GREATER HOUSTON FLOOD MITIGATION CONSORTIUM

GREATER HOUSTON

STRATEGIES FOR FLOOD MITIGATION

Edition 1
Updated April 09, 2018

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GREATER HOUSTON
FLOOD MITIGATION CONSORTIUM

Through the Greater Houston Flood Mitigation Consortium, leading researchers from institutions across Texas have come together to compile, analyze and share a rich array of scientifically-informed data about flooding risk and mitigation opportunities.

We want to protect and sustain our residents, particularly those most vulnerable, as well as our environment and our economy. We believe it is critical for our public officials to have access to the best possible information available to inform their deliberations. Similarly, we think our residents also deserve access to the best information that will help them better understand and advocate for the options that work best for their families and communities.

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Rice University
Kinder Institute for Urban Research

Rice University
SSPEED Center

Texas A&M University
College of Architecture

Texas A&M University-Corpus Christi
Harte Research Institute for Gulf of Mexico Studies

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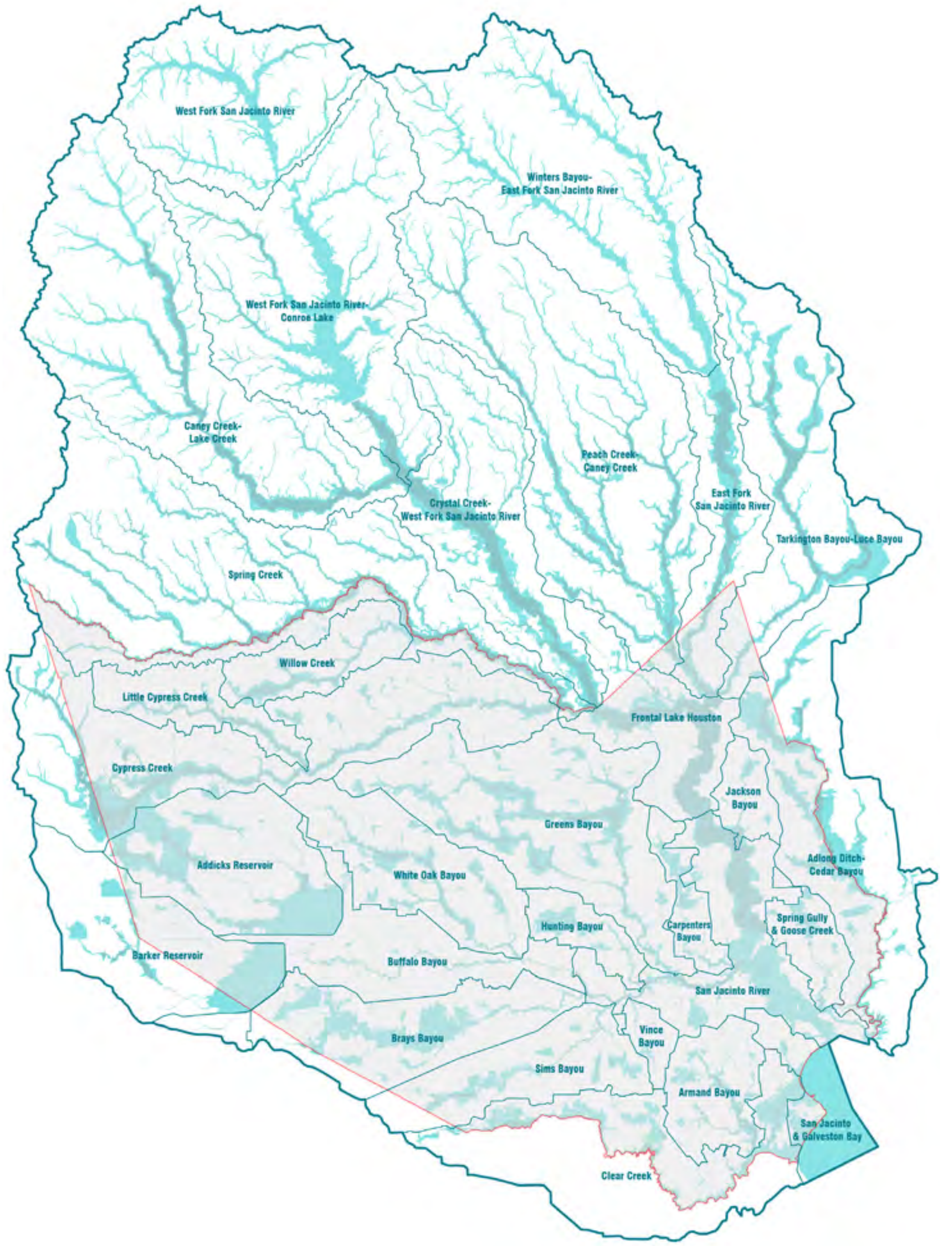
SCOPE OF STUDY AREA



GLOSSARY

ACRONYMS

CDBG-DR	Community Development Block Grant - Disaster Recovery
CRS	Community Rating System
ETJ	Extraterritorial Jurisdiction
FEMA	Federal Emergency Management Agency
FMA	Flood Mitigation Assistance
HCFCD	Harris County Flood Control District
HMGP	Hazard Mitigation Grant Program
HUD	Housing and Urban Development
LID	Low-Impact Development
MUD	Municipal Utility District
NFIP	National Flood Insurance Program
SHFA	Special Flood Hazard Area
TxDOT	Texas Department of Transportation
USACE	U.S. Army Corps of Engineers

DEFINITIONS

1 percent chance flood (100-year)	A flood event that has a 1 percent chance of occurring each year.
0.2 percent chance flood (500-year)	A flood event that has a 0.2 percent chance of occurring each year.
Base Flood Elevation	The depth of a flood during a given chance flood event.

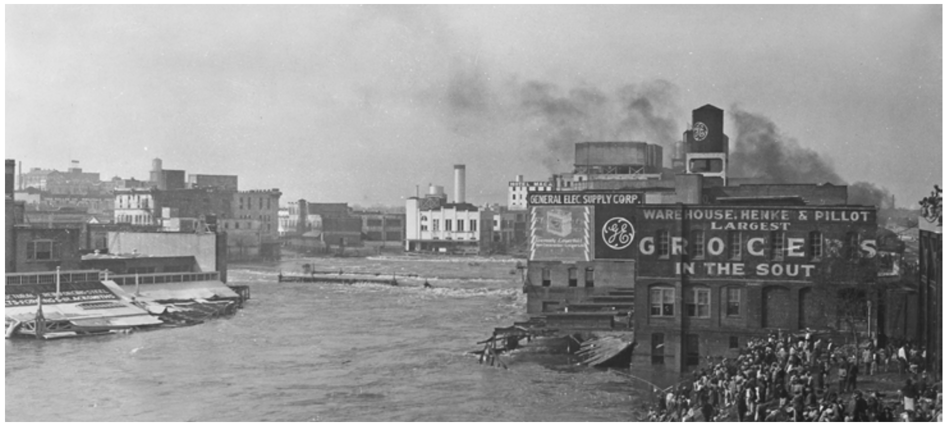


Figure 1.1 Downtown Buffalo Bayou During 1935 Flood

1 INTRODUCTION

About the Consortium

Hurricane Harvey dealt our region a devastating blow and laid bare the greater Houston region's vulnerabilities. It is time for bold action to protect our residents, economy and the region's vitality from the consequences of future flooding.

The Greater Houston Flood Mitigation Consortium was started to advance greater Houston's resiliency and to ensure that all communities benefit from flood mitigation efforts. This independent collaborative of expert researchers and community advocates is committed to compiling, analyzing and sharing a rich array of data about flooding risk and mitigation opportunities; and translating this data into information to engage the public and help guide and support decision-makers at all levels as they direct the Houston region's redevelopment. Consortium members are affiliated with local, regional and statewide universities, research centers and community organizations with deep expertise in hydrology, climate science, engineering, coastal resiliency, energy, community development and urban planning. Houston-based Huitt-Zollars, a planning, engineering and architectural firm, manages the consortium.

The consortium is focusing its work on Harris County's 22 watersheds, several of which extend into surrounding counties. The consortium began in fall 2017 with the intention of completing its work by mid-2018.

The consortium's explicit focus is on the subject of rainfall flooding, not storm surge. Storm surge is a significant hazard for the Houston region and consortium members recognize that a coastal barrier to protect against storm surge is essential. However, storm surge is excluded from the consortium's work product because this subject matter is already the focus of so much study.

Consortium members are collaborating on a broad range of research. This executive summary curates high-level information from this work. At the top of many pages, reference is made to more detailed work products with additional information, including papers, fact sheets, and briefing documents.

Edition 1 provides information relevant to the local, state and federal investments being discussed for flood mitigation projects in Harris County. Some work product on select topics is not yet available, and these sections remain in outline form. A second edition of this executive summary will include this information.

This report summarizes the strategies that are in the Houston area's toolbox and focuses on specific challenges and a variety of conclusions about how best to address both strategies and tactics. Consortium members believe the overall approach to mitigating flooding in a watershed should be focused at both the watershed and neighborhood level.

For More Information

Go to HoustonConsortium.com

New Era in Flood Mitigation

The damage caused by Hurricane Harvey provided overwhelming proof of Harris County's vulnerability to flooding. As greater Houston considers strategies and tactics for protecting residents from future storms, consortium members believe it is essential to acknowledge paradigm shifts that have occurred and to recognize that we are entering a new era in flood mitigation that will require bold thinking and actionable solutions.

For the century after Houston's founding in the 1830s, we had no choice but to accept flooding from heavy rainfall on the area's flat, coastal plain. We responded by building homes on piers and downtown buildings facing sidewalks high above the muddy streets. Disastrous floods in 1929 and 1935 led to the creation of the Harris County Flood Control District (HCFCD), which was charged with partnering with the U.S. Army Corps of Engineers (USACE) to adopt a regional response to flooding.

A half-century of structural solutions followed (such as the Addicks and Barker reservoirs), actions that at first seemed to tame the high waters. Stormwater runoff into the bayous increased dramatically, however, as farm fields and prairies were developed into subdivisions, malls and office parks throughout the 1960s, 1970s and 1980s. Flood infrastructure proved unable to keep up with growth. After a few decades, bayous that had been able to hold a 1 percent or "100-year" flooding event could barely handle a 10 percent, or "10-year" event.

After the 1970s, HCFCD and local decision-makers began applying a range of strategies beyond large dams and concrete channels. Local jurisdictions joined the Federal Emergency Management Agency (FEMA)-sponsored flood insurance program, adopted floodplain management and strengthened building and infrastructure regulations. The first Flood Insurance Rate Maps (FIRMs) for the region were added in the mid-1980s. In the early 1990s, the HCFCD, working with USACE, adopted new strategies that focused on preserving the natural and beneficial functions of floodplains and developing green infrastructure mitigation measures.

For example, the recently completed Sims Bayou project created a wide grass-lined channel and detention basins. Also, HCFCD began administering one of the nation's most extensive buyout programs to remove homes "hopelessly deep" in the floodplain. These measures have been effective; Sims performed well in Hurricane Harvey, and the buyouts removed many structures that would have flooded.

Our region, however, continues to be challenged by flooding, in large part due to the way that we have grown and continue to develop. Many of our communities were built before flood insurance and the advent of development regulations. Thus many homes are located deep in floodplains, in neighborhoods with inadequate neighborhood drainage systems or with floors low to the ground so that even shallow flooding results in damage. As a result, these areas are vulnerable to flooding from rising bayou waters as well as localized ponding (where water collects in low-lying areas) and sheet flow flooding (where water flows across the surface of the landscape). New development is generally more flood-resistant but can create new problems through increased runoff due to impervious surface and drainage systems that funnel water downstream quickly, if not adequately mitigated.

The ability to respond to flooding is limited by both funding and political will. HCFCD has focused much of its limited resources on addressing flooding in these older areas by adding needed capacity along nearby bayous. There is, however, a considerable backlog of identified but unfunded projects. The city of Houston adopted a funding strategy for drainage improvements through the Rebuild Houston program, but, at current funding levels, it will take decades to address every neighborhood. HCFCD, counties and cities have also adopted regulations that are intended to require that new upstream development not worsen downstream flooding by increasing impervious land and runoff, overloading the channels. The regulatory framework, though, is not uniform across watersheds, enforcement powers are limited, and there are instances when developers have found ways to work around the system.

Meanwhile, changing weather patterns have led to increasing rainfall amounts and frequencies. Current data indicates that the "100-year storm" (to which flood control infrastructure and development regulations have been calibrated) is now an underestimate.

Notes

Association of State Floodplain Managers. "Natural and Beneficial Floodplain Functions: Floodplain Management-More than Flood Loss Reduction," (2008).

While progress has been made, we are confident that new knowledge and improved technology can help drive a new era in flood mitigation, guided by the following principles:

- First, and most importantly, we recognize that we are all in this together. Our residents are our most valuable assets, and some of our most vulnerable populations live in the most flood-prone areas. It is crucial to equitably address the needs of all residents, value human impact over property values when weighing solutions and seek input on potential strategies from impacted communities across the region.
- We must determine the risk we as a community are willing to accept with the investments we are willing to fund. In doing so, we must recognize that there is no one silver bullet solution to flooding and no single policy or combination of strategies and tactics that will entirely prevent damages from future floods.
- Ensuring collaboration and coordination across jurisdictions is crucial to effective implementation of the flood mitigation strategies outlined in this report. Watersheds do not respect political boundaries thus it is essential to coordinate across city limits and county lines. Many agencies that are not explicitly tasked with addressing flooding—from housing authorities to school districts to public transportation providers—also make decisions that can mitigate or magnify the effects of flooding. It is critical to ensure that these entities are equipped to make informed decisions.
- Communicating about flood risks and providing transparency about decision-making processes is central to ensuring that the public can make informed decisions about personal safety and risk reduction.
- Balance structural and non-structural strategies. Flooding can be mitigated by building drainage infrastructure and green infrastructure, land use policies, restoration of natural systems, site-specific strategies, buyouts, relocation, floodproofing and elevation. It is likely that the best flood mitigation strategy in each watershed will be a combination of approaches.
- Balance strategies at different scales. Lot-by-lot site retrofits, street-by-street drainage upgrades and Low Impact Development measures can have a cumulative impact as significant as the impact of major projects.
- Preserve and restore the ecosystems in our watersheds that are resilient to heavy rains and maintain an extraordinary capacity to absorb and store floodwaters.
- Limit new development where necessary to mitigate downstream flooding and keep people and property out of harm's way.
- Ensure flood mitigation for various causes of flooding. Floods happen not just because of rising waters in our bayous but also because of inadequate neighborhood drainage systems and overland sheet flow.
- Work with the best available science to guide flood mitigation work, using a multidimensional risk-based approach rather than relying only on mapped floodplains to guide decisions.
- Learn from the experiences of other regions across the country and the world and apply innovative strategies and tactics that are relevant and in context to our specific needs and requirements.
- Recognize that flooding exacerbates other problems. Our region's gaps in health care, housing, access to food and transportation intensify when homes flood, cars are destroyed, businesses are disrupted and floodwaters carry pollution.

These principles have guided the work of the consortium and provided the basis for the findings in this document. We hope they serve a similar purpose for residents and decision-makers as we work together to chart the course for flood mitigation.

2 FULL RANGE OF SOLUTIONS

This document focuses on specific challenges and a variety of recommendations to address them, but first, this section summarizes the strategies that are in our region's toolbox. These strategies include structural and non-structural measures along with processes that can strengthen public support for these measures.

Historically, "flood control" focused on structural flood mitigation strategies that physically alter the flow of floods, such as reservoirs, channel improvements, drainage systems and detention ponds.

Non-structural flood mitigation refers to a wide range of measures, from policy actions to small-scale site modifications. Non-structural does not necessarily mean no construction; but rather than altering the flood, it minimizes susceptibility to flooding and financial losses by avoiding certain uses of the floodplain, making structures less susceptible to damage, and helping people prepare for and recover from floods. FEMA's "Multi-Hazard Identification and Risk Assessment," (1997) summarizes a range of non-structural flood mitigation measures:

Measures that Reduce Susceptibility to Floods	Measures that Reduce the Impact of Floods
Acquisition/buyout and demolition of structures	Public education and information access
Land swaps and relocation of structures	Updated flood maps
Elevation of structures in place	Flood emergency measures to reduce loss of life
Dry floodproofing (make structures watertight)	Flood insurance to reduce financial impacts
Wet floodproofing (allow water to flow through)	Disaster assistance to reduce financial impacts
Non-structural berms and secondary levees	Tax adjustments to reduce financial impacts
Floodplain regulations and building codes	Long-term recovery assistance
Zoning and land use	
Development policies	
Flood forecasting and warning systems	
Disaster preparedness and response plans	

Table 2.1 Non-structural Flood Mitigation Measures (adapted from FEMA)

A subset of the non-structural measures listed in Table 1 are site-specific measures that apply to individual structures, including elevating structures in place, floodproofing, installing small-scale non-structural berms that can deflect water away from a structure and acquiring or buying out property. A combination of criteria is used to determine which non-structural measures to employ in a given context. The depth of flooding, flow velocity, age and density of structures, and soil type are some examples of these criteria. Floodproofing and structural berms are generally applicable when expected flooding is shallow and slow. By elevating structures in place, even deeper, slow moving flood waters can be mitigated, (depending on the condition of the structure). Buyouts are appropriate in cases of deep and frequent flooding that cannot be resolved by structural solutions.

The benefits of flood mitigation have been found to outweigh the costs by a benefit-cost ratio of five to one based on a comprehensive analysis of 5,500 mitigation projects. Thus for every dollar invested in flood hazard mitigation, $5 in benefits accrue. Regarding benefits associated with non-structural flood mitigation measures only, an engineering analysis of 2,206 site-specific projects revealed an 85 percent reduction in expected annual damages. In other words, the use of non-structural measures significantly reduces a community's risk of flooding compared to the same community without non-structural mitigation. Non-structural mitigation solutions are an important component of a modern flood risk management strategy.

Notes

Adapted from Federal Emergency Management Agency. "Multi-Hazard Identification and Risk Assessment," (1997).

US Army Corps of Engineers National Non-Structural Committee. "Flood Damage Reduction Matrix." (2018), cdm16021.contentdm.oclc.org

Adam Rose, et al. "Benefit-Cost Analysis of FEMA Hazard Mitigation Grants," Natural Hazards Review 8:4, (2007).

Steve Cowdin, et al. "Evaluating Benefits of Non-Structural Measures in Flood Risk Management Feasibility Studies, (2015).

Robust Public Participation

Investing in healthy and meaningful public engagement around potential infrastructural projects and non-structural strategies can help to proactively prepare for future disasters in ways that ensure effective and equitable responses.

Public participation can be justified as an essential part of democracy, and a means for residents to have input on flood mitigation projects that are funded with their tax dollars and that will have broad impacts on their lives. However, public participation can also contribute to a project's efficacy and sustainability, as public support saves time, maintains political support, supports funding and fosters buy-in.

For example, invited experts from across the U.S. at the consortium's "Buyout Best Practices" event in February 2018 highlighted public participation as a step vital to proactive disaster response. Ongoing community planning and engagement positioned the public entities in their communities to do more thorough recovery and long-term planning work. Involving affected communities in the process led to greater buy-in and trust, which allowed for the cultivation of shared goals. In some communities across the U.S., this has increased the rates at which residents volunteered for buyouts. Longer engagement processes have also enabled the development and integration of additional funding sources and more diverse strategies in these communities. The engagement efforts also ensured that community support extended beyond buyouts to broader issues and flood mitigation efforts. The experts presented the following as critical elements to successful public engagement:

Education

Educating the public about proposed projects or approaches and the logic behind them is vital. Level setting conversations and the sharing of essential knowledge around projects is crucial to ensuring that public input provides meaningful feedback and helps support better choices.

Accessibility

Public involvement will reach more people if there are real opportunities for residents to learn and engage. It is important to offer a variety of formats, such as workshops, public meetings and online engagement, and offer multiple times and locations to engage to ensure that residents can attend (and that transportation challenges do not prevent participation). Ensuring that engagement efforts occur in sites that are physically accessible to people with disabilities and are carried out in multiple languages is also critical. Including community leaders and local community-based organizations early in the planning process will ensure that engagement strategies meet resident needs.

Accountability

The public engagement process is a space where officials can articulate the decision-making process for projects and plans. Such an effort can help residents understand where, when and how they can give feedback and to whom. It is important to ensure that any potential funding proposals to pay for flood mitigation include a clear strategy for allotting the funds and a description of the decision-makers. Likewise, to maximize transparency and public trust, it is critical that all funding processes be accompanied by a reporting structure that includes information on spending, project status, objectives and outcomes.

As a case study, New York State's Rising Community Reconstruction Program was formed after Superstorm Sandy. The program used Housing and Urban Development Disaster Recovery funds to pay for more than 100 community plans and concrete actions to aid recovery. The plans were formulated by committees comprised of residents and key stakeholders and gave communities both a voice and funding to directly shape the projects that would benefit their community. The state committed to spending up to $3 million in each of the 124 communities that qualified for the program in order to plan and implement community-driven ideas for resilience.

In another case study, the Kinnickinnic River Corridor in Milwaukee was a 10-year management planning process focused increasing the capacity of the river to handle a densely populated area of the city. The district led a community engagement process over 10 months, also working closely with the Sixteenth Street Community Health Clinic as a trusted partner. The effort focused on mitigating flooding impacts, but working with the neighborhood plan allowed the district to include broader improvements that stretched beyond the river into the wider neighborhood

Notes

Buchecker, M., et al. "How Much Does Participatory Flood Management Contribute to Stakeholders Social Capacity Building? Empirical Findings Based on a Triangulation of Three Evaluation Approaches." Natural Hazards and Earth System Science, vol. 13, no. 6, (5, June 2013)

Godschalk, David R., et al. "Public Participation in Natural Hazard Mitigation Policy Formation: Challenges for Comprehensive Planning." Journal of Environmental Planning and Management, vol. 46, no. (5, Apr. 2003)

How Does FAS Work?

Data

Collected on live rainfall information using Radar rainfall (NEXRAD), flow and stage gauge data and water levels via cams.

Modeling

Used to predict flood extents, these data are overlaid with models and maps, such as, Hydrologic Engineering Center's HEC-HMS, HEC-RAS and floodplain mapping.

Prediction

Together, these produce, real-time rainfall, flow hydrographs and floodplain map library (FPML).

Communication

With established warning thresholds, warnings are sent out via, text, email, FAS website, digital roadside warnings, news and radio.

Flood Warning System

Flood Warning Systems (FWS) provide accurate information to allow individuals and decision-makers to make informed decisions about whether to take emergency action during a flood event. Some FWS simply offer real-time data on flood conditions, but others use real-time data to predict future flood conditions several hours in advance. A Flood Alert System (FAS) notifies individuals and decision-makers when pre-defined actions need to be taken. These alerts are targeted to specific locations and are pushed out, rather than requiring someone to visit a website. A FAS, driven by a predictive FWS, can give individuals notice of flooding in their specific neighborhood with enough time to evacuate or move possessions out of harm's way.

HCFCD has strategically placed 133 gauges to monitor rainfall and water levels in the bayous and their tributaries. This real-time information is available to the public online and is updated every 15 minutes. At this time, the system does not predict future water levels of the bayous; it shows what is flooded in real-time, rather than predicting what may flood.

Rice University's SSPEED Center has operated a FWS on Brays Bayou through the Texas Medical Center since 1997. It gathers data from rainfall radar, puts that data into computer models and generates continuously updated predictions of future flood levels. During Hurricane Harvey, this system accurately predicted the flood levels in Brays Bayou two to three hours before the bayou peaked. That information was sent to the managers of the hospitals within the Texas Medical Center (TMC), giving them the time they needed to implement emergency measures, such as closing submarine doors to the underground tunnel system and installing temporary flood barriers to keep floodwaters out of underground parking garage and hospital entrances. This technology helps TMC avert millions of dollars in flood damage annually. These same or similar systems could be implemented in every watershed in the region to help homeowners and businesses prepare for flooding.

In 1985, the city of Austin implemented ATXfloods (www.ATXfloods.com), a program in which residents can sign up for text message alerts on flooding that target specific neighborhoods and provide localized information. During Harvey, residents along Brays Bayou could see SSPEED's data and predictions on a website; but an alert system like ATXfloods would automatically send updates to residents. It would also be useful for warning upstream or downstream residents of releases and levels from reservoirs like Addicks and Barker and Lakes Houston and Conroe. A flood alert system is most effective when implemented throughout a region.

Additionally, it is possible to execute flood warnings for transportation infrastructure. Knowing which roads are open is a key challenge faced by residents, first responders, and emergency managers during a flood event. It is possible to collect crowdsourced data from past events and integrate it to rainfall and bayou levels in order to predict which roads will be open during any level of a flood event. Cameras and sensors, like those that already drive high water warning signals (which the City of Houston recently received additional funding for), could link to a flood alert system. Computer models could predict bayou levels and water levels on key streets. Thus real-time information on which major roads are or would be flooded could be delivered to residents and emergency personnel.

The combination of these two systems—a predictive FWS and targeted FAS—could be coupled with public engagement and education on what resources exist and where to find them. A flood warning system for the entire county could likely be put in place for $5-$10 million—less than the cost of a single detention basin.

For More Information

See Briefing Document 1: Flood Warning Systems

Green Infrastructure and Land Conservation

As urban and suburban growth continues in the greater Houston area, the existence and protection of public green space and natural habitat (including riparian bayou corridors, wetlands, coastal prairies and forests) becomes an increasingly important issue. Together, these types of natural and managed green spaces provide benefits such as stormwater management, flood mitigation, improved air and water quality, protection of drinking water sources, protection of plant and animal diversity, carbon sequestration, access to recreational opportunities and enhanced health and quality of life for the region's residents.

Figure 2.1 Aerial of Sims Bayou

When applied to stormwater management, three approaches are often together referred to as "green infrastructure"—green spaces managed for public use, natural habitats and low impact development (LID) practices.

Figure 2.2 Arthur Storey Park

Due to the shallow topography of the Houston region, none of these strategies alone create a significant impact on stormwater management and flood mitigation. However, combined with other strategies detailed in this report, these can have a beneficial overall impact. Green infrastructure uses vegetation, soils and natural processes to manage stormwater flows, reduce erosion, trap sediments and remove pollutants. Of the different types of green infrastructure that can be implemented, natural habitats such as riparian corridors along bayous, coastal prairies, wetlands and forests provide a unique opportunity for the greater Houston areas.

As of 2010, more than 1.6 million acres of land in the six county region existed as grasslands, freshwater wetlands, and forests. While that number has decreased in the interceding years, large expanses of these natural lands still exist in Brazoria, Chambers, Fort Bend, Liberty, Montgomery and Waller counties, including in watersheds upstream of Harris County. These areas provide opportunities for large-scale implementation of habitat conservation projects for stormwater management, which can have benefits for downstream areas as well. Even small-scale habitat conservation projects can have a large impact—as more are added in a watershed, the positive impacts compound. Tools for green infrastructure include:

- Conservation Easements can be an effective tool to advance green infrastructure in greater Houston, where most open land is privately held and public agencies are not as proactive in conserving land as in other regions of the U.S. A conservation easement is a voluntary and cooperative legal agreement between a property owner and "holder" of the conservation easement (usually a qualified, nonprofit land trust). Conservation easements allow landowners to maintain ownership of their land while permanently protecting the land's conservation value. Conservation easements do not require public access and they allow the land to be sold in the future with the agreement remaining in place; future landowners are bound by the terms of the conservation easement. Conservation easements are recognized for legal and tax purposes by the State of Texas and for many, conservation easements provide important federal income tax and estate tax benefits. A number of nonprofit land trusts throughout Texas and in the Greater Houston region work with public and private property owners to implement conservation easement agreements. To date, land trusts have protected over 131,000 acres in the greater Houston region.
- Land Acquisition represents an important tool to protect habitats inside and outside of the floodplain while also providing public access to greenspace. Government agencies and nonprofit organizations purchase property for the purpose of habitat protection, flood mitigation, source water protection and public access to greenspace. Land acquisition projects are usually implemented in Texas by state and local governments and nonprofit organizations working with willing sellers to negotiate the sale of land at fair market value. Land acquisition projects for habitat conservation are typically coupled with conservation easements to protect the property in perpetuity. Examples of beneficial land acquisition projects in the Greater Houston region include Bayou Greenways 2020 and numerous flood mitigation projects of the Harris County Flood Control District.

Notes

Based on most recent data from NOAA C-CAP (2010) describing areal extent of grassland, forest and wetland land cover categories in the counties studied by the GHFMC; calculated with 85% accuracy specification.

GalvBayGrade.org/habitat/#wetlands

TexasLandTrustCouncil.org

Environmental Protection Agency. "Case Studies Analyzing the Economic Benefits of Low Impact Development and Green Infrastructure Programs," EPA-84-R-13 _ 004. August, 2013.

Houston-Galveston Area Council. Designing for Impact: A Regional Guide to Low Impact Development, (2016). h-gac.com

Anthony Kendrick, ENV SP. Lessons Learned from LID-Based Roadway.

Tetra Tech. (2009). City of Toledo, OH, Maywood Avenue Stormwater Volume Reduction Project Plan Set.

- Low Impact Development (LID) practices are designed to model natural hydrological and ecological processes that promote retention and infiltration of stormwater on site; serving to reduce the overall volume of storm water runoff and improve the quality of water. LID provides tools for cost-effective management of stormwater through use of bioretention systems, bioswales, rainwater harvesting, permeable pavements, green roofs and vegetated swales into landscaping and development projects. The use of LID results in social, financial and environmental benefits (i.e., triple-bottom-line benefits).

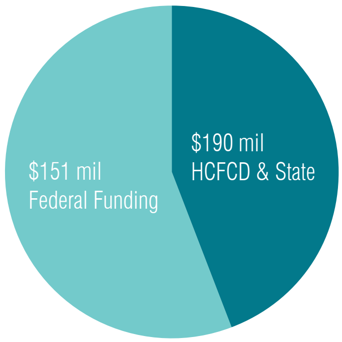
  LID practices can result in more developable land per parcel compared to traditional practices that require acreage-intensive detention basins. Less detention means a reduced cost per parcel for drainage infrastructure. In a study comparing traditional development practices with LID, the Houston-Galveston Area Council estimated that LID could result in an additional 24,000 square feet of leasable floor space and save 15 percent in landscaping and stormwater infrastructure costs for an eighty-acre commercial site. To encourage sustainable growth, smaller parcels can be engineered using LID design techniques that benefit the developer's bottom line. Municipalities and counties can also utilize LID to naturalize and modernize roadway development projects. The installation of a center median vegetative swale coupled with a High Performance Modular Biofiltration System instead of a traditional storm sewer saved Harris County seven percent per mile in roadway construction costs. Other developer benefits include reduced land clearing and grading costs, increased project marketability, improved aesthetics and lower maintenance costs.

A variety of ecosystem and community benefits can be achieved by incorporating green space at the site or neighborhood scale. Infiltration is often disrupted by impervious land cover such as roadways, parking lots and sod lawns. In a 2009 study of a residential roadside bioretention project, the average annual stormwater volume was reduced by approximately 64 percent and a peak flow reduction of 60 to 70 percent was achieved. However, infiltration rates vary in different soil types, and large parts of the Houston region consist of clays with low infiltration rates.

Case Study Quick Facts

Harris County Since 1985

(total $341 million)



2,075 Structures purchased with FEMA grants

960 Properties purchased with HCFCD funds

30 Structures purchased with Corp of Engineers funds

1,060 acres restored to floodplain

Buyouts, Elevation and Floodproofing

Buyout, elevation and floodproofing programs address existing structures in areas that are susceptible to flooding to prevent future damage and impacts on residents. Several strategies can be used, including:

- Acquiring developed properties for new flood control infrastructure, which removes homes and business from flood-prone areas and increases stormwater capacity through widened channels or new detention basins.
- Buying out developed properties and replacing them with open space removes structures from the floodplain, ensuring that they will not flood again.
- Demolishing existing buildings and replacing them with flood-resistant buildings on the same site.
- Elevating existing structures.
- Floodproofing buildings to handle a foot of floodwater.

These strategies can be very effective, particularly when coupled with a long-term plan and consideration of neighborhood values. A systems approach to protecting residents in flood-prone neighborhoods should involve multiple, possibly concurrent strategies; considering constructed improvements; carrying out public engagement to assure that residents are aware of the range of options for protecting or removing themselves from risk; and, when needed, coordinating closely with an affordable housing plan that offers alternative housing.

Buyouts are part of the greater Houston area's response to flooding. Since the 1980s, HCFCD has bought out over 3,000 properties, and the city of Houston is now participating in this program. In most cases, HCFCD uses federal funds provided after major floods for buyouts—these funds come with restrictions e.g., buyouts must be voluntary. Consequently, the pattern of bought-out properties can result in a "checkerboard effect" whereby some homes in a neighborhood are bought out and others remain, leaving a checkerboard of empty lots. This prevents acquired land from being used effectively for detention, open space or other flood mitigation projects, and requires local jurisdictions to continue to provide public services with a reduced tax base. Other jurisdictions across the country apply strategies intended to reduce the checkerboard effect, such as:

Community Engagement and Planning

Residents may not be familiar with the buyout process, and may believe that buyouts are being done "to them." However, if they participate in a stakeholder-driven process to establish community priorities, residents often come to the conclusion that buyouts make sense. Creating community buy-in can help craft strategies that achieve multiple goals and that appeal to the homeowner, such as parks and relocation methodologies. Community leaders often become ambassadors for buyouts among their neighbors, which further improves voluntary participation. While this process adds time on the front-end, it saves time later by reducing public concern.

Quick Action

Residents are most likely to accept a buyout immediately after a flood, when they may be displaced and have not yet invested in repairing their homes. By evaluating potential buyout areas and setting aside funds in advance, local jurisdictions could buy out quickly after the next disaster.

Affordable Housing Plan

Low-income residents often resist buyouts because of fewer good choices of where to live. Access to jobs, schools, services and support networks are important, and these needs are often met by the current neighborhood even after a flood. In addition to plans for communities, a broader affordable housing plan that includes a clear path for strategic coordination will offer options for relocation.

Case Management

Residents often face other challenges, ranging from lack of clear title to their home to a lack of awareness about financial and real estate issues. Case managers are invaluable to help people navigate the long, often complex buyout process, improve voluntary participation and build community trust.

For More Information

See Fact Sheet 8: What are Buyouts?

Relocation Assistance

Financial considerations are important to potential sellers. A buyout based simply on the current value of a property may not work for some, including those whose mortgages are "underwater" and those who live in old or substandard structures. If a resident cannot find a way to buy a new home for the amount they are offered they may not participate. FEMA restrictions can limit the ability to offer more, but alternative local funding sources can help bridge these gaps. Communities have found that simplifying relocation assistance, minimizing paperwork for eligibility and providing relocation assistance motivates property owners to participate.

Multiple Sources of Funding

FEMA funds come with restrictions that make it challenging to buy out all properties in an area with only those dollars. U.S. Housing and Urban Development (HUD) funds can help, but state, local and private funds can fill gaps. For example, state and local parks funding can be applied to properties that do not qualify for a buyout under federal rules but are critical to creating new green space and habitat sites. For example, the Charlotte/ Mecklenburg County area uses a stormwater fee similar to the city of Houston's drainage fee to help fund buyouts; and the city of Milwaukee uses its utility district's general fund. Other options for alternate funding include Tax Increment Reinvestment Zones (TIRZs) affordable housing dollars, social impact bonds, catastrophe bonds and resilience bonds. The city of Houston is partnering with HCFCD to implement buyouts using city funds, and the Houston Parks Board is helping fund buyouts that result in new park space.

Project Area Buyouts

If a scoring system is used to weigh and select eligible properties, a scattering of individual properties across a region may rise to the top, thus contributing to the "checkerboard effect" within neighborhoods. Identifying project areas and then averaging the scores for individual properties in each area could address this challenge. The project areas would be prioritized in order of highest average scores, with buyouts of all properties being the goal, using multiple funding sources to ensure full coverage.

Alternatives to Buyouts

Some areas that flood repeatedly are well located in terms of access to jobs and transit—and some are key parts of the cultural fabric of a neighborhood.

Sometimes, it may be preferred to keep a site in use for housing or business but renovate or reconstruct existing buildings so they are more flood resistant. The state of New York, for example, had a post-Sandy program that acquired homes that had flooded, demolished those homes and then sold the lots to homebuilders with restrictions attached to ensure that new homes would be elevated above flood levels. This preserved housing supply in these neighborhoods and costs were less than outright buyouts, helping maximize state funds.

Where flood depths are relatively shallow, houses can be floodproofed to handle a foot of floodwater, which can preserve neighborhoods and prove less expensive for the taxpayers than buyouts.

It may be possible to buy out only the highest-risk properties within a flooded community and redevelop the lots to create greater floodwater storage and mitigate the flood risk for the remaining properties. Milwaukee has used this strategy to allow communities to stay intact.

An example of collaborative problem solving is how the state of North Carolina worked with communities that experienced severe flooding after Hurricane Fran in 1996. Through a robust public engagement effort, the residents of certain high-risk neighborhoods explored the options available, and in some instances, entire communities chose to participate in buyouts and then relocate. In addition to removing residents from harm's way, this outcome created a significant amount of land that could be used for flood damage reduction purposes.

Also, the state created the North Carolina State Acquisition and Relocation Fund (SARF) in order to provide up to $75,000 to homeowners whose properties were being bought with federal money through the Hazard Grant Mitigation Program, which pays only the pre-disaster value of homes. The SARF program provided homeowners with additional funds of up to $75,000 to help make it feasible to move into a new home. The SARF funds were allocated from state revenue.

Development Regulations

Development regulations inside and outside of floodplains cannot change the amount of rainfall or the course of floods, but they can prevent homes from flooding and keep people and property out of harm's way. Site development regulations include detention to reduce runoff from new development, design of storm sewers and ditches in new developments, and the design of streets. Building regulations include the elevation of structures above flood levels, foundation types and floodproofing. These regulations can achieve two things: protecting a new development or structure from flooding, and reducing or eliminating the effects of new construction on existing downstream homes and businesses.

FEMA creates floodplain maps that are used by the National Flood Insurance Program (NFIP) to set flood insurance rates in participating communities. Cities and counties can choose to participate in the NFIP and adopt NFIP's minimum standards for development in the local floodplain management ordinance. Additionally, the adoption of the NFIP Community Rating System (CRS) incentivizes communities to go beyond the minimum protection standards. These regulations are intended to mitigate increased flooding due to development and construction. The zones that FEMA maps designate include: regulatory floodway, Special Hazard Flood Areas (SHFA), also known as the 1 percent chance flood zones, and the 0.2 percent chance flood zones.

There are several layers to flood regulations geared toward three overarching goals:

- Protecting structures through elevation or floodproofing to the flood elevation defined in the FEMA maps.
- Storing water through detention or balancing fill on site.
- Conveying water through requiring open foundations and regulating site drainage.

It is essential to balance these because while water must be drained away from structures and development quickly, it also must be removed slowly enough to avoid overloading drainage channels and bayous.

In greater Houston, newer development regulations and building codes have considerably reduced flood damage. Buildings with higher flood levels (as opposed to the low-slung foundations common in the 1960s and 1970s) streets deliberately depressed to hold and channel floodwaters, and larger storm sewers are effective in keeping water out of homes and businesses. However, clear challenges remain.

First, jurisdictions within the same basin or watersheds often adopt different sets of regulations. Some regulations are enforced by the authority whose political boundaries contain the project, which is complicated by the establishment of extraterritorial jurisdictions (ETJs) for cities. Other controls are not set by political boundaries at all. The governing authority for detention and runoff, for example, is determined by the facility in which the development drains. In the city of Houston, for example, bayous, drainage channels and storm drains under local streets may be owned and maintained by HCFCD, county precincts, municipal utility districts, the Texas Department of Transportation (TxDOT) or the city. Overlapping regulating authorities can make acquiring permits confusing. Better coordination between jurisdictions can fill these gaps.

Second, within a single jurisdiction, regulations which address flooding can be spread across multiple codes and enforcement mechanisms, making compliance more difficult and creating gaps. For example, the city of Houston floodplain ordinance requires a minimum building slab elevation above the base flood elevation while the building codes require slab elevation above the crown of the street and nearest sanitary manhole. Coordinated regulations are critical to ensuring consistency.

Third, regulations are usually limited to the mapped FEMA Special Flood Hazard Area (SFHA). As these maps evolve with data from more recent storms, structures that were outside the floodplain may be outlined in the floodplain now or in the future. Developers have also used FEMA processes, such as the Letter of Map Amendment or Revision, to redraw floodplains and remove their sites from the mapped floodplains. Most critically, a significant portion of flooding in greater Houston occurs outside the floodplains, due to local ponding and backups in ditches and storm sewers. Many of the affected homes

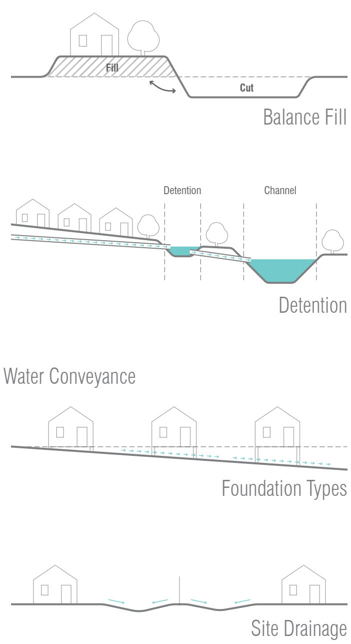


Figure 2.3 Flowrate

For More Information

See Briefing Document 3: Flood Regulations

and businesses are in areas outside the mapped SHFA where flood regulations do not currently apply. Local jurisdictions can create their risk maps and base regulations on those.

Fourth, counties do not have the same enforcement powers as cities. The unincorporated areas of Harris County have the population of a major city, with all the issues that come with that level of development. However, the county does not have the authority to use the tools that incorporated municipalities in Texas can use to respond to them. For example, while the city of Houston can quickly "red tag" a new building that does not comply with regulations and stop construction, the county can only take the developer to court, which can take months, during which time the developer can continue to build. Likewise, after a flood, the county cannot "red tag" buildings that are unsafe for habitation.

Finally, development regulations only address new or substantially improved structures. Tightening regulations will not protect owners or renters who live in homes built before 1980.

It is important to recognize that rainfall and runoff do not respect political boundaries and greater coordination and simplification in regulations across jurisdictions in the same watersheds is essential to addressing future flooding.

Local Drainage Systems

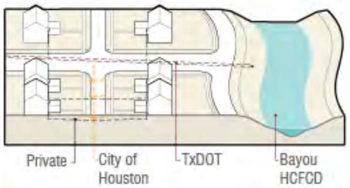


Figure 2.4 Who regulates?

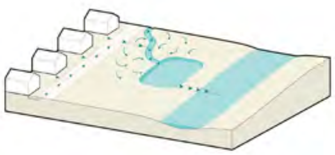


Figure 2.5 Path of water

The rain that falls in the Houston region eventually makes its way to the Gulf of Mexico through river and bayous. First, it has to make its way to the bayous through smaller scale local drainage systems. These systems are a critical part of flood resistance. How they are designed and how well they function determines whether localized flooding occurs in neighborhoods, and also affects flood levels within the bayous themselves by determining how quickly water makes it to the bayous.

In urban areas of the region, stormwater systems consisting of concrete pipes or roadside ditches are used to route normal amounts of rainwater into the nearest creek, bayou or detention facility. For example, the city of Houston generally requires that storm sewers be designed to handle a minimum two-year design storm of at least three hours duration. For reference, a two-year design storm has a 50 percent chance of occurring in any given year and, in Harris County, equates to about three inches of rainfall in a three hour period. This is intended to minimize nuisance flooding in neighborhood streets, on average, once every other year. For storm events beyond the two-year design, the storm sewer system will become full and overflow into the street. Under these conditions, the street network is intended to be used as a secondary drainage system to convey the excess storm water to the nearby creek, bayou or detention facility, and should be designed such that homes will not flood during a 100-year storm.

In many older neighborhoods, rainfall that exceeds the capacity of storm sewers and ditches runs to the bayous as sheet flow. As it runs across an area, this water can flood properties and buildings. New construction can lessen these flow patterns: a new building built on fill can will be raised out of the floodwaters and thus be safe, but that same fill could redirect stormwater into neighboring homes. Thus development regulations also provide that sheet flow from new, re- or in-fill development should not alter existing overland patterns, cannot increase or redirect water onto adjacent private or public property, and must be discharged only into the abutting public right-of-way.

Similar to cities, Municipal Utility Districts (MUDs) and the less-common Levee Improvement Districts can set their criteria for managing floods and designing urban infrastructure. However, they must meet the minimum standards of the underlying county. MUDs and Levee Improvement Districts that are built within the ETJ of a city may need to meet the minimum criteria of the city for possible annexation of the community at a later time. Deliberate and strategic coordination with the communities will lead to better results.

It is important to note that in many older neighborhoods in the Houston area, much of the existing storm sewer network cannot handle a two-year storm since those systems were designed for a much smaller amount of rainfall at the time they were built. Similarly, streets in older neighborhoods were not designed to convey storm waters and instead can act as a bowl—storing excess stormwater until levels get high enough to flow overland in an unplanned downhill direction. This water flow can include over and through empty lots and homes until the storm sewer network drains sufficiently, which allow flood water in the streets to subside.

In much of greater Houston, flooding occurs outside of the official, mapped 100-year floodplain, even for events smaller than the 100-year storm. Between 1999 and 2009, an estimated 47 percent of claims in Harris County, or $147 million dollars in FEMA paid losses, occurred outside of the mapped 100-year floodplain (Highfield et al. 2013). This number can be even higher in specific watersheds. For example, a 2013 study (Brody et al.) found that 55 percent of claims in the Clear Creek watershed occurred outside of floodplain boundaries. These claims were, on average, about 600 feet from the edge of the nearest floodplain. While this may be explained in part by inaccurate floodplain maps, lack of mapping of tributaries, local ponding, street flooding and site drainage issues in older neighborhoods can also drive flood losses. These issues are not captured by FEMA's or HCFCD's conventional floodplain mapping process. On average, homes built before the creation of the FIRM (Flood Insurance Rate Map), e.g., "pre-FIRM structures" experience the highest rate of damage on average in Harris County.

Some neighborhood hotspots for potential flood damage in Harris County are presented as a 'ponding layer' on HCFCD's Flood Education Mapping Tool (harriscountyfemt.org).

For More Information

See Fact Sheet 5:
How Does Rainfall Drain Away?

Issues

Ensure that developers have sufficient "upstream" information. Land development engineers typically focus on mitigating the runoff generated by their development project, and as such, flows entering onto their site from other sources may not be considered in their design analysis. Examining strategies to share information about upstream conditions with developers during the design analysis phase could help maximize site-based mitigation.

Communicate the role of streets in the drainage system. Many residents may not be aware that roads are intended to act as a secondary short-term storage system and/or conveyance pathway for water. This can lead to severe property damage and loss of life when residents do not move property out of harm's way. For example, recent street flooding has caused severe flooding of cars, which are frequently parked in the street. It is also important to note that 12 inches of water can float a sedan and 18-24 inches can float a larger vehicle, creating hazardous road conditions during extreme events. It is critical to develop a strategy to communicate to the public that streets are designed to be a secondary short-term storage system so that people can take action to prevent loss of property and life.

Address debris in streets and waterways. Maintaining clear openings to storm sewer inlets is a great way to help reduce street flooding. Flooding in many neighborhoods can be made worse by debris and floating trashcans that clog inlets. Additional city, county and MUD maintenance, or organized community efforts may be required.

Maximize on-site retention. Green infrastructure may provide a viable alternative for managing stormwater and reducing nuisance flooding through implementing on-site retention or by providing additional in-line storage capacity within the street (examples include Cottage Grove and Bagby Street).

Identify and target high-risk areas. Determining the neighborhoods most vulnerable to flooding from local drainage challenges would be a pivotal step to targeting public education and mitigation strategies.

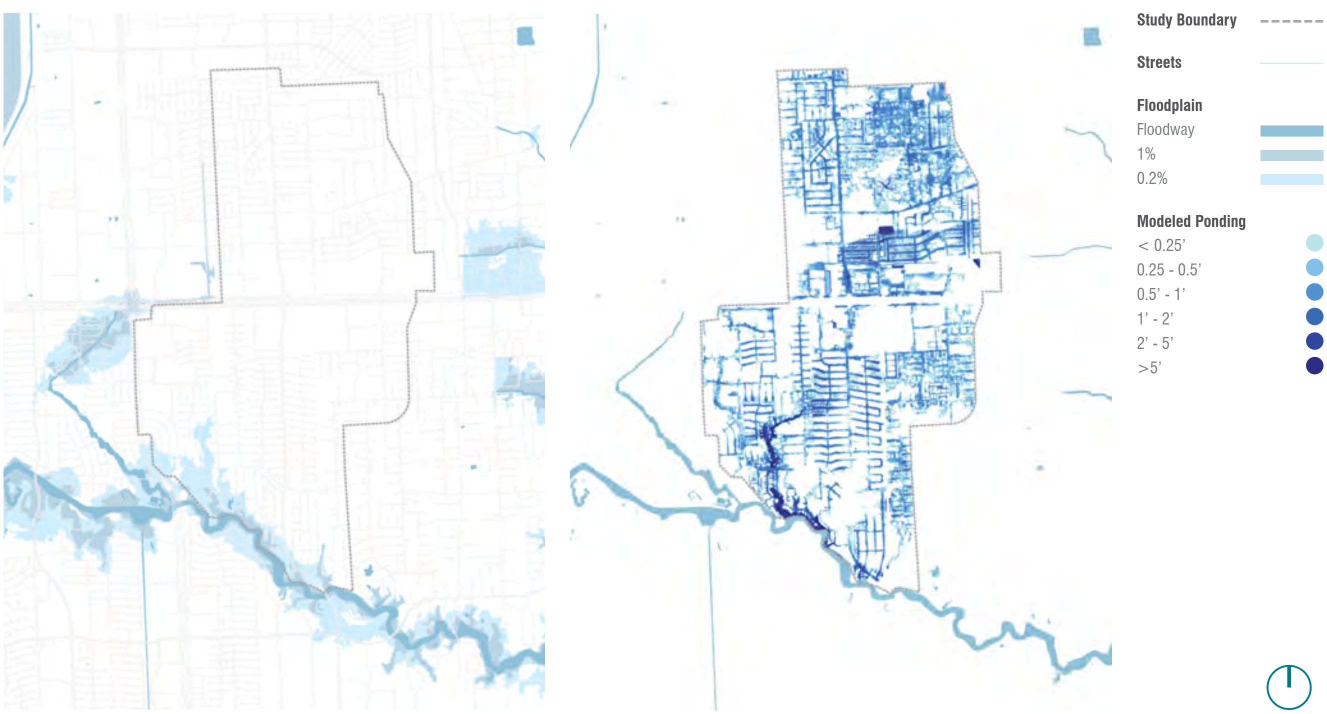


Figure 2.6 FEMA floodplain (left) versus modeled flood in TIRZ17 Drainage Study (right)

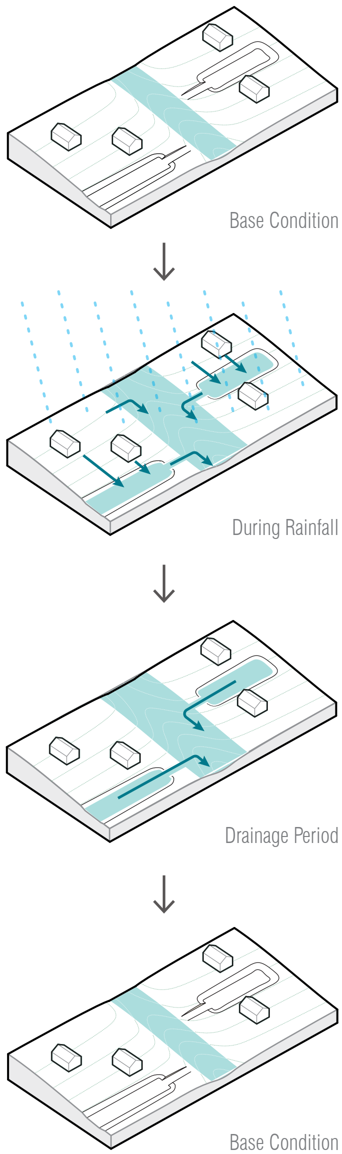


Figure 2.6 Flowrate

Structural Solutions

Reservoirs, detention basins, levees and increasing channel conveyance capacity by widening, and in some cases deepening, a channel are types of structural solutions used across greater Houston. Detention and conveyance are often used in tandem, typically with detention working best in the middle and upper ends of watersheds to slow water down, and increased channel conveyance capacity working best in the middle and lower areas of a watershed to speed water to the Galveston Bay. The recently completed Sims Bayou project used both strategies so effectively that its watershed did not flood during Hurricane Harvey from rising water in the bayou itself, though flooding did occur on local drainage systems and tributaries.

Reservoirs

Reservoirs can impound large volumes of water behind dams with controllable outflow structures e.g., gates. While some reservoirs are dry between flooding events, other reservoirs are permanent lakes that have room for additional floodwaters above the usual lake level. In addition to flood control, reservoirs can store water for municipal or agricultural use or generate electricity. Some have multiple purposes, but not all reservoirs are designed to have a flood control function. For example, Lake Conroe and Lake Houston were designed solely as part of the region's drinking water system. When designed to address flooding, reservoirs in the upper end of watersheds are an effective strategy. When greater Houston first adopted a regional approach to flood mitigation in 1937, the focus was on detaining water in the upper watersheds of Buffalo Bayou. Two large reservoirs, Addicks and Barker, extended across 40 square miles of what was then prairie and ranch land. The challenge to applying this strategy elsewhere in the region is that many watersheds are almost fully developed. For example, White Oak Bayou and Brays Bayou have no land available for a reservoir. On the other hand, upper Cypress Creek, Spring Creek, the areas upstream Addicks and Barker reservoirs, and the San Jacinto River watershed have undeveloped areas that could accommodate reservoirs as part of an overall flood mitigation strategy.

Detention Basins

Detention Basins are used to store water and release it at a slower-than-natural rate through smaller outlet pipes that only allow the water to drain out once water in the channel is lower than in the basin. A "dry bottom basin" may allow for recreational uses when not in use while "wet bottom basins" are lakes and wetlands that recreate habitats that have been largely lost to development in our region. Detention basins are most useful upstream and midstream as they can mitigate downstream flooding. They are not as useful farther downstream. There are three types of detention basins commonly used in greater Houston:

- On-site detention is built as part of private developments or public projects (e.g., highway expansions) to mitigate the impact of the development. On-site detention is usually required by city and county development regulations and funded by the developer or public agency building the infrastructure project.
- In-line detention consists of deep areas along the channel that can store floodwater once it begins rising in the channel.
- Regional detention is built by flood control agencies to address flooding on a larger geographic scale and is funded by taxes or stormwater fees paid by a number of developers. Regional detention is used to reduce existing flooding or help prevent increased flooding from new developments. Such detention areas can cover several hundred acres and include parks around them. Arthur Storey Park and Willow Waterhole in the Brays Bayou watershed are examples. These basins are generally most effective in the middle and upper reaches of a watershed.

For More Information

See Fact Sheet 3:
What is a Detention Basin?

Levees

Levees are large berms built alongside a river that contain floodwaters, keeping adjacent areas dry even if the water level in the river rises above the elevation of the surrounding land. When the river is high, rain that falls within the levee must either be stored or pumped up to river level. Levees are rare in Harris County, but are used extensively along the Brazos River in Fort Bend.

Channel Conveyance Capacity

Channel Conveyance Capacity can be increased using multiple strategies, including the following:

- Increasing the size of the channel itself by widening or deepening it. Conveyance strategies tend to shift flooding to downstream, and increasing conveyance is only helpful if downstream segments have the capacity for increased flow from upstream. Thus bottlenecks should be avoided along the stream and conveyance capacity should increase as you move farther downstream. For example, initial studies indicate that working on seven roadway, utility and pedestrian bridges on lower White Oak Bayou could reduce flood waters by several feet if implemented in conjunction with a bypass channel in downtown Houston, however, this would increase flows downstream in Buffalo Bayou and may require bank improvements to prevent erosion.
- Increasing the capacity of the channel by straightening it, cutting off extreme meanders or adding bypass channels.
- Smoothing the surfaces of the channel, as the flow of water is affected by the roughness of the channel. Smooth concrete or short grass allows more water to pass compared to dense vegetation.
- Modifying or replacing bridges. No matter how wide the channel, roadway, utility, railroad and pedestrian bridges can greatly restrict water flow, by being too low, too narrow or having too many or poorly-positioned piers.

It is important to note that conveyance projects can make flooding worse. The effect of a rainstorm on a watershed is determined partially by how fast water flows. Natural channels often convey water quite slowly, so that stormwater from the upper reaches of the watersheds only arrives downstream when stormwater from the lower reaches has already made its way to Galveston Bay. If tributaries and the main channel are straightened and expanded so that water flows more quickly, upstream and downstream rain can converge, raising flood levels. Thus, conveyance improvements have to be studied on a watershed wide level (as HCFCD has done on federal projects) and implemented together with other measures.

Channel conveyance is also affected by conditions where channels reach the Gulf of Mexico. Tides and storm surge can restrict flow at the mouth of a bayou, backing up water upstream. Projected sea level rise will likely exacerbate this challenge.

Flooding Data and Disclosures

Figure 2.7 Initial FEMA damage assessment

Good data is a key to the success of several aspects of flood mitigation. Up-to-date and clean data can help to identify areas of highest future risk, greatest damages, protection from existing and proposed flood mitigation strategies, and accurate flood predictions and warnings. Sharing data among researchers, public agencies and the public increases opportunities to ensure well-informed decisions.

Damage Assessment Data

Public agencies have access to a wide range of data on flood damage, including insurance claims, FEMA individual assistance claims, calls for assistance and damage surveys across dozens of major flooding events. These datasets are in invaluable in understanding the impact of past flood events and preparing for future ones. Investing in collecting, improving and sharing this data is critical to supporting decision-making about flood mitigation. In particular:

- Creating a consolidated, regional source of data that covers all jurisdictions in the area's watersheds would enable these jurisdictions to have the most complete information possible on which to base decisions.
- Ensuring that damage data is as complete possible is important. For example, insurance claims do not include homes that were not insured; FEMA data misses people who choose not to apply; and calls for assistance do not include people who were rescued by neighbors or those who were unable to get through to 911. By combining, comparing and weighing data in layers, it is possible to develop a complete picture.
- Implementing a regionally adopted protocol on collecting relevant data after an event could help to ensure completeness and uniformity.
- Sharing data with the public could contribute to building community awareness and trust, as well as enable research that contributes to innovative solutions.
- Data about building slab elevations is critically important. Existing LIDAR topographical information used to map flooding does not include building slab elevations so it is not possible to confirm if a model's mapped flood waters cover only exterior areas of land or extend inside the buildings located on that land.

Mapping

Nearly all decisions related to flood mitigation, from structural projects to buyouts to building regulations, are made based on data on rainfall events and floodplains. However, FEMA maps are often outdated and show incomplete flood risk. Creating local risk maps that include more information than standard FEMA maps, consider all forms of flooding and address the uncertainty of future climate change would be valuable to residents, businesses, and all relevant decision-makers.

Disclosures

Flood control projects are often evaluated using a cost-benefit analysis that assigns great weight on the value of a home or structure. This approach may skew investment and response to areas with higher property values and may leave under-resourced communities out of recovery plans. However, this cost-benefit approach is required to qualify for federal funding. It is important to ensure that major investments are spread equitably throughout the region so that all residents benefit to the extent possible, by taking into consideration factors such as population density, historic levels of investment and underinvestment, and the location of particularly vulnerable or politically disempowered populations. It is also important to assemble resources and establish processes that do not shift problems or burdens, but rather helps address them. For example, extensive case management and adequate relocation assistance should accompany buyout efforts, and plans for these programs should be vetted by an entire community, not just targeted homeowners. In some cases, local dollars will have to be used to avoid the federal cost-benefit trap.

Risk Management

Flood risk is not a static phenomenon; it is a forward-looking concept. The strategy behind mainstream floodplain management practice in the U.S. has relied exclusively on knowledge of past floods. The nation's response to Hurricane Katrina and the catastrophic breaches of federal levees resulted in a new state-of-the-art approach that is now called "flood risk management." This emerging approach takes advantage of advanced hydrodynamic, meteorological, geotechnical and other models to estimate the likelihood and impacts of all possible flood scenarios. Thousands of possible scenarios can be modeled to determine worst-case consequences. This is a major leap forward from the floodplain management approach, which designs to a single risk scenario (i.e., the 1 percent, or 100-year flood). The key difference is the use of probabilistic rather than deterministic analysis. For example, a modern analysis of flood risk can address the probability of failure, breach or overtopping of infrastructure. It analyzes risk on a systems basis, seeking to understand the consequences of failure in a system of components rather than only in individual components. All structural and non-structural elements and features that significantly affect flood risk are included in a modern risk analysis. Modern risk analysis includes, for example, an analysis of the hazard, a reliability analysis of the infrastructure system, a failure consequence analysis and an uncertainty analysis. The risk analysis after Hurricane Katrina involved over 76 hypothetical hurricanes and tens of thousands of downstream conditions. The result was an understanding of how flood risk is distributed across the region.

Social and Environmental Impact Assessment

Environmental impact assessment (EIA) and social impact assessment (SIA) were created in response to the failure of cost-benefit analysis (CBA) to recognize the non-quantifiable costs borne by people and the environment. EIA was first mandated under the National Environmental Policy Act of 1970 and then by many state governments and countries around the world. EIA is a planning tool for ensuring public participation and transparent analysis of the consequences of proposed government actions. EIA is used to identify unavoidable and/or irreversible adverse impacts to air, water, soil and groundwater, visual and noise, socioeconomic and cultural, and biological and ecological impacts; and to determine how such impacts will be mitigated. EIA also requires the formal consideration of alternatives to any proposed project. Social impact assessment (SIA) emerged after the realization that EIA often gave more weight to environmental impacts. SIA is used to understand the social consequences of government decisions, to emphasize the need for public disclosure, and to bring attention to disproportionate impacts on vulnerable and disadvantaged communities. EIA, SIA, and CBA are important tools for making evidence-based decisions that build resilience.

Notes

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Regional Systems Approach

The current state of flooding in the greater Houston region is directly connected to the natural history of the coastal plain and bayou landscape, the legacy of past decisions relating to economic development and regional growth, a changing climate and increasing risk of extreme weather events. For Houston to become more resilient, we must be able to adapt to changing environmental challenges and mitigate future risk. Our goal as a region should be to equitably lessen future impacts to communities to the greatest degree possible and implement strategies to recover as quickly as we can, should another disaster occur in the future. For this to happen, a paradigm shift in our way of thinking is required. Climate, precipitation, the natural environment, development practices, transportation, population growth, economic realities and social wellbeing are all parts of an integrated system.

Moving forward, a regional systems approach founded on science-based assessment, community planning and multi-sector consensus offers a path forward for real and lasting change. A systems approach recognizes that there is no single response to flood risk. Instead, a range of flood mitigation strategies can be implemented to reduce risk in an efficient and sustainable way. Strategies should include a suite of solutions (see Section II) including but not limited to robust public education and participation, structural measures, green infrastructure, land acquisition, buyouts and relocation, flood warning systems, stricter development regulations and repairs to local drainage systems.

Decision-making processes to implement risk mitigation and adaptation measures using a systems-based approach should be undertaken across multiple scales. Some strategies may respond to the natural and built environment and community needs of different watersheds, but responses should be coordinated at county and regional levels. Decision-making process should be continually adaptive and responsive over time as conditions change and more data and knowledge are acquired. Effective communication and frequent community input are vital for success.

It is critical that we move beyond existing single-watershed and single-project approaches. Implementing a systems approach in greater Houston would involve the collective action of government entities, decision-makers across all levels of government, interdisciplinary researchers, and public and private sector stakeholders including area residents, and likely many different sources of funding. If implemented across the region, a systems approach could create a culture of resilience based on greater public awareness and collective strategies that involve the considerations of public safety, equity and the environment, respect the region's natural history, support healthy communities and enable a strong economic future.

3 ANALYSIS OF WATERSHEDS IN HARRIS COUNTY

Harris County contains 22 watersheds that drain from their headwaters through the county's flat coastal plains and forests to Galveston Bay. Most of Harris County is served by waterways that are contained mainly within county boundaries, with the following exceptions:

- The Spring Creek watershed is shared with Montgomery County on the north
- The Clear Creek watershed is shared with Fort Bend, Brazoria, and Galveston Counties on the south
- The Cedar Bayou watershed is shared with Liberty and Chambers Counties on the east
- The upper reaches of Cypress Creek extend into Waller County to the west
- The upper reaches of Barker Reservoir's watershed is located in Fort Bend County to the west
- Small portions of the upper Brays and Sims Bayou watersheds are located in Fort Bend County
- The majority of the San Jacinto River watershed—both its East and West Forks—is in Montgomery County, and the West Fork extends well north of Lake Conroe into multiple counties.

Flood mitigation in five watersheds is partially addressed by federally funded projects that are described in Section IV—Brays Bayou, Clear Creek, Hunting Bayou, Greens Bayou and White Oak Bayou. Other watersheds, such as Buffalo Bayou and Cypress Creek, do not have major ongoing federal projects but have significant projects in discussion. There are other watersheds, however, that experience flooding and have little or no open projects or study. Watersheds without ongoing federal projects are addressed in Section V.

Equitable protection for all county residents is of fundamental importance, and before analyzing the merits of ongoing projects and offering concepts to further mitigate flooding in individual watersheds, the consortium conducted a high-level comparison of key data for each watershed, including:

- Ongoing and recently-completed flood mitigation investments by watershed
- The population of each watershed
- The total damage claims in each watershed after Harvey.

The claims data is inherently limited. Insurance data does not cover homes that were not insured or did not file a claim after flooding. The dollar value of damages is also not an accurate assessment of the negative impact of flooding on lives, families, communities, businesses, income, and transportation. A damaged $1 million home and a damaged $50,000 home each affect the family who lived there, and a lower-income family typically has fewer resources to recover from the damage.

By comparing this data, it is possible to determine if investments being planned or built are targeted to where the need is greatest. The key metric is claims per capita as compared to the value of the investments being made. Chart 3.1 summarizes the data. It is important to note that these comparisons are among whole watersheds. Sections IV and V also examine equity within watersheds and especially between areas along the main channels, which tend to be the focus of federal projects, and tributaries. This includes large channels such as Halls Bayou within the Greens watershed, Little White Oak Bayou within the White Oak watershed and Keegans Bayou within the Brays watershed.

The data shows that resources are already focused on several large watersheds that had significant Harvey damage. Projects on Brays and White Oak, for example, address some of the hardest hit areas. It is highly likely that had funding been sufficient to implement these proposed projects more quickly, fewer homes would have flooded during Hurricane Harvey and fewer lives would have been disrupted.

Some major watersheds like Greens, and its tributary, Halls, have been studied only in part, so projects underway in these watersheds do not adequately address the issues in the watershed, but work was already underway before Harvey to fully analyze these watersheds and identify further projects.

For More Information

"Greater Houston Flood Mitigation Projects by Watershed"

Fact Sheet 5: How Does Rainfall Drain Away?

Harvey focused attention on Buffalo Bayou and the San Jacinto River, neither of which have received recent investment. These two watersheds are unique in the fact that they have reservoirs, and the protocols for operating these reservoirs can play as critical a role in flood mitigation as structural projects.

Other watersheds such as Cypress Creek and Vince Bayou suffered significant damages during Harvey but have few major flood mitigation projects underway. These watersheds are discussed in more detail in sections IV and V.

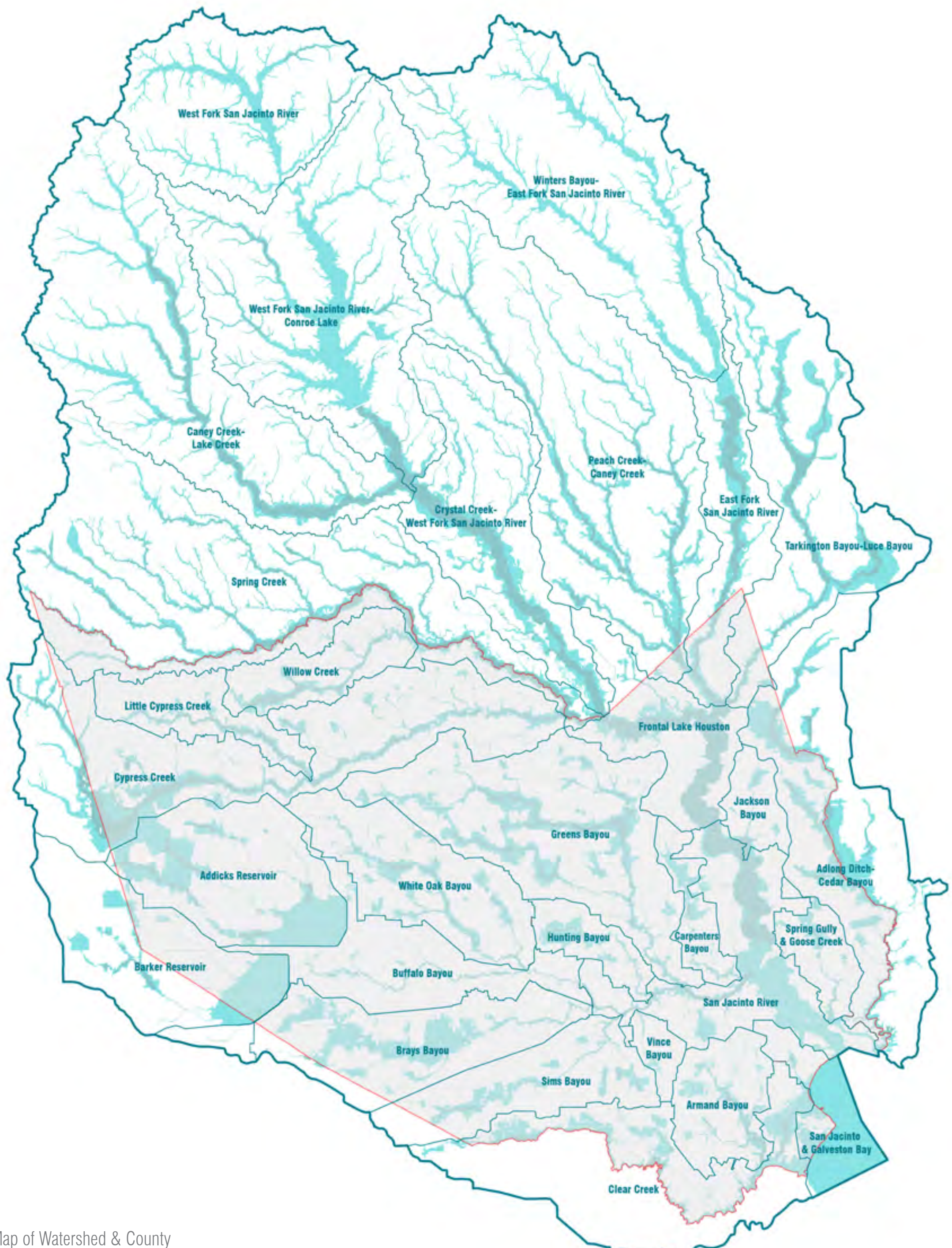
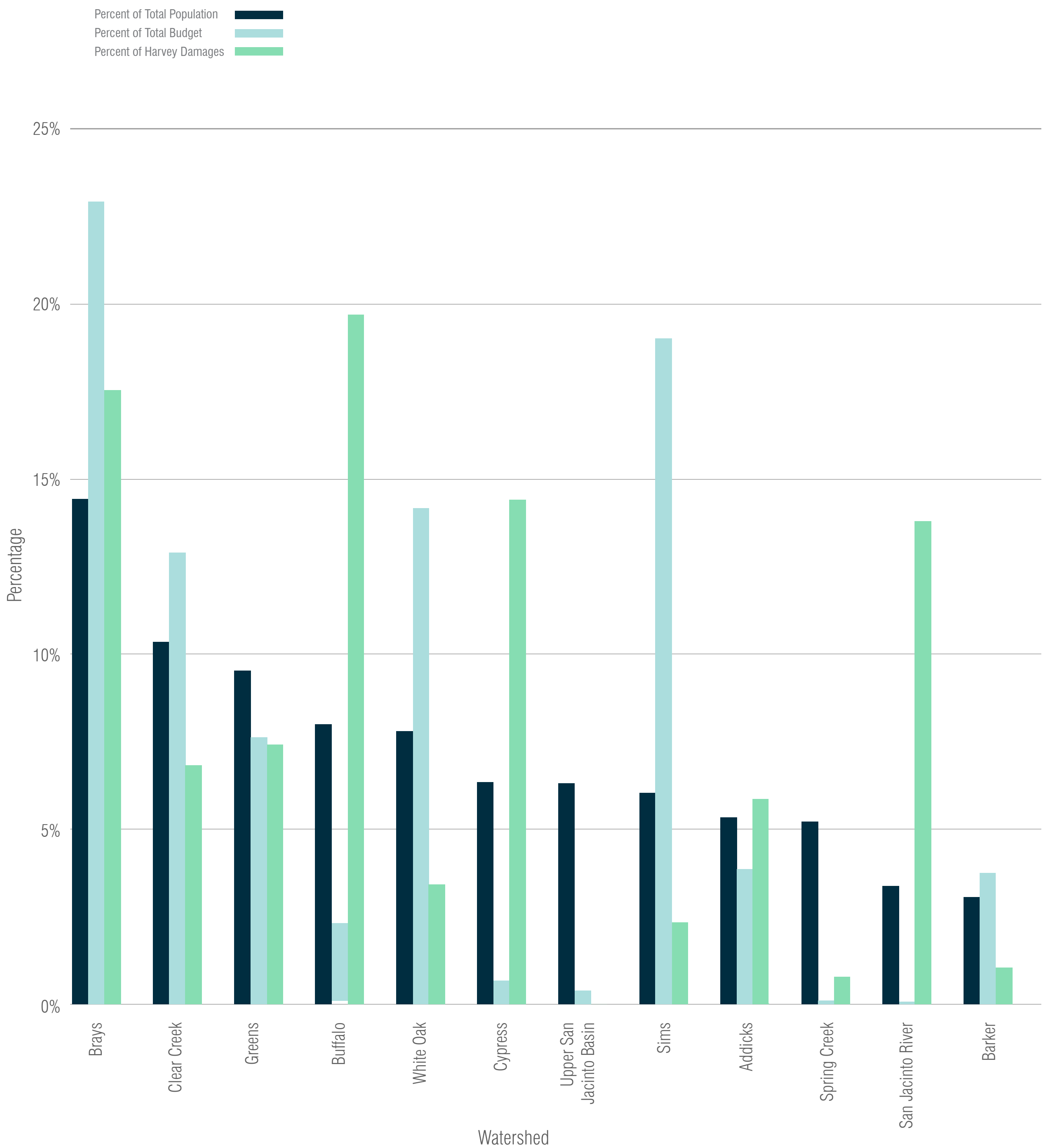
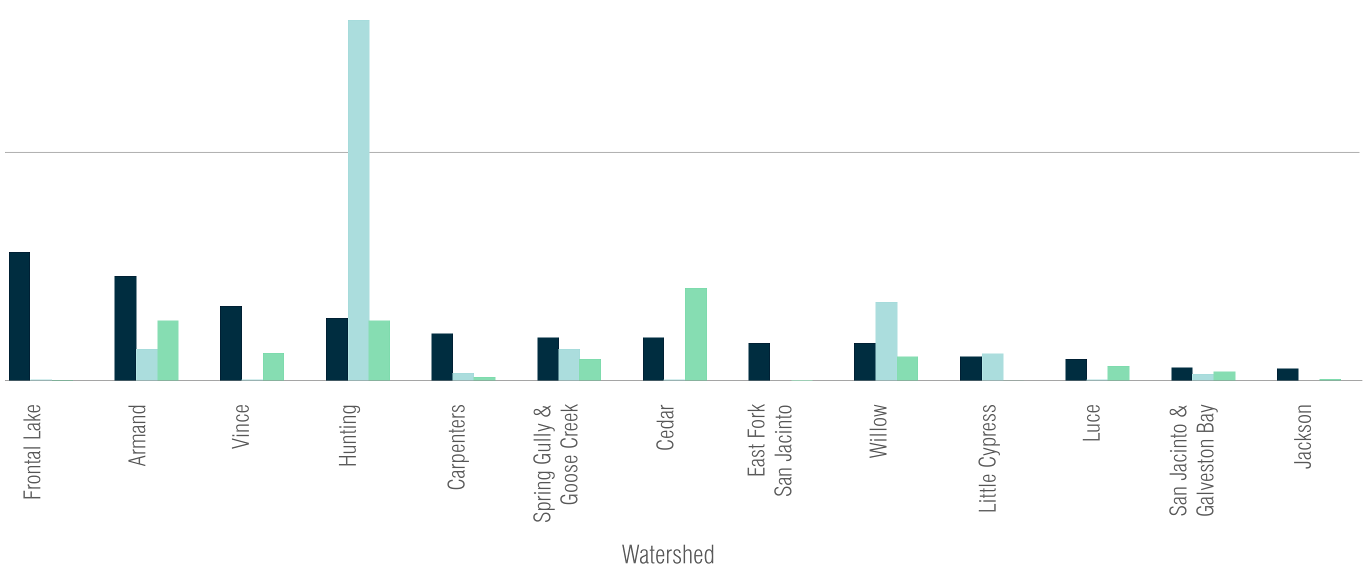


Figure 3.1 Map of Watershed & County Boundaries

Chart 3.1 Watersheds Analysis



	% OF TOTAL POPULATION	WATERSHED POPULATION	% OF TOTAL BUDGET	BUDGET PER WATERSHED	% OF HARVEY DAMAGES	HARVEY DAMAGES
Brays	14%	800,682	23%	$496,356,585	18%	$164,536,910
Clear Creek	10%	574,172	13%	$279,363,308	7%	$63,980,473
Greens	10%	528,720	8%	$165,085,888	7%	$69,564,864
Buffalo	8%	444,602	2%	$50,343,239	20%	$184,651,450
White Oak	8%	433,250	14%	$306,705,497	3%	$32,160,022
Cypress	6%	351,882	1%	$14,756,881	14%	$135,172,490
Upper San Jacinto Basin	6%	350,000	0%	$8,675,000	N/A	N/A
Sims	6%	334,727	19%	$411,565,145	2%	$21,893,485
Addicks	5%	295,694	4%	$83,716,203	6%	$55,030,247
Spring Creek	5%	289,476	0%	$2,375,006	1%	$7,390,500
San Jacinto River	3%	187,570	0%	$1,619,969	14%	$129,409,865
Barker	3%	169,429	4%	$81,274,105	1%	$9,750,868
Frontal Lake Houston	3%	156,472	0%	$7,820	N/A	N/A
Armand	2%	127,350	1%	$16,946,427	1%	$12,211,341
Vince	2%	89,753	0%	$18,084	1%	$5,500,012
Hunting	1%	75,908	8%	$175,921,766	1%	$12,302,286
Carpenters	1%	57,249	0%	$3,866,830	0%	$711,800
Spring Gully & Goose Creek	1%	52,386	1%	$14,440,505	0%	$4,343,553
Cedar	1%	51,840	0%	$416,667	2%	$18,945,343
East Fork San Jacinto	1%	45,890	0%	$166,667	N/A	N/A
Willow	1%	45,890	2%	$37,302,668	1%	$4,914,309
Little Cypress	1%	28,879	1%	$12,777,593	N/A	N/A
Luce	0%	26,000	0%	$166,667	0%	$2,852,650
San Jacinto & Galveston Bay	0%	14,952	0%	$3,310,650	0%	$1,707,825
Jackson	0%	14,014	0%	0	0%	$301,000
TOTAL	**100%**	**5,546,787**	**100%**	**2,167,179,170**	**100%**	**937,331,293**



4 WATERSHED WITH FEDERALLY-FUNDED PROJECTS

There are five watersheds in Harris County with a combined population of over 2.9 million that have ongoing federally-funded projects: Brays, Hunting, White Oak, Greens Bayous and Clear Creek. These projects will reduce flood risk in their respective watersheds, however, it is important to note that their completion will not eliminate flooding in these areas. This issue is fundamental—the currently active FEMA 1 percent floodplain does not reflect our actual flood risk. Moreover, based on new National Oceanic and Atmospheric Administration (NOAA)-projected rainfall totals, it is reasonably certain that flooding during a 1 percent event will continue to extend beyond the existing floodplains. This means at least some areas that these projects were supposed to remove from the 1 percent floodplain will actually remain within it. With this caveat in mind, there are three additional limitations on each project's benefits:

- None of these projects will completely eliminate flooding in the 1 percent design event. In all cases, some neighborhoods remain in the projected 1 percent floodplain.
- Most of the federal projects sole focus is mitigating riverine flooding along the main channels and not on along major and minor tributaries that may also flood homes and businesses.
- Many areas flood because of inadequate drainage systems e.g., storm sewers, ditches, overland sheet flow that are the responsibility of cities, counties, MUDs and Levee Improvement Districts (rather than rising water in channels, which is HCFCD's responsibility).

The project schedules are dependent upon Federal authorizations and appropriations and local commitment to funding a portion of the project (e.g., a "local match"). Many of these projects have fallen behind schedule because Congress and the President did not authorize funding promptly. Thus each project is only partially complete. With the 2018 Congressional funding bill, however, the local match may be all that is required, potentially using HCFCD bonds. The status of each project as of 2016 is as follows (noting that projects with $0 federal funding spent illustrate the extent to which HCFCD has been bearing the burden of funding these projects to maintain progress):

Brays Bayou	$350 million of $480 million spent to date; $203 million of $240 million federal contributions spent
Clear Creek	$55 million of $193 million spent to date; $35 million of $125 million federal contributions spent
Hunting Bayou	$40 million of $110 million spent to date; $0 of $60 million federal contributions spent
White Oak Bayou	$85 million of $124 million spent to date; $0 of $70 million federal contributions spent
Greens Bayou	$19 million of $45 million spent to date; $17 million of $34 million federal contributions spent

These federal projects usually focus on mitigating flooding using structural solutions, including bigger channels; higher, wider bridges; in-line detention along channels; and off-line detention basins. Because of lengthy federal review requirements, modifying these components of the ongoing projects to further reduce flooding will not be practical, but consideration should be given to additional projects along the main channels and their tributaries that can be funded separately from these projects. Where it is not feasible to reduce flooding through additional structural components, buyouts, floodproofing or elevation could be considered to reduce the vulnerability of homes and businesses that remain at serious risk of flooding. The initial suggestions in this section serve as a basis for a more detailed analysis now underway, which will be added in Edition II of this report. Thus these are intended as preliminary observations and not final recommendations.

For More Information

"Policy Brief: Preliminary Analysis of Proposed Federal Flood Control Projects in Four Houston Watersheds and Possible Opportunities for Further Flood Mitigation" by the SSPEED Center at Rice University

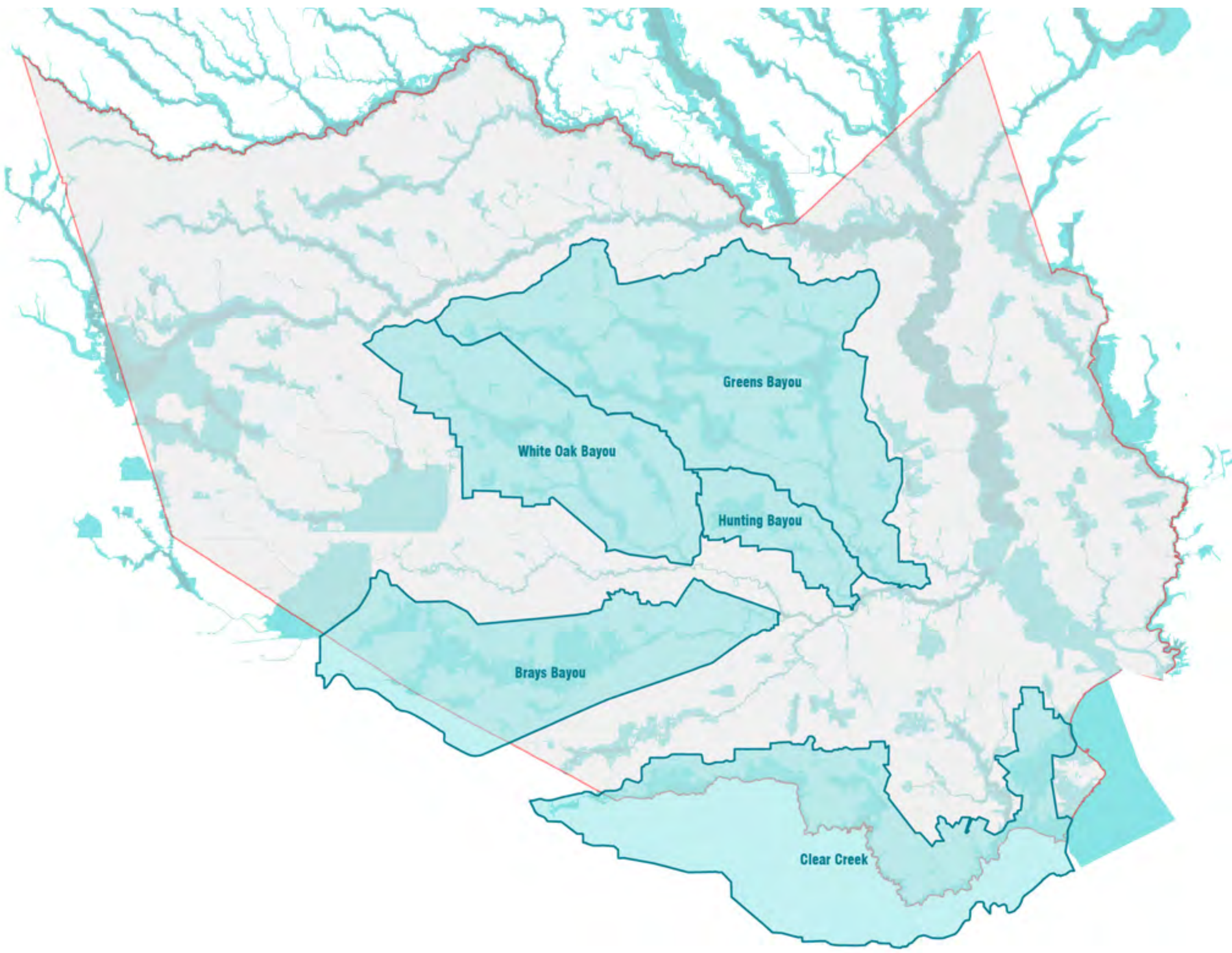


Figure 4.1 Watersheds With On-going Major Federally-funded Projects

Brays Bayou

Brays Bayou is one of Houston's most flood-prone watersheds. It drains approximately 130 square miles of southwest Houston via 124 miles of natural and man-made channels. It is 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.

Repeated flooding prompted the initiation of a second federal project called "Project Brays" in the early 1990s, a partnership between USACE and HCFCD. It consists of four detention basins, channel widening using retaining walls and bridge replacements or renovations. It was originally to be completed in 2014 but is now scheduled to be completed in 2021. Total projected cost is estimated to be $480 million.

During the first phase of construction from 2004-2016, three new detention basins in the upstream portion of the bayou were implemented, including Arthur Storey Park, Mike Driscoll Park and Bishop Fiorenza Park, and a detention basin was added on Willow Waterhole Bayou. Each allows rising water to spill over into these basins during floods. The second phase of the project is underway and consists of widening the channel in more than 18 miles of its middle and lower reaches to increase conveyance capacity and replacing or renovating 30 bridges to allow more flood water to pass beneath them. Project Brays is projected to yield substantial flood reduction benefits, with over 15,000 homes removed from the current 1 percent floodplain. Pre- and post-project 1 percent floodplains along the main channel are shown on the opposite page.

Even though Project Brays will considerably reduce flood damage, recent events have demonstrated that these improvements will not eliminate all flood risk, especially during major floods. For example, Hurricane Harvey damaged over 10,000 flooded houses in the watershed. Areas of significant vulnerability include Braes Heights to Meyerland inside and outside the West Loop; areas along Keegan's Bayou; and portions of Alief, although flooding also occurred along MacGregor Drive where the channel has been widened but bridges have not yet been replaced. Even with the current 100-year design storm, significant areas, including residential neighborhoods, will remain in the floodplain. To reduce flooding in these areas beyond what Project Brays will accomplish upon its completion, the following should be considered:

- Additional detention basins can reduce flooding in highly vulnerable houses closest to the bayou in Meyerland. Given the dense development upstream of Meyerland, land available for detention is limited. One approach would be to reconfigure existing green spaces to store floodwaters during major flood events, while maintaining their existing park functions.
- Brays is tightly bounded by roadways and development along most of its length. Buyouts of homes and businesses along the bayou may allow for channel improvements and in-line detention in key areas, or to create green space.
- The flooding issue along Brays is exacerbated by low-lying homes. Continuing efforts to elevate homes, or replacing homes with new homes at a higher elevation, could greatly reduce damage and human impacts.
- Almost the entire watershed is within the city of Houston, and significant areas flooded due to inadequate drainage systems and poor overland water flow flooding structures. These areas can be addressed with local drainage improvements.
- Brays Bayou floodplains are generally broad but shallow, and retrofitting to floodproof structures can be an effective strategy in many areas.

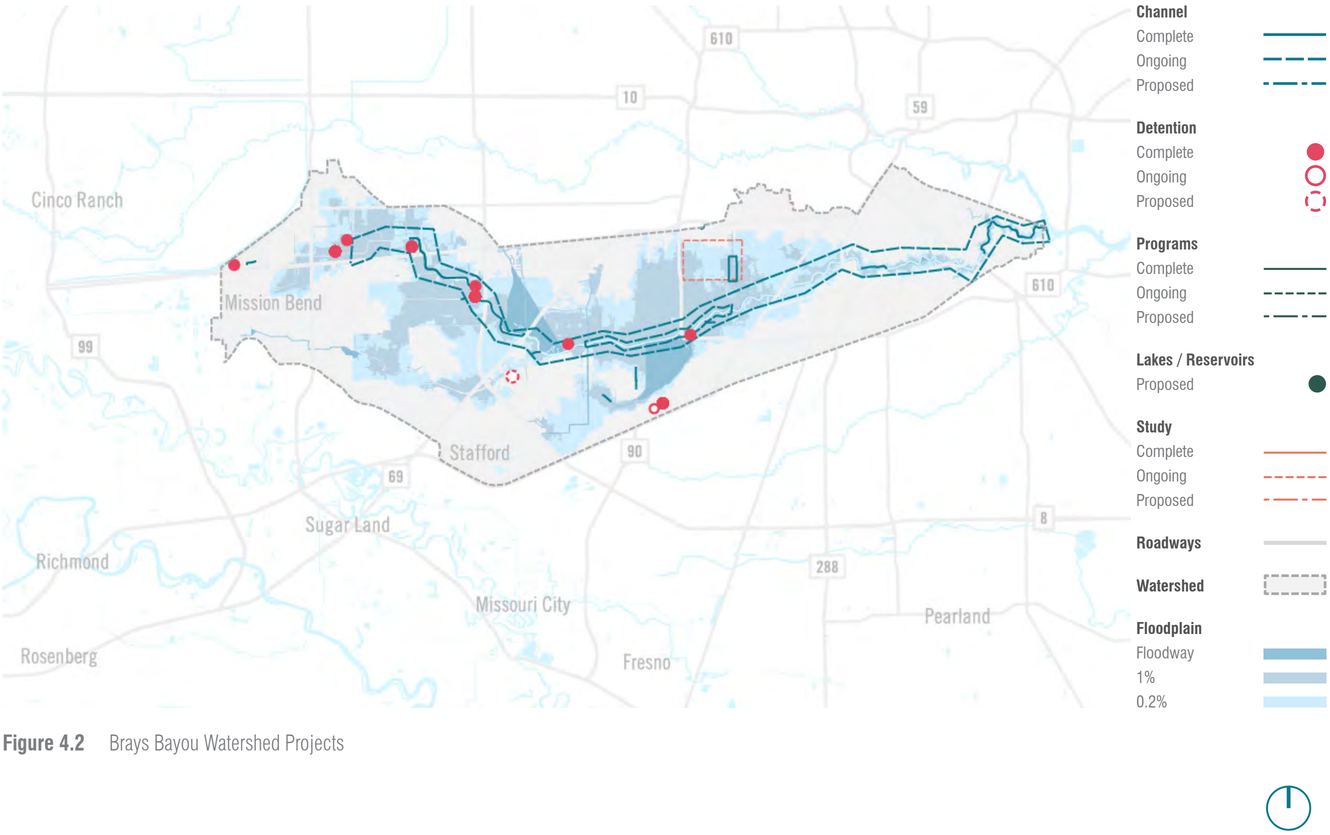


Figure 4.2 Brays Bayou Watershed Projects

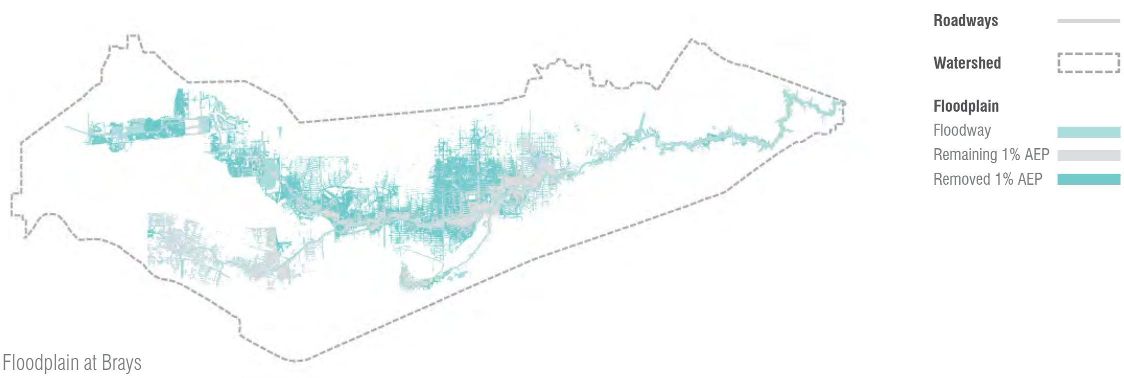


Figure 4.3 Residual 1% Floodplain at Brays Bayou After Project Completion

Clear Creek

Clear Creek forms the southern border of Harris County and the northern border of Galveston and Brazoria counties. Its watershed includes Pearland, Friendswood, Webster, League City and southern parts of Houston. Clear Creek flows into Clear Lake, which is also the outlet for the Armand Bayou watershed, and then into Galveston Bay. 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. A series of parks in this area help preserve the waterway. The upper channel has been cleared, somewhat straightened, graded but not lined in concrete.

There has been a history of flooding in the watershed. While in some spaces the floodplains are contained, in other areas the 1 percent and 0.2 percent floodplains extend several miles from the channel. The mouth of the channel is subject to storm surge from Galveston Bay.

The federal project for the Clear Creek watershed was initiated in 1986, then put on hold in the late 1990s. The work completed by that point included:

- A second outlet channel from Clear Lake to Galveston Bay, with a gated control structure. This was designed to add capacity for upstream floodwaters while retaining the ability to shut the gates to keep storm surge out of Clear Lake.
- Plans and ROW started from Clear Lake to SH 3 (3.5 miles);
- Bridges – 8 of 11 bridges had been replaced or modified;
- Utility adjustments - Almost completed up to SH 3; and
- Soil placement areas - 1 completed.

Later in 2013, the project was resumed. The current scope consists of the following features:

- Clear Creek - 15.1 miles of channel rectification from Dixie Farm Road to State Highway 288, and a 500 acre-foot in-line detention basin
- Mud Gully - 0.8 miles of channel rectification
- Turkey Creek - 2.4 miles of channel rectification
- Mary's Creek - 2.1 miles of channel rectification and a 900 acre-foot detention basin

These projects are being implemented by HCFCD, Galveston County and Brazoria Drainage District #4.

These projects are projected to remove 2,100 homes from the mapped 1 percent floodplain. However, 1,570 homes would remain in the floodplain, and further upstream development could increase that number.

Because Clear Creek is on a county line, regulation is even more patchwork than it is in other watersheds. Following Hurricane Harvey, Friendswood has been applying 1999 floodplain maps to new development, rather than using 2007 maps that show a higher floodplain. Thus, homes that flooded in Harvey are being rebuilt at elevations that are well below the currently mapped flood levels.

Strategies to further mitigate flooding in the Clear Creek watershed include:

- Buyouts in repeat flooding areas
- Local drainage improvements
- Stronger development regulations
- Floodproofing of homes in shallow flooding areas
- Additional detention projects
- Habitat preservation and restoration

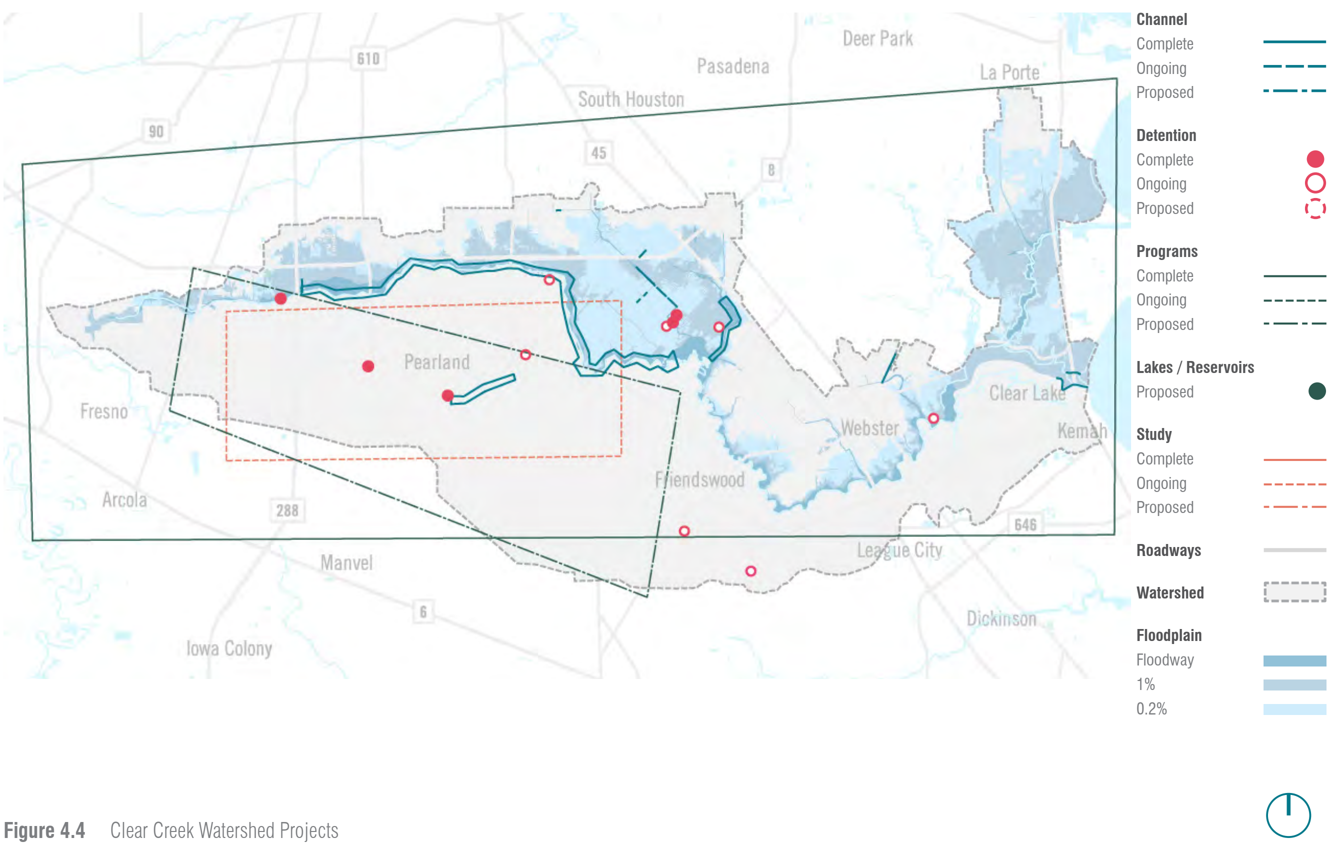


Figure 4.4 Clear Creek Watershed Projects

Greens Bayou

The Greens Bayou watershed covers approximately 212 square miles, with 308 miles of open streams and a population of 528,720. The main channel flows eastward, then southward into the Houston Ship Channel. This southbound stretch consists of existing channel improvements upstream of U.S. Highway 90 and a three-mile navigation channel along the most downstream section of Greens Bayou. There are three other significant tributaries in the watershed: Garners Bayou, Halls Bayou and Reinhardt Bayou. Halls Bayou is currently being studied by HCFCD as part of the "Halls Ahead" project.

HCFCD owns and operates a 961-acre wetland mitigation bank in northeast Harris County where Greens Bayou takes its southward turn just inside Beltway 8. The Greens Bayou Wetland Mitigation Bank is an excellent example of green infrastructure forming a system of ponds, marshes and forests that help to offset flooding on Greens Bayou downstream. It is the most successful example of a mitigation bank in the greater Houston region based on criteria that include quality of wetlands, close proximity of the mitigation site in relation to wetland impacts and transparency in management.

Greens Bayou has flooded repeatedly during the last two decades. The current 1 percent and 0.2 percent floodplains are shown on the opposite page. One of the watershed's most flood-prone areas is Greenspoint, which is located in the upstream section between Interstate 45 and the Hardy Toll Road. It has one of Houston's largest concentrations of apartment complexes, and many of its residents live below the poverty line. In a 2012 study, more than 70 percent of the multi-family units in Greenspoint were found to be within the 1 percent floodplain, and, a substantial portion are in the floodway. Widespread flooding also occurred along Halls Bayou in the Mesa Road area where whole neighborhoods went under multiple feet of water.

HCFCD recently built several large detention basins along upper Greens Bayou and two more along Halls Bayou west of Interstate 69. With recent federal funding, two more detention basins are being built now, one north of Beltway 8 near Kuykendahl, and one just east of Interstate 45. HCFCD also is building a third detention basin on Halls Bayou immediately east of Interstate 69. HCFCD also has several buyout areas of interest downstream of Greenspoint and has plans for more detention basins in that area. It also is in the early stage of a channel widening study. To reduce flooding further, the following should be considered:

- Develop a comprehensive housing and flood mitigation plan for Greenspoint, combining flood control infrastructure and demolition of flood-prone apartment complexes with the construction of new affordable housing that is either outside the floodplain or elevated to keep it out of floodwaters.
- Below the HCFCD wetland mitigation bank, adjacent land uses consist of parkland and industrial uses/landfills with a mix of residential areas near Tidwell Road and south of U.S. Highway 90. Given these conditions, an approach in this area may be to buy out properties and create a significant green space system along the channel, which remains largely natural.
- Flooding immediately upstream of the wetland mitigation bank occurs on land used for a golf course and large cemetery with only limited commercial and residential development. It may be best to focus on land acquisition in this area rather than implement expensive structural improvements.
- Once the additional detention basins upstream of Greenspoint are completed, and those downstream of Greenspoint are added, open up the constriction point at the Union Pacific Railroad bridge at the Hardy Toll Road. These actions are likely to reduce the floodplain in Greenspoint significantly.
- HCFCD is conducting a separate study for Halls Bayou. In addition to the detention basin that is under construction, some channel widening may be justified along with studies of three railroad trestle bridges that may be impeding water flow. Several large city parks and additional land (recently acquired by the Houston Parks Board) should provide an opportunity to widen the channel (in conjunction with parks and trails improvements) without relying on extensive gray infrastructure.

Notes

Gonzalez, Jacob et al. "Toward wetland protection in the Houston-Galveston region: assessing mitigation practices and facilitating watershed-based decision-making". (2017). HarcResearch.org/publication/1866

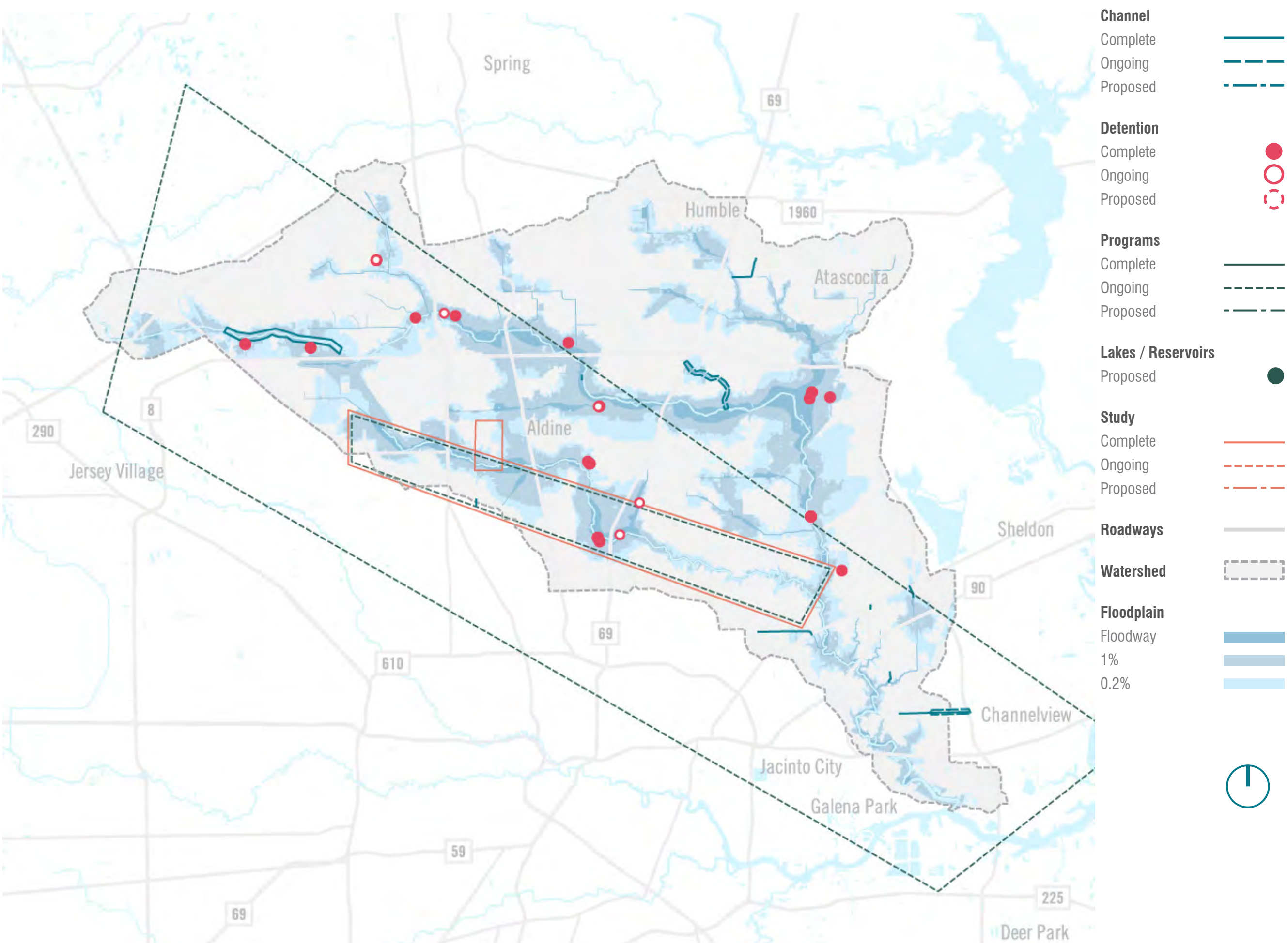


Figure 4.5 Greens Bayou Watershed Projects

Hunting Bayou

Hunting Bayou drains approximately 30 square miles from the Hardy Toll Road near Loop 610 Northeast and then south to the Houston Ship Channel. Its watershed is located primarily within Houston with smaller areas in Galena Park and Jacinto City. It contains about 45 miles of open streams, many of which are natural, winding, small and shallow. In 2010, the watershed's population was 75,908.

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.

"Project Hunting," a $176 million federal project is currently under construction from Interstate 69 downstream to North Wayside Drive, roughly at Liberty Road. The project will widen about four miles in this upstream reach, replacing or modifying 20 bridges, including a series of railroad trestle bridges at the Liberty Railroad Yard, and add a stormwater detention basin between the bayou and Trinity Gardens the basin is partially built and is scheduled for expansion. In addition, flood benches are being implemented upstream of this basin in Kashmere Gardens. When complete, it will significantly reduce the size of the floodplain and remove approximately 87 percent of the structures currently subject to a 100-year flood, the majority of which are located in the upstream portion of the watershed.

Although repeated flooding has occurred in the Northshore area south of U.S. Highway 90 East to Interstate 10 East, this lower reach is not included in the project's scope. This reach of the Authorized Project was dropped in part due to its environmental impacts through this area. HCFCD, however, has been conducting buyouts along the immediate channel. After the federal project is completed, the floodplain in the midstream portion of the watershed, between Liberty Road and U.S. Highway 90, will also remain. This area is mostly comprised of industrial and commercial properties, with some residential subdivisions in the land use mix. Beyond what Project Hunting will accomplish upon completion, the following should be considered to reduce flooding in these areas:

- An old railroad trestle bridge parallel to Market Street south of Interstate 10 East may be impeding floodwaters, and its replacement may reduce flooding in the Northshore area. South of this point, the bayou quickly reaches a Port of Houston dredge disposal area where flooding is not a concern.
- Herman Brown Park is located in the mid-to-lower portion of the watershed and has potential flood storage capacity. It is important to note that it may not be in an ideal location to reduce the residual floodplain. If channel improvements were made in the midstream portion of the watershed to reduce flooding, however, Herman Brown Park could be considered as a detention site to avoid increasing the size of the floodplain downstream in the Northshore area where continued buyouts may be the most pragmatic strategy.
- Modifying the mid-stream reach of the main channel could further mitigate riverine flooding in the mid-stream portion of the watershed.
- Sheet flow across properties and into homes and businesses could be addressed by improving local drainage along roadside ditches or bypass channels to alleviate flood risk. It may be possible to construct new drainage channels in the Kashmere area that discharge into Hunting Bayou further downstream, reducing local drainage issues and reducing the amount of water in the relatively shallow upper portions of the bayou
- Many of the areas of Kashmere Gardens that remain in the floodplain will be subject to relatively shallow flooding. In these areas, elevating existing homes, or building new homes with higher floor elevations, could make a significant difference. This could be coordinated with an affordable housing program to maintain a supply of affordable housing in the neighborhood and allow existing residents to stay in the neighborhood.

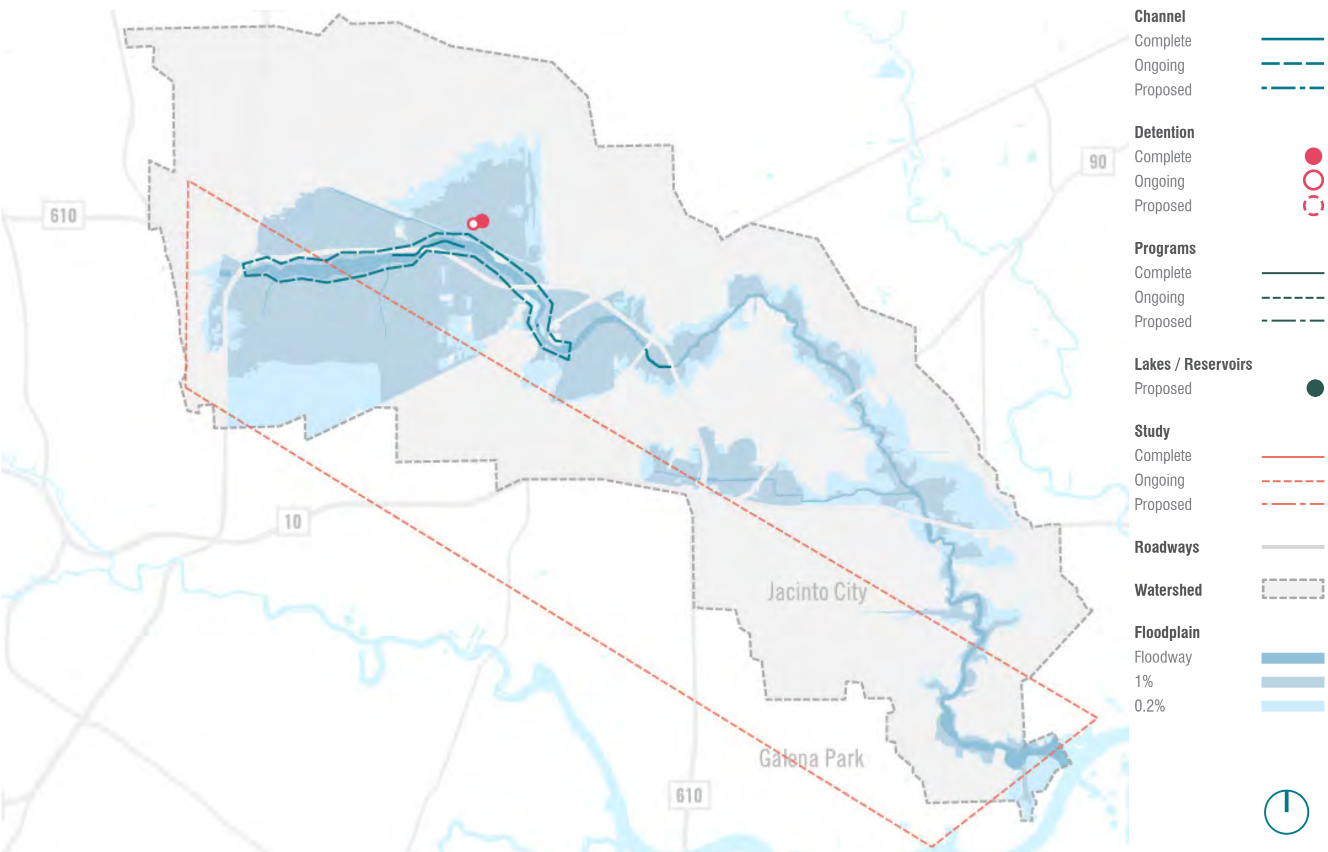


Figure 4.6 Hunting Bayou Watershed Projects

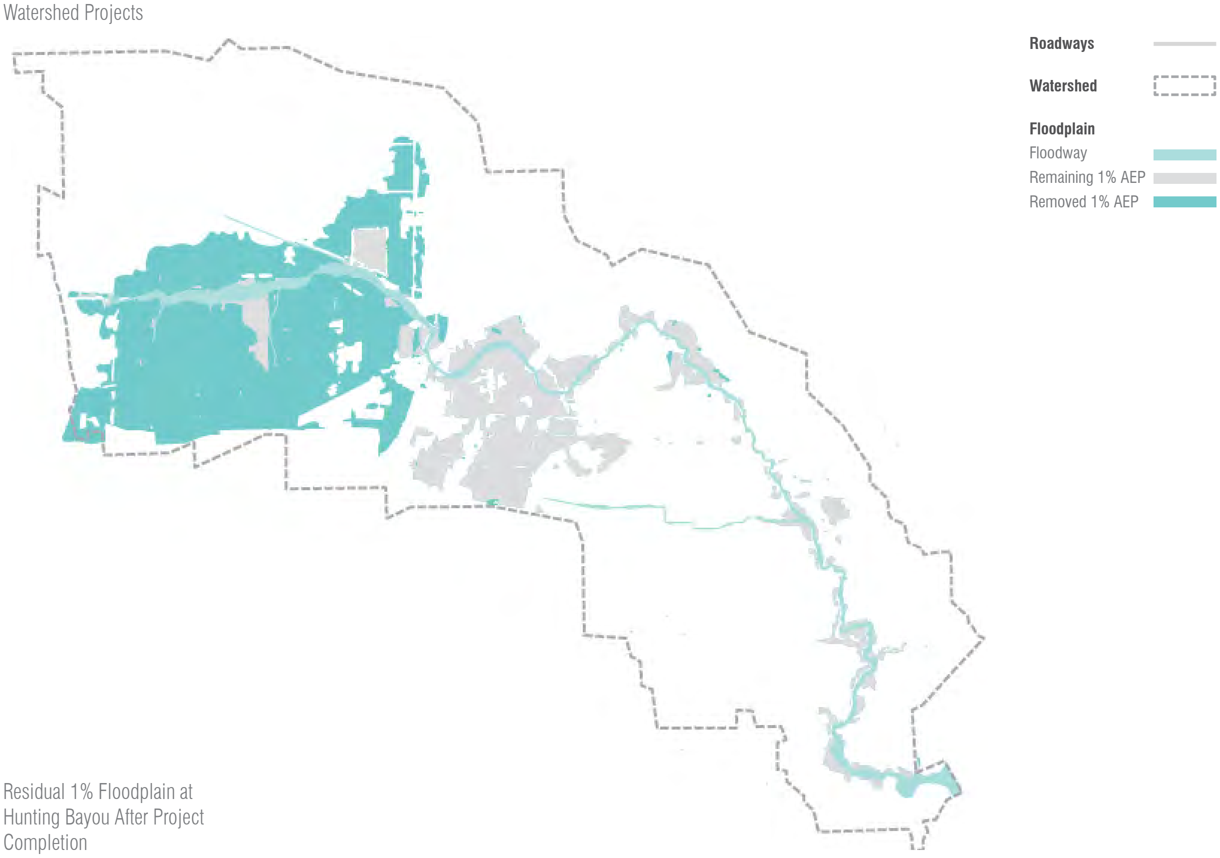


Figure 4.7 Residual 1% Floodplain at Hunting Bayou After Project Completion

White Oak Bayou

White Oak Bayou originates in northwest Harris County and flows southeast for about 25 miles through Jersey Village and Houston where it joins Buffalo Bayou in the north end of downtown. The watershed drains about 110 square miles and is roughly 90 percent developed with a population of 433,250. Major tributaries include Little White Oak Bayou, Brickhouse Gully, Cole Creek and Vogel Creek.

A 10.7-mile federal channel project from Allen's Landing in downtown to Cole Creek, which is located a few miles outside Interstate 610, was completed in the mid-1970s to address flooding in the lower and middle reaches of the main channel. As development proceeded upstream, significant flooding occurred along the bayou just upstream of this federal project. HCFCD sought to address the resulting flooding with additional upstream channel improvements and regional detention basins. However, significant flooding continued to impact the entire bayou. For example, in 1998, Tropical Storm Frances damaged about 1,200 homes, and in 2001, Tropical Storm Allison damaged 11,000 homes.

"Project White Oak" is an ongoing $166 million federal project that will substantially reduce flooding and is designed to contain the 10-year flood event within the channel's banks. The federal-HCFCD partnership began 1998 and is approaching completion. It includes six detention basins, about 15.4 miles of channel improvements upstream of Cole Creek to FM 1960, and the Jersey Village Diversion Channel. When complete, water levels will go down by 0.5 to 1.5 feet during a 1 percent flood event and average annual damages should decline from $61.2 million to approximately $25.7 million. See the opposite page for the residual 100-year floodplain after the project is completed.

However, significant flooding will still occur along the main channel in the mid portion, between Beltway 8 and Interstate 610, and lower portion, downstream of Interstate 610, of the bayou during extreme flood events, and many homes in this area will still be located deep in the floodplain. Using current rainfall rates, approximately 1,333 homes will remain within the 10 percent floodplain and 6,074 structures will remain within 1 percent floodplain. To reduce flooding in these areas beyond what Project White Oak will accomplish, the following should be considered:

- Implement the North Canal Bypass channel in downtown to increase the conveyance of storm water out of White Oak Bayou by bypassing Allen's Landing to Buffalo Bayou's wider channel downstream.
- Elevate or reduce the columns of roadway, old railroad and utility bridges, especially upstream of Studemont to Yale Street. Along with the North Canal, this work could remove almost all homes south of Loop 610 from the current 1 percent floodplain.
- Redevelop abandoned apartment complexes/properties in the mid-to-upstream reaches as green space and detention or build new more flood- resilient housing there.
- Add detention basins on all upstream tributaries.
- It may be best to buy out, elevate or floodproof remaining homes located deep in the floodplain.
- Because of extensive publicly owned land below Studemont Street, it may be possible to remove the concrete lining (which is reaching the end of its design life) as part of an overall plan to improve spatial quality in the watershed.

White Oak Bayou has several significant tributaries that are not addressed by the federal project. Little White Oak Bayou, Cole Creek and Brickhouse Gully have large floodplains and neighborhoods that have experienced repeated flooding, and current projects do not address these. There are significant opportunities to address this:

- Much of the flood problem on Little White Oak is related to culverts and channels built in conjunction with the original construction of Interstate 45, such as the constriction point at the culvert under Interstate 610 that appears to increase flooding in Independence Heights. These issues can be addressed as part of the planned North Houston Highway Improvement Project to address flooding along Little White Oak.
- Additional channel work, detention basins and/or buyouts along Cole Creek and Brickhouse Gully would serve to reduce flooding in these areas.

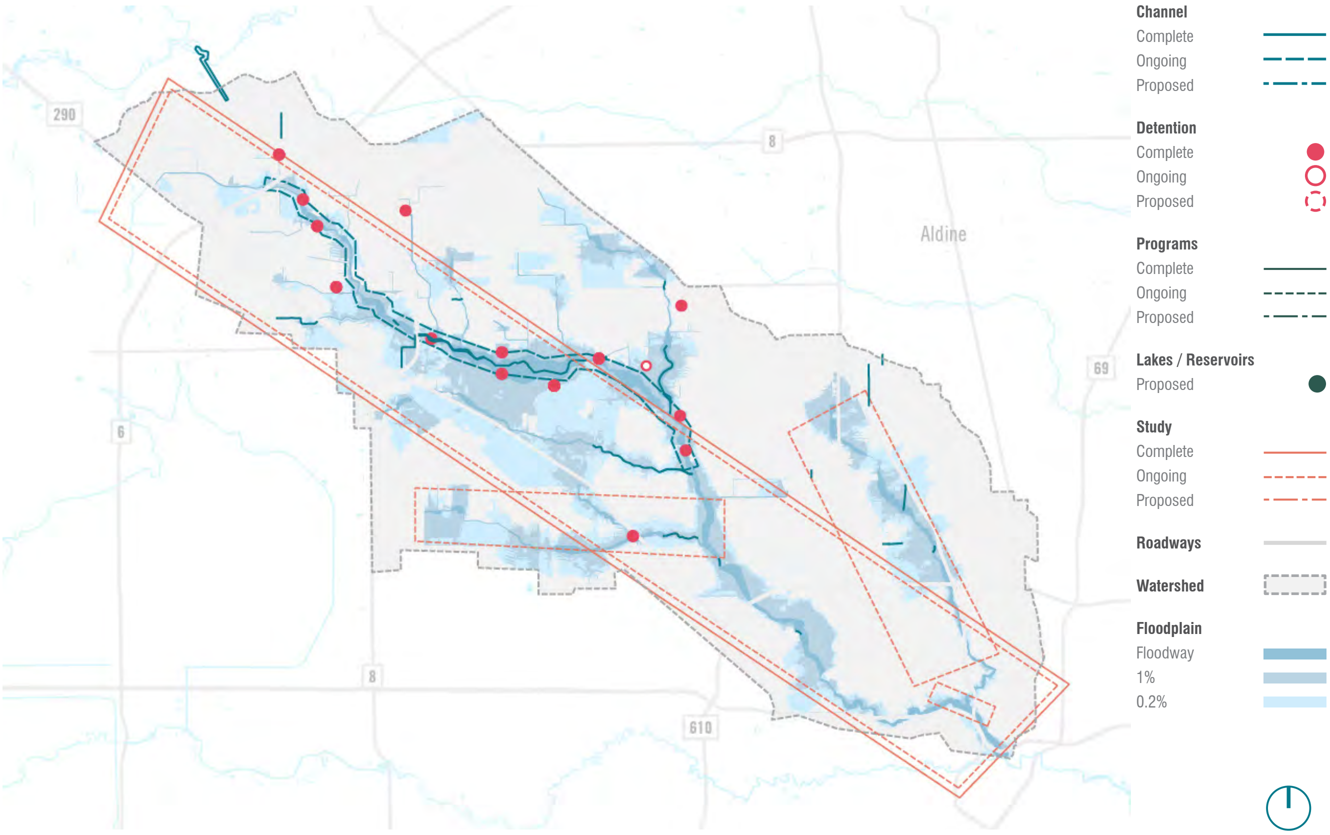


Figure 4.8 White Oak Bayou Watershed Projects

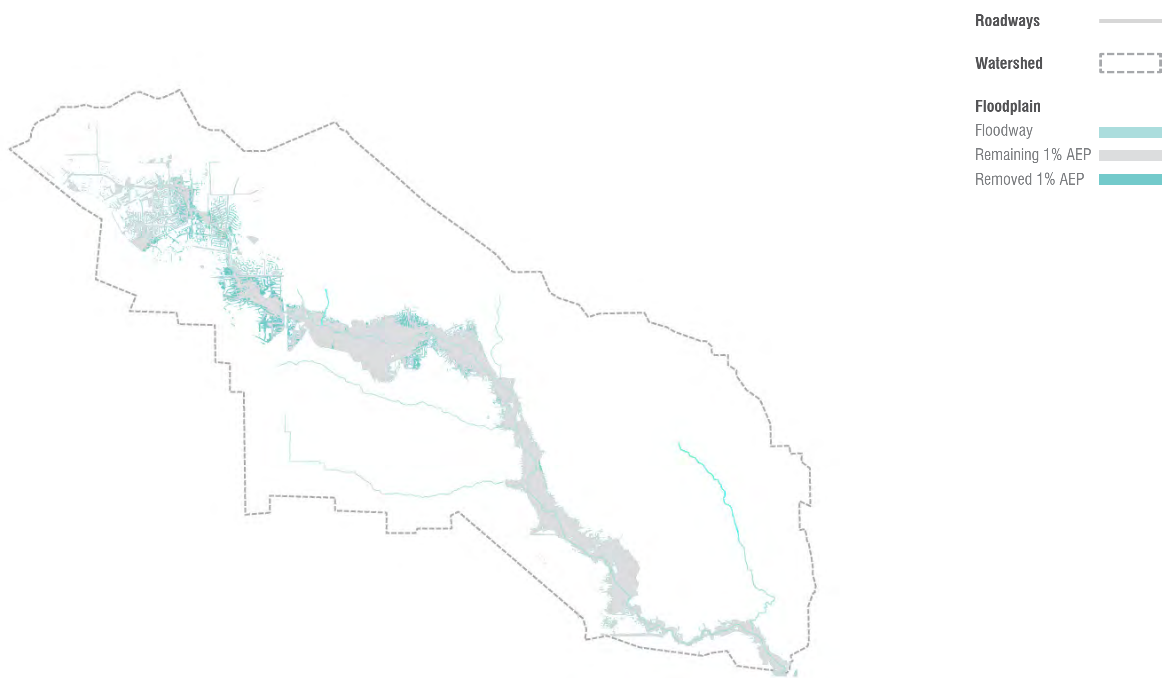


Figure 4.9 Residual 1% Floodplain Along Mid White Oak Bayou After Project Completion

5 WATERSHEDS WITHOUT OPEN FEDERAL PROJECTS

As Section IV indicates, the absence of an ongoing federally funded project does not mean that a watershed should not be a priority for investment in flood mitigation. Seven watersheds experienced much higher total damages than the other 22 in Harris County, but four of them have no ongoing federally funded project at this time.

This section summarizes conditions, challenges and ideas for flood mitigation in each watershed, but it is important to note that good data is not available in most cases because such data usually is generated as part of a major project. The watersheds are designed in accordance with their population size with the "third reservoir," Addicks and Barker reservoirs, Buffalo Bayou and Cypress Creek first because of the very large combined population of these interrelated watersheds. The watershed with the most unique challenges is the combination of the San Jacinto River above Lake Houston and "Frontal Lake Houston," which includes the properties surrounding the lake itself, many in Kingwood. The combined Harris County population of these watersheds is about 506,000. Another 400,000 people live in the San Jacinto River and East San Jacinto River watersheds outside of Harris County.

The remaining 10 watersheds are not insignificant—they have a total population of just fewer than 900,000 people. One half of this population total lives in the Spring Creek watershed in northern Harris County or the Armand Bayou watershed in the Clear Lake area. These watersheds are included at the end of this section.

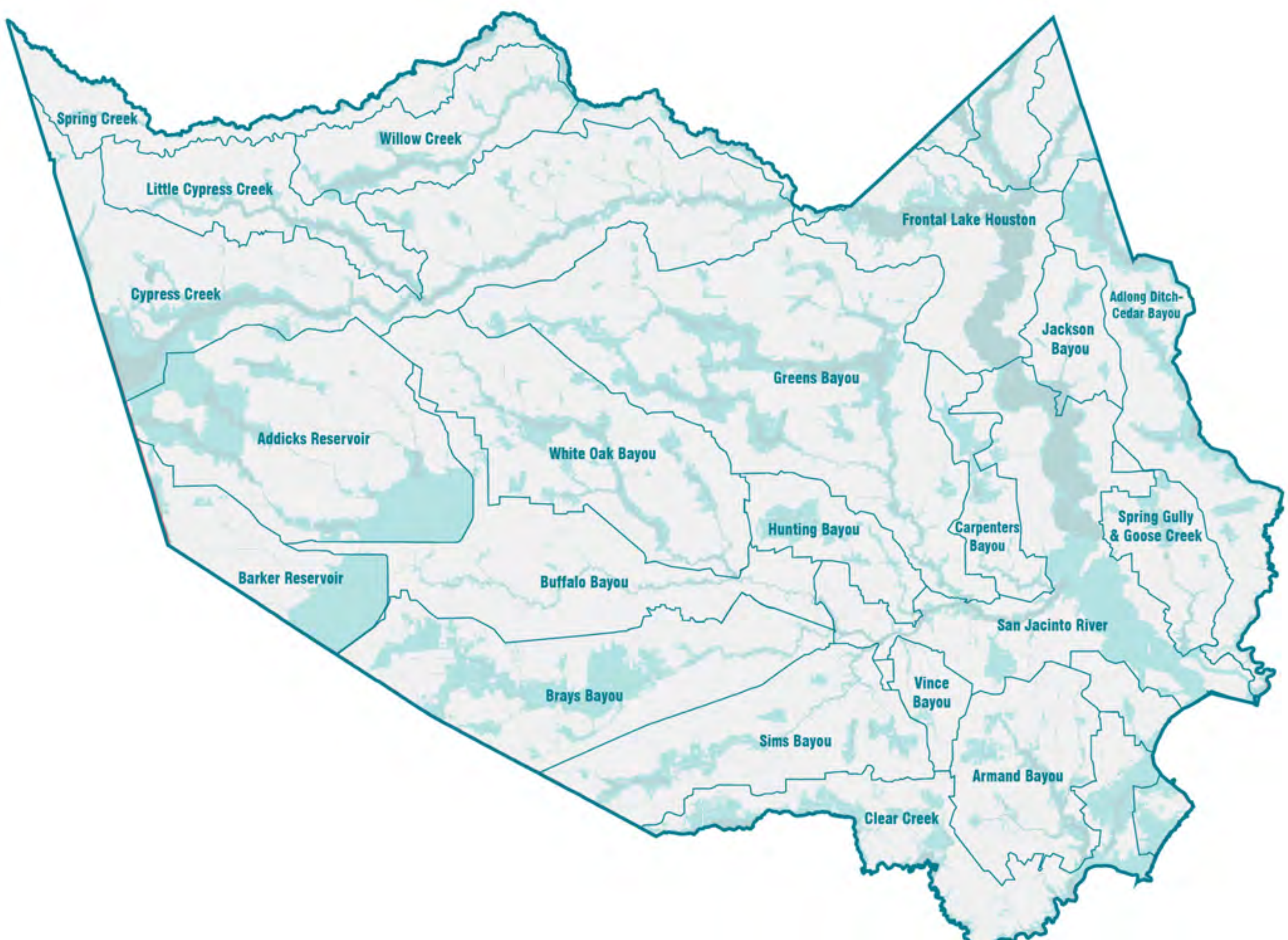


Figure 5.1 Harris County Watersheds

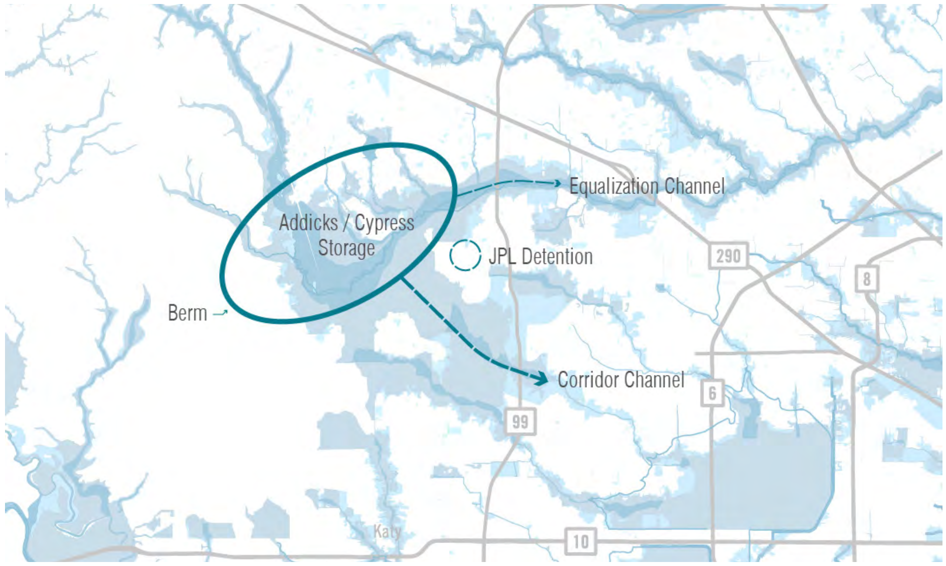
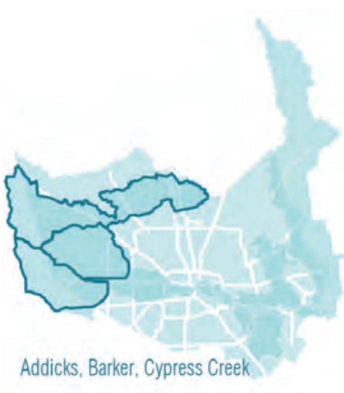


Figure 5.3 Third Reservoir Plan 5



Addicks, Barker and Upper Cypress Creek

Few watersheds have garnered as much attention after Hurricane Harvey as the Addicks, Barker and Buffalo Bayou watersheds. Many neighborhoods upstream of Addicks and Barker flooded; releases from the dams put sections of the Energy Corridor and Memorial underwater for weeks; and the Downtown Theater District was devastated. This damage has focused discussion on the reservoirs and on potential flood control projects, including the "third reservoir."

In many ways, however, this watershed is a success story. As noted in Section III, large reservoirs at the upper end of watersheds can be highly effective, and the 75-year history of Addicks and Barker Reservoirs is a case in point. Until Hurricane Harvey, few homes flooded in the Buffalo Bayou watershed while neighborhoods along other bayous flooded repeatedly. A gradual reduction in the reservoirs' capacity (due to silt and vegetation) has reduced its effectiveness, but Buffalo Bayou still has significantly better flood protection than other watersheds. If they are maintained in a state of good repair, in their current configuration, Addicks and Barker reservoirs provide better than one percent protection for the Buffalo Bayou watershed. Other watersheds in greater Houston do not receive that level of protection and will not, even if the federal projects underway in these watersheds are completed.

That said, there are significant issues in the Addicks, Barker and Buffalo watersheds. Many relate to the reservoirs but are often distinct challenges, such as:

- Uncertainty about the integrity of Addicks and Barker dams.
- Flooding along Buffalo Bayou downstream from Addicks and Barker due to reservoir releases.
- Flooding of neighborhoods within the flood pools of Addicks and Barker.
- Uncontrolled flooding downstream from Addicks and Barker spillways at far ends of the dams. It is not fully understand where water that spills over the spillways would go, which both leads to uncertainty in a flooding event and may lead the USACE to release more water downstream to avoid the water level overtopping the spillways.
- Increased runoff due to new development upstream from Addicks and Barker.
- Flooding of undeveloped land north of Addicks due to the Cypress Creek overflow.
- Flooding in the Cypress Creek watershed.

For More Information

See Briefing Document 2: Addicks and Barker Reservoirs

The first issue noted above is worth emphasizing – data indicate that if either the Addicks dam or the Barker dam were to fail, there could be extensive loss of life and property damage across a wide swath of Houston. The condition of these dams is not publicly known; it is possible major investment is required to ensure the dams are safe and thus to preserve the current level of protection.

Because of these uncertain but considerable risks, it is critical that the agencies responsible for these watersheds fully disclose the risks and level of flood protection to the public.

There are many possible strategies to address flooding issues in western and northwestern Harris County, the Addicks/Barker/Buffalo Bayou watersheds and the Cypress Creek watershed. These include:

- Conducting a detailed study and risk analysis of Addicks and Barker reservoirs and implementing dam improvements as required to minimize risk of failure when reservoirs are full.
- Changing or clearly defining operational procedures for Addicks and Barker to release as much water as possible without creating downstream flooding in order to hold more water entering the reservoirs from upstream areas.
- Increasing capacity inside Addicks and Barker by clearing out vegetation and excavating silt deposits.
- Modeling flow of water if water overflows the spillways and then improving those spillways and overflow channels so that the full volume of the reservoirs can be used.
- Connecting Addicks and Barker to allow water transfer between reservoirs when one is fuller than the other.
- Buying out, elevating or floodproofing homes that are within the flood pools up to the spillway elevation.
- Preserving lands that store water, including at least 30,000-50,000 acres of the Katy Prairie (an amount researchers have determined would be sufficient to provide local and downstream benefits) and nearby agricultural lands.
- Restoring portions of the Katy Prairie that have been converted to agricultural land, increasing the flood control benefit of that land.
- Adopting stricter detention, infrastructure and development regulations for new development.
- A new reservoir designed to mitigate future development upstream of Addicks Reservoir
- A new reservoir design to mitigate current flooding in the Cypress Creek watershed.

There has been extensive study of a new reservoir upstream of Addicks Reservoir. During a major rain event, there is a massive overland flow of floodwater from the Cypress Creek watershed into streams feeding Addicks Reservoir. This is unusual since water is flowing from one watershed to another, but it is an outcome of the natural topography, and it was not a problem when the area was undeveloped since the natural ecosystems of the Katy Prairie handled these flows easily. Without this overflow, the already significant and repeated flood damage in Cypress Creek would be considerably worse.

The "Plan 5" reservoir defined by the Cypress Creek Overflow Study was specifically designed to address future development upstream of Addicks reservoir, not to address any shortcomings of Addicks and Barker or to prevent flooding in Buffalo Bayou. It would capture Cypress Creek overflows, hold that water and release it slowly into Addicks Reservoir through well-defined channels. Thus, the biggest outcome of the reservoir would be to eliminate the overland flow across the open land north of Addicks Reservoir. This would open up 18,000 acres of currently flood-prone land for development. The study explicitly accounted for this development, and the mitigation of increased runoff caused by the conversion of slowly draining agricultural land and native prairie to subdivisions with fully developed drainage systems was one of the goals of the study. However, the Cypress Creek Overflow Study did not have the goal of reducing the inflows into Addicks and Barker Reservoirs, reducing downstream flooding on Buffalo Bayou or reducing downstream flooding on Cypress Creek. This version of the "third reservoir" was not designed to solve any of the problems experienced in Harvey; it was designed to enable more development in the Katy Prairie.

A different reservoir, in the same area but with very different design goals, could be of real benefit to Cypress Creek, which has significant flooding issues. A reservoir in the upper Cypress Creek watershed that is designed to hold water that would otherwise drain into Cypress may be able to reduce flooding in that watershed. Such a reservoir would require new analysis because the Cypress Creek Overflow Study did not attempt to study flooding in this watershed.

The undeveloped land in northwest Harris County already plays a vital role in flood mitigation. The native prairies soak up water, reducing flooding downstream. Merely preserving this valuable habitat is an effective flood control strategy. Any reservoir plans would need to consider the impact of a reservoir on this area. A deep reservoir like Addicks and Barker that holds water for an extended period will destroy the native prairie ecosystem. A shallow reservoir that holds water only for a few days may be able to function without impacting native plants. This is important because this is some of the most critical natural habitat in the region. The Katy Prairie Conservancy, an organization committed to preserving this natural habitat, owns or has conservation easements in place in this area.

As individual strategies and combinations of strategies are studied, there are some key policy questions that should be considered:

- What are the flood mitigation goals in these watersheds?
- Which strategies achieve these goals most cost-effectively?
- Should new infrastructure address flooding in currently undeveloped land thus opening it up for development? Should developers bear that cost or should that land remain undeveloped?
- What level of protection should this area have? If Harvey was more than a 1 percent event, should we design for future “Harveys” in this portion of the region when other watersheds are being designed for a 1 percent (or even 10 percent) event?

Strategies	Problems: Uncertainty about the integrity of Addicks & Barker dams	Flooding downstream from dams due to reservoir releases	Flooding within flood pools of Addicks & Barker	Flooding downstream from Addicks & Barker spillways	Increased runoff upstream of Addicks due to expected future development	Flooding of undeveloped land upstream of Addicks due to Cypress Creek overflow	Flooding in the Cypress Creek watershed
Detailed study and risk analysis of the dams	●						
Dam improvements as required	●						
Change or clearly define operational procedures for releases		●					
Clear out vegetation inside Addicks & Barker		●	●				
Excavate silt deposits inside Addicks & Barker		●	●				
Connect Addicks and Barker to allow water transfer between reservoirs		●					
Improve spillways & overflow channels		●					
Model flow of water if water overflows into spillways		●	●	●			
Buy out homes up to the spillway elevation			●	●			
New channels carrying water away from spillways if required				●			
Preserve agricultural & natural land instead of developing it	●				●	●	●
Increased detention, infrastructure, and development regulations for new development	●				●		
Preserve Katy Prairie	●				●	●	●
Reservoir upstream of Cypress Creek							●

Lower Cypress Creek

Current trends in Harris County indicate significant amounts of new development and thus increased impervious ground in the upper part of the Cypress Creek watershed. This will add more stormwater to a watershed that has already had repeated substantial flooding.

HCFCD has undertaken and completed several channel improvements in this watershed in the past years using up-to-date technology, including improvements utilizing fluvial geomorphology science. HCFCD spent over $3.5 million on repairing erosion and desilting along Cypress Creek; a detention basin was completed in 2013; and there have been several erosion repair projects on tributaries. Also, a key flood control project along Cypress has been Harris County Precinct 4's work in partnership with the Cypress Creek Flood Control Coalition to acquire land along the bayou—preserving the natural floodplain and opening it up for recreational use. These additional measures (at a substantial scale) are needed to address the flooding issues in this watershed.

The following strategies address flooding issues along Cypress Creek:

- A detailed flooding study along the creek would contribute to a better understanding of the problem.
- As noted in the prior section, a reservoir in the upper reaches of Cypress Creek would provide significant flood control benefits if it were designed to address existing flooding issues.
- Continued acquisition of undeveloped land along Cypress Creek, along with buyouts, would give the bayou room to flood without affecting people or structures.
- Flooding in the upper watershed would be addressed by limiting future development to preserve prairie and agricultural land or by implementing stricter development regulations in that area such as greater detention and open foundation systems.

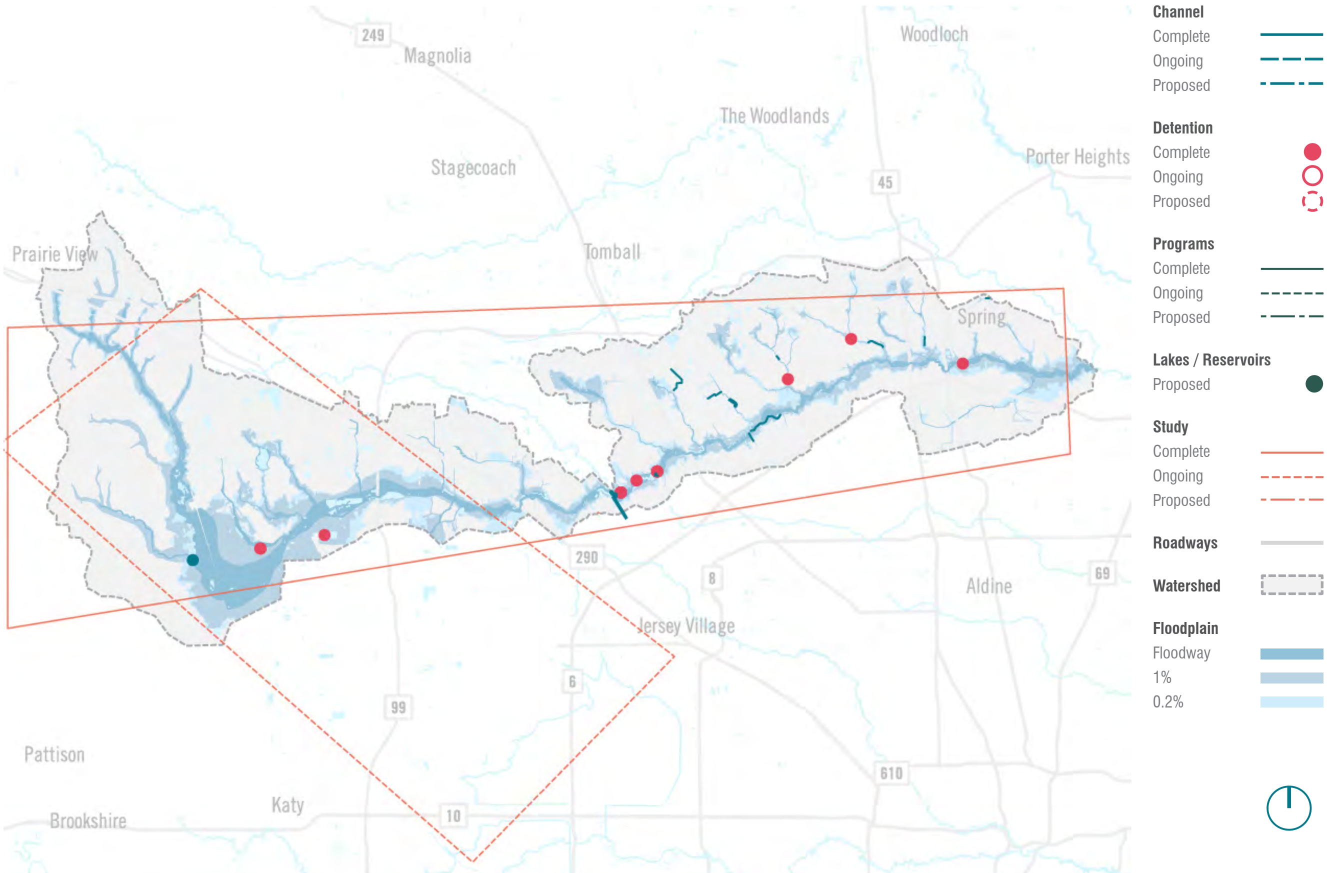


Figure 5.4 Figures for Cypress Creek

Buffalo Bayou

As noted in the previous sections, the reservoirs in the upper reaches of Buffalo Bayou have worked remarkably well. Even in Hurricane Harvey, where record-breaking rainfall overwhelmed the reservoirs, Buffalo Bayou did not see the extent of flooding as other watersheds. The comparatively lower density of development in the Buffalo Bayou watershed also contributed to its lower rates of flooding because more pervious areas and green infrastructure, including natural streams, open ditches and swales, slowed floodwaters down and allowed some water to be absorbed before running off.

As a result, flooding was not a major issue on Buffalo Bayou until Hurricane Harvey (except in the downtown's Historic District and Theater District). Due to several factors, including: a combination of the reservoirs; many natural drainage systems; park space that the bayou can spread into in a flood event; and lower-density development that reduces run-off, the watershed performs well. If capacity of the reservoirs is improved to better manage a Harvey-scale event, most flooding issues on Buffalo Bayou should be mitigated except in the downtown area.

A key challenge on Buffalo Bayou is erosion and bank failures. Large areas of Memorial Park have been lost to erosion and the channel east of downtown suffered from major bank collapses during Harvey due to unusually high water volumes over an extended period of time. Buffalo Bayou's largely natural channel requires sensitivity in implementing erosion control measures and long sections of the bayou banks are in private ownership.

The following strategies address flooding issues along Buffalo Bayou:

- Addressing the challenges of the Addicks and Barker reservoirs would address many of the challenges along Buffalo Bayou.

- Erosion is a primary issue between the reservoirs and downtown. Developing a strategy to address this erosion that does not impact the natural character of the bayou and without the aim of increasing conveyance capacity is critical.

- The proposed North Canal project on White Oak will lower water levels in downtown on Buffalo Bayou to the point that the Theater District garage and Wortham Center would likely not have flooded during Harvey. Bank stabilization and erosion control along Buffalo Bayou east of downtown should accompany the increased flow of water via the North Canal project.

- A South Canal through the Clayton Homes site, implemented as part of TxDOT's North Houston Highway Improvement Project, could further increase capacity near downtown.

- The large detention basins proposed as part of the North Houston Highway Improvement Project could be expanded further to help address regional issues as well as direct impacts of this project. Study is required, though, to determine how useful detention would be in this section of the bayou.

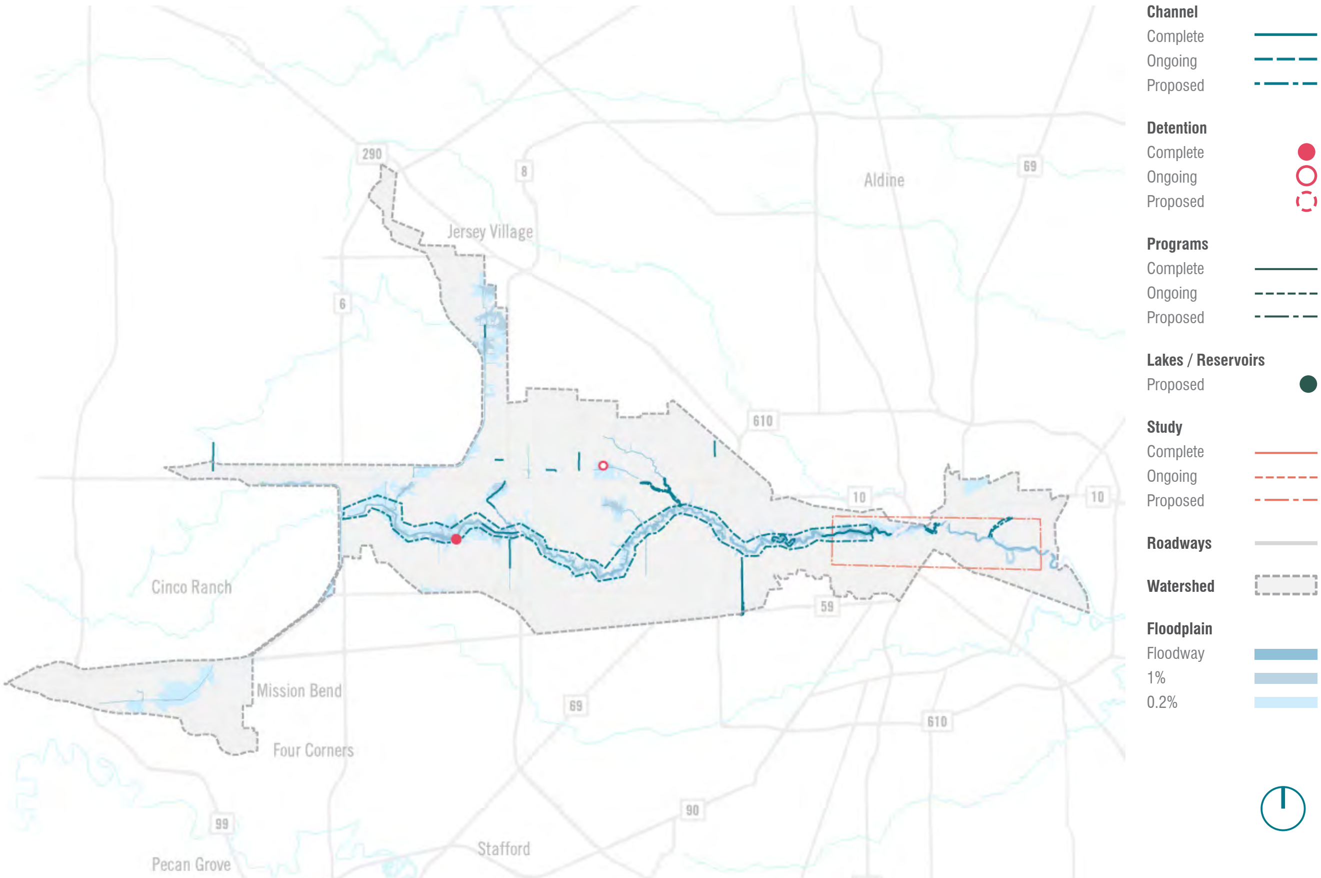


Figure 5.5 Figures for Buffalo Bayou

San Jacinto Basin and Watershed

The San Jacinto River Basin is a large geographic area that includes multiple watersheds extending from the East and West Forks of the San Jacinto River in Montgomery County southward to the Houston Ship Channel in Harris County. The San Jacinto River has numerous watersheds that feed into it including the East and West Forks of the San Jacinto River, Luce Bayou, Peach Creek, Caney Creek, Lake Creek, Spring Creek and Cypress Creek.

The San Jacinto River has two major water supply reservoirs: Lake Conroe in Montgomery County and Lake Houston in northeast Harris County. Sheldon Lake, a lesser reservoir managed by the Texas Parks and Wildlife Department as a state park, is also located in the watershed. The San Jacinto River extends downstream of Lake Houston as far as the Fred Hartman Bridge, where the river flows into the Houston Ship Channel and Galveston Bay. 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.

The San Jacinto River Authority (SJRA) has jurisdiction within the San Jacinto River Basin outside of Harris County. The SJRA owns and operates Lake Conroe in partnership with the City of Houston. The SJRA also owns and operates the Highlands System which supplies raw water from Lake Houston and the Trinity River to customers along the San Jacinto River in east Harris County. Both Lake Conroe and the Highlands System have State of Texas water rights for supplying municipal and industrial customers under long-term contracts. The SJRA is one of Texas' 17 river authorities —regional government agencies authorized by the Texas Legislature to develop, conserve and protect the state's water resources.

Flooding problems along the San Jacinto River are complicated due to the number of watersheds that flow into the river. Residential areas located along the San Jacinto River north and south of Lake Houston have flooded repeatedly. There are relatively few large-scale flood infrastructure projects, as the basin includes the 160,000-acre Sam Houston National Forest and the 6,000-acre Cook's Branch Conservancy, home to the endangered red-cockaded woodpecker. Both protected areas are examples of green infrastructure that mitigate flooding.

Much of the sand used for construction activities in greater Houston comes from the floodplains of the East and West Forks of the San Jacinto River. Sand is harvested by clearing the riverbanks of vegetation and excavating underlying sand from large, open pits. While licensed operators conforming to existing state rules carry out many of these mining activities, a number of unregistered operators illegally mine sand deposits along the river. Because quarried sand pits lack restored vegetation to stabilize the soils, floodwaters pick up the sand and deposit large volumes downstream. The combination of high riverine flows associated with Hurricane Harvey and sand and gravel-mining operations along the river generated a high sand and silt load that was deposited in Lake Houston and farther downstream in the Houston Ship Channel. This problem will persist if abandoned sand mines are not restored and re-vegetated to stabilize sediments and prevent erosion of riverbanks and other floodplain areas. That said, the sand mines are not the only source of siltation.

Lake Conroe and Lake Houston are reservoirs built for regional drinking water supply. The man-made reservoirs are not operated as flood control reservoirs and, while they do hold some flood waters temporarily during a storm, do not have the storage capacity to hold extra water after storms. Because they are water supply reservoirs, both lakes must maintain water storage in adequate volumes for drinking water in times of drought. Additionally, both reservoirs are surrounded by lakefront development and are important recreational assets for the region.

As a water supply reservoir, Lake Conroe was designed to hold water, staying at near full capacity and passing flows downstream during storm events. The dam was constructed such that gates operated by SJRA are opened as the reservoir levels rise. Lake Houston was also designed to serve as a water supply reservoir. Lake Houston is owned by the city of Houston and is operated and maintained by the Coastal Water Authority for municipal, industrial, recreational, mining and irrigation purposes. Lake Houston's dam consists of a concrete slab and buttress spillway with a long overflow weir that allows water to

Notes

The Galveston Bay Estuary Program is one of two estuary programs in Texas and one of 28 National Estuary Programs (NEPs) in the United States. Information on the Galveston Bay Plan — the Comprehensive Conservation Management Plan for Galveston Bay can be found online at gbep.state.tx.us

TWDB. (2014). River Authorities and Special Law Districts of Texas Map. twdb.texas.gov

twdb.texas.gov

YourConroeNews.com

Technical memorandum on Lake Houston water surface reduction alternatives interim findings. Freese & Nichols. February 5, 2018.

discharge freely over it during flood events without the need to open gates. The Lake Houston spillway is structurally very different from the narrow spillway and large tainter gates at Lake Conroe.

There is much discussion about creating a new prerelease operating policy for Lake Conroe, which would release water from the reservoir when a storm is forecasted, freeing up capacity in the lake for new rainfall. It should be noted that SJRA states that it would takes weeks of release to accomplish an adequate drop in lake levels to mitigate a major rain event. Additionally, prerelease would send water to downstream areas, pre-filling reaches of the West Fork San Jacinto River and Lake Houston possibly contributing to additional flooding during a storm event. A 2018 study by Freese and Nichols for Lake Houston concluded, "No prerelease operating policy is recommended. The risk of losing large quantities of water supply is substantial with the scenarios considered while the potential benefit on peak flood levels directly from this prerelease policy is negligible."

Prerelease operating procedures for flood mitigation on Lakes Conroe and Houston must consider that the primary purpose of these reservoirs is drinking water supply. Any changes to reservoir operations should take into account the likelihood of summer drought conditions that overlap in time with hurricane season and the need for critical supplies of stored water for a major metropolitan region.

Challenges identified by local decision makers and members of the community include:

- Flooding in communities downstream of Lake Conroe and Lake Houston
- Reduced water storage capacity of Lake Houston
- Increased runoff due to development in watersheds upstream of Lake Houston
- Large volume of sand and silt deposited along San Jacinto River, in Lake Houston and in the Houston Ship Channel

The following strategies could address flooding issues within the San Jacinto Basin and Watershed:

- In-depth engineering studies and science-based hydrologic and ecological assessments to determine the cost, benefits and risks associated with the following proposed flood mitigation strategies:
    - Making structural alterations to Lake Houston dam and spillway
    - Dredging along the San Jacinto River and in Lake Houston
    - Construction of a Montgomery County reservoir system / fourth reservoir
- Stricter regulation of sand mining operations, acquisition and complete restoration of land associated with past sand mining operations. Enact stricter state regulations and enforce penalties to shut down illegal mine operations that do not have required permits; strict enforcement of existing rules; require full restoration and/or create an in lieu fee program to finance restoration of closed and abandoned sand mining sites.
- Stricter development regulations for the watersheds in the San Jacinto River Basin
- Outreach to stakeholders and communities in the San Jacinto River Basin to increase awareness and facilitate greater transparency in reservoir operation and management and development of flood mitigation strategies.
- Increased deployment of green infrastructure strategies including conservation easements, land acquisition and LID as population growth and development continues at a rapid pace. Creation of a regional LID guidelines template for use by local and county governments and LID performance criteria needed.
- Create a San Jacinto River Community Advisory Council that meets regularly with public operators and functions similarly to community advisory councils in Houston Ship Channel industrial communities.
- Stricter floodplain development regulations extending beyond the 500-year floodplain based on Atlas14 rainfall estimates.

Armand Bayou

Armand Bayou flows southward into Clear Lake, draining 60-square-miles, including portions of Pasadena, Deer Park and Houston and has 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.

HCFCD has completed several detention basins in this watershed. The only future plan for flood infrastructure currently includes channel improvements and widening along Armand Bayou due to the expansion of the toll road. Increased development is expected in the near future, but there are also ongoing studies to link the regional detention basins and parks within the watershed to provide corridor for recreation and habitat. Efforts also are underway to acquire additional undeveloped land upstream of Armand Bayou Park, but these are limited by budget constraints. It would be beneficial to acquire all land in this area and restore it to prairie.

Harvey damage claims in this watershed were estimated around $12 million. While Armand Bayou watershed suffered during Harvey, greater damages were seen in the past from Tropical Storm Allison. The construction of regional detention basins likely played a part in reducing damages from Harvey. Buyouts are an important flood mitigation solution to be considered in this area, as many homes are located well within floodplain boundaries.

Vince Bayou

Vince Bayou watershed has a population of approximately 89,750, 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. Strategies in this watershed should include smaller localized mitigation projects, as flooding generally occurs before the floodwaters even reach the main channels.

Cedar Bayou

Cedar Bayou runs north-south to the east of the San Jacinto River draining into Galveston Bay. The bayou forms the boundary between Harris County and Liberty and Chambers counties and contains the cities of Baytown and Mont Belvieu within its 200-square-mile drainage area. The watershed is largely rural, with a population of 51,840, but there is considerable development near Interstate 10. The floodplain is fairly wide in the northern portion of the watershed, where flooding would affect mostly farmland and roadways. Although the floodplain is smaller in the more urbanized areas, it has experienced significant flooding in several events, including smaller storms, due to overflow from Cedar Bayou watershed and storm surge from Galveston Bay.

Cedar Bayou watershed had an estimated $19 million in Harvey damage claims. HCFCD has completed several maintenance and desilting projects to increase conveyance in tributaries. A feasibility study is underway to develop an implementation plan for improvements to the main stem of Cedar Bayou as well as other studied and unstudied tributaries. No other major flood infrastructure projects are currently planned.

It is important to undertake a detailed study on Cedar, and it is likely that land acquisition, detention and/or a reservoir may be useful tactics.

Luce Bayou

Luce Bayou drains into Lake Houston and the East Fork San Jacinto River from the northeast. Luce Bayou watershed has a population of 26,000 with a drainage area of 227 square miles. Due to its large drainage area, starting in the Sam Houston National Forest, the floodplain is significant in some areas. The watershed is largely undeveloped and heavily wooded, with development concentrated near the mouth of the bayou and the city of Cleveland. Luce Bayou is the only primary stream in the watershed and remains in a natural, vegetated state for most of its length. The lower part of the bayou is frequently inundated due to the influence of Lake Houston.

Luce Bayou watershed had an estimated $3 million in Harvey damage claims. Liberty County is planning to re-channelize feeder creeks and complete a master drainage study, but there are no other proposed plans for flood infrastructure in Luce Bayou watershed.

It is important to complete the study on Luce and identify projects, and it is likely that land acquisition, detention and/or a reservoir may be useful tactics.

6 CONCLUSIONS

We are seeing a paradigm shift in how the Houston area contemplates flooding and its consequences. From the general public to business to policy-makers—greater Houston must fully embrace this shift as to how the region responds to the challenges and consequences of flooding.

In the past three decades, HCFCD and its partners have abandoned the previous approach of straightening bayous and lining them in concrete in favor of a new approach that uses detention basins and natural channel design. We have now seen that approach work in multiple flood events; completing projects already underway and extending this approach to more watersheds will help hundreds of thousands of residents.

Similar shifts in thinking in other aspects of flooding could be equally valid. Instead of seeing buyouts merely as a strategy for removing homes from the floodplain, we can implement them as part of coordinated neighborhood plans that also deploy other tools like reconstruction and floodproofing and that address housing, open space, connectivity and social needs in the entire community. Instead of planning for the inevitable development of watersheds, we can protect natural and agricultural lands for their ability to absorb and retain stormwater and their ability to accommodate flooding without damaging structures or lives. Instead of seeing mapped floodplains as the only measure of flood risk, we can apply more sophisticated risk models that recognize that flooding can happen anywhere—not just along bayous—and that nearly every property is at some risk.

Based on the consortium's work to date, we have drawn a number of key conclusions, which reflect the consensus of our members. In the coming months, watershed analyses will be completed, which will allow for more detailed conclusions. Edition II will include these findings.

General Conclusions

There is no way to completely eliminate flooding in Houston. We can only minimize its impacts. Rather than treating flooding itself as the problem, we should focus on reducing the effect and consequences flooding has on people's lives. Resiliency—the ability to respond and recover—is a feasible goal; complete control of flooding is not. We can, however, measure the impact of flooding in terms of the disruption to people's lives. An elevated home surrounded by floodwaters can be acceptable if the residents will not suffer financial impact from the loss of pay or health issues from being confined for the duration of a flood. The tools we have to minimize the impact of flooding go far beyond infrastructure projects that lower water levels during a flood.

Most flood control assessments, including the federal government's cost-benefit ratio, calculate benefits through economic value, not impact on human lives. This overvalues high-income areas, essentially defining a family being displaced from a $1,000,000 home as being 10 times as valuable as a family displaced from a $100,000 home. Alternately, we can measure projects by the number of people who benefit or use more sophisticated tools like a Social Impact Assessment.

Data about building slab elevations is critical to understanding the full extent of damages due to flooding depths. We cannot minimize damage to property if we do not know the elevations of buildings slabs. It is one thing for someone's lawn to flood and altogether another for their home to flood. Our current topographical data only provides the elevation of exterior areas. We must prioritize the creation of a database of building slab elevations if we want to plan the most effective and cost-efficient flood mitigation strategies.

A flood risk mapping approach that estimates the likelihood of all flood scenarios will be more useful than the traditional flood plain mapping approach. Flood risk is not a static phenomenon; it is a forward-looking concept. The strategy behind mainstream floodplain management practice in the United States has relied exclusively on historical flood data. Flood risk management takes advantage of advanced hydrodynamic, meteorological, geotechnical and other models to estimate the likelihood and impacts of all possible flood scenarios, using probabilistic analysis, rather than deterministic analysis. It also recognizes that every location has some risk—there is no sharp line where properties located on one side are at risk of flooding and properties on the other side are not.

The level of flood protection across watersheds is not equitable. Addicks and Barker reservoirs are already able to handle the current 1 percent event, as can much of the Buffalo Bayou channel. Even with the federal projects, through Brays Bayou, Clear Creek, Hunting Bayou, White Oak Bayou and Greens Bayou will not be able to handle the 1 percent event, and several other major bayous have not been studied in detail.

Public Education, Involvement and Awareness

An educated public is fundamental to building and sustaining support for the long work of mitigating the devastating impact of flooding in the Houston region. Media attention since Hurricane Harvey has been significant, however, it would be beneficial to implement ongoing fact- and science-based education programs that continually inform greater Houston's residents about the risks of flooding, similar to how Californians are constantly made aware of earthquake risks.

Robust public engagement throughout decision-making processes related to flooding mitigation will help improve results, ensure more equitable outcomes and build support and trust. This engagement can happen at a watershed level, but would also require regional coordination. Effective public involvement begins as studies are initiated—before projects have been identified—and continues through implementation. Public input on goals and priorities is as vital as public input on projects. Continued public engagement can also keep flooding issues in the public eye between flooding events.

Coordinating community-planning initiatives in each watershed would improve flood mitigation efforts. Such plans would help to identify community values, provide community education, source ideas and begin building trust for the buy-in of strategies for flood mitigation. Such processes create new opportunities for initiatives that help achieve multiple outcomes (e.g., flood mitigation, recreational space, community supported design standards, housing) and identify additional funding sources to meet broader strategic goals.

A countywide flood alert and warning system can be implemented cost-effectively and would be invaluable in future storms. While such a system would not reduce flooding, it would provide time for people to protect themselves and their valued possessions. It also could provide information to emergency responders about routes not impacted by floodwaters.

Disclosing flood risks as a required part of any real estate transaction, whether it is a property sale or a rental contract, would help to ensure that owners and renters fully understand their flooding risk. Flood risks include both flooding of structures and flooding of access routes. In addition, flood risk is dynamic, so periodic updates provided to renters and property owners would be beneficial as flood mitigation projects and new modeling alter their risk. These updates could be "pushed out" through the mail or electronic means to better ensure that everyone is aware of the changing risk.

Regulations

The existing regulatory system overseen by multiple jurisdictions is confusing at best and possibly counter-productive. Requirements vary among jurisdictions; different places in the same watershed (sometimes, even on opposite banks of the same bayou) have different rules. Even on one specific property, detention may be regulated by one entity while another governs floodplain management and building codes. Regulatory oversight outside of cities but within their ETJs is especially confusing. This patchwork approach makes it difficult to address watersheds and, as a whole, can allow harmful projects to slip through the gaps.

Counties have limited ability to enforce regulations in unincorporated areas. The population of unincorporated Harris County is more than 2 million, yet, without ordinance-making power, the county cannot stop illegal development. The county can only file a lawsuit that takes time to resolve while the development proceeds unimpeded. Regulations in ETJs are further complicated by the fact that the county has authority over floodplain management, while the city maintains authority over platting.

Under current detention regulations, new development, especially in previously undeveloped areas, still increases downstream flooding. Native prairies and woods—and to some extent agricultural land—absorb several inches of rainfall and the stormwater that does run off does so slowly. The grading of sites, installation of storm sewer systems speeds of stormwater, and the shallow roots of typical landscaping do not absorb water the way native prairies do. While current detention regulations limit the rate of water, the assumed conditions in those calculations overestimate pre-development runoff rate and thus underestimate the increase in runoff. Furthermore, the regulations do not limit total runoff volume, which can make a big difference in a multi-day rain event.

Regulations should address the large areas of the region that were developed before flood regulations were in place. Floodproofing buildings that are at risk of shallow flooding only could reduce the number of properties subject to more expensive regulatory requirements under current rules. In addition, the impact of the overall regulatory framework on the region's supply of affordable housing should be considered, as much of our affordable housing is located in floodplains.

Local Drainage

Many of the Houston region's worst flooding problems are due to localized drainage, which often leads to flooding far from bayous. Projects that address this flooding can be as effective as bayou projects in reducing flood damage and human impact, but this flooding has not been adequately assessed. Comprehensively mapping where localized flooding occurs will identify the greatest needs and populations that should be notified of this risk. These studies can also determine street inundation and indicate where street improvements can keep critical corridors open during flood events. Addressing local drainage will require both funding and expertise, and require continued maintenance as smaller jurisdictions often lack technical knowledge and capacity to address these important projects.

Some flooding problems are due to the limitations of local drainage networks, such as storm sewers and roadside ditches. Local drainage networks managed by cities, MUDs and counties are as critical as the large-scale drainage infrastructure operated by HCFCD and USACE. Studies and projects that consider both networks together, regardless of jurisdiction, can be particularly effective. For example, upstream detention linked to a neighborhood storm sewer network can reduce flows into the main channel, reducing flooding downstream. Conversely, additional water flow into the main channel from an improved storm sewer system can be accommodated with additional detention or conveyance in the main channel.

Small-scale, lot-by-lot strategies, such as the regrading of lots or the widening of ditches to detain small volumes of water, can reduce the impacts of flooding in existing neighborhoods. Typically overland flow—water running across the surface—accounts for 90-95 percent of stormwater flow. Storm sewers are designed only to accommodate two inches of rain, or a 2-year storm. In modern subdivisions, most of the overland flow is accommodated within streets. In older neighborhoods, it often flows directly through lots, flooding yards and homes. This flooding can be addressed by small-scale site strategies that channel water around homes and store stormwater in place.

Buyouts

Buyouts are currently being used as a way to address flooding that cannot be addressed with new flood control infrastructure. Instead, they could be studied alongside flood control infrastructure to determine what the most effective and least expensive solutions are for each watershed. Buyouts can also have incremental benefits, including providing land for better flood control infrastructure, new parks and open space, and improved housing stock.

Voluntary buyout programs could be more effective if they are done with extensive public outreach and coupled with active case management and generous relocation assistance. Active community engagement and planning has been used effectively across the United States to increase voluntary participation in buyouts, making buyout programs more attractive thus more effective.

More flexible funding from non-federal sources can allow more properties to be included in buyout programs and encourage more property owners to participate in buyouts, aiding in avoiding the "checkerboard effect." Federal funding comes with limitations on which properties can be bought out and how much can be paid for those properties. Local and philanthropic funding can be used in a more flexible manner, addressing properties within a buyout area that don't meet federal requirements—offering compensation and relocation assistance that makes moving feasible for residents, and reusing properties for public purposes, such as parkland and habitat preservation.

Without a coordinated housing plan that creates new housing concurrently with buyouts, extensive buyout programs could significantly reduce the supply of affordable housing in the region, and more people will agree to buyouts if viable relocation options made possible by an affordable housing plan. Flooding is closely related to housing issues. Much of the affordable housing stock in the region is in floodplains, and flooding dramatically impacts these residents. Effective flood mitigation can make this housing more secure. On the other hand, in some instances flood mitigation projects can exacerbate housing issues—for example, buyouts can remove units from the market, increase housing costs and displace residents away from jobs and transit. Successful flood mitigation can also make neighborhoods more desirable, accelerating displacement and gentrification. A countywide housing plan could anticipate future housing needs, particularly after a flood even and identify locations with access to work, schools, and social services.

In addition to buyouts, home elevations, floodproofing and acquisition of property for reconstruction can be useful tools. Elevating existing structures that allow current residents to move back is already being done in the region. It can also be effective to acquire existing structures and relocate residents, demolish those structures and sell the property to homebuilders with covenants requiring elevated construction, resulting in new floodproof homes for new residents. Structures that are in shallow floodplain areas can be floodproofed in place, and changes to building codes and funding programs can make this more feasible.

Flood Mitigation Infrastructure

Increasing channel conveyance capacity in and of itself is not the most effective flood mitigation strategy. Increasing conveyance in bayous and tributaries generally speeds up water. This means that runoff from the upper reaches of the watershed makes its way downstream quickly, catching up with water from the same storm that fell in the middle reaches and raising flood levels. This phenomenon is largely responsible for the catastrophic flooding in Brays Bayou, where the bayou itself and many of its tributary ditches were lined in concrete in the 1950s through the 1980s to increase conveyance. Our region has learned that slowing down water through detention, winding natural channels and room for the bayous to spread is more effective. Conveyance can be effective, though, in the lower reaches of a waterway.

Where watersheds remain undeveloped, acquisition of land along the bayous and creeks is a cost-effective flood mitigation tool. Whether in the upper undeveloped watershed or downstream along the channel and its tributaries, undeveloped land gives the water room to spread out in a flood event, to prevent the impacts that new development on that land would have, and to preserve these green spaces for flood mitigation.

The current federal projects on Brays Bayou, Clear Creek, Hunting Bayou, White Oak Bayou and Greens Bayou are valuable. There are opportunities for additional detention, bridge reconstruction, channel improvement and land acquisition projects in all of these watersheds. The completion of these projects will address many serious riverine flooding issues and reduce the flood risk for many homes. However, these projects are not projected to eliminate all flooding of neighborhoods in the current design 1 percent event. In some cases, homes will still flood in a 10 percent event, and analysis will likely conclude that the actual 1 percent event is larger than the design event, meaning that even more property will be in harm's way. As a result, completing these projects does not "solve" flooding in these watersheds. In fact, no project can, since storms can exceed the 1 percent event. However, there are opportunities for additional projects that can be implemented separately (to avoid further delays in completing the federal projects), which are outlined in this report.

The federal projects on major bayous do not address all of the tributaries of those bayous, some of which have had considerable flooding. It is important to address certain tributaries that experience flooding, including Little White Oak Bayou, Brickhouse Gully, Cole Creek in the White Oak watershed and Keegan's Bayou in the Brays Bayou watershed, as they are not addressed by the current federal projects. Some possible projects are outlined in this report.

Several key watersheds, including Cypress Creek, Armand Bayou, Vince Bayou, Luce Bayou and sections of Greens Bayou, have seen considerable flooding damage but have not been fully studied in detail or had projects identified. In addition, Cedar Bayou and Halls Bayou have studies underway that have not concluded or resulted in finalized project lists. This means that, while there have been some projects in these watersheds, the full set of potential projects has not been considered and included in published project lists, and there are likely useful and cost-effective projects that have not been identified. Some possible projects are outlined in this report.

Many of the bayous have flooding issues caused by roads, highway bridges and railroads that restrict the channel. Collaborative efforts between the HCFCD, railroads and TxDOT could address these. Bridges over channels, including those owned by cities, railroads and TxDOT often raise flood levels by several feet. If the jurisdictional and legal issues of addressing these can be solved then there would be significant potential for flood mitigation. A cooperative effort with the railroads, coordinated with watershed-level studies, could address these bottlenecks and reduce upstream flooding while making sure there are no downstream effects. Flooding can also be considered in every highway-planning project, with the goal of not just maintaining pre-project conditions but reducing flooding.

The cumulative impacts of the various flood mitigation proposals for the San Jacinto River are not fully understood. An additional reservoir, changes to the Lake Conroe and Lake Houston dams, excavation of silt from the river bed, revised regulation of sand pit operations and revised governance of the watershed would have significant funding and policy implications. The health of the river and the safety of the residents who live along it depend upon a comprehensive plan to address flooding in this watershed.

The potential failure of Addicks and Barker reservoirs is likely the most dangerous flooding scenario in the region, and the ongoing USACE study needs to be completed as soon as possible to know what the risk of that failure is and how much investment is required to keep the reservoirs safe. The reservoirs are effective and critical parts of the region's flood control infrastructure. The dams are now 70 years old, however, and failures would be catastrophic. There is no publicly available information as to the condition of the dams and the risk of failure. A better study of the dams, including public transparency on risks and any required structural improvements based on the results of that study, is needed to allow the dams to continue to provide their current function.

The "third reservoir" as proposed is primarily intended to mitigate new development, not reduce flooding in Buffalo Bayou, and does not solve the issues with Addicks and Barker reservoirs. The Plan 5 "third reservoir" that was studied in 2012-2015 primarily addresses future development of the Katy Prairie area by making it easier to develop land that currently floods and by mitigating the effects of that development, with the intent that this infrastructure could be partially funded by that new development. The study was not designed to solve the issues of Addicks, Barker and the Buffalo Bayou watershed, or to reduce downstream flooding on Cypress Creek. Improvements to Addicks and Barker, preservation and restoration of native prairie, and appropriate restrictions on new development could be effective in addressing current flooding in these watersheds and preventing future development from worsening flooding.

A new reservoir in northwest Harris County specifically designed to address the Cypress Creek watershed could mitigate repeated flooding along Cypress. There is potential that a "third reservoir" in the same general area as has been discussed but targeted at reducing flooding in the badly damaged Cypress Creek watershed could be very effective in addressing repeated flooding in downstream areas of that watershed. The design of that reservoir is critical and could be part of a strategy to preserve critical natural habitat in the Katy Prairie if done right. On the other hand, if done poorly, it could destroy large parts of the prairie.

The "north canal" near downtown Houston could significantly reduce flooding along White Oak Bayou and Buffalo Bayou in downtown. If Addicks and Barker dams are addressed, Buffalo Bayou has few flooding issues except in downtown. White Oak Bayou will continue to have considerable flooding after the federal project is complete. The North Canal, coupled with channel improvements near downtown and erosion protection, effectively addresses flooding both along Buffalo Bayou in downtown and in the lower White Oak watershed.