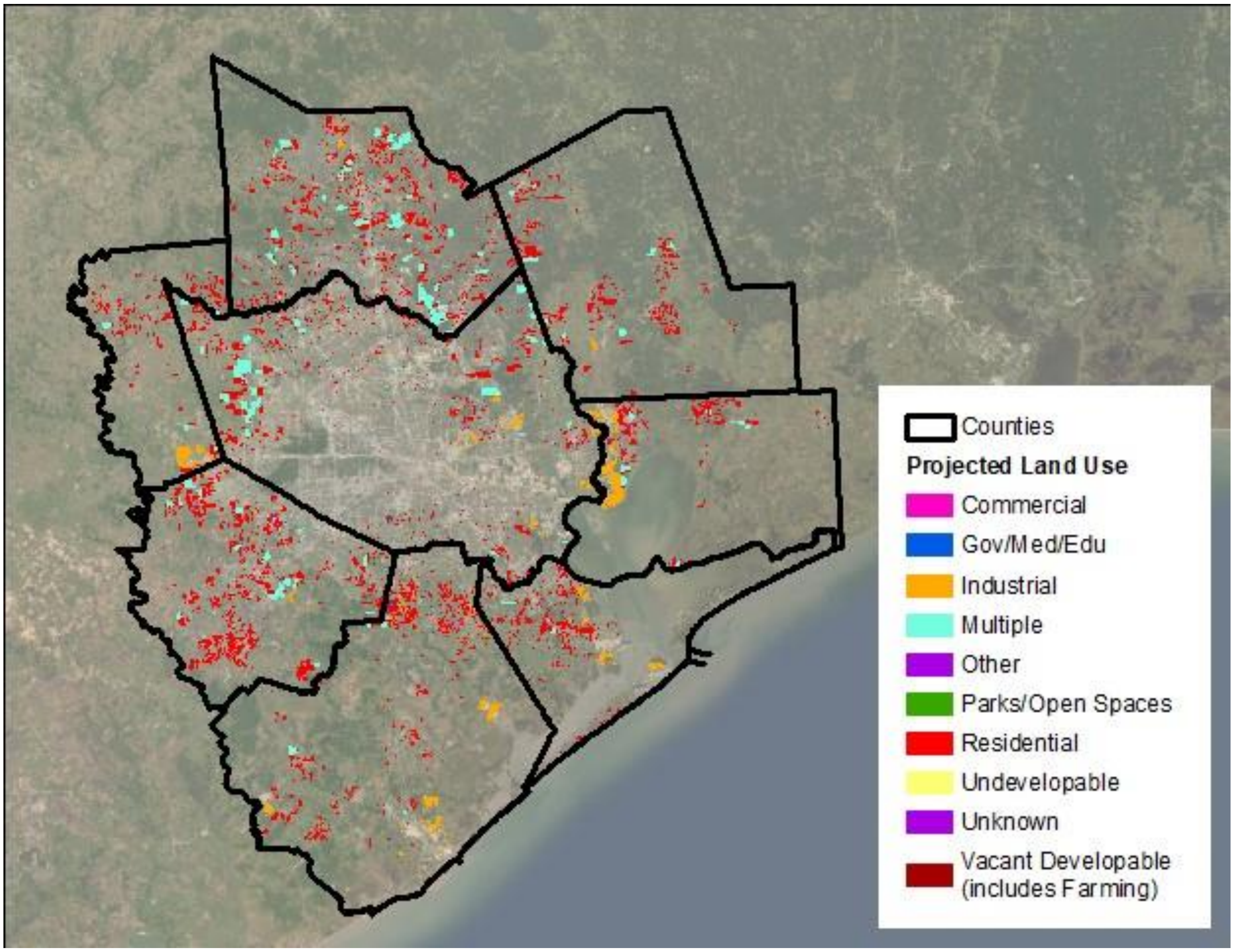


Figure 19 - Projected land use in 2045 of parcels designated as "Vacant Developable (includes Farming)" in 2015 (HGAC, 2019)

<u>Residual risk from prior projects</u>

Many federal projects only addressed flooding along the main stem of a bayou and could leave residual risk in tributaries or related to unaddressed pluvial flooding. While several federal projects, e.g., Brays Bayou, Sims Bayou, White Oak Bayou, have been successful in reducing flood damages, there are still structures in the 1% floodplain. The fluvial flood hazard extents will also be changing with MAAPnext and the incorporation of Atlas 14 rainfall in the hydrologic and hydraulic modeling.

<u>Summary of flood hazard contributions</u>

The flood hazard in the Houston area stems from a combination of physical factors and changed conditions. Gravity drainage is aided by elevated gradients which Houston lacks. The shear amount of event-based rainfall Houston sees surpasses much of the rest of the United States for a specified frequency and duration. This, combined with the poorly drained soils, makes for significant flood hazard that is not easily addressed. Many areas of Houston were developed before regulations meant to minimize the impacts of development were in place. Many tributaries have homes built very near the banks which restricts the available space for channel projects without acquisition.

6.4. FLOOD RISK DISCUSSION

Flood risk is at the intersection of hazard and consequence. The flood hazard in an area consists of the stage frequency relationship from the various flood hazards. The consequence can take several forms, most significantly structural flooding, that typically scales with the depth of inundation. Here we will consider some areas and circumstances in the Metro Houston area to compare and contrast flood risk. Floodplain extent discussions are generally based on the National Flood Hazard Layer, the current effective floodplain map. The mapping for all watersheds is currently being updated and will be released by HCFCD shortly after the release of the final report for this project. Therefore, the maps will look different, but the conceptual discussion herein should remain relevant.

As previously noted, there are several existing large FRM projects in the Houston area which perform exceptionally well. These are principally in developed areas or protect developed areas. Buffalo Bayou and the surrounding areas between SH6 and the HSC are protected by the Addicks and Barker reservoirs on the west side of Houston. Figure 20 shows the current floodplain extent for Buffalo Bayou downstream of the Addicks and Barker reservoirs. Compared to other locations in Metro Houston, the floodplain extent is minimal because of the runoff impounded in the reservoirs and regulated releases. Since their construction, the Addicks and Barker reservoirs have provided billions in avoided damages for the Metro Houston area.

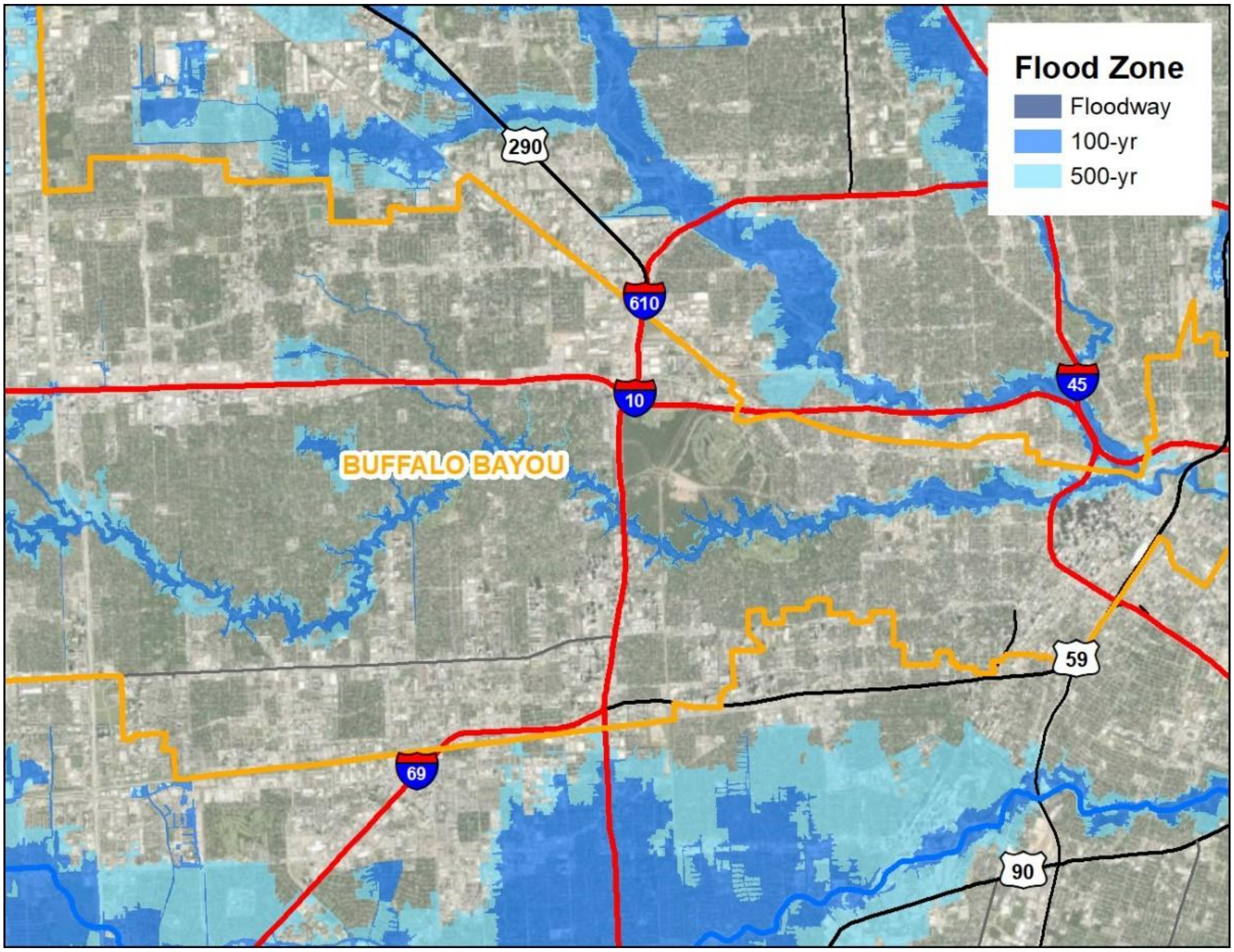


Figure 20 - Current floodplain extents in the Buffalo Bayou watershed

Outside of Addicks and Barker there are projects that have been completed such as along Sims Bayou which has limited the floodplain. Some residual risk remains near the main stem of the bayou because of historic development.

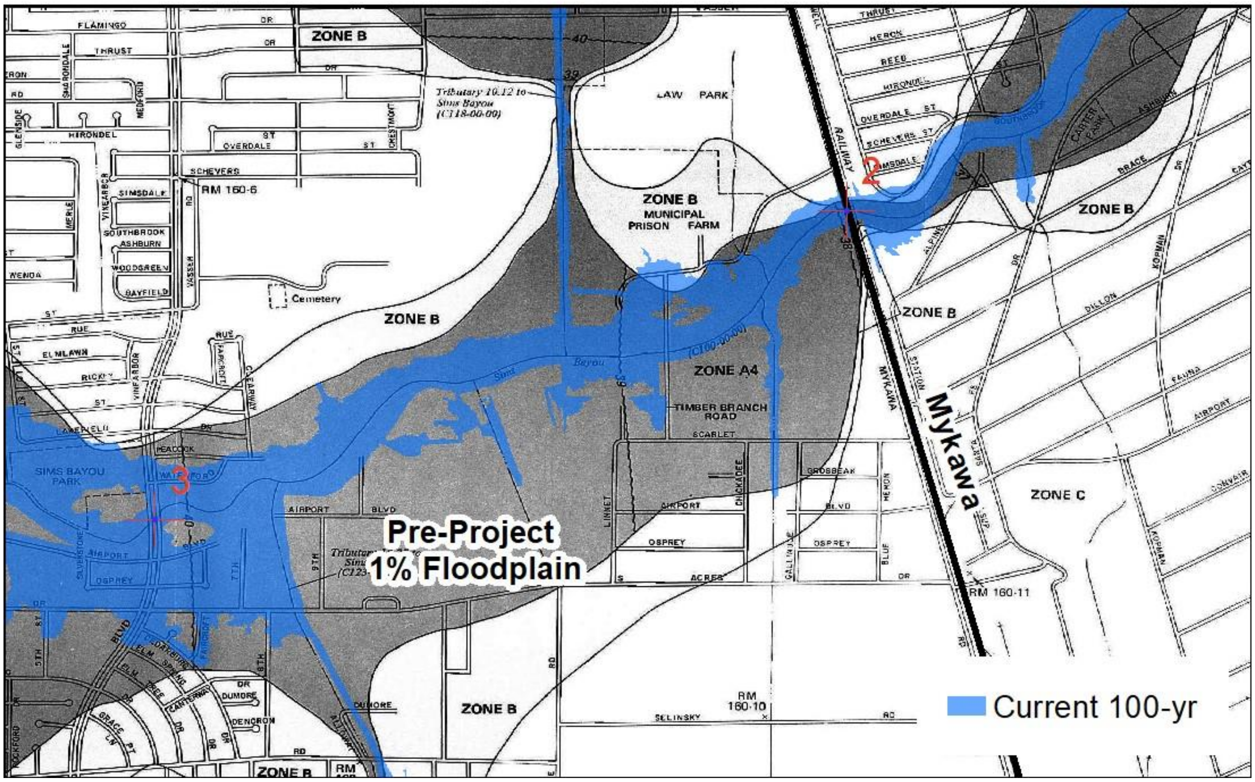


Figure 21 - Sims Bayou floodplain extents near Mykawa Rd. prior to implementation of the Sims Bayou Federal Project, and after project implementation (current extent)

One additional consideration is the coastal storm risk in areas near Galveston Bay. The Clear Creek watershed is a good example (though there are others). The area is susceptible to both flooding from rainfall runoff and storm surge.

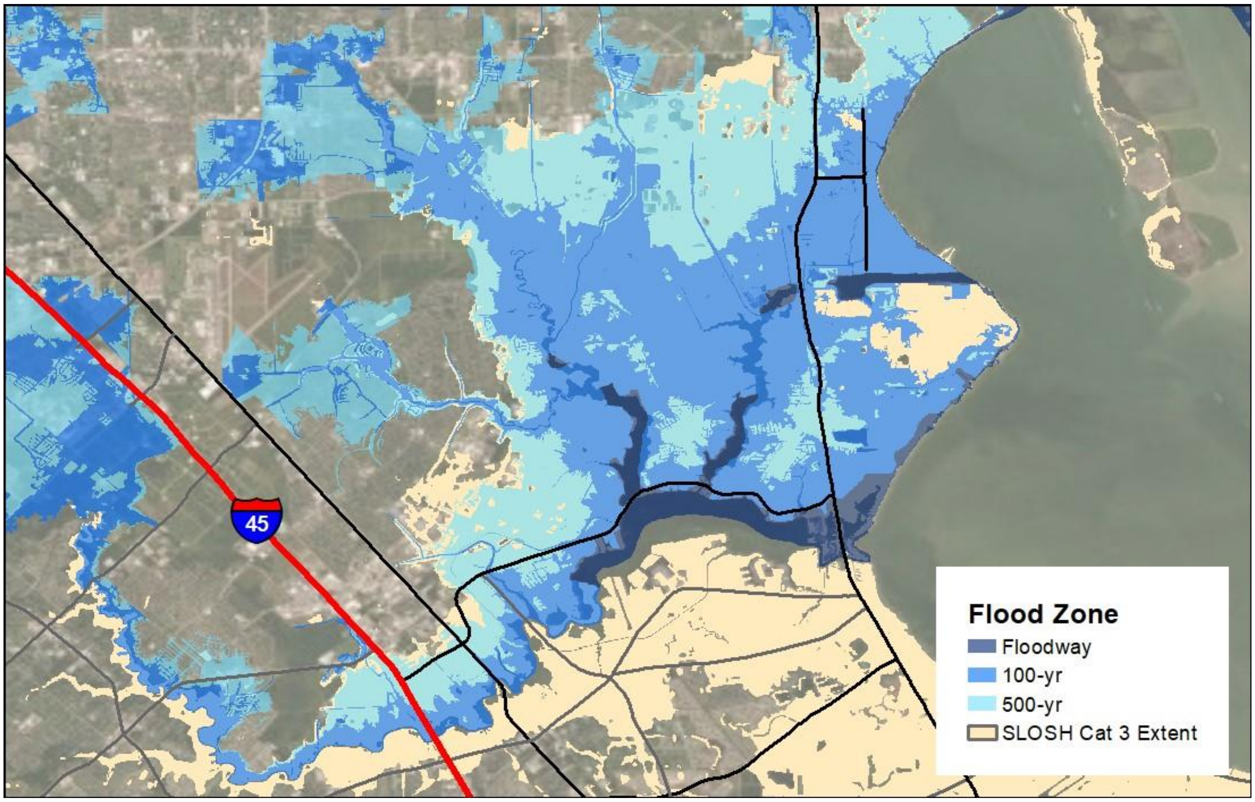


Figure 22 - Floodplain information in the Clear Lake area with the inundation extent from the NOAA SLOSH model for a Category 3 hurricane

7. ENGINEERING APPROACHES – DRAIN, DETAIN, CONVEY

Regional flood risk is a function of the physical and climatological conditions in the region, but also the concentration of homes, businesses, industry, and support infrastructure. The flood risk has been addressed over time with constructed features to drain, detain and convey floodwater away from structures and populations and into bayous and receiving bodies.

When rain events deliver water to a region, the physical characteristics of the region determine the amount of runoff and flow in the drainage network. Rainfall is absorbed into the ground where soil or other pervious land cover exists. Different soil types infiltrate precipitation at different rates, sandy soils on the high side, and clay soils on the lower end of the range. Precipitation on impervious areas, e.g., traditional pavement, rooftops, etc., and that beyond the capacity of pervious areas becomes runoff to be handled by the drainage network. Population growth, and associated development, has contributed to the conversion of natural land cover to impervious cover types which causes more runoff.

The majority of the drainage system is driven by gravity. The physical characteristics of the Metro Houston region have low lying expanses that limit gravity drainage, and an overall low slope that limits the potential flow in the drainage network.

Engineering approaches to flood risk include three fundamental actions: drain, detain and convey. FRM tools to address can be described as added detention, conveyance, and drainage. When the water exceeds the volume that can be conveyed within a channel, detention can remove flow from the channels in the watershed. Detention is also an important tool for development to mitigate for what would be increased peak flow from the site relative to the undeveloped condition.

Structural measures constructed to reduce flood risk in the region have performed as designed, but dense development remains vulnerable to flood risk when extreme storms impact the area in events that exceed the design level of the FRM feature. Continued investment is necessary to upgrade the existing infrastructure within densely developed areas where space for construction is limited and upgrade needs are considerable

7.1. DRAIN

Drainage networks are an essential layer of infrastructure to reduce flood damage. Residential and commercial development in the Houston region has kept pace with demand over time by growing outward. Drainage networks for each development are based on standards set by the relevant municipality or county. Pipes are now designed based on the two-year storm with ponding allowed in the roadway right-of-way during more extreme events up to the 100 year (City of Houston Infrastructure Design Manual).

As development replaced soils with asphalt and concrete, naturally absorbent surfaces were lost, and drainage systems built during earlier decades are undersized for the rainfall combined with runoff. Drainage network upgrades are needed across much of the region but must compete for funding with upgrades for roadways and utilities that often generate more tangible, and immediate service to the community.

As a result, FRM investment is often prioritized following storm events, when the community is more willing to accept cost and impacts, once their awareness of the risk influenced by the new awareness of the vulnerability.

7.2. DETAIN AND CONVEY

Bayous and tributaries carry rainfall away from damage centers into the receiving waterbody. Typical FRM approaches are to widen, deepen, and remove friction in the existing channel to speed conveyance of water away from structures and into receiving bodies. These channel improvements can vary in scale, from small additions to significant expansions.

When the flow rate of stormwater exceeds the capacity of the drainage or conveyance system, detention basins can hold excess water. Detaining water reduces flooding from overbanking the channel by delaying its addition to the waterway. Detention is also provided in association with development to mitigate for what would be increases to peak runoff from the undeveloped conditions. Similarities in flood vulnerability exist across many sub watersheds, however some have different flood sources and development patterns.

8. CURRENT FRM ACTIVITIES

The built components of FRM include traditional measures such as reservoirs, flood walls, levees, and channel improvements, as well as natural and nature-based features (NNBF), green infrastructure (GI) and low impact development (LID) alternatives. Non-structural measures include changes in land management, building acquisition and relocation, regulatory changes, and enhanced flood warning systems. Harris County and HCFCD discourage construction of levees for the purpose of reclaiming floodplain areas for development.

Structural flood control projects seek to control the flow of water and are intended to prevent flood waters from reaching land, structures, or other property at risk of damage. There are several types of FRM features and interventions that have a range of applicable scale and other considerations. A more detailed catalogue of the FRM features applicable in the region is presented in Appendix A. Appendix B: Climate Change Considerations in FRM reviews the necessary considerations of climate change in the design and application of FRM solutions in the region.

A summary of key agencies and their FRM efforts in the region is provided the sections below. This brief summary characterizes the relative contribution, priorities and authority for FRM in the region to identify gaps or opportunities.

8.1. Federal Agencies

PB 2019-01 requires the PDT to coordinate with the Secretaries of the Interior, Agriculture, Commerce and the heads of other appropriate agencies; and consult with appropriate Federal, tribal, state, interstate, and local governmental entities. Initial outreach with required Federal and local agencies and tribes was conducted following passage of the Bipartisan Budget Act for all resulting studies and efforts. Responding representatives expressed interest in future progress updates in the Assessment but communicated no specific concerns. Summaries of most relevant Federal agencies in FRM is provided in the following sections.

8.1.1. Federal Emergency Management Agency (FEMA)

FEMA’s mission is helping people before, during and after disasters. FEMA funds recovery efforts after extreme events, and coordinates relief efforts with USACE in many instances. FEMA offers proactive funding to communities to plan and implement risk reduction efforts. FEMA manages the National Flood Insurance Program (NFIP). The NFIP provides flood insurance to property owners, renters and businesses, and having this coverage helps them recover faster when floodwaters recede. The NFIP works with communities required to adopt and enforce floodplain management regulations that help mitigate flooding effects. Flood insurance is available to anyone living in one of the 23,000 participating NFIP communities. Homes and businesses in high-risk flood areas with mortgages from government-backed lenders are required to have flood insurance.

8.1.2. Housing and Urban Development (HUD)

The Community Development Block Grant (CDBG) program provides annual grants to metropolitan city and county governments and to state governments to develop, enhance, and preserve viable urban communities, benefit low to moderate income (LMI) persons, aid in the elimination of slum or blight, or meet other community development needs having specific urgency. CDBG funds were allocated for proactive risk reduction in the region. One billion dollars were provided for Houston and Harris County in Post Harvey CDBG funds, primarily for housing assistance.

8.1.3. US Geological Survey (USGS)

The U.S. Geological Survey is the sole science agency for the Department of the Interior. It provides natural science expertise and earth and biological data to agencies and partners. USGS stream gages are an essential FRM data source.

8.1.4. National Oceanic and Atmospheric Administration (NOAA)

The National Oceanic and Atmospheric Administration provides daily weather forecasts, severe storm warnings, and climate monitoring. Their mission is to understand and predict changes in climate, weather, oceans, and coasts, to share that knowledge and information with others, and to conserve and manage coastal and marine ecosystems and resources. NOAA's scientists apply cutting-edge research and high-tech instrumentation to provide citizens, planners, emergency managers and other decision makers with reliable information. NOAA produced the Atlas 14 precipitation updates that will inform the remapping of the region's flood risk. The National Weather Service (NWS) is a fundamental component of NOAA and is the official flood forecasting agency. In addition, the Center for Operational Oceanographic Products and Services (CO-OPS) provides coastal water-level data that is critically important for a coastal city like Houston.

8.1.5. US Environmental Protection Agency (USEPA)

The USEPA encourages and supports watershed planning to meet water quality standards and protect water resources The Clean Water Act requires EPA to develop criteria for surface water quality. USEPA technical staff consulted with the PDT use part of the study area as a demonstration example of their Watershed Management Optimization Support Tool (WMOST). The model application was delayed when EPA funds were depleted, but it may be an effective tool to demonstrate tradeoffs when assessing the viability of best management practices or natural and nature-based features on a smaller scale than typical USACE feasibility studies.

8.1.6. US Army Corps of Engineers (USACE)

The USACE has a long history of participation in regional water resource infrastructure. Congressional authorizations direct the USACE to consider federal participation in specific missions, Navigation, Flood Risk Management, Coastal Storm Risk Management, Ecosystem Restoration, Water Supply, and Recreation with cost share from a non-federal sponsor.

A USACE feasibility study involves identifying problems and opportunities related to water resources, developing alternative solutions to address those problems, comparing those solutions and justifying plan selection using either National Economic Development (NED) or National Ecosystem Restoration (NER) guidelines prescribed by Congress, or, in some cases, additional, important considerations such as Life Safety.

NED guidelines prescribe the minimum acceptable economic benefit-to-cost ratio for a civil works project. For each dollar spent, there should be an equal amount of future cost savings. NER guidelines describe the standards by which the benefits of an ecosystem restoration project are quantified. Since February 2012, Corps feasibility studies have been guided by the "3x3x3 rule," which states that feasibility reports will be produced in no more than three years; with a cost not greater than $3 million; and involve all three levels of Corps review – district, division and headquarters – throughout the study process. A waiver process exists to request additional time or funds to complete complex studies that warrant more time or funds to evaluate the water resources problem.

Any recommendation for Federal participation must consider and disclose all potential environmental impacts and complete the National Environmental Policy Act (NEPA) process.

Plan formulation strives to avoid, minimize and mitigate for environmental impacts, and defend the selection of the plan for implementation considering the potential impacts.

The Galveston District has been a critical participant in the development and construction of features within the study area that reduce flood risk along area bayous and waterbodies. Policy does not allow participation in drainage under 800 cubic feet per second (cfs), which is considered a local government responsibility, and the hydrology and hydraulics (H&H) analysis does not assess drainage at all in the with and without project conditions. Table 1 and Figure 24 present a summary of large FRM structures in the region.

Table 1 - Large Flood Projects in Harris County

History of Flood Control Projects in Harris County, Texas

Federal Flood Control Projects	Project Authorization	Construction Complete
Completed:		
Addicks & Barker Reservoirs, Buffalo Bayou	1940	1948
Brays Bayou	1954	1968
White Oak Bayou	1954, 1965	1976
Vince Bayou	1962	1980
Little Vince Bayou	1962	1988
Cypress Creek	1988	2001
Sims Bayou	1986, 1990, 1992	2015
Under Construction:		
Brays Bayou*	1990	Estimated 2021
Hunting Bayou*	1990	Estimated 2021
White Oak Bayou*	1986	Estimated 2021
Greens Bayou	1990	Estimated 2022
Clear Creek*	1968	Estimated 2023

* Harris County Flood Control District (HCFCD) Led Projects

Number	Name
1	Lower South Mayde Creek
2	Addicks Reservoir Channels Rehabilitation
2	Addicks Reservoir Channels Rehabilitation
3	Bear Creek
4	Armand Bayou Channel Improvements
5	Armand Bayou Floodplain Preservation
6	Armand Bayou Watershed Plan
7	Barker Reservoir Upstream Channel Rehabilitatior
8	Brays Bayou
9	Willow Waterhole Bayou Flood Risk Reduction
10	Willow Waterhole Prairie Management Area
11	Spring Branch Creek Erosion Study
12	Memorial Park Demonstration Project
13	Buffalo Bayou Park Revegetation
14	Carpenter's Bayou Watershed Planning Project
15	Cedar Bayou Tributary Analysis
16	Crosby Eastgate Mitigation Bank
17	Cedar Bayou Flood Risk Reduction Study
18	Mud Gully Channel Improvements
19	Taylor Bayou Improvements
20	Clear Creek Channel Maintenance
21	Clear Creek Flood Risk Management Project
22	Cypress Creek Floodplain Preservation
23	Pillot Gully Restoration
24	Katy Hockley Mitigation Bank
25	Cypress Creek Overflow Management Plan
26	Greens Bayou Wetland Mitigation Bank
27	Greeens Bayou Flood Risk Management
28	Mid-Reach Greens Bayou Project
29	Halls Bayou Watershed Project Implementation
30	Project Hunting
31	Jackson Bayou Watershed Planning Project
32	Little Cypress Creek Frontier Program
33	Luce Bayou Watershed Planning Projecft
34	Luce Bayou Floodplain Preservation
35	Galveston Bay Watershed Planning Project
36	San Jacinto River Watershed Study
37	Boggy Bayou Improvements Study
38	Panther Creek Improvements Study
39	Sims Bayou Flood Damage Reduction
40	Berry Bayou Improvements
41	Spring Creek Reservoir Study
42	Spring Creek Floodplain Preservation
43	Spring Creek Watershed Planning Project
44	Goose Creek Watershed Planning Project
45	Spring Gully Improvements
46	Vince Bayou Watershed Planning Project
47	White Oak Bayou Flood Risk Management
48	Lower White Oak Bayou Restoration Study
49	Willow Creek Floodplain Preservation
50	Willow Creek Watershed Planning Project
51	Buffalo Bayou Tributaries Resiliency Study
52	Hunting Bayou
53	Addicks Reservoir
54	Barker Reservoir
55	Vince Bayou
55	Little Vince Bayou
56	Cypress Creek
57	Cedar Bayou

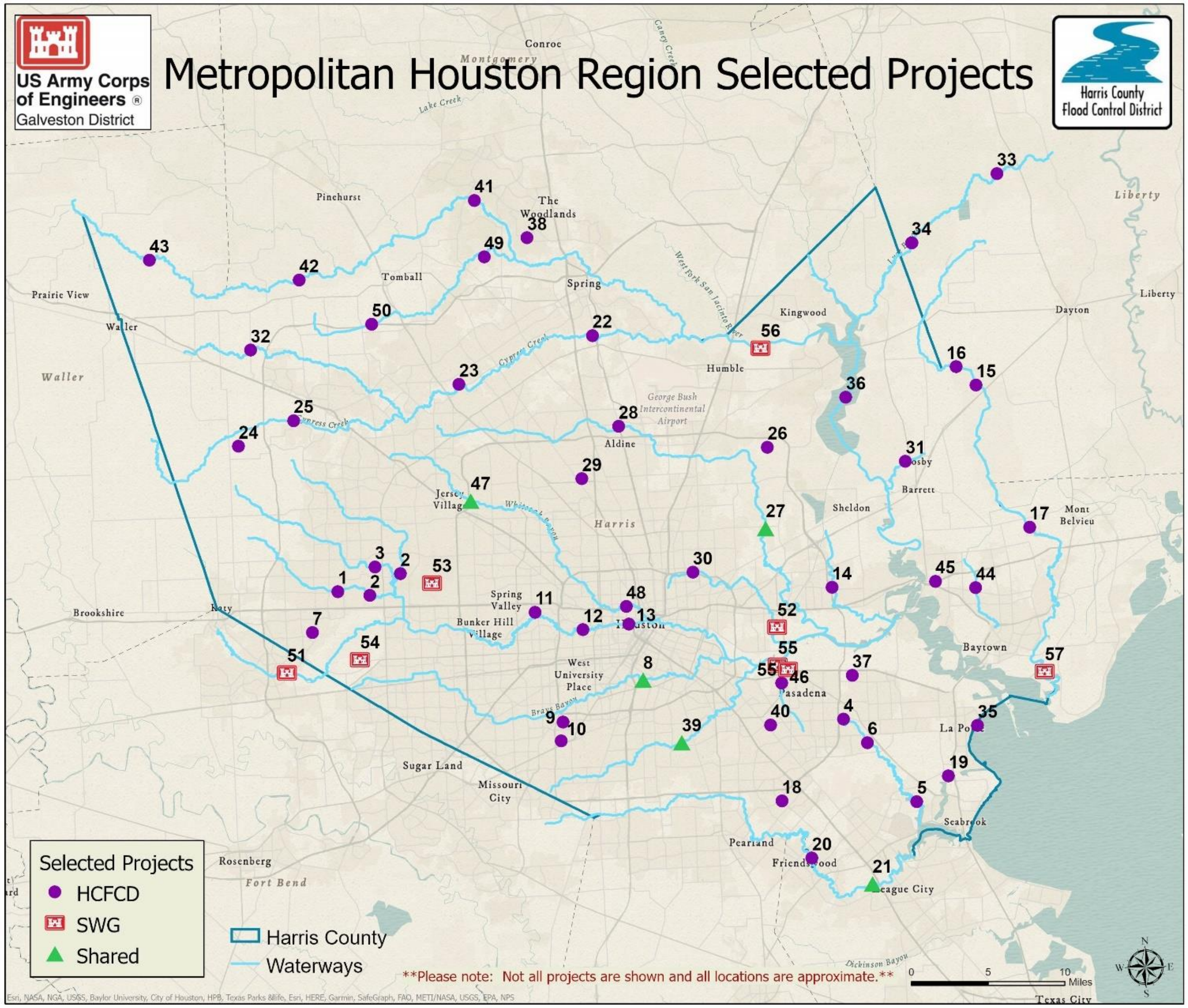


Figure 23 – Structural FRM Projects in the Region

Buffalo Bayou and Tributaries Resiliency Study

The Buffalo Bayou and Tributaries Resiliency Study (BB&TRS) is an ongoing FRM feasibility study. The BB&TRS was initiated in response to several recent flood events in the Houston metro area, including Hurricane Harvey that struck Texas with devastating effects in August 2017.

An interim feasibility report was produced in October 2020 to document the initial analyses conducted by the PDT but did not present final conclusions and recommendations. The report is a mid-point technical document for review prior to recommending a Tentatively Selected Plan (TSP).

The interim report described that Addicks and Barker Dams were constructed in the 1940s in response to damaging floods on Buffalo Bayou that struck Houston in 1929 and 1935. The dams have performed well over their 70 plus years in operation, preventing loss of life and billions of dollars in property damage along Buffalo Bayou. Hydrologic and climate trends suggest an increasing frequency of high-rainfall storms that will place increasing pressures on the dams.

The interim report for the BBTRS describes that the purpose is to evaluate changed conditions since the projects were constructed. The objective is to identify, evaluate, and recommend actions to address the changed conditions, including potential modifications to the Buffalo Bayou system to reduce flood risks to people, property, and communities.

The BB&TRS evaluates six watersheds that overlap with a portion of the study area of the Assessment, including Upper Cypress Creek (267 square miles), White Oak Bayou (111 square miles), Brays Bayou (127 square miles), Addicks Reservoir (138 square miles), Barker Reservoir (126 square miles); and Buffalo Bayou (102 square miles) (fig. 24). The six watersheds are included in the modeling and technical analyses of flooding, but the Interim Report describes the primary scope of that study is to reduce flood risk for the Addicks, Barker, and Buffalo Bayou watersheds.

The feasibility study demonstrates a significant challenge to addressing flood risk in the region. Past structural solutions to flooding have successfully reduced the damages that would occur from smaller, more frequent flood events. The economic justification required for USACE participation is challenging when the flood risk to be addressed is from extreme storms that can cause significant damage to structures and contents but which occur less often. The economic benefits expected over a fifty-year period of analysis, the typical period for a USACE study, cannot offset the cost of a structural solution to address flood events in excess of the current FRM structures.

The BB&TRS interim report identified three potential alternatives to reduce flood risks downstream and upstream of Addicks and Barker Dams. They included a new reservoir, estimated to cost between $2 and $3B; Buffalo Bayou Channel improvements at approximately $1B, or a plan that combines the reservoir and channel improvements at an estimated cost of $3 – $4B. Real estate acquisition of ~14,000 – 24,000 properties is also scoped as a possible alternative with a cost range of $8.1B – $13.1B.

Concurrent HCFCD investigation into a tunnel alternative confirmed that the geotechnical conditions would support construction and operation of a tunnel. The BBTRS estimate of cost and benefits found the tunnel alternative to be cost prohibitive for Corps participation, since it provided a comparable level of risk reduction as other alternatives at a higher cost.

Public response to the interim report and the array of potential alternatives ranged from expressions of urgency for action, and proposals for an interim measure to address risk while a larger solution is designed and constructed. Support that was expressed for a solution was often conditioned by disapproval of impacts to access, species or views of more natural habitats.

Strict policy interpretation suggests that federal participation in a larger alternative is not justified. However, the unique flood risk coupled with a thriving metropolitan region that is home to nationally significant industry suggests that a creative solution might be found.

The BB&TRS PDT will incorporate feedback from the interim report into the study, develop recommendations, and publish a draft feasibility report and draft environmental impact statement for further review. The draft report and draft environmental impact statement will undergo review by the public, resource agencies, and technical and policy staff at USACE and HCFCD.

The inventory phase of the Assessment considered current flood risk, available tools and authorities in the larger region to develop recommendations to improve efficiency of FRM in the future. The inventory considered the public and agency feedback on the BB&TRS in the development of recommendations, as well as the USACE feasibility process and criteria for plan selection.

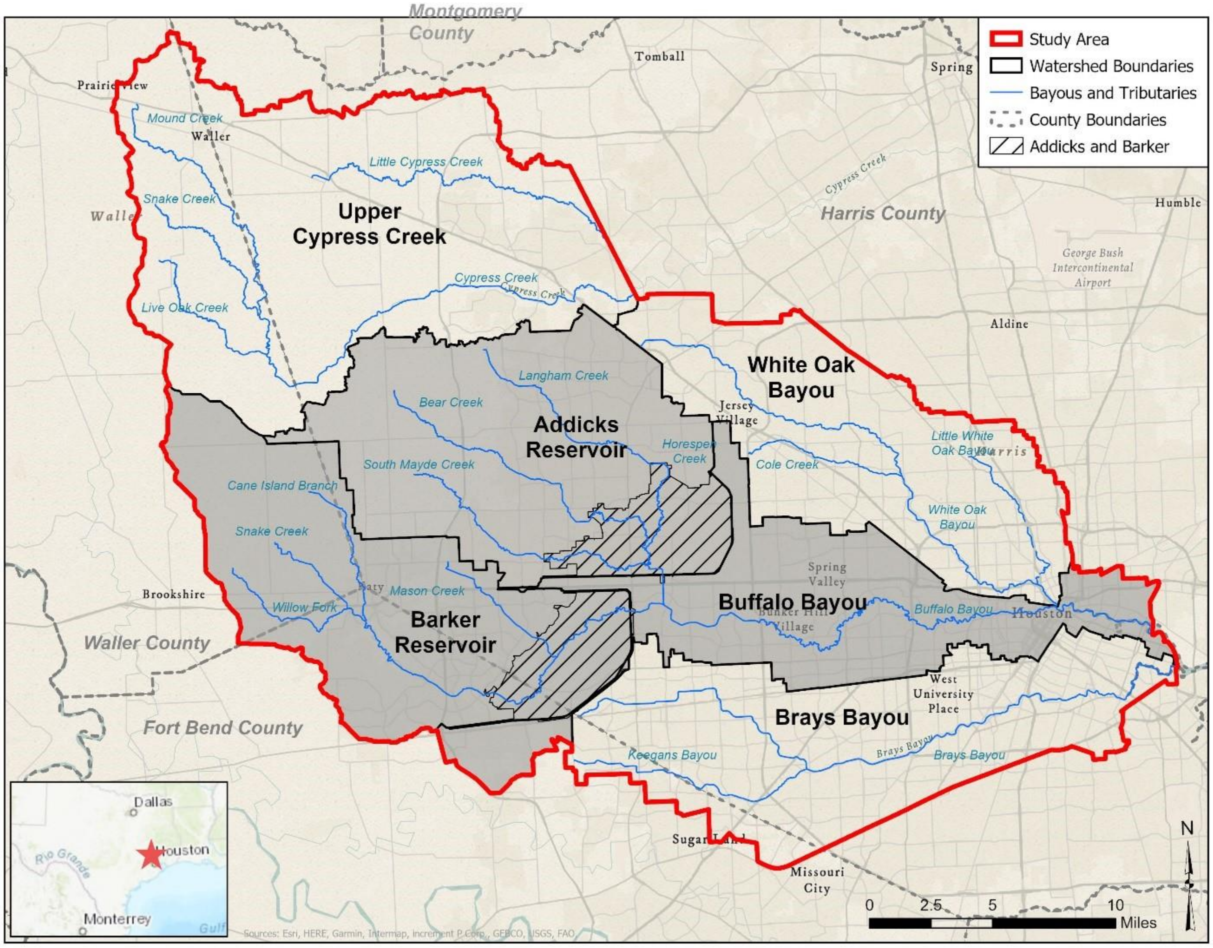


Figure 23 - Addicks and Barker Reservoirs and Buffalo Bayou, Texas Study Area Map

8.2. HARRIS COUNTY FLOOD CONTROL DISTRICT (HCFCD)

HCFCD is a special purpose district created by the Texas Legislature in 1937 and governed by Harris County Commissioners Court. It was created in response to devastating floods that struck the region in 1929 and 1935. The Flood Control District's jurisdictional boundaries are set to coincide with Harris County, a community of more than 4.5 million people (2015) that includes the City of Houston. The HCFCD is the primary cost share sponsor for USACE FRM efforts in the Metro Houston area.

The HCFCD also builds, manages and improves conveyance systems within their jurisdiction independent of USACE participation. Over time, the HCFCD has invested in FRM features, tools and innovations to address flood risk. Following Hurricane Harvey, Harris County voters approved $2.5 billion in bonds to finance flood damage reduction projects. The 2018 Bond Program includes funding for more than $1.2 billion in channel conveyance improvements, $400 million for building stormwater detention basins, $242 million for floodplain land acquisition, $12.5 million for new floodplain mapping, and $1.25 million for improving our flood warning system.

8.2.1. HCFCD Technical Tools

Several efforts funded by the Bond program are especially relevant for the Assessment. HCFCD analytical tools and data sets are being upgraded to incorporate improved data and provide greater specificity of the flood risk in the region through the Modeling, Assessment and Awareness Project (MAAPnext). Upgrades include an updated hydrologic methodology that uses a basin development factor (BDF), use of both one-dimensional and two-dimensional hydraulic models to better resolve complicated hydraulic conditions, inclusion of updated rainfall depths, and use of the latest topographic data. This will be the first major update to the model since the county was mapped during the Tropical Storm Allison Recovery Project (TSARP) in 2007. The pending update will improve model accuracy and would render any major modeling effort in the Assessment duplicative, since it would be completed with the older HCFCD model with less engineering detail than the pending updated model. Draft mapping products from the MAAPnext initiative are expected by the end of 2021.

8.2.2. Level of Service Analysis

HCFCD is also working on a level of service (LOS) analysis for their streams. The LOS for a given reach is the return period associated with the water-surface elevation that instantiates structural flooding in that reach. The channel segments will be color coded on a map to visually represent the findings of the analysis. The analysis will also include a planning-level assessment of future expansion needs of reach.

8.2.3. Model and Map Management (M3) System

HCFCD’s Model and Map Management (M3) System is an interactive tool designed to communicate and share changes to FEMA’s effective floodplain models for Harris County. The goal of the M3 System is to distribute FEMA effective models to the general public, to track ongoing changes to the models resulting from development projects, and facilitate communication between FEMA, HCFCD, Local Floodplain Administrators, and the community.

8.2.4. HCFCD Tunnel Feasibility Study

Following Hurricane Harvey, a deep, large-diameter, stormwater conveyance tunnel concept was proposed as an alternative to increase stormwater conveyance capacity through urban areas and mitigate future flood risks. HCFCD initiated evaluation of a tunnel solution in several phases.

Phase 1 of the study was undertaken to validate the feasibility of a deep tunnel concept and provide preliminary information for further development in future phases. The Phase 1 Study has determined that:

- Tunneling in Harris County is feasible based on the geotechnical conditions and project experience in similar soils
- Geological faults may require special design and construction considerations where crossed by the tunnel but are not fatal flaws (Tunneling Applicability Analysis),
- Tunnels can move a significant rate of stormwater operating entirely by gravity as an inverted siphon (Inverted Siphon Hydraulic Analysis),

- Tunnel costs including a 50% contingency for a representative 10-mile-long, 25- and 40-foot diameter tunnels are approximately $1 billion and $1.5 billion respectively (Conceptual Tunnel Cost Analysis)

Phase 2 began in the spring of 2020 and was expected to take about one year to complete and was scoped to:

- Consider how to measure tunnel success,
- Recommend tunnel alignments that reduce flooding risks along major bayous and creeks while not causing negative impacts at the discharge locations,
- Estimate cost – including the cost of community disruption -- as compared to potential flood risk reduction benefits,
- Determine an estimated timeline for building tunnel projects,
- Identify environmental impacts and permit requirements, and
- Compare tunnel costs, benefits and implementation timelines to those of other flood risk reduction projects.

Following this work, Phase 2 will recommend and continue to refine no more than three potential "actionable" tunnel projects in distinct locations in Harris County. An "actionable" tunnel project is defined as one that – based on the opinion of the Flood Control District after input from the public – provides adequate flood damage reduction benefits to justify its construction and operation, as well as its implementation timeline.

Phase 3 of Preliminary Engineering will follow if there are actionable recommendations as a result of Phase 2.

8.2.5. HCFCD LED FEASIBILITY STUDIES

Several USACE projects are now NFS led design and construction efforts to expedite implementation under the authority of Section 211(f) of WRDA 1996 and since WRDA 2007 authorized USACE cost share for design and construction if the study process complies with USACE regulations.

1.1.1.1 Brays Bayou

Brays Bayou is in construction with features that include an upstream element west of Sam Houston Tollway, 3 detention basins and 3.7 miles of channel conveyance improvements, including control structures, from Old Westheimer Rd. to SH 6. The downstream element east of Sam Houston Tollway includes 17.5 miles of channel conveyance improvements, 1 detention basin, 30 bridge replacements/modifications, and/or channel conveyance improvements under bridges and wetland creation, trees and shrubs, and aesthetic layouts.

HCFCD manages, designs, and builds the project; buys land, easements, rights-of-way (ROW); relocates utilities; adjusts bridges (except for railroads); operates and maintains the channel after construction. USACE monitors the overall project to confirm that HCFCD work complies with USACE policy and reimburses the design and construction cost. Much of this project has already been completed with primarily bridge replacements left. Information on the project is available at projectbrays.org.

1.1.1.2 Clear Creek

Clear Creek proposed further improvements to a project that has been under study and construction since 1986. Project features include 15.1 miles of channel rectification and 500 acre-foot in-line detention from Dixie Farm Road to State Highway 288, and several lengths of channel rectification on Mud Gully, Turkey Creek and Mary's Creek ranging from 0.8 to 2.1 miles in length. The project scope is under revision and awaiting USACE HQ approval. The remaining scope, once approved, will be built by HCFCD under Section 1043.

A second outlet and gate to release excess upstream floodwaters into Galveston Bay was completed in 1998.

1.1.1.3 Hunting Bayou

The Hunting Bayou project proposed 3.8 miles grass-lined channel conveyance improvement, a 75-acre detention basin storing 1,000 acre-feet of water, 17 bridge replacements/modifications, and/or channel conveyance improvements under bridges, and aesthetic and environmental quality features.

Two communities within Hunting Bayou are Kashmere Gardens and Trinity/Houston Gardens appear to experience flooding as a result of the railyards that extend from southwest of Loop 610 to northeast of Loop 610 and parallel to Wayside Drive north of Loop 610. A large portion of these neighborhoods fall within the pre-Atlas 14 500-year floodplain, which is expected to be remapped as 100-year floodplain.

USACE monitors the overall project to confirm that HCFCD work complies with USACE policy and reimburses the design and construction cost. HCFCD manages, designs, and builds the project; buys land, easements, rights-of-way; relocates utilities; adjusts bridges (except for railroads); and operates and maintains the project features after construction.

1.1.1.4 Sims Bayou – Ongoing Construction

Completed in 2015, the Sims Bayou Federal Flood Damage Reduction Project was a partnership project between the USACE and the HCFCD. USACE is the lead agency for this project, which included 19.3 miles of bayou enlargements and environmental enhancements along Sims Bayou from the Houston Ship Channel to Croquet Lane, just west of South Post Oak Road and the replacement or modification of 22 bridges that cross Sims Bayou. In addition, the federal project was supplemented by the construction of three stormwater detention basins on Sims Bayou – these basins were excavated using local funds.

As the local sponsor, the Flood Control District was responsible for property acquisition, utility relocation, and the modification/replacement of the bridges, which were designed to minimize obstruction to the flow of stormwater in Sims Bayou.

Local and regional projects are underway to complement this project.

1.1.1.5 White Oak Bayou

Ten downstream miles of White Oak Bayou from just outside Loop 610 north to the confluence with Buffalo Bayou in downtown Houston were channelized by the U.S. Army Corps of Engineers in the 1960s. This project proposes channelization and detention ponds for the upstream portion. It includes 15.3 miles grass-lined channel conveyance improvement, 4 detention basin complexes, 12 miles of linear park/trails along the channel and multi-purpose fields, play areas, trails, etc. in detention basins and aesthetic and environmental quality features.

Between Farm to Market Road 1960 and Hollister Street. The $20.6 million effort will widen White Oak Bayou and replace or modify storm pipes and outfall structures, per a release. Work will also be done on the inflow and outflow weirs to the stormwater detention basins.

USACE monitors the overall project to confirm that HCFCD work complies with USACE policy and reimburses the design and construction cost. HCFCD manages, designs, and builds the project; buys land, easements, rights-of-way; relocates utilities; adjusts bridges (except for railroads); and operates and maintains the project features after construction. Project performance and justification was completed with prior WSE and pre-Atlas 14 H&H.

8.3. City of Houston (CoH)

The City of Houston (CoH) establishes building standards, including base flood elevation and drainage standards. The CoH is also responsible for drainage structure maintenance and upgrades in the city.

8.3.1. ReBuild Houston

The CoH has a significant role in stormwater management throughout the metropolitan area. CoH is responsible for rainfall-runoff between where the rain falls and the outfall into larger drainage facilities, and in the Metro area these are often HCFCD channels. The ReBuild Houston initiative was approved by Houston voters in 2010 and created a dedicated funding source for street and drainage improvements. The pay-as-you-go fund was proposed to provide $20 billion in funding through the year 2040 for projects that benefit the CoH's service area if reapproved by voters. It applied a 'repair-the-worst-first' approach toward infrastructure improvements with the objectives of reducing street flooding, improving mobility, and reducing structural flooding.

8.3.2. Resilient Houston

The CoH launched the Resilient Houston strategy in February 2020. It established a framework for collective action for every Houstonian; across diverse neighborhoods and watersheds; City departments; and local, regional, and global partners. The strategy links existing efforts with new ones that will collectively work to protect Houston against future disasters—from hurricanes to extreme heat waves—and chronic stresses such as aging infrastructure, poor air quality, and flooding. Resilient Houston was developed in partnership with diverse stakeholders who determined goals and targets. It provides detailed actions and a framework for achieving them

The Resilient Houston framework is particularly relevant to the evaluation of FRM efforts within the Metropolitan Houston region because it evaluates stressors, such as flood events, in light of their long-term impacts to the community, environment, and economy. Goals and targets were developed in partnership with stakeholders, and the framework scopes a broad series of steps to leverage present and future partnerships at the individual, neighborhood, bayou, city, and regional scale enable the community to withstand those stressors.

8.4. SAN JACINTO REGION

The San Jacinto River Regional Watershed Master Drainage Plan (SJMDP) was led by four study partners, HCFCD, the San Jacinto River Authority, Montgomery County, and the City of Houston, and was recently completed. This comprehensive regional flood study developed regional H&H models using updated rainfall and terrain information for the watershed, and an inventory of structures, acres of land, properties, miles of roadway, critical infrastructure, and evacuation routes within the inundated area. The study identified 6 priority channel improvement and 10 priority stormwater detention basins or reservoirs in the region.

8.5. LEAGUE CITY AND DICKINSON – SILVER JACKETS

A recent evaluation of FRM solutions evaluated alternatives along the lower portion of the Clear Creek watershed and the Dickinson Bayou watershed with neighboring towns. It included a proposal for underground tunnels which would run for miles beneath League City, Friendswood, Webster, and the Clear Lake area. The tunnels, proposed at least 75 feet underground, would allow Clear Creek overflow to drop in at several points and be moved via pressure to an outlet, such as Clear Lake or Galveston Bay. One proposed tunnel would run 8 miles from FM 2351 at Clear Creek to Clear Lake. The process considered some “out-of-the-box” unique concepts to move water.

8.6. STATE OF TEXAS

The State of Texas implements varied programs that enhance resilience in the state and the Metropolitan Houston region. Pre and post storm emergency management efforts promote proactive life safety precautions.

The Texas Division of Emergency Management (TDEM) is charged with carrying out a comprehensive all-hazard emergency management program for the State and for assisting cities, counties, and state agencies in planning and implementing their emergency management programs. A comprehensive emergency management program includes pre- and post-disaster mitigation of known hazards to reduce their impact; preparedness activities, such as emergency planning, training, and exercises; provisions for effective response to emergency situations; and recovery programs for major disasters. Chapter 418 of the Texas Government Code lays out an extensive set of specific responsibilities assigned to the Division.

The state has also funded risk reduction studies independently and in cooperation with others for many years. The Texas General Land Office (TxGLO) has cost shared many USACE feasibility studies and continues to support infrastructure investments across the state. Two recent programs managed by TxGLO and Texas Water Development Board (TWDB) have significantly increased the state’s participation in FRM efforts and demonstrate the growing awareness of the flood risk in the region.

8.6.1. GENERAL LAND OFFICE (TXGLO)

Flood Studies within Combined River Basins

Three regionalized studies, based on Texas' major river basins, will evaluate mitigation and abatement strategies to reduce disaster impacts and increase community resiliency. The studies will consider structural and nonstructural infrastructure improvements, coding and zoning practices, and regional communication and control as each relates to flood control.

The CDBG funded program will provide technical support for region specific development of flood risk projects for further implementation through USACE or other authorities. The program managers are coordinating the program with USACE and other federal agencies to ensure that proposals are developed consistent with agency standards to maximize the potential for project implementation.

Texas Coastal Flooding Initiative

The TxGLO is coordinating with state and federal agencies to address study gaps but ensure that no planning efforts are duplicated. Recent discussions among the agencies have inspired several creative solutions for FRM planning. USGS has already taken the initiative to develop a planning study to better coordinate data collection, visualization, modeling, and disaster planning for state and federal entities. This planning study would align with the Harvey Action Plan by standardizing "methods through regional coordination and planning at a level that has not yet been achieved through CDBG-DR funds in Texas." This effort will build a comprehensive framework for evaluating compound flood risk along the coast.

8.6.2. TEXAS WATER DEVELOPMENT BOARD

The 2019 Texas Legislature authorized, and Governor Abbott greatly expanded, a constitutional amendment to expand the TWDB's role in flood planning and financing. In addition to their existing flood programs, the TWDB is administering a new state and regional flood planning process with flood planning regions based on river basins. The regional flood planning process was developed and initial regional flood planning groups, with broad representation from community, agencies and industry were formed in mid-2020. The regional groups will create regional flood plans in 2023, and the first state flood plan will be created in September 1, 2024. See the Flood Planning page for details.

The legislature also made a one-time transfer of $793 million from the state's Economic Stabilization or "Rainy Day" Fund to create a new flood financial assistance program to be administered by the TWDB. The Flood Infrastructure Fund program is designed to make the implementation of drainage and flood projects more affordable for Texas communities and to meet immediate needs for funding. See the Flood Infrastructure Fund program page for details.

In addition, the legislature provided the TWDB with funds to collect more flood-related data, advance its river and coastal modeling capabilities, and distribute critical flood information through an online dashboard.

The Flood Information Clearinghouse Committee is a multi-agency effort, including TxGLO and the Texas Division of Emergency Management (TDEM) to maximize effective utilization of public funding resources to help communities access the most suitable public fund source for their effort. Visit the Flood Funding Information Clearinghouse.

9. POST HARVEY RECOMMENDATIONS

Several independent assessments of FRM in the region have been published. These summaries and recommendations provide an initial insight into successes and gaps in regional FRM priorities, and some are summarized below.

9.1. GREATER HOUSTON STRATEGIES FOR FLOOD MITIGATION

A group of academic researchers, including Rice University, Texas A&M, Texas Southern University and Texas State University, University of Houston and University of Texas at Austin, known as the Greater Houston Flood Mitigation Consortium (GHFMC), produced a report in 2018 titled “Greater Houston Strategies for Flood Mitigation,” which focused on strategies for flood mitigation. The group also published research papers documenting drainage, detention, and development regulations. These documents presented a thorough assessment of ongoing efforts and involved agencies. The 2018 report summarized Harvey impacts by watershed, reviewed a range of FRM solutions,and presented problems and strategies for overall resiliency of individuals and the community. Conclusions included:

- There is no way to completely eliminate flooding in Houston.
- Most flood control assessments, including the federal government’s cost-benefit ratio, calculate benefits through economic value, not impact on human lives.
- Data about building slab elevations is critical to understanding the full extent of damages due to flooding depths.
- A flood risk mapping approach that estimates the likelihood of all flood scenarios will be more useful than the traditional flood plain mapping approach.
- The level of flood protection across watersheds is not equitable.

A final report was published in 2019 entitled “The Flood Next Time: What We Can Do Now.” That document identified needs that are consistent with the recommendations in this Assessment: coordination, communication, resources, and political will.

9.2. HOUSTON A YEAR AFTER HARVEY: WHERE WE ARE AND WHERE DO WE NEED TO BE

The Rice University Baker Institute and the Severe Storm Prediction, Education, & Evacuation from Disasters (SSPEED) Center prepared a summary paper to assess flood risk in Houston and apply lessons learned from Hurricane Harvey. It evaluates three topics, obsolete flood maps, a geographic overview of watershed specific issues, and FRM concepts for three of the zones in the region. The paper concludes with an assertion that difficult issues and choices in the region will require creative thinking and leadership. The report quotes meteorologist Jeff Lindner’s final report on Harvey for HCFCD, which noted that Harvey caused about $125 billion in damages, with over 150,000 homes and thousands of businesses flooded (Lindner and Fitzgerald 2018). Harvey’s financial impact was the same as that of Hurricane Katrina (NOAA 2018a).

9.3. LIVING WITH WATER

A conceptual plan prepared for the CoH following public workshops highlighted concepts that accept water as an aspect within a community and scope several recommendations for a resilient coexistence. The top priorities in the "Living with Water" report include:

- Prioritize safety first. Critical Facilities and access corridors should be elevated or retrofitted. Development should be incentivized to build in flood-safe areas.
- Hold water where it falls. Holding runoff closest to where it starts lessens downstream impact. Once water enters the bayous, it enters another scale of infrastructure and is more difficult to control.
- Educate public & private sectors about water. Especially in areas where flood risk is not immediately apparent, outreach on flood risk, the location of flood-prone land, the function of the bayou system, and the causes of flooding can shape public and private commitment toward water resilience. Solutions and advocacy at every scale require a similar public outreach.
- Align transportation system to waterway functions. In certain cases, improve choke points where transportation crossings (road and rail) obstruct water flows only when upstream downstream areas will not be impacted. Major transportation corridors should manage their own runoff and take on additional detention if possible. Retrofitting parking lots and other paved areas to have plantings and pervious paving lowers the impact highly impervious surfaces have on the speed and volume of runoff entering the drainage system.
- Make Space for Bayous. Constriction in the bayous must be resolved, whether it is in the form of choke points at bridges and culverts or properties located in the floodway. Water must be given space in a way that does not harmfully displace people or amplify downstream flooding. Working in tandem with the Bayou Greenways 2020, new bayou space can become a recreational amenity and the front yard of Houston.
- Bring back the prairie. Prairie conservation efforts in the greater Houston region reduces runoff, preserves a recreational and ecological amenity, and lowers the urban heat island effect.
- Increase water storage ambition over time. Climate change, updated storm data and ongoing development makes water storage goals a moving target. Developing water-aware development culture and increasing water storage ambition helps to keep up with increasing future risk.

9.4. WEST HOUSTON 2060 (WH 2060)

The West Houston Association (WHA) was formed in 1979 as a not-for-profit group to promote high quality, sustainable growth for an area of 1,000 square miles in the western portion of Harris County and parts of Fort Bend and Waller Counties ("Greater West Houston").

Greater West Houston, including the Energy Corridor, Westchase, and Memorial District regional centers, is home to over thirty master planned communities and industries. The WH 2060 Plan is an update from the WH 2050 Plan and asserts that continued growth in the region is unsustainable without addressing Transportation, Water Supply & Quality, Flood Control & Drainage, Education, Parks & Open Space, Quality Planned Development, and Sustainable Infrastructure.

FRM related recommendations include:

- Transportation upgrades and resiliency during extreme events should be prioritized.
- Current investment in projects to provide adequate regional surface water supplies through 2060 prevents subsidence and associated increased flood risks.
- Regional flood mitigation planning is critical since floodwaters do not stop at jurisdictional boundaries.
- A comprehensive park and open space system benefits current and future area communities while creating sustainable benefits

Flood control and drainage goals include:

- Invest $20 billion per year regionally and $500 million per year in the WHA service area from Federal, State, County and City sources.
- Create a regional master drainage plan to provide a level of service that will safely convey 14 inches of rainfall runoff in a 24-hour period.
- Enhance the environment using green infrastructure corridors

9.5. Houston Stronger

Houston Stronger (https://houstonstronger.net/resources) was formed to work with federal, state and local officials to increase funding for flood mitigation and flood-related infrastructure improvements. Houston Stronger supported Proposition A, the bond that proposed a $2.5 billion investment to equitably reduce Harris County's flood risk by executing over 230 regional flood control projects in all of Harris County's 22 watersheds. Houston Stronger also supported Senate Bills 6, 7, and 8 during the 86th legislative session which provided over $2 billion in funding for flood control, recovery, and resiliency across Texas. The group is currently proposing the BB&TRS analyze additional alternatives.

Houston Stronger provided comments on the BB&TRS Interim Feasibility Report, released on October 2, 2020 (Interim Report) by USACE and requested increased transparency and community engagement in the feasibility study and proposed several alternative components be studied. Some specific elements included:

- Add conveyance downstream of Barker and Addicks Reservoirs without channelizing Buffalo Bayou.
- Reduce flooding conditions in Buffalo Bayou watershed downstream of the reservoirs resulting from local rainfall.
- Minimize environmental impacts and enhance long term environmental benefits.
- Have broad and prolonged community support from a diverse group of stakeholders.

10. BROAD FINDINGS

The inventory process provided insight into the current FRM initiatives, agency priorities and strengths, and public perception of flood risk and FRM project implementation. Several common themes were raised by distinct stakeholders, whether advocacy groups, or agencies implementing FRM programs.

A fundamental finding is that the region is especially flood prone, which is a function of topography and soils, and extreme rainfall amounts. Structural projects constructed by HCFCD and USACE function as designed and reduce impacts during flood events. However, residual risk of flooding remains when the flood event exceeds the capacity of the feature, typically during lower frequency events.

Typical development patterns replace soils with paved surfaces, which increases runoff and competes for available space to build or augment existing FRM features. Detention requirements are meant to mitigate for increases in runoff rate (flow) but not for the total volume produced.

Multiple agencies are engaged and contributing technical expertise and funding to the FRM effort. These agencies recognize that engineered solutions alone cannot address the flood vulnerability. The two new regional efforts by the State of Texas, which create new FRM functions within existing agencies, the resilience framework of the City of Houston, and the bond program of HCFCD demonstrate that agencies recognize that flooding requires attention.

Several general areas of opportunity to increase the effectiveness of regional FRM efforts became evident after consultation with stakeholders, agencies, and review of public feedback on feasibility studies. The broad areas of priority focus can be characterized as Risk Communication, Regional Coordination, and Equitable Distribution. Screening tradeoffs are a subset of Equitable Distribution but are treated in more detail in this section.

10.1. RISK COMMUNICATION

Many engaged members of the community believe that engineering solutions can address existing risk if only the correct scale of a feature would be constructed at the right location. Members of the community underestimate the shear amount of water the system must handle during low frequency events, and accordingly, underestimate the acceptable tradeoffs and compromises of many solutions. People may also perceive flood risk as event-based and may assume their area is not as flood prone as another area where a storm event produced more rainfall. To say “I didn’t flood during Harvey” does not confer immunity from flood impacts during a future event.

Rainfall and flood events are not only characterized by source but by severity and chance of occurrence using statistical methods referred to as frequency analysis. Precipitation frequency analysis is used to estimate the probability that a given storm magnitude will be equaled or exceeded in any given year. This probability relates to an average recurrence interval, a nomenclature often used, e.g., 100-yr event. The probability that a given rainfall amount accumulated over a given duration will be equaled or exceeded in any given year is the Annual Exceedance Probability (AEP). Once Harris County is remapped at the conclusion of the MAAPnext initiative, we anticipate that many of the current 0.2% AEP flood zones will be as approximately the new 0.1% AEP flood zones. Data also confirms that flood damages regularly occur outside of mapped riverine and coastal flood zones.

Assessment of the hazard map confirms that structural FRM measures are functioning as designed and that flood risk from events that do not exceed the design performance standard for each measure are reduced. Consequences are also reduced in these areas when the flood event exceeds the design performance standard, but some damages still occur. However, continued development, even when designed to current building standards at higher elevations still add population to areas that will be at risk from flood events larger than the design level of the features in place.

10.2. Regional Coordination

The magnitude of the flood risk in the region, combined with the continued growth that adds paved surfaces, structures and people to the region, will require a concerted effort to implement FRM features. Flood risk reduction will require innovative measures and proactive efforts that combine agency missions and phase efforts to remove constraints over time.

A comprehensive, layered application of FRM solutions will warrant coordination among agencies to achieve risk reduction. A phased program to implement effective FRM with current authorities will require analysis of regional priorities and existing gaps to address risk and establish support systems. Coordination may also achieve increased efficiency through recognizing the strengths and aptitudes of each agency, and by directing proposals to the agency with the most applicable justification criteria for implementation.

10.3. Equitable Distribution

Each agency must justify participation in an FRM solution according to their specific policies. USACE requirement to maximize net benefits can challenge justification of a solution when an earlier feature is in place and functioning. The damages reduced may be large for extreme events, but too small for higher-frequency events over the lifecycle to justify construction of another structural measure. The requirement to maximize net benefits can generate smaller scale recommendations when larger scales may be effective but are not the NED plan. This has been criticized as biased toward higher property value areas that produce higher value damages avoided, since areas with lower depreciated replacement costs are difficult to justify a project because the benefits don't add up quickly

Public comments also suggest that the justification of structural solutions is the result of inequitable valuation of impacts. The process to identify and screen plans often emphasizes function, and the consideration of greener solutions is not evident in many documents, or the consideration of the environment is limited to assessing and mitigating for environmental impacts. The perception remains that the common criteria favor selection of structural solutions despite their potential environmental impacts or over more nature-based approaches and the tradeoffs are not considered equally.

10.4. Screening Tradeoffs

A full array of FRM measures includes structural, non-structural, and programmatic/regulatory actions. They vary in their applicability, performance, design and environmental considerations, and their long-term resilience.

Feasibility studies evaluate potential FRM solutions by comparing tradeoffs and selecting the cost-effective solution that achieves the study goals and project performance against specific criteria. These tradeoffs require thorough evaluation of the performance of the plan, its cost, potential impacts, and specific needs and attributes of each alternative. Many of the criteria that are assessed will be reflected in the cost estimate, such as real estate needs or operations and maintenance, but many tradeoffs will require comparisons of dissimilar impacts that aren't directly comparable. This comparison is complicated by the complexity of the comparisons, since most features would perform differently against the criteria at different times, under different conditions, and address different risks.

Traditional structural measures that include concrete and hardened structures are often described as gray infrastructure. Gray infrastructure strategies can be applied on a large scale but often lack robustness in terms of sustainability in their delivery due to unbalanced social, economic and environmental performance (DC Water, 2015; American Rivers et al, 2012). LID and GI solutions provide more holistic social and environmental benefits. However, some LID and GI strategies provide challenges in already urbanized areas or provide smaller levels of service than traditional measures depending on their level of implementation. Implementing hybrid solutions that combine master planning in less developed watersheds, green retrofits in highly developed watersheds and complementing those measures with gray infrastructure solutions where necessary may mitigate some of the shortcomings of both FRM approaches. The built components of FRM include traditional measures such as detention, flood walls, levees and channel improvements as well as natural and nature-based features, green infrastructure (GI) and low impact development (LID) alternatives. Non-structural measures focus on changes in land management, building acquisition and relocation, regulatory changes and enhanced flood warning systems.

Formulating an appropriate FRM strategy requires an understanding of the many factors that contribute to the level of risk exposure from flood hazards. This includes factors such as rainfall severity and frequency; topography of the surrounding landscape; downstream water levels; soil, vegetation, and groundwater characteristics as well as the size, shape and nature of existing water bodies. Comparison and selection of measures requires evaluation of multiple characteristics of measures, and the resulting tradeoffs, which do not easily define "best." Each section below includes a visual to demonstrate how the relative position of each measure falls along a gradient to convey how different measures achieve the characteristic. The ordering can be different under different scenarios, such as extreme events or nuisance events or densely developed areas or rural areas.

10.4.1. PERFORMANCE

Project performance is the risk reduction achieved by the alternative, and it is measured differently across agencies. USACE typically measures performance by estimating potential damages avoided in dollars through a specified process. Engineering models estimate water surface elevations in the "with" and "without" project condition, and economic models estimate the reduced damages that result from the lower water surface elevations with the measure in place. Life Safety impacts can be estimated with models that translate changed water surface conditions into potential life risk. Flood risk and life safety risk vary across multiple conditions within a study area. They are captured in the engineering models through statistical flood risk over potential storm conditions informed by historic rainfall data including volumes and duration, and site conditions.

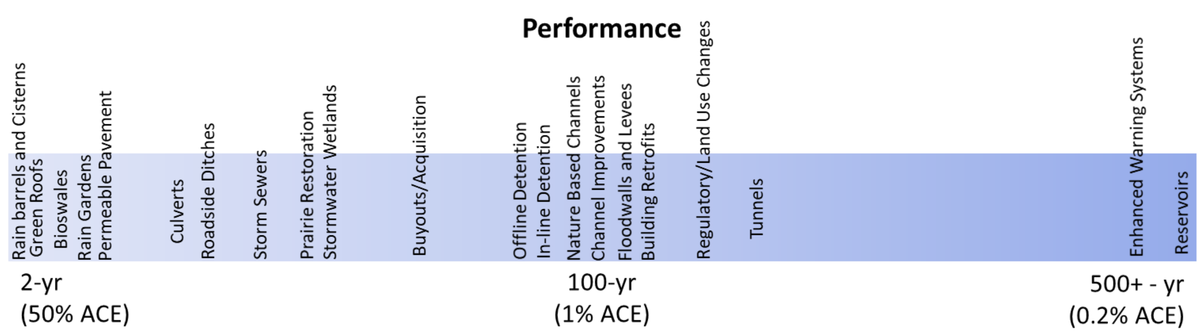
HCFCD assesses performance of proposed measures as a function of population or structures served by the measure.

The performance of a measure has several considerations. The engineering performance is generally the overall level of risk reduction provided by the measure or combination of measures. The scale of implementation is important in that a small-scale feature likely has a lower level of effectiveness than a larger feature. This isn't to say there is no role for small scale features, only that their maximum effectiveness is often restricted to higher frequency events. For lower frequency events, the design of a small feature will be exceeded and a contribution to the overall performance reduced. In this way multiple scales of features can be layered to complement each other.

The long-term performance and reliability of a feature is predicated on proper operations and maintenance. These vary depending on the type of feature and are often captured in terms of lifecycle cost since more intensive operations and maintenance would be more costly.

There is also a temporal aspect to performance that can be dependent on the type of feature implemented. The engineering performance is typically fully realized at the conclusion of construction. That level of performance can be degraded over time because of both chronic stressors, e.g., climate change effects, or acute shocks, e.g., damage during a large rainfall event. Performance of a feature can be restored following acute shocks by construction efforts. Decline in performance from chronic stressors can be addressed through adaptability features, e.g., raising a levee, or adding features to the larger system, e.g., adding a new detention pond.

Contrary to the engineering performance of a feature which is typically realized immediately at the conclusion of construction, performance of environmental features often takes time. The full performance of habitat included in a project takes time to establish. The type of habitat selected also impacts the expected time to realize the full benefits.



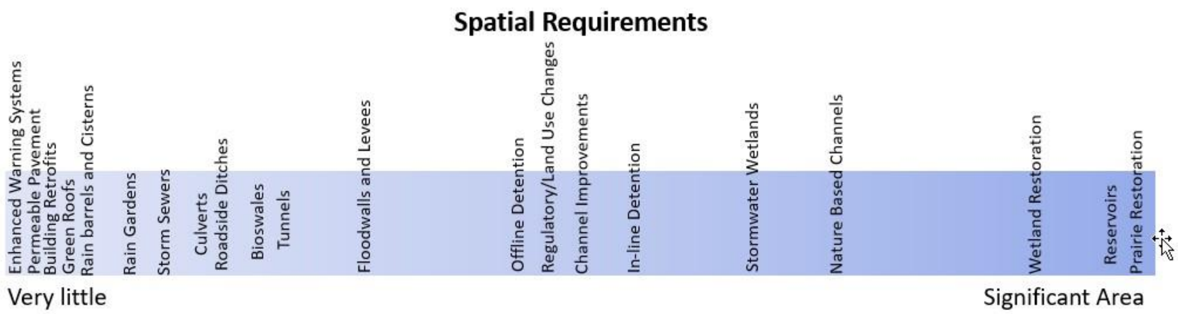
10.4.2. SPATIAL CONSTRAINTS

The space required for a structural measure can be a significant constraint. Limited available space may mean fewer alternatives can be constructed to reduce risk. The overall area requirements for an alternative can add real estate cost, and displace existing uses, either replacing habitat or requiring buyouts or easements.

Some alternatives may perform similarly but have different spatial needs. Reservoirs require more space than an underground tunnel but both can provide significant risk reduction. A natural or nature-based feature often requires considerably more space than some structural solutions like channel improvements to meet the same level of performance

Some structures may require specific site characteristics, such as soil types or gradients, to be effective while others may work in any conditions.

Lastly, some densely developed areas that are vulnerable to flooding have limited undeveloped space to accommodate risk reduction measures or adaptation to existing measures. Measure selection requires consideration of performance versus spatial needs that may require displacement of existing uses. Property acquisition can affect implementation of the measure through bureaucratic delay or legal challenge, and impact the community when homes, businesses, or habitat are removed to accommodate the FRM infrastructure.



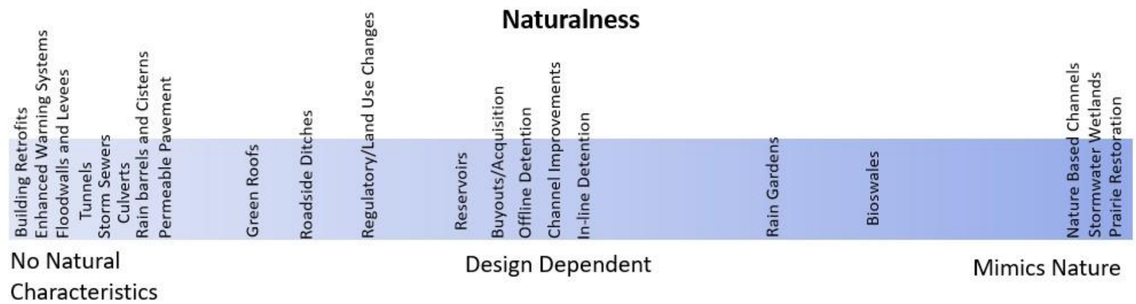
10.4.3. NATURALNESS

Traditional FRM infrastructure has increased conveyance in channels and bayous by replacing natural habitat with “gray” features. The loss of natural stream features has been considered an acceptable tradeoff for faster drainage or conveyance where the primary criteria is dollar damages reduced to structures and contents.

Public comments often express support for natural conditions and propose engineering with nature (EWN) or natural and nature-based features (NNBFs) over gray approaches. NNBFs can achieve detention to provide risk reduction, while sustaining habitat that provides additional benefits, and avoids environmental impacts.

Natural stream restoration has been shown to be effective but can be more easily implemented in areas where space is available, risk is less extreme, and conditions are stable enough to sustain natural form when high flows transit the region. It’s also more successful to preserve natural conditions than to recreate natural conditions once an area has been disturbed.

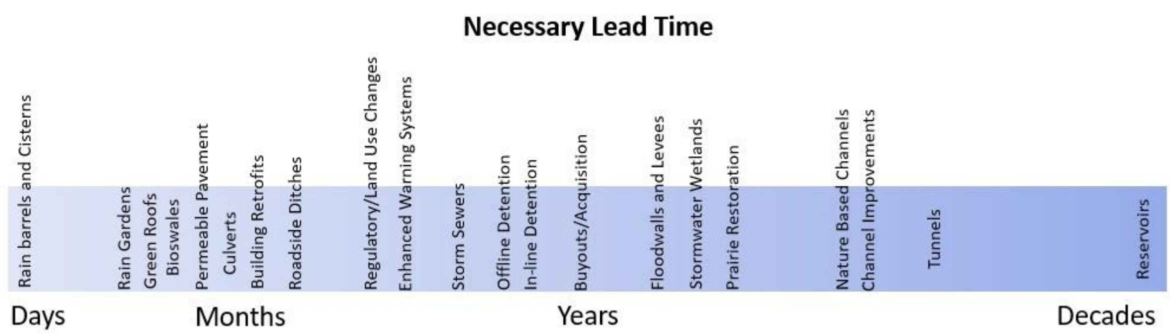
Innovation can bring cost and life safety risk compared to demonstrated measures that have been proven to perform in earlier applications.



10.4.4. NECESSARY LEAD TIME

Several measures vary in the timeline to implementation. Lead time impacts both cost and benefits. Longer lead time means that flood vulnerable communities wait longer for risk reduction and study costs increase. Elements that influence lead time include data collection, design, permit and regulatory requirements, environmental compliance, real estate acquisition, and construction duration. Traditional measures may be designed for specific site conditions and face typical environmental compliance issues that allow swifter implementation and risk reduction at an earlier time frame. However, even traditional measures may take longer to implement if funding is inconsistent or delayed.

Innovative measures may require additional study, longer permitting and compliance processes, and additional precautions that add to cost and performance risk. Agencies and companies can be hesitant to spend money to construct a feature that introduces additional risk over time and require repair or adaptation cost.



11. IMPACTS OF FLOODING

The current level of investment across federal, state and local agencies is evidence of the commitment to reduce impacts created by flood events. Flood risk is the combination of likelihood and consequences. Earlier chapters described the sources of flood risk in the study area. The characterization of likelihood has translated years of record into flood mapping. Flood events vary from frequent, low impact events to less frequent, but extreme events. Accordingly, the consequences of flooding range from nuisance impacts to life threatening, including economic losses and environmental impacts across the region. Risk exists when flooding occurs without a solution in place, and residual risk includes the consequence of flooding when the design measure is exceeded, and flood impacts occur because the event is extreme, and the structural solution was not scaled to address a statistically improbably event.

11.1. LIFE RISK

Flood events create life safety risk through multiple routes. Fluvial flooding risk is relatively well characterized through floodplain mapping. Residents and workers can be made aware of flooding potential in areas where they live, work or transit between different locations. Life loss from inundation in structures is rare but possible in extreme flood events. Small amounts of flowing water can sweep people off their feet, which can make small flood events dangerous. Floodwaters can bring risk from electrical currents and impede emergency services in the case of a medical emergency. Cleanup and repair of flood impacted properties create the potential for injuries or exposure to chemicals and dust, and flood damaged properties may lead to mold exposure. Overall health can be impacted from the stress during and after flood events.

Flooding also brings contamination and disease. Floodwaters can carry raw sewage, leaked toxic chemicals, and runoff. They can pollute drinking water supplies and cause eye, ear, skin, and gastrointestinal infections. When floodwaters recede, bacteria and mold may remain, increasing rates of respiratory illnesses, such as asthma. Flooding may also contribute to mental health problems as a result of stress and displacement.

11.2. ECONOMIC DISRUPTION

Economic impacts result from all scales of flood events. Low level events can limit access to the business, so workers can't arrive or products can't be shipped in or out for a period of time. Larger flood events can send water into structures, which damages both the structure and contents within, including inventory and machinery and utilities. Production is interrupted, businesses lose revenue, workers may lose income, and in Houston specific industries, national impacts may be felt when resources such as fuel or petrochemical production is halted even temporarily.

11.3. HOUSEHOLD LOSSES

Household impacts range from social to economic disruptions across the range of likely of flood events. Transportation delays can be expected from poor drainage or low roadways, and access to work, school or events create losses or inconvenience. Traditional benefit estimates for Corps studies recognize the structure and content losses in NED benefits, but the loss to property value, and the opportunity cost of replacement and repair can drain household income and is not captured in the dollar denominated benefits. Flood prone properties have lower market value and appreciate less over time than less flood prone homes. Since home equity is a large percentage of household wealth, homes that lose value due to flooding reduce economic wellbeing across a community.

11.4. COMMUNITY IMPACTS

Community impacts overlap with many of the impacts described in earlier subsections. Although floods can affect anyone in their path regardless of wealth or ethnicity, it is most often lower-income people, the elderly, and minority communities who suffer the greatest impacts. These populations are least likely to have flood insurance, access to transportation during an evacuation, cash on hand, or the ability to relocate. Communities that experience frequent flooding have properties that appreciate less and suffer neglect or lower commercial investment as a result. Damages may threaten community resources, such as cultural sites, critical facilities and employment opportunities. Property acquisition, or “buyout” programs, may be proposed to address repetitive flood risk, but can alter the community characteristics. Because buyout programs are generally recommended for lower value properties, the negative social impacts of community fragmentation on historically marginalized communities can be compounded. Economic impacts to less wealthy households can also be compounded by buyouts when the compensation offered by the government is not enough to purchase a home in an area with lower flood risk, and when relocation takes people further from their jobs and other critical resources, such as health care and transportation. A 2018 study by Rice University and the University of Pittsburgh found that whites accumulate more wealth after a natural disaster from insurance payouts and other aid while residents of color accumulate less or lose money. Damage caused by natural disasters, and recovery efforts launched in their aftermaths were found to increase the racial wealth gap in Harris County by an average of $87,000 between 1999 and 2013.

Historic properties and landscapes, which are a fundamental component of our cultural heritage, can be irrevocably damaged and destroyed by flooding. Archaeological sites, which can help us learn from over 11,000 years of human behavior and climate resilience in the region, can be swept away in a single flood event. Because cultural resources representing the Latino, African American, Asian American, Native American, LGBTQ and other historic communities of the study area are underrepresented on the National Register of Historic Places and are often overlooked in FRM planning, these resources remain more vulnerable to adverse effects from flooding. Appendix C: Cultural Resources Considerations in FRM provide a more detailed review of the potential risk to cultural resources from both flood events and implementation of FRM measures.

11.5. ENVIRONMENTAL IMPACTS

Flood risk is the result of likelihood of an event and the consequences of that event. Flooding can be considered a natural occurrence, and wetland habitats are the areas that are sustained by seasonal overflow of water that submerges land and saturates soil. In some habitats it can stress plants, leading to oxygen and energy deprivation, and impede proper root respiration. Nevertheless, some important plants such as deepwater rice are adapted to cyclical flood. (https://www.nature.com/subjects/flooding)

Within a developed area, floodwaters carry pollutants across communities and habitats. Industrial facilities are vulnerable to damage that releases chemicals or raw materials into waterways. Demolition and reconstruction of damaged properties use resources, as debris is transported and disposed in landfills and materials are transported for rebuilding.

11.6. IMPACTS OF FRM AS USUAL

FRM is typically implemented by government agencies through specific evaluation and justification processes intended to ensure cost effective investments are made. Funding for

FRM projects is provided in agency budgets that also fund other governmental functions, such as transportation infrastructure, public safety, and community and economic development. Consequently, FRM progress is often made in annual increments of study and construction, to build or maintain FRM infrastructure.

The largest allocation of funds for FRM is usually committed post-disaster, when the consequences of flooding are made obvious, when large expanses of destruction are documented and priorities are reevaluated. The post disaster recovery phase presents an opportunity to rethink solutions in a changed landscape, but recovery often means communities restore their structures and businesses as longer phase studies begin or continue.

Proactive FRM planning is often undertaken by individual agencies to apply a broad focus to assess innovative technologies to refine the applicability or public acceptance or reduce cost or achieve co-benefits. Two frequent funding sources for these efforts are FEMA hazard mitigation grants and CDBG Mitigation Program. These federal funding sources are intended to encourage risk reduction and resiliency to reduce the impacts and expense of extreme events, but many agencies are fully engaged in day to day management and may not have the tools or time to develop grant proposals and take advantage of these programs.

Coastal storm risk management (CSRM) has increasingly adapted analysis and recommendations to incorporate the potential impact of relative sea level change (RSLC). Most practitioners agree that data and analysis has confirmed that RSLC is real, although the specific timing remains uncertain. As a result, CSRM projects can adapt CSRM measures to be resilient under different rates of sea level change, or adaptable in response to different rates of sea level change.

Incorporation of climate change impacts in FRM planning is not as straightforward as RSLC impacts are for CSRM. There is no clear consensus on the rainfall data to consider climate change impacts. Without coordination, FRM efforts may vary widely in their consideration of climate change adaptations.

12. FEDERAL INVESTMENT

The federal government constructs FRM infrastructure, offers flood insurance, and provides disaster aid. USACE is considered the primary agency with the technical capability to engineer large scale FRM solutions, and FEMA the primary agency to support disaster preparedness and response. Current federal programs and flood control projects generally target on reducing property damage and vulnerability to a 100-year flood. The General Land Office FRM initiative underway in Texas is funded by a combination of CDBG and FEMA-MIT funds.

FEMA's hazard mitigation assistance provides funding for eligible mitigation measures that reduce disaster losses. The funds are targeted to:

- Reduce vulnerability of communities to disasters and their effects.
- Promote individual and community safety and their ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies (resilience).
- Promote community vitality after a disaster.

- Lessen response and recovery resource requirements after a disaster.
- Create safer communities that are less reliant on external financial assistance.

The CDBG provides annual grants on a formula basis to states, cities, and counties to develop viable urban communities by providing decent housing and a suitable living environment, and by expanding economic opportunities, principally for low- and moderate-income persons. The CDBG-MIT Program is a unique and significant opportunity for eligible grantees to use this assistance in areas impacted by recent disasters to carry out strategic and high-impact activities to mitigate disaster risks and reduce future losses. Congress appropriated $12 billion in CDBG funds in February 2018 specifically for mitigation activities for qualifying disasters in 2015, 2016, and 2017, and HUD was able to allocate an additional $3.9 billion, bringing the amount available for mitigation to nearly $16 billion. The program defines mitigation as activities that increase resilience to disasters and reduce or eliminate the long-term risk of loss of life, injury, damage to and loss of property, and suffering and hardship by lessening the impact of future disasters.

Flood consequences extend into many areas that the federal government considers a priority function beyond the roles of USACE and FEMA. Economic impacts result from short disruptions to long downturns in regional productivity, risk of injury or death to citizens and first responders, and income and housing insecurity. Proactive policies to reduce flood consequences are consistent with the missions of the Departments of Commerce, Transportation, Health and Human Services, Housing and Urban Development and Energy. Federal investment is already funding programs to address consequences of flooding, and a broader, coordinated view of the impacts of flooding can more effectively direct federal investment to solve technical problems. Since infrastructure development by state and local governments is guided by federal policies, federal investment can encourage proactive investments across the whole range of government functions.

13. MISSED OPPORTUNITIES

The Assessment provides an opportunity to align agency efforts and more efficiently fund and implement projects that reduce current and future risks and conditions and maximize regional benefits and minimize adverse impacts in the watershed. Several missed opportunities may be addressed through improved agency communication and collaboration. They include:

- Identifying and addressing primary obstacles for improving availability, eligibility, efficiency, and timeliness of funding FRM efforts in the watershed.
- Achieving regional consensus around key policy and regulatory issues and reconciling inconsistent regulatory interpretation and application to develop without increasing population at risk
- Maximizing funding efficiencies through regional planning efforts to limit duplication of studies; and to advance knowledge and best practice sharing
- preserving and restoring natural areas with regional benefits for reducing flood risk.
- Leveraging the advanced hydrological modeling, data and research capabilities of regional academic institutions studying flood risks, for regional benefit.

14. RECOMMENDATIONS

Many reports have proposed specific actions in response to intense storms that produced flood events in recent years. Recommendations were assembled from these recent agency publications and developed from USACE perspective of risk priorities and complementary missions. The potential actions to improve the cost-effective application of FRM within the region range from small, specific technical approaches, to broad efforts that align activities, create funding sources, and revisit existing authorities and missions.

The unprecedented program of FRM efforts across agencies efforts created a unique challenge for preparation of this Assessment, as it limited the agencies' contributions to the recommendations. An effort was made to reflect public and stakeholder feedback on past FRM proposals from USACE and others. During the study initiation, the following federally recognized tribes, state, and federal agencies were contacted to determine their interest in the study: the Comanche Nation of Oklahoma, the Alabama-Coushatta Tribe of Texas, the Coushatta Tribe of Louisiana, the Tonkawa Tribe of Oklahoma, the Kickapoo Traditional Tribe of Texas, the Kiowa Tribe of Oklahoma, the Mescalero Apache Tribe, the Texas State Historic Preservation Officer, Texas General Land Office, Texas Water Development Board, Texas Parks and Wildlife Division, U.S. Department of Agriculture, National Park Service, National Marine Fisheries Service, U.S. Fish & Wildlife Service, Federal Emergency Management Agency, U.S. Environmental Protection Agency, U.S. Coast Guard, and the Texas Commission on Environmental Quality. The publication and comment period may provide greater opportunity to incorporate more specific agency and stakeholder feedback, and recommendations may be adapted to reflect that input.

The MAAPnext initiative is especially significant to the Assessment focus since the updated modeling capabilities will provide thorough regional flood vulnerability mapping after the Assessment is completed.

As a result, this Assessment recommends coordinating actions and several future studies to interpret the new data to maximize the effectiveness of future FRM efforts. Many recommendations highlight the Metro Houston challenge of residual risk, where extreme flood events may exceed the design performance of functioning structural solutions in the region. Potential adaptations to USACE justification thresholds were proposed to clarify the limitations of USACE process to address those residual risks, to demonstrate that the USACE process is not well suited to address the remaining flood vulnerability without layered, collaborative efforts.

A fundamental recommendation proposes creation of a regional coordinating body to review data gaps and set priorities, and participants should coordinate actions to align efforts at current and future phases and assess how to leverage necessary funding. Constraints should be identified and addressed, so that future actions can achieve FRM goals without unnecessary expense or disruption. This recommendation echoes a strategy that was proposed by the GHFMC in 2018, which would support joint priority setting and information and data sharing efficiencies.

An engagement will be hosted following publication of this draft assessment to assess the best format for Metro Houston Regional Coordination format, and an appendix to the final report will summarize agency feedback on regional coordination approaches.

A related recommendation is that this Assessment should not be a one-time effort. The program of regional FRM efforts should be reassessed on a regular interval to update priorities, reflect successes and missteps, and to coordinate regional efforts. This commitment to revisit the watershed conditions and status is recommended to expand the focus to the joint development of a resilience framework, that considers preparation, recovery and adaptation after flood events. The CoH Resilience Strategy is an example of a proactive effort identify and address stressors in the region and to influence the future with project conditions for FRM implementation. This recommendation aligns with a strategy proposed by the GHFMC in 2018, which to review flood risk solutions through a resiliency lens, to engage broader agency awareness and participation to identify flood stressors and shocks and address them and include all agencies with infrastructure authorities, such as railroads, highways, and utilities.

Several recommendations address the risk characterization applications of the MAAPnext updates, and related products under development for HCFCD. Pluvial flooding is underrepresented in mapping and Corps studies, and any comprehensive risk reduction effort should be transparent about the residual risks. Application of the new mapping is recommended to assess the potential to adapt Corps processes to identify and address pluvial flooding and residual risk where structural solutions are proposed or have been built. The GHFMC document also proposed several strategies in 2018, to increase awareness of the flood hazard and more informative flood mapping. The MAAPnext program is addressing one component of this strategy, and application of the modeling and data updates will allow more detailed risk characterization across the region.

Priority recommendations were identified to support cost effective coordination among the ongoing FRM efforts and avoid duplication of efforts or wasteful spending. Recommendations considered which actions would be best informed by the updated modeling, and which could guide strategic actions now. Tables 1 through 4 present the individual recommendations collected during the assessment process, presented in four applicable scales, household, neighborhood, bayou, and region.

The following paragraphs describe the broader recommendations that address the opportunities that were identified for priority action. The broad categories of Primary Recommendations include regional coordination, risk communication, equitable distribution, and greater reliance on green features.

a. Regional Coordination should be formalized to capture technical efficiencies through model review and data sharing, to identify and leverage funding sources for prioritize efforts, priorities, and strategically implement FRM.

    - An initial workshop can convene agencies and stakeholders to review and update the Assessment, refine summaries and review draft recommendations,
    - Sample regional coordination formats from other regions should be compared to clarify agency expectations and preferences to scope candidate formats for a Metro Houston Regional Coordinating body.
    - Participation in the TWDB State Flood Plan or TxGLO FRM program should be considered to further assess regional FRM needs and opportunities as proposals are scoped and evaluated.

- The San Jacinto Regional Watershed Master Drainage Plan and HCFCD's Bond Program should be considered for their relevance as recent collaborations of local FRM entities on numerous projects.

b. Risk Communication should be undertaken to clarify the scale of the problem to public and affected parties. These efforts will inform residents and businesses of actions that can reduce risk for them individually and for their community or region more broadly.

   The USACE Galveston District can support these actions by maintaining dynamic and informative content on the District "Hub". The web access typically used for accessing draft and final USACE studies and products can apply storymap technology to:

   - Apply "storymap" technology to increase access to summaries of report findings.
   - Encourage greater public engagement on general FRM themes to increase flood risk awareness and agency policy limitations through Dynamic and frequently updated content.
   - Develop awareness of impact and risk reduction tradeoffs to influence public support for proposed projects.
   - Include drainage in risk characterization summaries, in feasibility studies or hazard maps.

c. Explore means to implement cost-prohibitive but technically effective measures in areas where residual risk remains after older solutions were implemented and scaled for lower WSE, outdated precipitation data, and older land cover development data and climatological probabilities. Potential solutions could consider:

   - Create special threshold for federal participation where regions meet specific criteria for a cost prohibitive betterment.
   - More fully develop components of the four accounts to include OSE, RED, and NED to supplement the NED benefits, by exploring quantification of opportunity cost for regional resources, generational wealth accumulation and property values, or cultural resources.
   - Evaluate scales of acquisition projects for high damage areas for implementation post storm, to capture willing participants. Delays in funding and implementation can reduce participation if post storm repairs have been undertaken before project roll out. The areas of repetitive damage identified by FEMA and HCFCD should be assessed for application in increments post disaster.

d. Implement or incentivize layered FRM features, including "green" or EWN actions, pervious surfaces, and micro scale actions that might achieve a level of risk reduction when implemented in large numbers. These would:

   - Demonstrate feasibility of multiple benefits from complementary efforts and encourage innovation
   - Reduce risk to downstream communities and broaden awareness of shared responsibility

e. Revisit mitigation approaches for wetland impacts, explore mitigation bank creation and preserve coastal prairie and pervious land cover.

- Undertake an innovative Ecosystem Restoration Feasibility Study of mitigation bank creation within the existing Addicks and Barker reservoirs could assess habitat benefits, beneficial reservoir land cover changes, and reduced cost of FRM efforts within the region through lower cost mitigation.
- Arrange for USACE assistance in development of planning tools and guidance with wetland preservation and stream assessments.

⌂ Household Scale Recommendations		
FRM Investment Distribution	**Risk Communication**	**Drainage**
• Participate in layered detention or risk reduction • Harvest rainwater through rain barrels or cisterns to layer detention, aggregated small scale detention can reduce risk downstream • Floodproof existing homes and properties • Build structures that exceed regulations/requirements as proactive risk reduction/resilience • Use LID/GI strategies such as rain gardens, vegetated swales, green roofs and permeable pavements to reduce sheetflow • Purchase flood insurance in areas outside 100-year floodplain, since risk mapping is imperfect and flooding occurs away from the bayou.	• Assess flood risk at floodfactor.org. Their methodology provides a reasonable first order approximation of risk. • Develop maps/story maps that overlay flood risk/vulnerability with other factors such as existing public infrastructure and buildings (schools, hospitals, etc.), demographic information (population with variables, income/poverty, housing)	• Maintain cleared gutters to ensure proper drainage away from property. • Maintain proper coatings and sealants to prevents rain from entering homes in situations not associated with flooding. • Prioritize maintaining perviousness of property through structural and non-structural measures.

⌂⌂ Neighborhood Scale Recommendations		
FRM Investment/EQUITY	**Risk Communication**	**Drainage**
• Use the BMP siting tool to conduct screening level analysis for stormwater BMPs	• Develop maps/story maps to overlay flood risk/vulnerability with other factors such as existing public	• Hold water where it falls before it enters the bayous (RH25.2). Characterize GSI strategies as site-

• Integrate recreational opportunities into FRM projects • Preserve or restore the natural hydrologic function of the sites (this may require buyouts in highly developed areas but could be incorporated into "master plans" of the lesser developed watersheds)	infrastructure and buildings (schools, hospitals, etc.), demographic information (population with variables, income/poverty, housing)	specific to identify most applicable strategies. • Identify regulatory, non-structural, or structural measures for portions of the metro area developed before regulations were in place. • Critically consider the role of local drainage in the overall flood risk. Flooding occurs away from bayous because of inadequate or poorly maintain drainage systems promote more detailed drainage studies with MAAPnext updates to better characterize the risk.

⌂⌂⌂ **Bayou Scale Recommendations**		
FRM Investment/EQUITY	**Risk Communication**	**Drainage**
• Preserve or restore natural hydrologic connectivity from the neighborhood scale to bayou scale.	• Include additional scenarios in H&H modeling that consider the backwater from a downstream confluence. This differs from modeling that looks at flooding from a particular bayou or tributary as the flooding directly affiliated with rainfall in that catchment. The normal depth boundary condition could underestimate the actual downstream water-surface elevation if the receiving stream's catchment is also flooding.	• Expand the detention capacity of bayou corridors (RH 25.3) through a combination of GSI type strategies. • Promote natural infiltration and treatment of stormwater by wetlands, prairies, and woodlands. (RH 26.3) • Leverage existing open space for additional, short term detention during rainfall events. {AccelerateH20)

⌂⌂⌂⌂ **Regional Scale Recommendations**		
FRM Investment/EQUITY	**Risk Communication**	**Drainage**
• Support grant funding applications of regional agencies through tech support and model sharing • Assess EJ community specific needs in disaster planning, response, and recovery (RH 20.5) for impact assessment and support	• Grow climate awareness through USACE methodology for considering climate change • Expand flood warning systems beyond Harris County, incorporate	• Adopt Atlas 14 region wide, show differences in flooding using new vs. old. • Apply the latest hydraulic modeling methodologies, such as 1D/2D capabilities where it will increase accuracy, particularly in broad and flat

• Incentivize and promote innovative "water-aware" development that expands local examples of how to live with water. (RH 30.3) • Create metrics that quantify social vulnerability as an alternative (or parallel) way to evaluate FRM projects outside of BCR. emphasizes incorporation of RED and OSE more robustly • Identify any constraints to strategic updates of FEMA maps on a more regular basis than the required update every 5 years or consider the flood risk "unknown," • Align TWBD efforts to map all of TX, with FEMA models and subsequently the flood maps. • Support regional land conservation and discourage development in sensitive upstream areas (RH 51.2)	better spatial resolution technology. • Leverage probabilistic flood mapping to emphasize that flooding is inherently probabilistic. Include an envelope of inundation associated with the 1% ACE (or other frequency) event). • Develop success metrics and/or annual reports to quantify the benefits of implemented FRM projects to demonstrate that, while the flooding problems cannot be entirely eliminated, implemented projects are effective in reducing risk.	floodplains, locations of more complex flow) • Increase water storage ambition over time to adapt as the climate changes. (RH 25.5) Assess or create IDF curves for future conditions to address climate change and detention capacity. • Assess whether flooding outside the floodplain is due to undersized storm sewers and inadequate FFE elevations. • Prioritize and invest in resilient infrastructure. (RH 58.3) • Adopt multiple layers of defense through layered applications to address inland flooding. Flood risk exceeds one single scale of engineering response to reduce flooding impacts. • Incorporate recommendations from the San Jacinto Regional Watershed Master Drainage Plan.

15. CONCLUSION

This Assessment confirmed that the Metro Houston Region is vulnerable to flooding from multiple sources, and that Federal, state and local agencies are fully engaged in FRM measures within their missions and authorities. The combination of the region's flood vulnerability, the continued growth in the region, and climate change considerations will require coordinated efforts across all levels of government, local, state, federal, USACE, ASA/CW and Congress is required to reduce risk in the region. Regional coordination efforts, coupled with clear and consistent risk communication can identify and address incremental actions to achieve risk reduction through specific actions in the near term, and scoping proactive, phased implementation of resilience policies to guide future decisions by multiple agencies.