



# HOUSTON A YEAR AFTER HARVEY: WHERE WE ARE AND WHERE WE NEED TO BE

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“Houston a Year after Harvey: Where We Are and Where We Need to Be”

It has been almost a year since Hurricane Harvey hit the Texas Gulf Coast. Throughout the Houston community, there are many things that must be done to repair the damage from Harvey, and many challenges remain. In this paper, we provide some background information on critical flooding problems in the Houston and Harris County areas, present an update on progress made to date, discuss successes and shortcomings of existing flood mitigation plans, and share some ideas about moving forward with plans for the future.

## I. Introduction

In 2017, Houston and Harris County experienced what may be the most damaging storm in United States history according to a 2018 report from the National Oceanic and Atmospheric Administration (NOAA 2018a). As set out in meteorologist Jeff Lindner's final report on Harvey for Harris County Flood Control District (HCFCD), Harvey caused about \$125 billion in damages, with over 150,000 homes being flooded as well as thousands of businesses (Lindner and Fitzgerald 2018). Harvey's financial impact is the same as that of Hurricane Katrina (NOAA 2018a). If nothing else, the last year has revealed the full extent of the problems generated by Harvey as well as by past flood control policies and practices. There are difficult issues and choices ahead that require creative thinking and leadership to come out of this situation positively.

One clear accomplishment in the months since Harvey is the decision by the Harris County Judge and Commissioners to call an election for the public to vote on the issuance of \$2.5 billion in flood control bonds to finance various local and federal projects (HCFCD 2018a). The election has been set for August 25, 2018—a Saturday that is also the one-year anniversary of Harvey. The special election date was selected by the Harris County Commissioner's Court and subsequently authorized by Texas Governor Greg Abbot. As this is being written, a series of public meetings have been initiated by Harris County to discuss and solicit possible projects to be funded by this bond money, providing the kind of transparency and public involvement demanded by those harmed by catastrophic flooding events in Harris County, including Harvey, the Tax Day Flood of 2016, the Memorial Day Flood of 2015, and Tropical Storm Allison of 2001.

Harvey jolted the local community, causing many to take an interest in flooding matters that often have been conducted out of the public eye. This has led to demands for more information and transparency by governmental entities responsible for flood control, such as the HCFCD. Those desiring to participate in the public meetings to identify flood-related projects to potentially be funded by the bonds had the opportunity to do so during June and July of 2018 prior to the upcoming election on August 25. This transparency is one clear result of Harvey, and it is necessary, important, and refreshing. A second clear result of Harvey is that Congress has appropriated \$15 billion for infrastructure projects for areas affected by Hurricanes Harvey, Irma, and Maria in HR 1892 (Bipartisan Budget Act of 2018). Due to the congressional prohibition on earmarks in appropriations, it is not clear exactly where these funds will be spent or on which projects. Additionally, the language in the bill is confusing—the entire construction appropriations section is one sentence with over 500 words—but it is clear that at least some of the infrastructure money is destined

for the Houston area and the Texas coast. In fact, the U.S. Army Corps of Engineers announced in July that \$4.88 billion had been set aside for Texas (Pulsinelli 2018). There is also additional funding coming from both the Federal Emergency Management Agency (FEMA) and the U.S. Department of Housing and Urban Development, with an initial \$1 billion in Community Development Block Grant funding designated for the city of Houston and another \$1 billion for Harris County. For many federal projects, a local match is required, which is one reason for the proposed August 25 bond vote. If it passes, a substantial amount of money will be available to begin addressing key flooding problems in Harris County.

The mere availability of funds, however, does not guarantee success in addressing the area's flooding problems. Good decisions and good choices must be made about spending these funds, and such decisions require information. The current paper is written on the heels of an excellent publication by the Greater Houston Flood Mitigation Consortium (GHFMC), which is composed of academic researchers. Their report, "Greater Houston Strategies for Flood Mitigation," is primarily focused on strategies for flood mitigation and is an excellent primer on many of the issues covered herein (GHFMC 2018). The current paper differs from the consortium report in its focus on certain policy issues and in its presentation of an overall flood management vision.

To this end, this paper is organized as follows. First, the issues of obsolete 100-year floodplain maps and increasing rainfall are discussed because they are key to fully understanding the current dilemma and shaping alternative concepts for long-term protection. Second, a geographic overview of the flood issues and potential responses to various watersheds across Harris County are set out. Third, different flood management concepts are discussed for three zones of the Houston area that have different flooding issues.

## II. Obsolete Floodplain Maps

This section discusses the problems with the floodplain maps that the Houston community uses to help guide decisions about where to build relative to flooding patterns. Before beginning this discussion, it is first important to define some unfamiliar words and concepts. For that reason, this section will start with a primer on flooding and flood-related terminology and then will move into a discussion of the problems with the 100-year flood maps. If you know all of these terms, skip to Section IIB.

### *A. Basic Terminology*

Two basic types of flooding generally occur in the Houston area: rainfall-related flooding and coastal surge flooding associated with the landfall of tropical storms or hurricanes. Rainfall-related flooding can happen any time of the year and can arise from tropical systems that bring in unprecedented rain from the Gulf of Mexico, such as Hurricane Harvey and Tropical Storm Allison. This flooding can also arise from rain associated with the movement of cold fronts coming into the area from the north or northwest, such as the Tax Day and Memorial Day events. In contrast, serious coastal surge flooding is usually



only associated with hurricanes that push coastal water ashore in addition to bringing rainfall and high winds. Coastal surge flooding is less frequent than rainfall-related flooding, but it is potentially much more dangerous due to the high winds that drive waves on top of the surge flooding, creating violent conditions seldom equaled by rainfall flooding. Both types of flooding are real threats to Harris County.

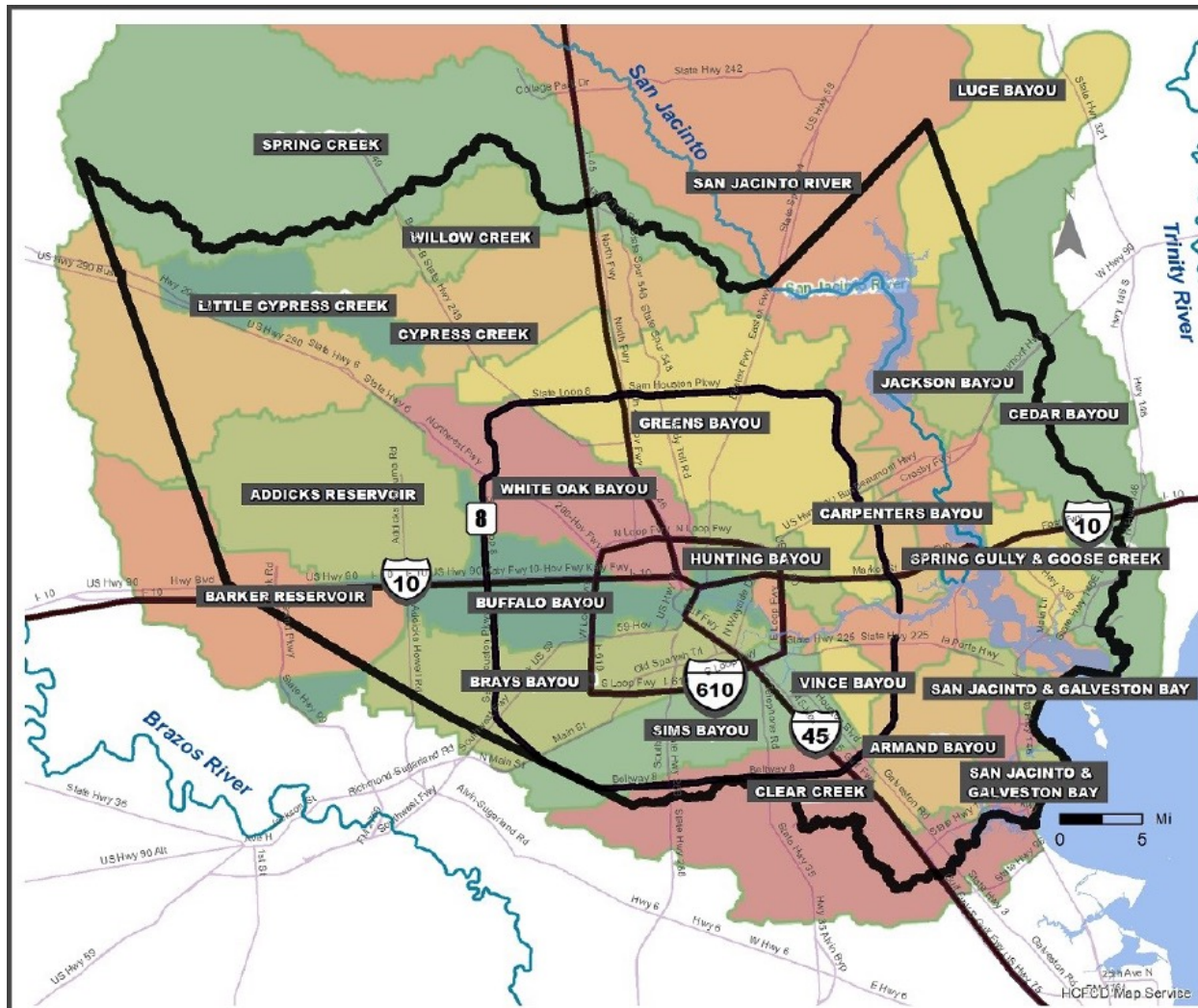
In addition, there are two types of rainfall-related flooding. One is stream or bayou flooding, and the other is localized street and overland flooding. These are both important in Harris County, but local overland flooding receives much less attention than does stream or bayou flooding due to the existence of flood monitoring systems and flood control projects (e.g., federal flood programs) that focus on stream flooding rather than local overland drainage systems.

A bayou, creek, or river is known as a natural watercourse, which is an area cut into earth's surface over thousands of years by the flow of water. Natural watercourses have defined beds and banks where the water usually flows, and they also have areas that they drain called watersheds. When rain falls, most of it flows from high points to lower points across the landscape due to gravity. A watercourse is a geographic low point, and its associated watershed is defined by surrounding areas of higher elevation that determine whether rainwater goes to one watercourse or another. Watersheds are the basic flood management units, and they are key to understanding flooding in Harris County.

The Harris County Flood Control District, the county's technical leader on flooding, has divided Harris County into 22 watersheds. These watersheds range from Spring Creek and the San Jacinto River to the north, the area draining into Addicks and Barker Reservoirs and Buffalo Bayou to the west, Clear Creek to the south, and Cedar Bayou to the east, all of which ultimately drain into Galveston Bay. These watersheds are shown in Figure 1. Within these natural watersheds are numerous smaller watercourses, both natural and man-made (such as ditches, channels, and canals), that create a network for collecting storm waters and transporting them downstream into Galveston Bay and the Gulf of Mexico. These Harris County watersheds, with the exception of the San Jacinto River and Galveston Bay, are not large, regional drainage systems. They are relatively small geographic areas and the water in these creeks and bayous can rise and fall relatively quickly, particularly in the developed core of Harris County and the city of Houston.

All bayous, streams, and rivers naturally flood. The bed and banks—the areas where water flows most of the time—hold an average amount of water for a given watercourse under normal conditions. As rain falls and water runs off the watershed and into the watercourse, the water level rises and can eventually overflow the banks, spreading into the adjacent area. This area is generally called the floodplain. The amount of area flooded, or extent of the floodplain, depends upon the amount of rain, as well as how much of it falls and how fast it runs off into the watercourses.

Figure 1. The 22 Watersheds Identified by Harris County



Source: Image prepared by Christina Walsh for the author(s)

In Houston, small rainfall amounts of up to an inch or two are very common. A thunderstorm in the area can drop an inch of rain in a short amount of time, and that water will likely only fill the area in between the banks of a watercourse. However, Houston also gets larger storms, although not as often. The increased rainfall associated with these larger storms can flood streets and sometimes make isolated streams overtop their banks at certain locations, leading to localized flooding. Houston can also get very large rains that last for several hours, in which major flooding along multiple bayous can occur. The varying rainfall amounts in the area are routinely measured and reported, and in many areas of Harris County, so are the water levels and flows in creeks and bayous. This creates a database of information about the frequency and intensity of rainfall and resulting runoff that can be translated into rainfall and flooding predictions.

When this data is analyzed, it is possible to predict what amount of rain is likely to occur over a specific time period (e.g., minutes, hours, or days). In this way, we can roughly estimate the rainfall amount Houston is likely to see at least once every year (i.e., rainfall occurring 100% of the years) and the rainfall amounts the area is likely to see more rarely, like once every 10 or 100 years (i.e., 10% of the years or 1% of the years). These estimates become the predicted risk of a certain amount of rain falling in a particular watershed. These rainfall risks can then be translated into the risk of a flood occurring at different places within the watershed. This can be done by using engineering and computing methods to determine how much rain becomes runoff and how fast it runs into local bayous and creeks. Over the past several decades, these data have been collected and analyzed to create a profile of Houston's rainfall that can be used to determine the risk of various rainfall amounts and flood levels occurring.

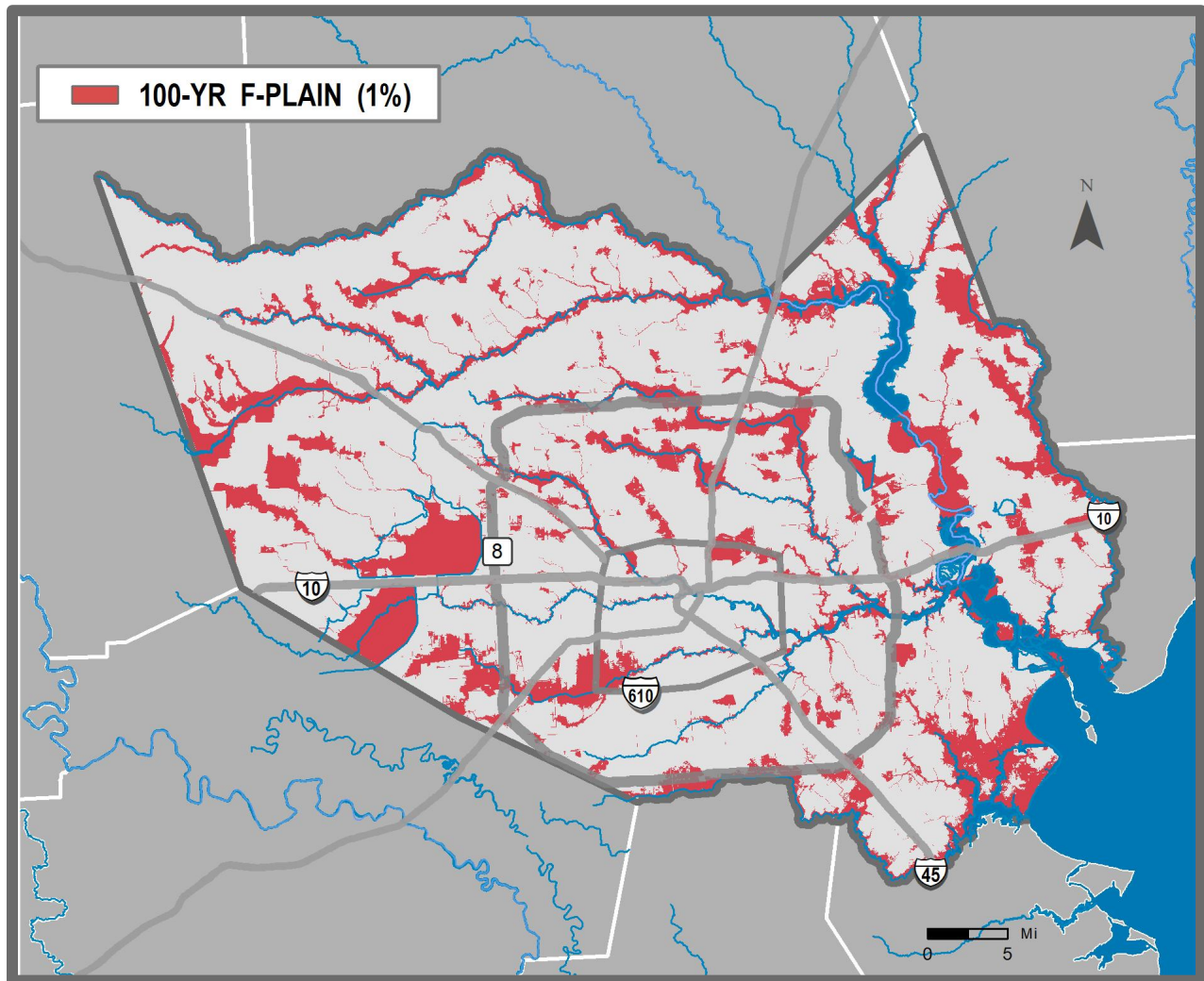
As homes and buildings are developed within local watersheds, experts have become concerned about how developed lands might have increased the extent of local floodplains and how often existing developed lands adjacent to creeks and bayous are at risk of flooding. In the late 1960s and early 1970s, a decision was made by Congress to provide such at-risk developed lands with flood insurance, which was impossible to purchase from private insurers at a reasonable cost. This flood insurance was subsidized by the federal government and made available to local citizens if their communities enacted floodplain regulations.

As part of this program, the federal government determined that communities should require any new homes being built in the floodplain to be above the 1% flood level, which is determined based on the 1% rainfall risk predictions. Such a flood has a 1% risk of occurring in any given year and is also called the 100-year flood, while the flooded area is called the 100-year floodplain. The location of the 100-year floodplain has been placed on a map so the public can understand where 100-year floods might occur. The floodplain maps also usually include the 0.2% floodplain (also called the 500-year floodplain). These floodplain estimates are made even though reliable data going back very many years do not exist. A map of the current 100-year floodplain of Harris County is shown in Figure 2. By using geographic mapping techniques, the author has determined that about 22% of the land in Harris County is within the currently mapped 100-year floodplain, and about 33% of the county is within the 500-year floodplain.

During Harvey, much of the flooding occurred outside of the mapped 100-year and 500-year floodplains. This was primarily due to overland flow. Flooding from overland flow is not directly from stream or bayou flooding, but is instead from localized rainfall that is unable to enter the overloaded underground storm sewer system and thus drains into bayous by traveling overland via streets and yards. Overland flow flooding is not routinely identified and is not shown on the mapped 100-year floodplain set out in Figure 2, which is based upon overbank flooding of watercourses (and coastal surge flooding to a limited extent). In contrast, overland flooding is localized, and may be caused by inadequate or poorly maintained storm sewers and drainage ditches or by extremely heavy rainfall events that simply overwhelm the drainage system and subsequently fill streets, yards, and

sometimes homes with water. Overland flow problems can also be compounded when bayous fill up and block local drainage systems from draining into bayous. These localized problems are in many respects much more difficult to identify, analyze, and address than is bayou flooding, and the responsibility for fixing overland flow flooding is often hard to determine between the city and the county.

**Figure 2.** The Current (2018) 100-year Floodplain Map for Harris County



Note: Approximately 22% of Harris County is in the 100-year floodplain.

Source: Graphic prepared by Christina Walsh for the author(s) based on data from FEMA and the HCFCFCD

Flood control or management involves various methods of reducing the extent of flooding or flood damages. In the past, one common method was to dig out watercourses by widening and deepening them. Another common method was to sometimes further increase the flow of water in a channel by lining it with concrete, which allows more rainwater to flow in the channel rather than overtopping the banks and flooding adjacent land. Engineered channels have a design capacity, meaning that they can maintain the runoff from a certain intensity of storm within the banks. In this way, a channel can be designed to accommodate the 10-year, 25-year, or 100-year storm. When such modifications are made, the extent of the floodplain is reduced to some degree depending upon the channel design.

Other alternatives exist besides widening and deepening channels. Harris County is very flat and does not have much natural slope, which means that rainfall often does not run off very fast. When new land is developed, the rainwater that doesn't soak into the ground gets quickly routed into streets and storm sewers and then into drainage ditches that flow into bayous. In this way, new developments can change the behavior of rainwater on the ground, thereby also changing the natural character of bayou and stream flows. This has been particularly evident in the past in both Brays and White Oak Bayous, in which flooding has increased over time due to upstream development. In such flat terrain, constructed detention ponds that hold back rainwater can be very effective flood management tools, as can open green spaces or levee-protected areas where water can rise and fall in the bayou without damaging any homes. All flood management approaches generally try to reduce the risk of flood damages. In the past, it was assumed that although land development patterns may change, rainfall amounts and patterns would not. This assumption is no longer true, and changing rainfall patterns must be taken into account as future building plans are developed.

### *B. The Obsolete 100-Year Floodplain Maps*

Hurricane Harvey was a historic rainfall event. Over a period of several days, more than 40 inches of rain fell across much of southeast Texas. As such, Harvey is likely the single largest storm in United States history. Harvey, however, was not the only large rainfall event to hit the region in recent memory. The Houston area has experienced several large storms over the last two decades that are changing the statistical database used to estimate the 100-year and 500-year rainfall amounts. The bottom line is that the current estimates of 100-year and 500-year rainfall amounts, and the size of their associated floodplains, are no longer accurate. They simply are too small given recent storm experiences and rainfall trends.

As can be seen in Figure 3, there have been four storms in the last 24 years that have been overly large, each exceeding the estimated 500-year storm event for one or more averaging periods (per hour, per multiple hours, per day, and/or per several days). Figure 3 also shows the current estimated 100-year and 500-year rainfall amounts used for planning in Harris County for the same time periods. Note, for instance, that Harvey exceeded the current 500-year rainfall in Harris County for every duration. Also note that three of the four 12-hour, 24-hour, 2-day, and 4-day storms exceeded the 500-year level in Figure 3. Houston-area storms have been increasing in severity over the last several decades.



**Figure 3.** Recorded Rainfall for Severe Storms in Harris County and Current 100- and 500-year Rainfall Amounts

Duration	Harvey August 2017	Allison June 2001	Tax Day April 2016	October 1994	100 Year Rain (inches)	500 Year Rain (inches)
1-hr	6.8	5.7	4.7	3.7	4.3	5.5
2-hr	11.9	9.9	7.3	4.7	5.7	7.6
3-hr	14.8	13.5	8.3	5.3	6.7	9.2
6-hr	18.9	21.2	13.9	7.2	8.9	12.8
12-hr	20.9	28.3	16.7	12.0	10.8	15.5
24-hr	25.6	28.4	17.4	20.9	13.2	18.9
2 days	35.2	28.5	17.5	23.1	14.5	20
4 days	47.7	38.5	n/a	28.9	15.9	21.1

Note: Chart showing the recorded rainfall amounts (in inches) for four severe storms on the left. On the right are the current rainfall estimates used for the 100-year storm and the 500-year storm for the same time intervals. The amounts shown in red indicate the highest rainfall recorded for the time period.

Source: Table on the left by Jeff Lindner of the HCFCD; table on the right added by the author(s)

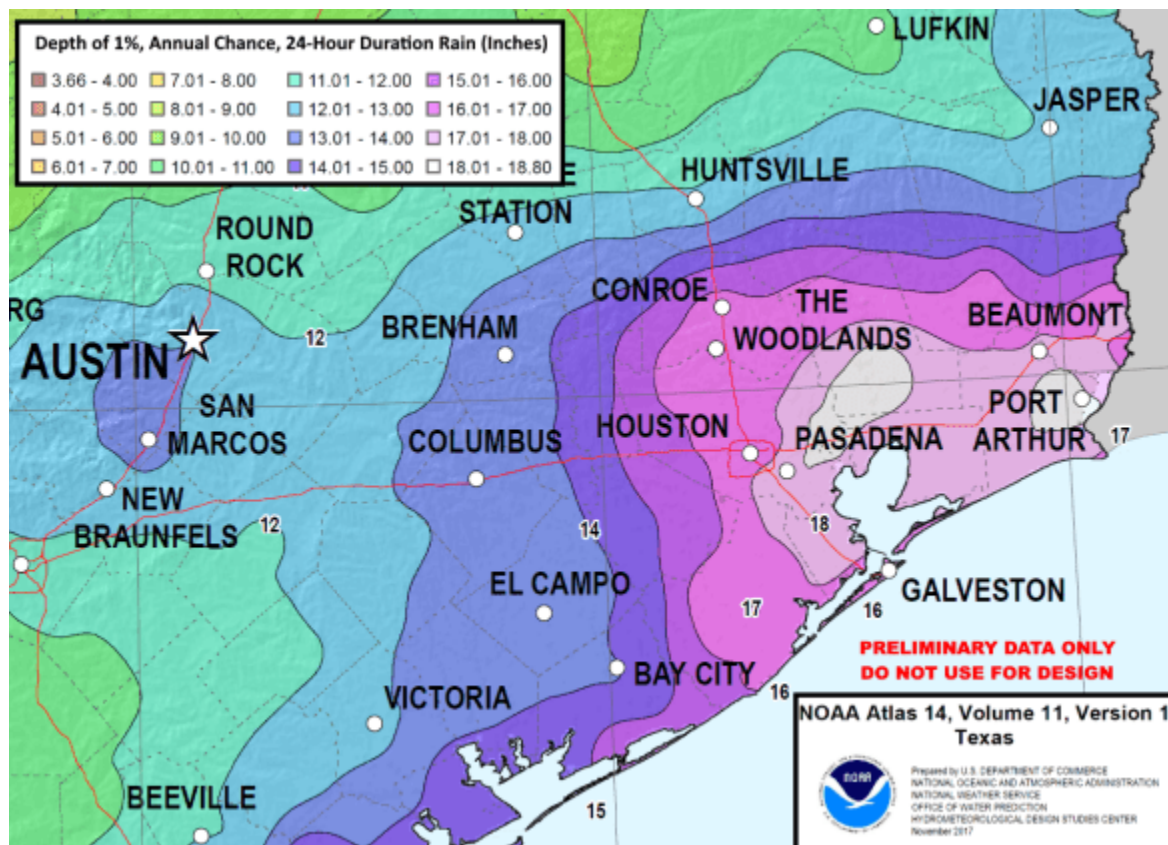
The storms listed in Figure 3 and other similarly severe storms have led to the realization that the 100-year and 500-year floodplain maps currently used by Harris County, the city of Houston, and other local jurisdictions are out of date and obsolete, and do not reliably account for actual severe rainfall events. These maps need to be corrected. The current 100-year floodplain map is shown in Figure 2. After Hurricane Harvey, the Harris County Commissioner's Court, the mayor, and the Houston City Council voted to utilize the 500-year floodplain, instead of the customary 100-year floodplain, for floodplain regulatory purposes due to the new understanding that the 100-year floodplain map is not correct. This decision requires new construction to be raised two feet above the 500-year floodplain, a requirement that has generated significant pushback from some builders, developers, and engineers. These new requirements are thus far the only major regulatory changes that have been adopted post-Harvey.

Although these efforts by the city and the county are important first steps, there are still more changes needed with regard to these obsolete floodplain maps. Over the last four decades, these 100-year floodplain maps have become a central element in engineering and infrastructure design. The 100-year floodplain is used by state and federal agencies for issuing state and federal permits for sewage and water treatment plants, hazardous waste facilities, landfills, and designing state-funded and federally funded projects such as highways. These entities have not adopted the 500-year floodplain after Harvey, at least to date. Given the noted problems with the 100-year floodplain map that make it obsolete, it is clear that essential community facilities and functions are operating today at greater risk from flooding than was originally predicted, and it is also now clear that new facilities will likely be built at elevations that are too low to protect against the 100-year and 500-year

flooding events unless these floodplain maps are changed as soon as possible. This means action by both the local and federal governments, something that has not happened yet.

A draft study released by the National Weather Service and NOAA, titled “NOAA Atlas 14,” has recently corroborated local observations and data indicating that the existing 100-year floodplain map is obsolete (NOAA 2018b). This study analyzed historic data on the 24-hour interval for 100-year rainstorms, and it determined that the rainfall estimate for this duration needs to be increased from 13 inches to 16-to-17 inches over 24 hours in central Harris County, with higher rainfall estimates to the east and lower estimates to the west. An image of the preliminary map generated by this study is shown in Figure 4. The estimated 500-year rainfall amounts are also expected to be much higher than current values.

Figure 4. New Rainfall Estimates for 100-year Floods in Southeast Texas



Note: The new rainfall estimate for a 24-hour time period in downtown Houston is suggested as 16-to-17 inches for 100-year storms.

Source: NOAA (2018b)

It should be noted that this update is based on the historic record of past rainfall amounts and does not include an assessment of future rainfall trends and patterns. This is a very important limitation. Climate change studies indicate that the frequency of severe storms is expected to rise due to hotter air temperatures and rising water temperatures in the Gulf of Mexico, Caribbean Sea, and Atlantic Ocean, which fuel tropical storms and evaporate massive amounts of water. Harvey was clearly an example of such a storm, and according to multiple scientists presenting at the February 2018 SSPEED (Severe Storm Prediction, Education, & Evacuation from Disasters) Center conference at Rice University, more Harvey-like storms can be expected in the future. We are living in an era of changing climate, and those changes are not being addressed as needed for the future.

A recent study by Kerry Emanuel of the Massachusetts Institute of Technology (MIT) has evaluated the recent and future severe storm changes in the Houston area and the impact of these changes on storm frequency (Emanuel 2017). Emanuel (2017) estimated that the amount of rain that fell during 100-year (1%) rainfall events in Texas between 1981-2000 was about 20 inches. Using climate models, he estimated that such 20-inch rainfall will become the 18% (5.5-year) rainfall for the period between 2081-2100. For 2017, he estimated that such 20-inch rainfall was the 6% (16-year) rainfall based on this projection. Emanuel (2017) admits that this analysis was preliminary, but he is also one of the premier climate scientists and modelers in the United States.

For now, we seem destined to continue to adjust the floodplain maps every so often to update them as rainfall estimates change. Instead, we should consider how to get ahead of this issue, something we can only do if we stop arguing about whether or not the climate is changing and instead start analyzing and understanding this serious problem. If we do not look forward, we will not see the increasing rain in our future, and this could have large implications for flood risk and the loss of lives and property. We need to be smarter and more resilient in our thinking about future rainfall and potential flooding.

### **III. The Status of Various Watersheds**

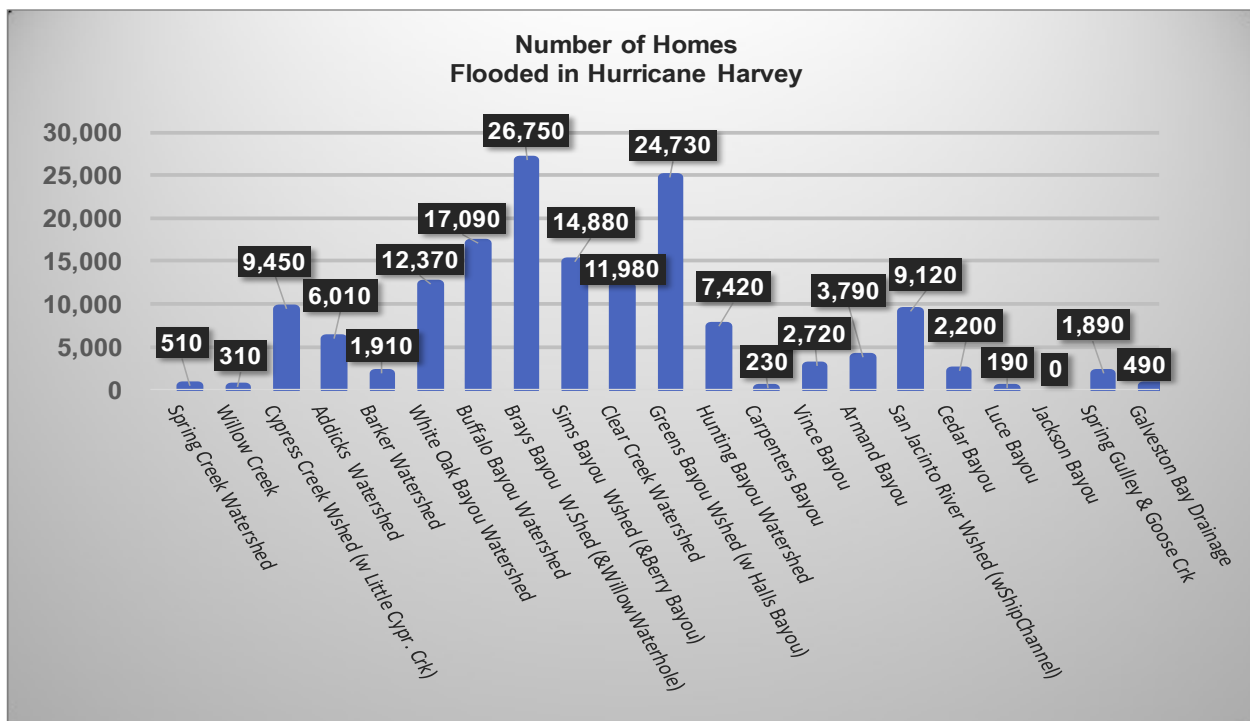
Another key to understanding flooding in Harris County is understanding watersheds—where creeks and bayous start and end, the areas that they drain, the status of their development, the nature and extent of flooding problems, proposed plans and remedies for flooding problems, and residual flooding issues. These pieces of information are necessary for an informed policy discussion. A map of Harris County watersheds is shown in Figure 1. In the sections that follow, various watersheds will be discussed relative to some current plans and identified issues for flood mitigation.

This section of the paper presents information about a number of watersheds in Harris County. We present information on four watersheds that have either proposed or ongoing federal flood control projects (White Oak Bayou, Hunting Bayou, Brays Bayou, and Clear Creek). We also discuss three watersheds that are at-risk of upstream development impacting downstream properties, including Sims Bayou, Cypress Creek, and Spring Creek. In addition, we present information on Buffalo Bayou, which includes the Addicks

and Barker Dams and Reservoirs. Buffalo Bayou saw extensive Harvey flooding due to the U.S. Army Corps of Engineers' operations of those federal dams. Finally, we provide information about Greens and Halls Bayous and their flooding issues.

Before discussing these watersheds in detail, it is worth noting the overall flood damages that occurred in each of these watersheds during Harvey. Jeff Lindner and Steve Fitzgerald of the HCFCFCD have provided an excellent source of information in a recent damage compilation, which identifies a total of 154,170 homes flooded in Harris County during Harvey and damages amounting to over \$120 billion (Lindner and Fitzgerald 2018). A summary of homes flooded by watershed is adapted from Lindner's data and is set out in Figure 5. It is interesting to note that many of these watersheds have had a history of flooding prior to Harvey, and yet not all of them have ongoing or proposed federal flood control projects.

**Figure 5. Number of Homes Flooded in Hurricane Harvey per Watershed**



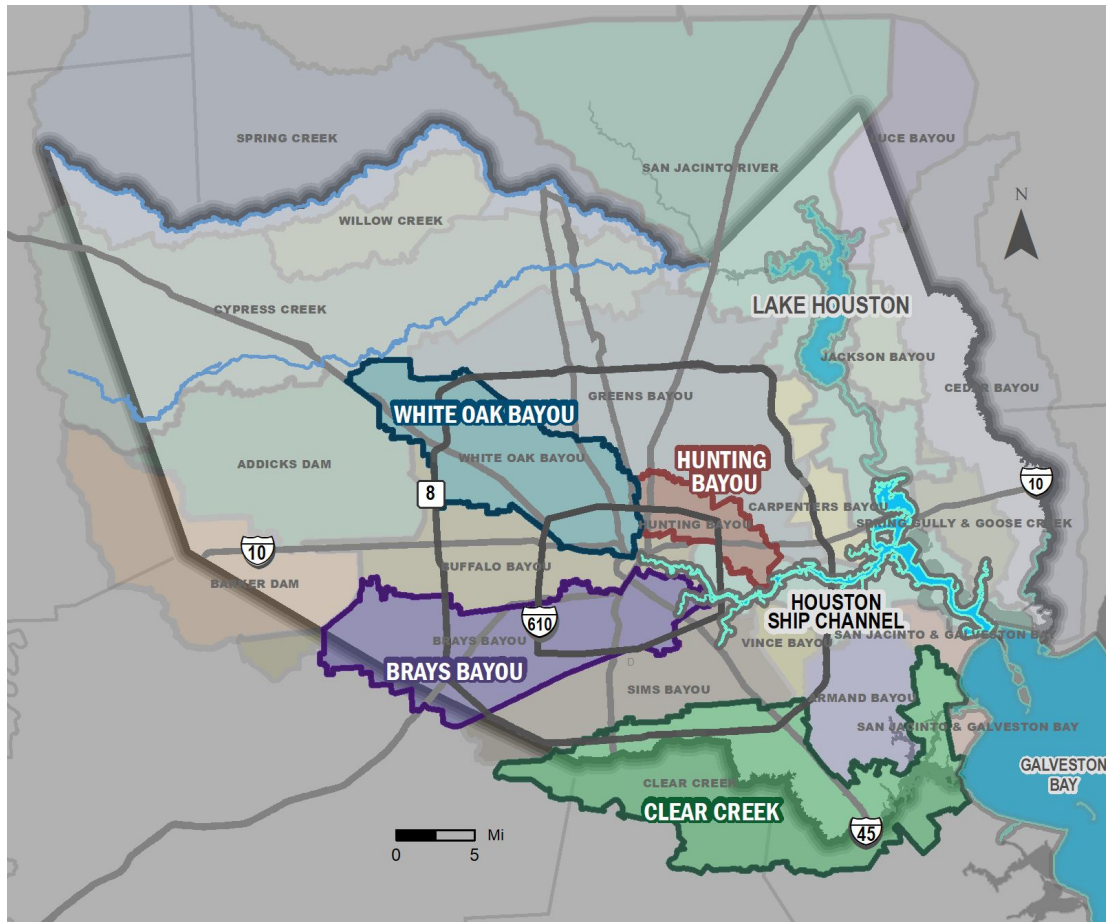
Source: Adapted from data presented by Lindner and Fitzgerald (2018)

### *A. The Four Proposed Federal Projects*

Four watersheds are discussed here that have also been studied by the U.S. Army Corps of Engineers and for which federal projects have been developed and approved, waiting only for appropriations that were approved by Congress in February 2018 and allocated by the Corps in June 2018. These four watersheds are White Oak Bayou, Hunting Bayou, Brays Bayou, and Clear Creek. If Harris County passes a flood bond issue on August 25, 2018 (the

special election date set by the commissioners and enabled by Governor Abbott), a portion of the money from this bond issue will provide the local match to the federal money for these projects. A map showing these four watersheds is presented in Figure 6.

**Figure 6.** Map of the Four Harris County Watersheds with Proposed Federal Projects



Source: Image prepared by Christina Walsh for the author(s)

### 1. Brays Bayou

Brays Bayou has had major flooding problems, as demonstrated by the over 23,000 homes flooded in Harvey. Brays Bayou was channelized by the U.S. Army Corps of Engineers in the late 1950s. For decades, this bayou provided excellent flood protection that was lost over time due to poorly anticipated runoff increases due to upstream development, paved parking lots, storm sewers, and improved drainage ditches. More recently, the U.S. Army Corps of Engineers and HCFCD have initiated “Project Brays,” which has been underway for several years and is not yet completed (Project Brays 2018). Additional appropriations are necessary to complete Project Brays. According to the Project Brays website:



Upon its completion, Project Brays will provide a 1 percent (100-year) level of protection along the main stem of Brays Bayou upstream of Beltway 8. After the construction of all elements of Project Brays, the area downstream of Beltway 8 will see the removal of the 1 percent (100-year) floodplain from 15,000 homes/businesses in the Brays Bayou watershed. (Project Brays 2018)

The overall cost of the project is over \$500 million, with about half of the work on 71 distinct projects being completed at the time of this writing. This project cost translates to an estimated cost of \$36,650 per home liberated from the 100-year floodplain.

It is important to note that while there will certainly be improvement associated with Project Brays, certain areas will remain in the current 100-year floodplain after completion of the project, as shown in Figure 7. Although some of these remaining areas are along the main stem of the bayou, primarily between Loop 610 and Beltway 8, substantial acreage in tributaries such as Keegan's Bayou at the Southwest Freeway will also remain within the expected floodplain following the completion of this project. The U.S. Army Corps of Engineers' projects on main channels often are not intended to improve conveyance in the tributaries to the main channel.

The proposed effectiveness of this project will be altered by correcting the 100-year floodplain estimates, as discussed in the first section of this paper. As the 100-year rainfall estimate has increased from 13 inches in 24 hours (which is accounted for in Figure 7) to 16 or 17 inches in 24 hours, much of the area shown as liberated from the current 100-year floodplain map will once again become subject to the updated 100-year event when the new rainfall estimates are applied. It will be difficult for citizens to keep up with these changing floodplain maps and realities. It will be the responsibility of elected officials to make sure citizens are informed of the fact that while their risk of flooding may be reduced by these flood control projects, the reduced 100-year floodplain may only be temporary, as it will be increased again when the new 100-year rainfall estimates are applied to the map.

The bottom line with regard to Brays Bayou is that Project Brays will help reduce the current flooding problem, but a serious flooding problem will continue to exist in many of the areas that have been impacted by flooding in the past. It is important that the public be made aware of the risks that will continue to exist in areas around Brays Bayou.

## 2. White Oak Bayou

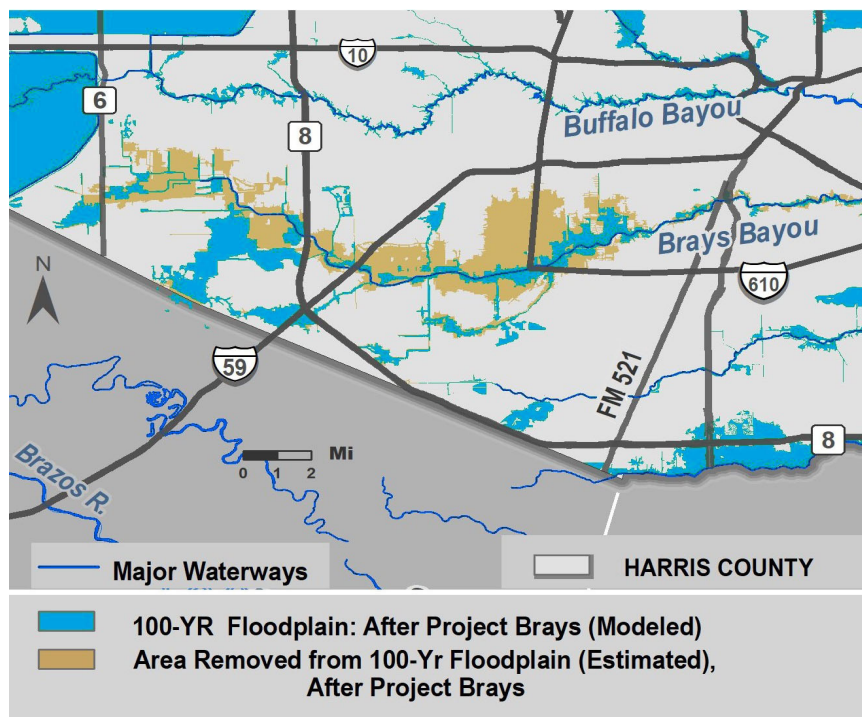
The White Oak Bayou Project is a federal flood control project including channelization and regional detention ponds proposed for the area upstream of the currently channelized lower portion of White Oak Bayou. The area to be channelized extends roughly from Loop 610 northwest to Highway 99 (the Grand Parkway). The downstream ten miles of White Oak Bayou from just outside Loop 610 north to the confluence with Buffalo Bayou in downtown Houston was channelized by the U.S. Army Corps of Engineers in the 1960s. The proposed federal project for White Oak is shown in Figure 8. The proposed cost to complete this project is \$237 million, with about \$80 million of this amount being the local share. According to Corps documents:

Upon project completion, the Flood Control District estimates that within the project area, most areas along White Oak Bayou will see water surface elevation reductions of 0.5 to 1.5 feet for the 1 percent (100-year) flooding event. (HCFCD 2018f)

[T]he proposed project reduces the extent of the 10 percent [10-year] and 1 percent [100-year] flood plain areas so that 1,285 and 1,511 structures, respectively, would now be located outside of the two reduced flood plain areas, leaving 48 and 4,563 structures, respectively within the two reduced flood plain areas. (U.S. Army Corps of Engineers 2012)

The proposed project cost translates to a cost of about \$158,000 per structure liberated from the 100-year floodplain. Again, it is important to keep in mind that the 10-year and 100-year flood events do not reflect the more recent rainfall information that will increase the intensity and spatial flooding of these storm events.

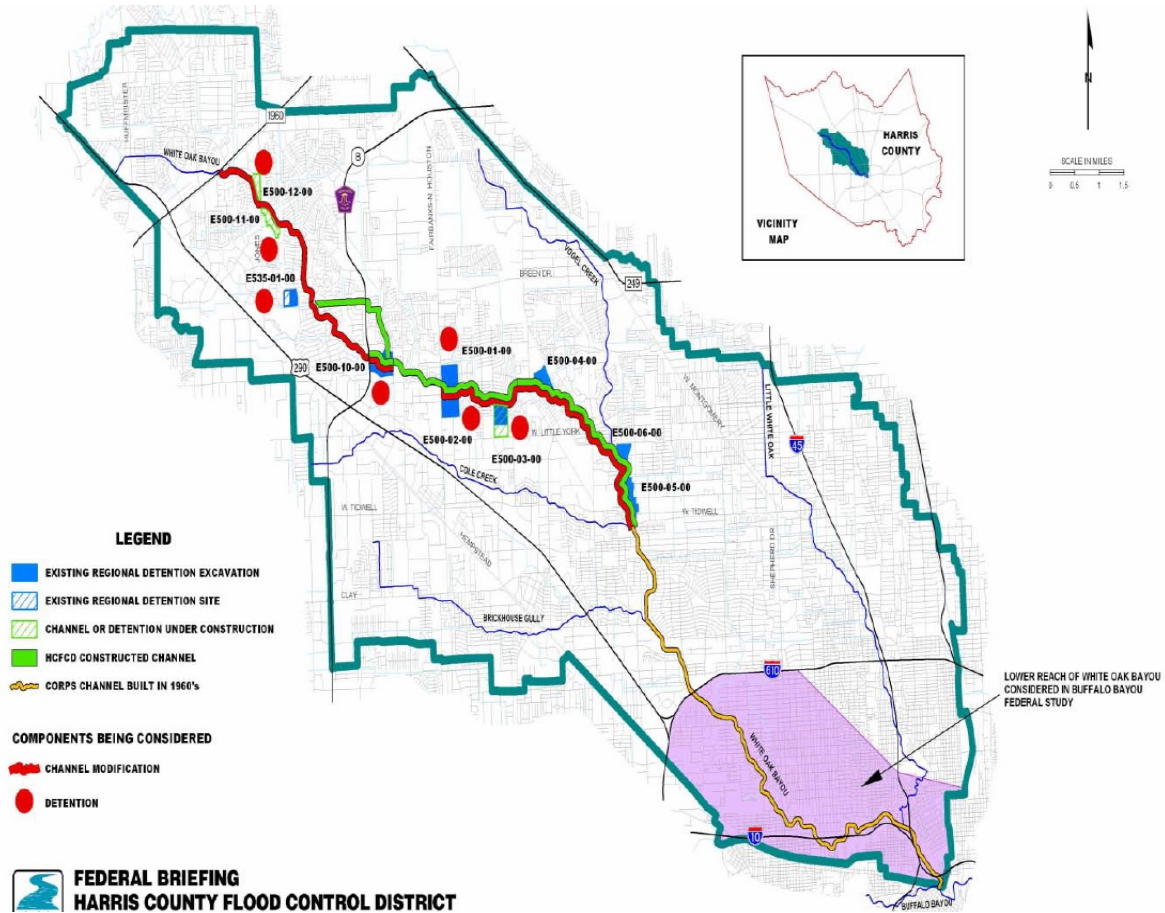
**Figure 7.** The Proposed 100-year Floodplain after Project Brays



Note: The altered 100-year floodplain after the completion of Project Brays is shown in blue. The area shown in brown will be removed from the current 100-year floodplain upon the completion of Project Brays.

Source: Project Brays (2018)

Figure 8. Proposed Federal White Oak Bayou Channel Enlargement and Detention Pond



Note: The red line indicates proposed channelization and the green line indicates existing channel improvements by the HCFCD. The red circles are proposed detention ponds. The blue rectangles are existing regional detention excavations completed by the HCFCD.

Source: U.S. Army Corps of Engineers (2012)

### 3. Hunting Bayou

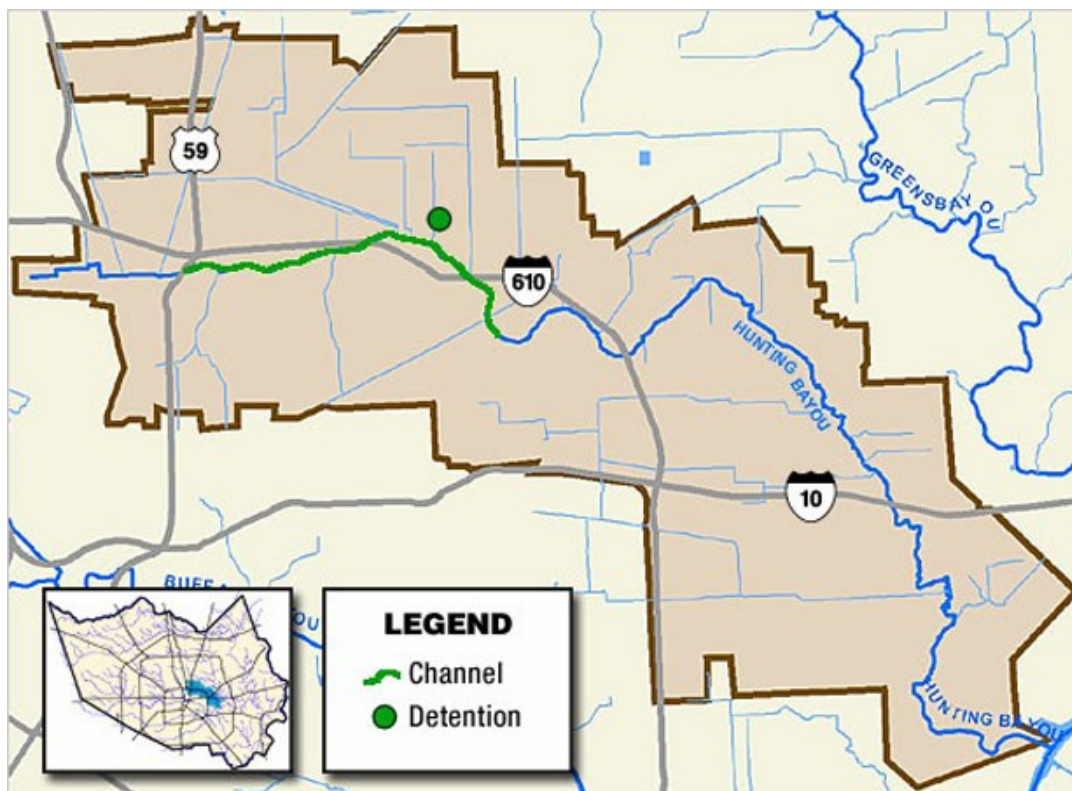
The U.S. Army Corps of Engineers Hunting Bayou Project is also at a stage where it is awaiting federal project funding. This project in the northeastern sector of Houston will increase Hunting Bayou's stormwater conveyance capacity and will include one major detention basin just north of Loop 610 and multiple bridge replacements. This project costs just over \$187 million, with about \$85 million of this being the local share according to a 2013 Corps report. According to the Harris County Flood Control District web site:

When this project is complete, most neighborhoods near the bayou will see water surface elevation reductions of 3-4 feet for the 1 percent (100-year) flooding event. The number of homes and businesses subject to the 1 percent (100-year) flooding

event would drop from 5,100 to 650, and all homes and businesses will benefit from the reduced frequency and depth of flooding. (HCFCD 2018c)

The project cost translates to a cost of \$38,390 per home liberated from the 100-year floodplain. No work is proposed downstream of the intersection of Hunting Bayou with the rail yard just south of Loop 610, which appears to be a source of flooding in the area, as it represents a major impediment to overland flow of stormwater. The proposed federal project for Hunting Bayou is shown in Figure 9. It is important to note that this project barely qualified for federal funding under the benefit-to-cost criteria used by the Corps. Other bayous in lower-income watersheds have been unable to meet this cost qualification criterion, which has raised serious equity issues that are discussed further in the Greens Bayou section of this report.

**Figure 9.** Proposed Federal Projects for Hunting Bayou



Note: Proposed federal project improvements shown in green include channel improvements and a detention pond.

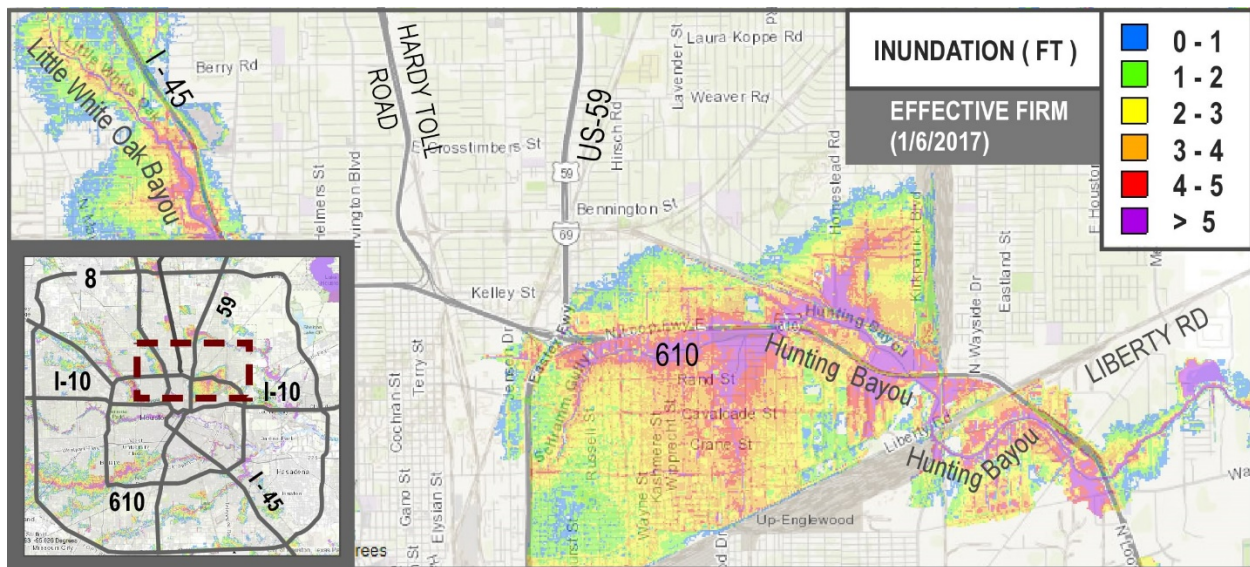
Source: HCFCD (2018c)

The existing problem in Hunting Bayou in the Kashmere Gardens and Trinity/Houston Gardens areas appears to be related to the rail yards that extend from southwest of Loop 610 to northeast of Loop 610 and parallel to Wayside Drive north of Loop 610. As can be



seen in Figure 10, the existing 500-year floodplain, which will soon be used by the city of Houston for regulating building elevation, extends over a significant portion of these neighborhoods. While the proposed federal project will offer some much-needed relief, a substantial localized flooding problem will remain and should become a priority, as this area will continue to flood after completion of this project.

**Figure 10.** The 500-year Floodplain of Houston with Focus on Hunting Bayou



Note: The purple area indicates inundation of five feet or deeper, with other colors gradated in one-foot increments to blue.

Source: City of Houston Public Works and Engineering (2018)

#### 4. Clear Creek

The fourth proposed federal project is on Clear Creek. This project has been under study and construction since 1986, and additional work was proposed in 2013. There are several features to this proposed work. First, the proposed project identifies channel work to be done along the entire length of the creek to Clear Lake, as well as construction of a new outlet and gate into Galveston Bay to release excess floodwaters from upstream. Additional work is proposed to be completed upstream of IH-45 on Clear Creek tributaries such as Mary's Creek, Mud Gully, and Turkey Creek. Detention ponding will also be constructed alongside the main stems of Clear Creek and Mary's Creek. This project also includes environmental enhancements that are currently estimated to cost \$249 million, with the estimated cost share being \$151 million (61%) federal and \$98 million (39%) local (HCFCD 2018b).

When completed, the project is estimated to protect an estimated 2,100 structures in the current (obsolete) 100-year floodplain. As with the other three federal projects, the 100-year floodplain for Clear Creek will be increased when the new 100-year rainfall amounts



are incorporated into the floodplain map. This project cost translates into a cost of approximately \$118,500 per structure protected by this federal project.

## 5. Discussion

It is interesting to note the difference in the performance of these federal projects. On Brays Bayou, the estimated average cost per home removed from the 100-year floodplain is \$36,650. On White Oak Bayou, the cost per structure removed from the 100-year floodplain is estimated to be about \$158,000. On Hunting Bayou, the cost per home liberated from the 100-year floodplain is \$38,390. Finally, on Clear Creek, the cost per structure removed from the floodplain is estimated to be \$118,500. These cost-per-home-protected differences bring into focus one of the more difficult issues—how do we determine when to spend money for major structural improvements, such as increasing channel conveyance capacity or adding detention storage capacity? Alternatively, when do we utilize other options, such as buying out or flood-proofing houses? As discussed, the 100-year (1%) solution envisioned by these federal projects is based on old rainfall amounts (and in some cases, floodplain maps predating the major revisions after Tropical Storm Allison) and not on the new norm. The level of protection predicted by these past studies is simply too little given the changing rainfall amounts. In part 3 of this report, certain concepts for creative use of buyouts to address this problem will be discussed.

As of this writing, the U.S. Army Corps of Engineers has announced its most recent allocation of money appropriated by Congress in the Bipartisan Budget Act of 2018 (HR 1892). In this announcement, the Corps allocated \$295 million to the Clear Creek Project, \$75 million to complete the Brays Bayou Project, \$65 million to complete the Hunting Bayou Project, and \$45 million to complete the White Oak Bayou project. Based on prior information about these projects, there will be a requirement for Harris County as the local sponsor to provide some amount of local funding to secure this federal authorization.

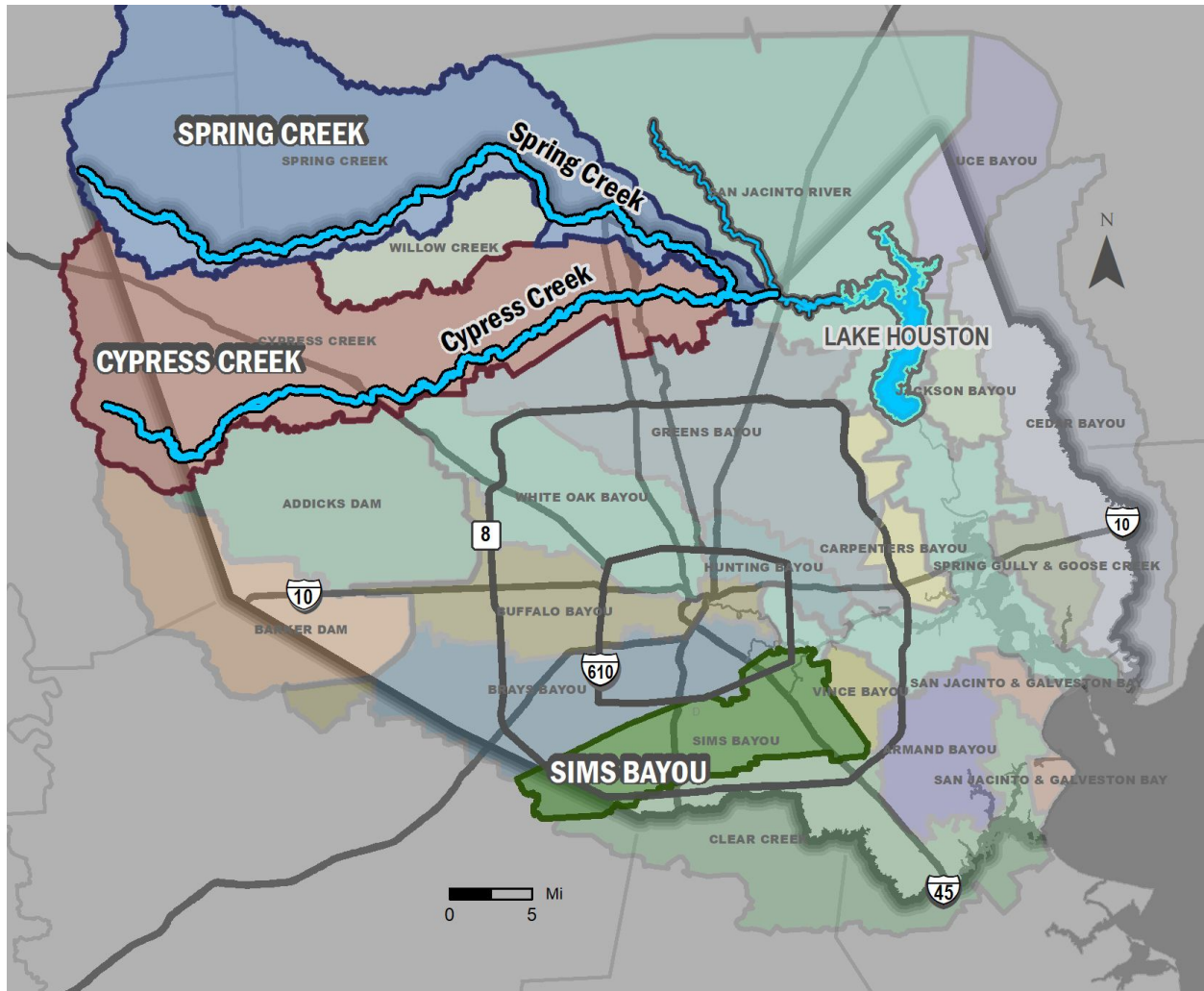
### *B. Three Watersheds at Risk from Upstream Development*

Of the 22 watersheds in Harris County, three stand out as being particularly vulnerable to downstream flooding due to upstream development. These are Sims Bayou, Cypress Creek, and Spring Creek, and they are shown in Figure 11. These three are singled out due to the fact that unlike many other major Harris County watersheds, significant undeveloped land remains in the upstream portions of these watersheds, and it lies in the path of development. In these watersheds, the runoff from new development, if permitted under current development criteria, could potentially increase downstream flooding problems.

There is no doubt that upstream development can and has worsened flooding downstream for a variety of reasons. This situation has already occurred on several major bayous, such as Brays Bayou. Brays Bayou was channelized in the late 1950s to handle a storm judged at the time to be well in excess of the 100-year flood event. Meyerland and other areas that flood repeatedly today were deemed to be protected when the channelization was complete. However, over the years, upstream development that increased impermeable surfaces, storm sewers, and drainage ditches progressively increased the water flow at

downstream locations to the extent that the channel today likely can only handle a 5-year to 10-year flood event.

**Figure 11.** Three Watersheds at Risk of Flooding Due to Upstream Development

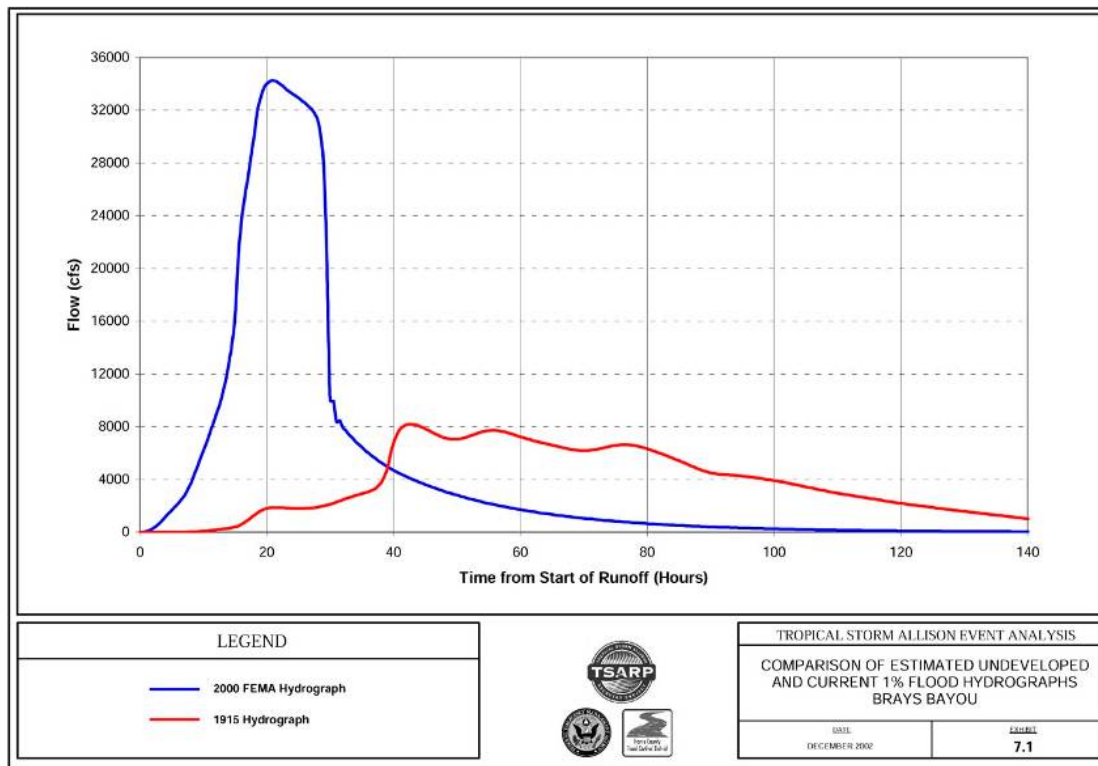


Source: Image prepared by Christina Walsh for the author(s)

This increase in downstream flow is depicted in Figure 12, which shows the pattern of water flow for a 100-year rain event for the undeveloped (year-1915) watershed in red. As indicated, it took 140 hours—almost six days—for the flow from that rain to pass a particular location, but the peak flow never got above 8,000 cubic feet of water per second (cfs). However, when the same amount of rain is dropped on the developed (year-2000) watershed, the flow rises to about 34,000 cfs, representing over 4 times more water flowing past the same spot every second. This is why Brays Bayou floods so dramatically. Harris County and the city of Houston increased downstream flooding with the approval of

upstream development that did not require adequate flood mitigation, which essentially subsidized upstream development by flooding downstream homes.

**Figure 12.** Comparison of Water Flow in Brays Bayou between 1915 and 2000



Note: The blue line shows the increase in flow past a single location in the year 2000, after most of the watershed was developed. The red line shows the flow based on 1915 undeveloped conditions. The result is that peak flows (and flooding potential) have increased fourfold for the same 100-year rainfall event.

Source: FEMA and the HCFCD, Tropical Storm Allison Event Analysis (FEMA, n.d.)

Many of Houston's bayous have already experienced significant impacts from upstream development, including Brays Bayou, White Oak Bayou, Hunting Bayou, and Clear Creek, to name a few. However, Sims Bayou and Cypress and Spring Creeks have significant remaining undeveloped land and are in a position to be impacted by increased runoff from upcoming upstream development. Currently, flooding adjacent to Sims Bayou is in relatively good shape due to a recently completed channelization project, but that capacity could be lost just as it was lost on Brays Bayou if upstream development is not adequately regulated and mitigated. Similar problems can and will arise on Cypress and Spring Creeks. Among other things, it has been suggested that Harris County adopt the same development regulations that are applicable in Fort Bend County—regulations that are more stringent

than current Harris County and city of Houston requirements. While the HCFCD has recently developed stricter criteria for stormwater detention ponds in the Addicks and Barker watersheds and upper Cypress Creek and Little Cypress Creek, these criteria are still much less stringent than in Fort Bend County for the same type of development.

Two points about these bayous are noteworthy. Although Sims Bayou had been recently channelized, there was still major flood damage from Harvey within the watershed that flooded over 20,000 homes. Much of this flooding occurred on Berry Bayou, a tributary not improved by the Sims Bayou project. Significant flooding also occurred away from the bayou due to inadequate neighborhood-level overland flow capacity, an issue that exists in much of the community and is not addressed in this paper.

It is also important to note that Cypress Creek is one of the most neglected bayous in Harris County. For various reasons, Cypress Creek has not qualified for a federal project and has not been the focus of local channelization or regional retention/detention projects. Cypress Creek has arguably received the least amount of funding of any major watershed, even though it is the fifth-most populated watershed. It also flooded about 8,700 homes in Harvey, making it the sixth-worst flooded watershed in the area. The relative population per watershed of Cypress Creek is compared to other watersheds within Harris County in Figure 13.

### *C. Buffalo Bayou*

Buffalo Bayou was one of the most heavily impacted watersheds during Harvey due to rainfall flooding, bayou overflow, and releases from and impoundment behind Addicks and Barker Dams/Reservoirs. In the following section, Addicks and Barker Dam/Reservoir issues are discussed initially, followed by a more general discussion of Buffalo Bayou.

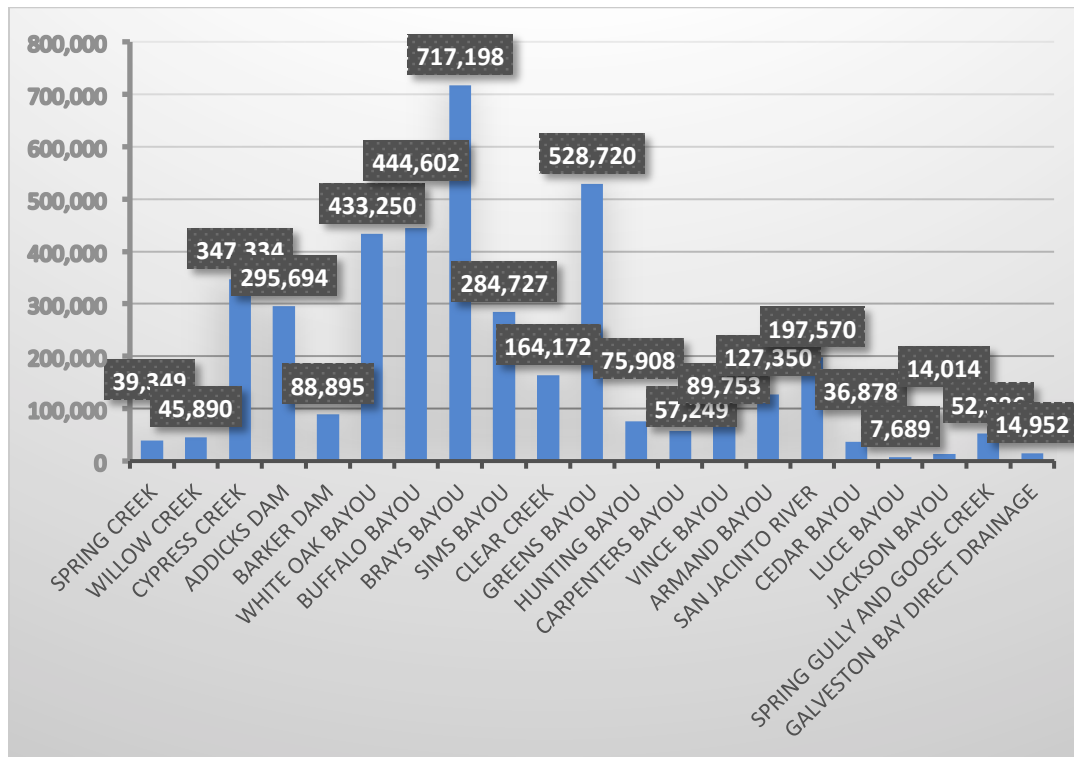
#### 1. Addicks and Barker Dams/Reservoirs

One of the most noticeable flood issues arising from Harvey was the flooding related to Addicks and Barker Dams/Reservoirs, which were initially constructed in the 1940s. As Figure 14 shows, Addicks and Barker Dams were constructed in the upper (western) portion of the Buffalo Bayou watershed. Addicks Dam collects runoff from several tributaries—South Mayde Creek, Bear Creek, Langham Creek, and Horsepen Creek—and Barker Dam collects runoff from Mason Creek and Upper Buffalo Bayou. Addicks also receives overflow from the Cypress Creek watershed west of US 290 during high flow events such as Harvey.

There are multiple issues associated with Addicks and Barker Dams. First, these dams were identified by the U.S. Army Corps of Engineers in 2009 as having classification DSAC 1, the highest risk level in the Corps evaluation methodology, meaning that “the dam is almost certain to fail under normal operations within a time frame from immediately to within a few years without intervention or the combination of life or economic consequences with probability of failure is extremely high” (U.S. Army Corps of Engineers 2010, 2). The Corps determined that they were at risk of “catastrophic failure” due to issues with the outflow gate structures and the presence of structural stability issues at the spillways. To date, these

issues have not been completely resolved, and these dams remain vulnerable to structural integrity issues, particularly if flows go around the ends of the emergency spillways, as occurred at Addicks during Harvey. Fixing these dams should be the number one priority. Concern about the structural stability of these dams was certainly a factor in the decision to open the outflow gates and release stored water that caused or contributed to the flooding of homes downstream on Buffalo Bayou. These weakened structures represent an ongoing threat to community safety.

**Figure 13.** Population per Watershed in Harris County



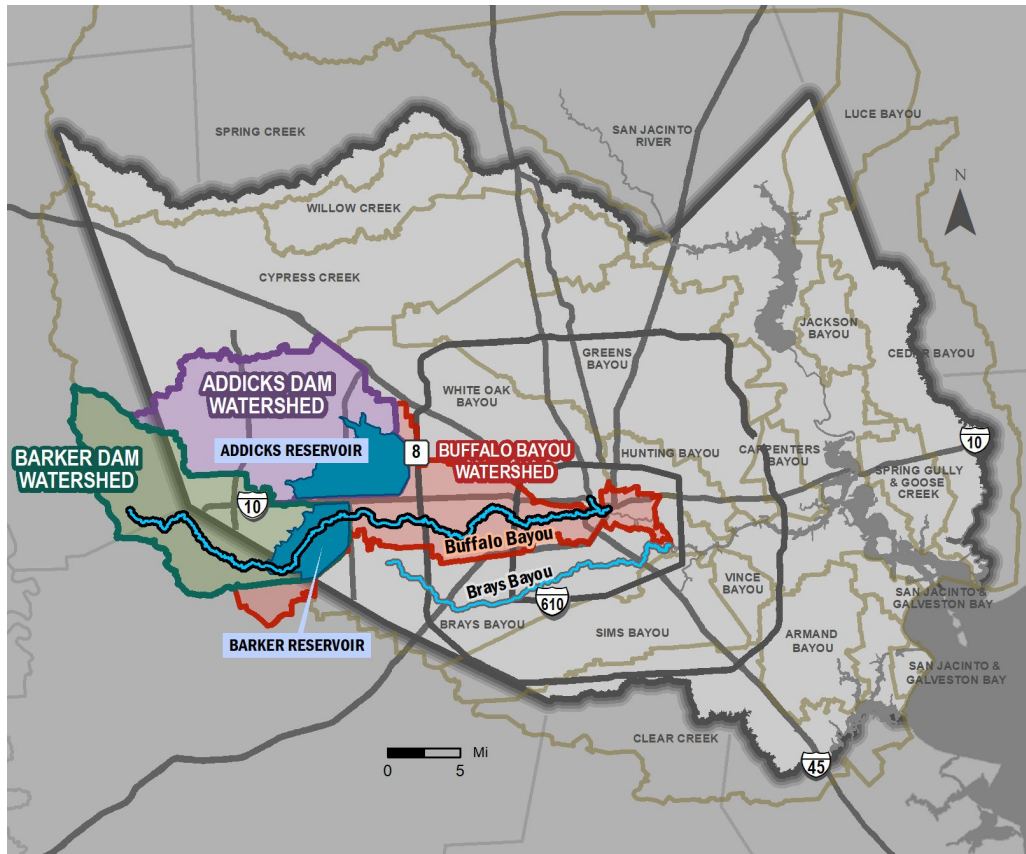
Source: HCFCD (2018e)

Second, about 10,000 residential and commercial properties were flooded upstream of the Addicks and Barker Dams, at the western edge of both Addicks and Barker Reservoirs. These homes were built in the flood pool of these reservoirs, meaning that they were below the elevation of the emergency spillways and would therefore flood when the Addicks and Barker Reservoirs became full, as was the case with Harvey. Homes were allowed to be developed and sold in this flood pool area with the knowledge of the federal, state, and local governments. No clear warnings were issued to would-be purchasers of these homes about intended reservoir pool flooding, and no limitations were placed on allowing homes in these areas to prevent them from being flooded by the reservoir flood pool. Unless the land fell within the 100-year floodplain (which was not the case for most of this developed flood pool area), flood insurance was not required. It seems clear that our



collective judgment, both technical and ethical, was lacking in the way this development was allowed to occur.

**Figure 14.** Map of Buffalo Bayou, Addicks Dam Watershed, and Barker Dam Watershed



Source: Image prepared by Christina Walsh for the author(s)

In addition, there is a third, more recent issue that many believe to represent a major lapse by either the Corps, the local governments, or both. Documents from the Corps reveal that as early as Thursday, August 24, 2017 (when Harvey was still in the Gulf—see Figure 15), Corps hydrologists conducted computer analyses of projected rainfall amounts that indicated homes would flood behind Addicks and Barker Dams. By Friday morning, the internal Corps analysis still indicated that homes would flood behind both Addicks and Barker Dams, and these projections were continued forward on Saturday and into Sunday with flood projections worsening daily. It is hard to understand why this information was not released to the public—particularly by Saturday when it was clear that the predicted flooding was going to occur (see Figure 16 for the Corps' internal prediction issued Saturday, August 26, 2018). The sad reality was that most residents did not find out about potential flooding until they woke up Sunday night or Monday morning and stepped into floodwaters next to their beds. This failure to adequately inform the public about the potential flooding of homes in general and the imminent flooding of homes during Harvey

is a major policy concern, as is the failure of both the Corps and the local government to prioritize fixing Addicks and Barker Dams.

Figure 15. Map of Hurricane Harvey's Path and History



Note: As early as August 24, 2017, the U.S. Army Corps of Engineers had undertaken computer modeling based on projected rainfall that showed homes would be flooded behind Addicks and Barker Dams.

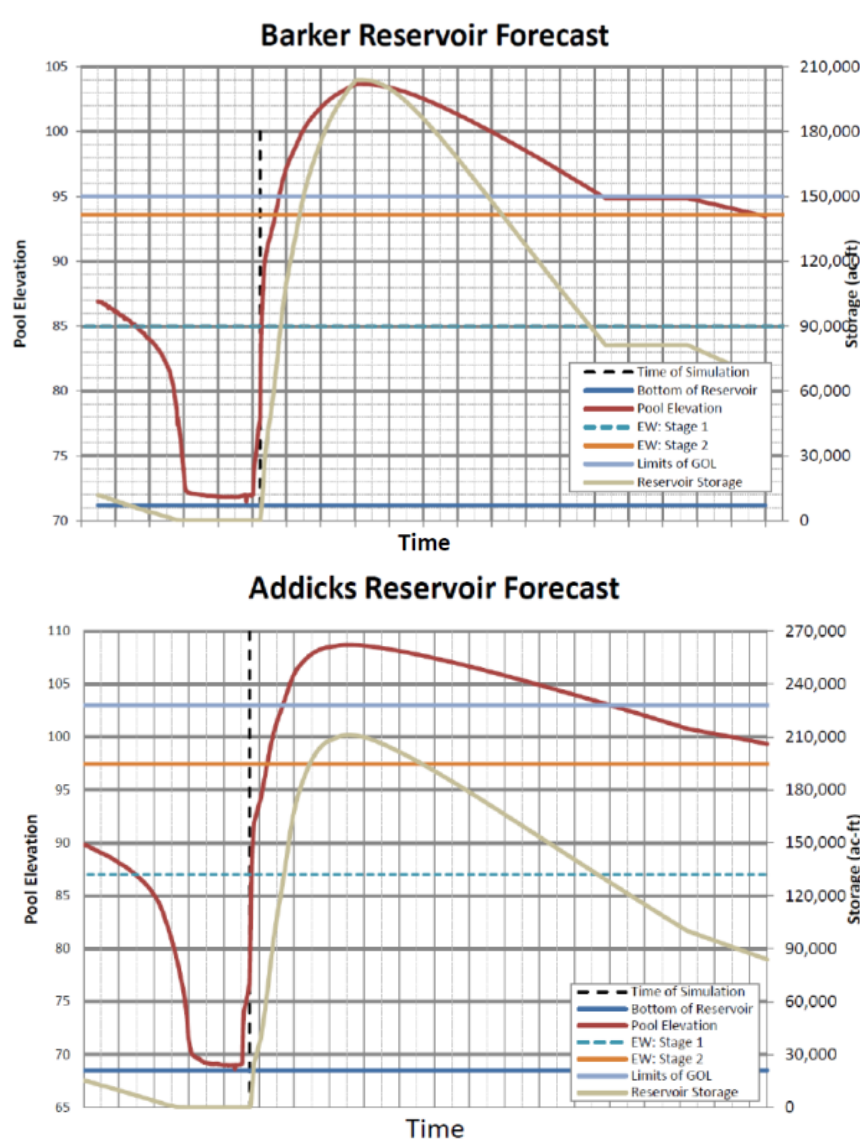
Source: Graphic courtesy of The Weather Channel

In the future, there is the potential for creating additional storage capacity within these two reservoirs (e.g., by building upstream reservoirs or excavating within these two reservoirs) to provide even more flood benefits, and the sooner this additional storage capacity can be created, the better. At present, it is clear that these two reservoirs have become liabilities when they should be assets. In addition, current policies about effectively providing high quality information to the public need to be seriously reconsidered.

## 2. Buffalo Bayou Flooding Generally

In addition to the problems directly associated with the release of water from Addicks and Barker Dams, there was also flooding on Buffalo Bayou associated with local runoff from rainfall. This problem was particularly evident on Saturday, August 26, 2017, at least a full day before the two dam releases that further worsened downstream flooding. It is important to note that prior to Harvey, Buffalo Bayou had performed better than most bayous in Houston, primarily due to the existence of Addicks and Barker Dams. However, it is clear that with the more intense rains of Harvey and other recent storms, there is greater vulnerability here than had previously been realized. This is especially true given the potential for dam failure at Addicks and Barker. These problems have to be fully studied and considered, including the impact of future rainfall.

**Figure 16.** Modeling Results for the Water Levels in Barker and Addicks Reservoirs Prior to Hurricane Harvey



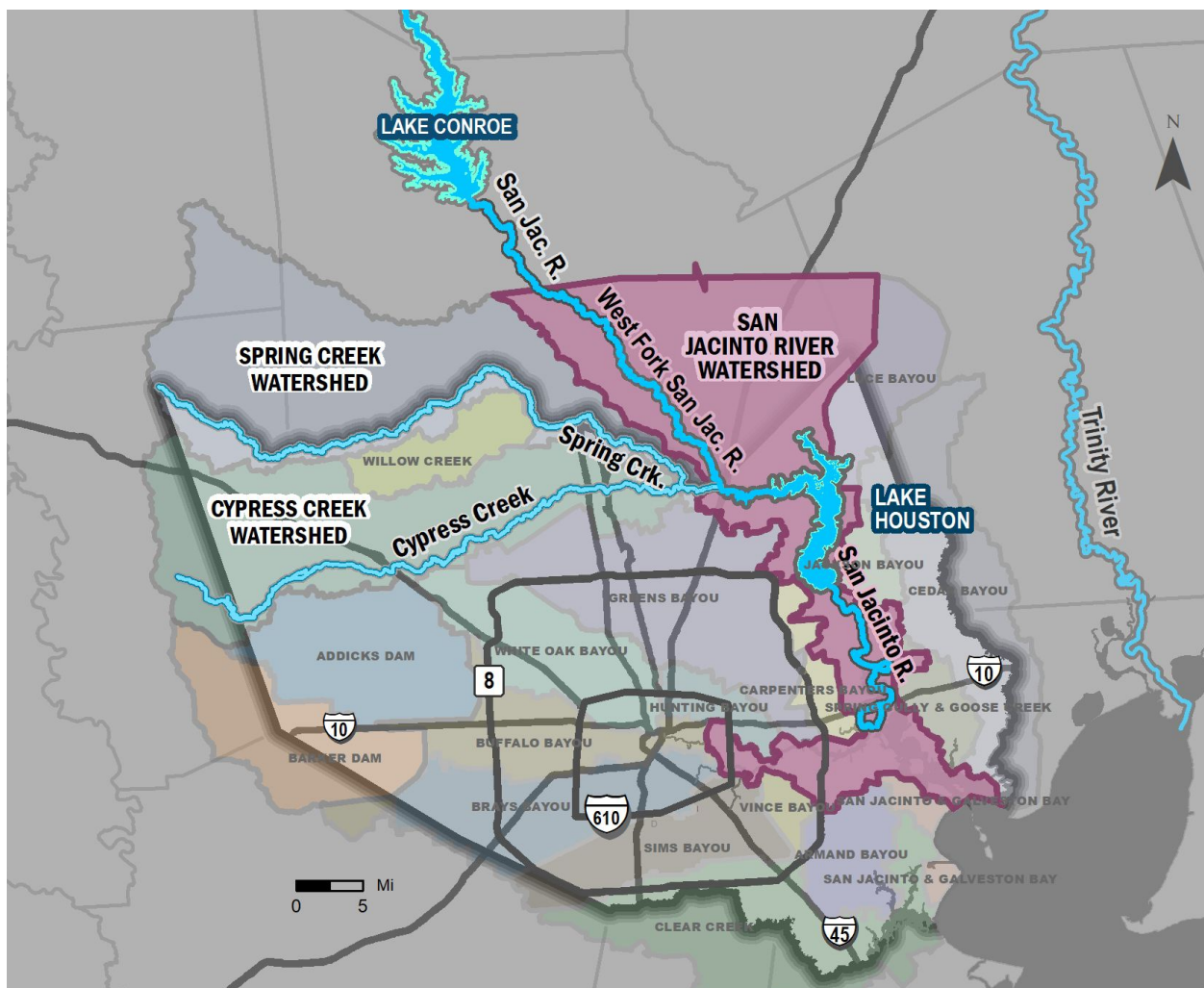
Note: Modeling results completed on Saturday, August 26, 2017 at 11:00 hours, showing that water levels in both Addicks and Barker Reservoirs would exceed the extent of government-owned lands (top light blue line) by the amount shown in the red line. This indicated that flooding would be about nine feet higher than the extent of the government-owned lands in Barker and about six feet higher in Addicks. Most homes did not flood behind Addicks and Barker Dams until after midnight on Monday, August 28, 2017.

Source: U.S. Army Corps of Engineers Internal Modeling Results 2017

*D. West Fork of the San Jacinto River: The Kingwood, Atascocita, and Lake Houston Areas*

One of the more heavily impacted areas by Hurricane Harvey was along the west fork of the San Jacinto River where it flows into Lake Houston. This watershed extends from the Lake Conroe area in Montgomery County south into Harris County, where it is joined by Spring and Cypress Creeks, as shown in Figure 17. Here, the Kingwood subdivision on the north and the Atascocita subdivision on the south were both heavily impacted by Harvey, with thousands of homes and businesses flooded on both sides of Lake Houston. The issues here are quite a bit different from other areas within Harris County, adding weight to the conclusion that the county has a number of different flooding problems across several major watersheds.

**Figure 17.** Map of the West Fork of the San Jacinto River



Source: Image prepared by Christina Walsh for the author(s)



Two specific issues have arisen in the context of the Kingwood and Atascocita flooding. First, the river downstream of the US 59 North bridge is full of sand and silt from sand pits and storage piles upstream between Lake Houston and Lake Conroe, as well as erosion along Cypress Creek. These sand pits are poorly regulated by the state of Texas, and many of the stockpiles were unprotected from flooding. In some cases, drainage into the river from the Kingwood subdivisions was blocked by sand dunes that appeared in the river, as shown in Figure 18. These pits need to be better regulated, something that should be noted by both state and federal government officials, and it will likely be necessary to dredge the river to provide adequate carrying capacity for future flood events.

**Figure 18.** Sand in the West Fork of the San Jacinto River after Harvey



Source: Image by Bob Rehak for the author(s)

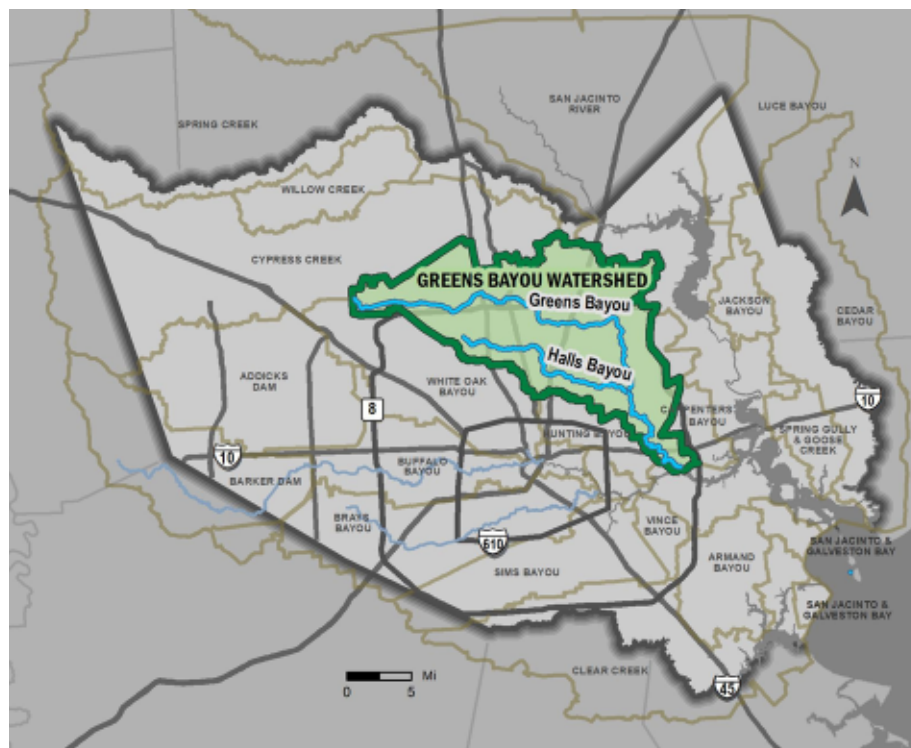
Second, this flooding has called attention to a design issue in both Lake Conroe and Lake Houston. Both of these reservoirs were designed for water supply purposes and were therefore not designed with space reserved for flood storage. Substantial volumes of water were released from Lake Conroe during the Harvey event, leading to outcry from flooded downstream residents who believed that water should have been released from the reservoir in anticipation of major rainfall. The same outcry has also been applied to Lake Houston, where residents have argued that water should have been released in advance of

the floodwaters coming down the river so that there was capacity within the lake to hold the flood. In both cases, these reservoirs are operated for water supply and recreational purposes, and both the city of Houston and the San Jacinto River Authority would likely be hesitant, although potentially willing, to release stored drinking water in anticipation of—but without any guarantee of—rainfall to fill the lake back up again. Clearly the flooding from Harvey has generated a need for reconsidering the operating rules for these reservoirs as well as community priorities relative to drinking water, recreation, and flooding. Recently, the Texas Commission on Environmental Quality has approved prerelease procedures proposed for these two lakes.

### *E. Greens and Halls Bayous*

Greens and Halls Bayous lie on the northern periphery of the city of Houston, flowing from west to east and then south. Greens Bayou is the larger system, and Halls Bayou flows into Greens after it turns south, with all water eventually draining into the Houston Ship Channel. The HCFCD considers Halls to be a tributary of Greens, and both comprise the Greens Bayou watershed, as classified by the HCFCD. During Harvey, Greens Bayou flooded more homes than any other watershed except for Brays Bayou. The flooding from Greens Bayou affected over 24,000 homes, representing almost 16% of the home flooding in Harris County. A map showing the Greens Bayou watershed (including Halls Bayou) is shown in Figure 19.

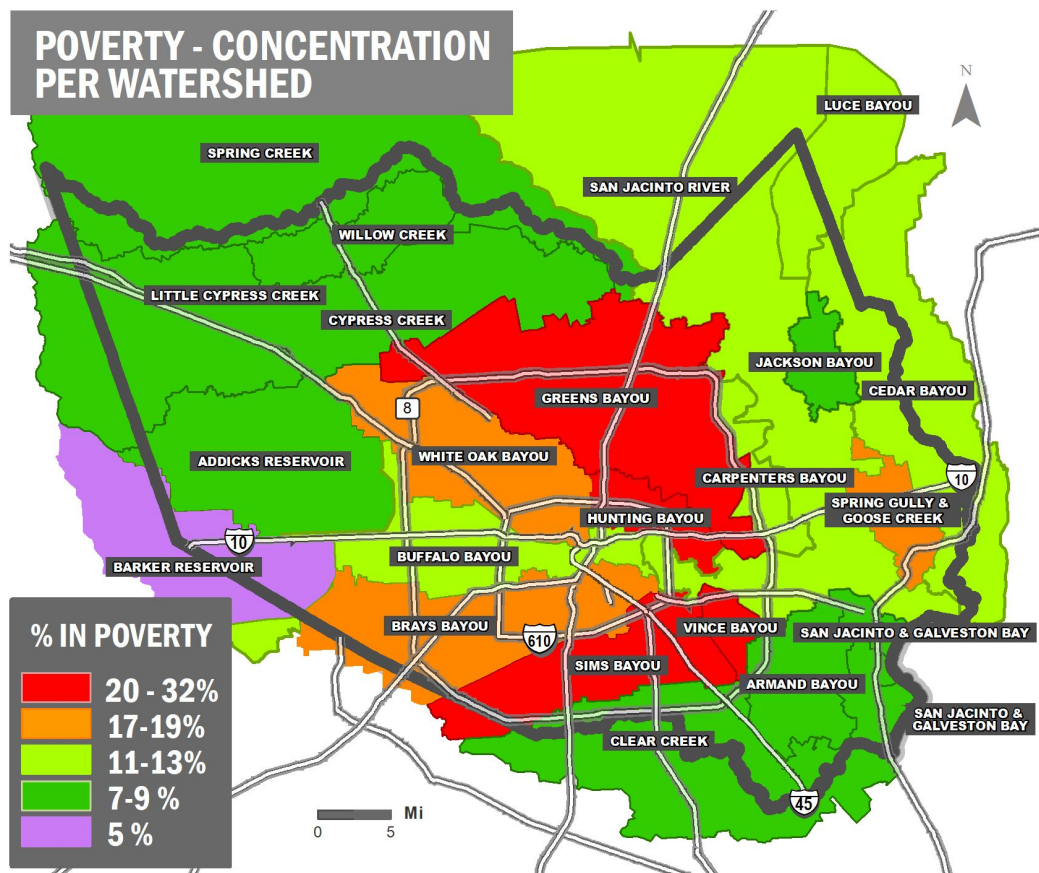
**Figure 19.** Map of Greens and Halls Bayous



Source: Image prepared by Christina Walsh for the author(s)

It is notable that Greens Bayou, with its extensive flooding and continued upstream development, has only recently been getting some much-needed attention and has thus far only qualified for a limited federal project. This is due in part to two issues. First, the area encompassing the Greens Bayou watershed is one of the poorest areas in Harris County, making it more difficult for that watershed to meet federal benefit-cost criteria. For example, if a project protects two \$5 million homes for \$2 million in project cost, that is a much better benefit-to-cost ratio (5-1) than a project that costs \$2 million that protects nineteen \$100,000 homes (1.9-2). In this simplistic example, although 19 units were protected as opposed to 2 units, the 19-unit project will fail on the straight benefit-to-cost comparison basis used for determining federal funding. This is one possible example of environmental justice issues that are present in the current system of determining how flood funding is spent at the federal level. The relative ranking of Greens Bayou based on the percentage of the watershed living in poverty is shown in Figure 20, and it is similar to Sims, Vince, and Hunting Bayous.

**Figure 20.** Map of the Poverty Concentration per Watershed



Source: Image prepared by Christina Walsh for the author(s)

Second, Halls Bayou is considered to be a tributary of Greens Bayou, and the U.S. Army Corps of Engineers' projects are generally limited to the main stream within a watershed, which in this case would be Greens. In this manner, Halls Bayou may not have received full consideration for work. Fortunately, Harris County is not under the federal budgetary constraints and is therefore free to develop its own criteria for funding flood-related projects. To the extent that federal money is required, significant legal research and advocacy will be necessary to find underutilized and obscure provisions that may be available under the federal rules applicable to Corps projects or that may have been discussed in federal court cases challenging Corps decision-making processes.

#### *F. Conclusion*

The above overview of local watersheds is not a complete inventory of all watersheds in the area or all issues within those watersheds. Instead, it is intended to provide some insight into certain activities and issues that are typical for creeks and bayous in Harris County. As shown in Figure 5, all watersheds in the county suffered some level of flooding. Much of this flooding was outside of the mapped 100-year floodplain, with estimates ranging as high as 50% of the damaged homes being outside the mapped area. In many cases, the obsolete floodplain maps contribute to this disparity, but in others, the cause is more difficult to pinpoint. Houston's streets are designed to fill up with water from a major storm event and when streets become full, the water flows overland and goes into adjacent yards and homes. In addition, some storm sewers are blocked or inadequate, and older streets were not designed to convey stormwater to the nearest bayou or creek. In these situations, it is often difficult to know if the responsibility to fix flood-related problems falls upon the city or the county, a situation often worsened by the difficulty in finding officials within either organization that will work on these problems. This situation must be improved.

### **IV. The Houston Ship Channel and Southeast Harris County**

It would be irresponsible to discuss major flooding issues and not discuss the problem of hurricane surge flooding, which many believe to be the most dangerous and important type of flooding because it can have broad impacts for the health and safety of the county, as well as the economic welfare of the region, state, and nation. Although Harvey was a Category 4 storm, its storm surge was limited to the landfall area near Port Aransas and Rockport, and it was not a factor up the coast in the Houston region. Instead, Hurricane Harvey's major flooding in the Houston area was not from storm surge but rather from rainfall. There is no doubt that Harvey's damages would be surpassed when compared to the impacts of landfall from a larger category 3 (or 4 or 5) hurricane with a major surge component coming ashore at the south end of Galveston Island.

In 2008, Hurricane Ike was "only" a Category 2 storm, but it generated a surge that was 16-17 feet high in the relatively undeveloped lands of coastal Chambers and Jefferson Counties. Ike produced less than a 13-foot surge in the Houston Ship Channel area and essentially missed much of the west side of Galveston Bay and the Houston Ship Channel industrial complex, yet it caused over \$24 billion in damage. A large surge-generating

storm coming ashore near the south end of Galveston Island would generate catastrophic flooding both on the island and inland along the western bay shore. Such a storm would also cause massive damage both to residences and to the refining and chemical production complex along the Houston Ship Channel that fuels the regional and state economies and is a key producer of military-grade jet fuel, gasoline, and plastics, among other products. The environmental impacts to the bay would likewise be devastating.

The SSPEED Center has undertaken computer simulations of Category 2 storms such as Ike, as well as stronger Category 5 storms like Irma coming ashore at this location on the south end of Galveston Island. Based on these simulations, the effects on the west side of the bay and the ship channel complex would be disastrous. As shown in Figure 21, even a weak Category 4 storm would generate about 20 feet of storm surge at the coastline, overtopping the sea wall in Galveston by about 3 feet. The storm surge in Galveston Bay would be magnified by the funneling effect of the bay, with surge ultimately rising to about 23-24 feet in the Clear Lake-NASA area of southeast Harris County and up to 25 feet within the Houston Ship Channel.

The water levels from such a Category 4 storm would further be worsened by wave action that would add a powerful force that could potentially destroy houses, storage tanks, and industrial processing units. Surge flooding is not like bayou or riverine flooding—it does not involve flowing waters, but rather involves flooded areas becoming part of the bay, accompanied by violent and powerful crashing waves destroying houses and ripping them from their foundations, as seen on Bolivar Peninsula during Hurricane Ike. However, the local and federal governments and industry do not fully respect this potential threat because such surge has not yet been experienced. However, we had never seen a storm like Harvey before it caused massive flooding across the region.

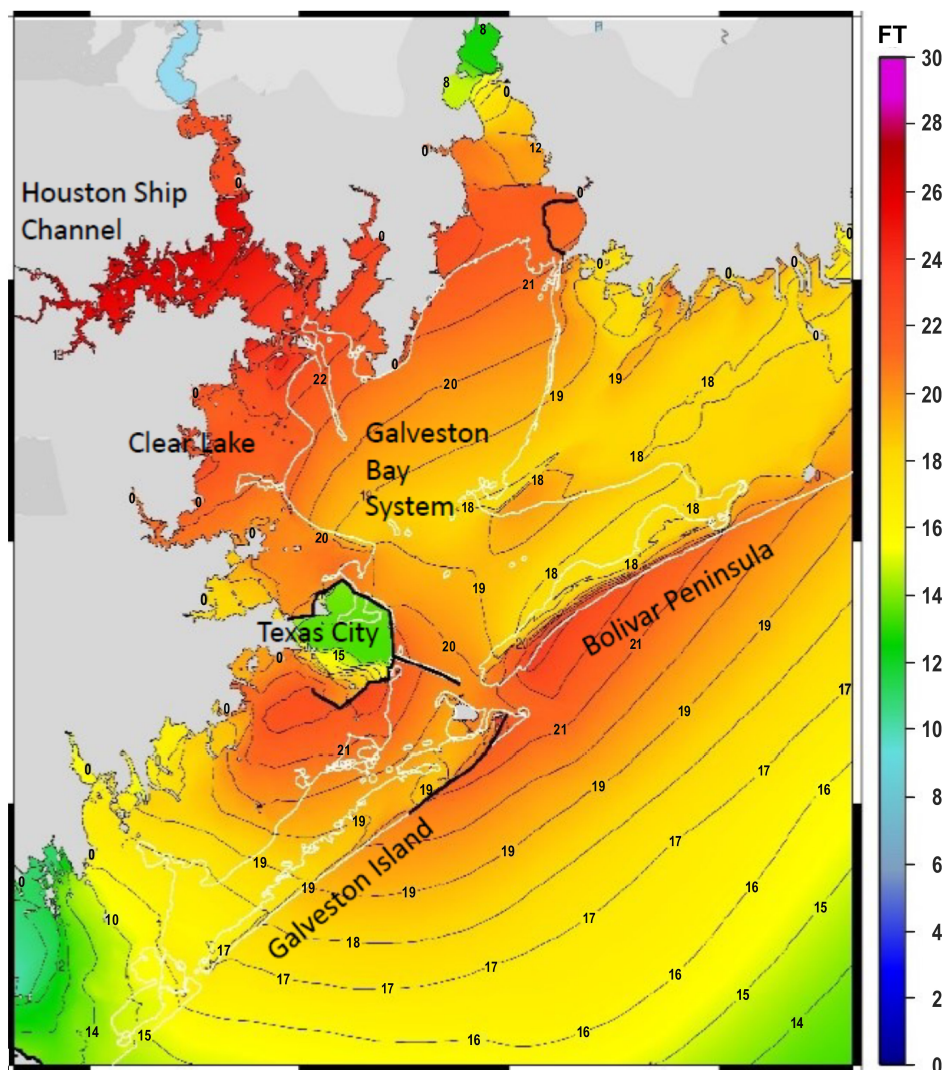
Larger storms were also analyzed and modeled by the SSPEED Center, including a Category 5 hurricane with 160 mph winds like Hurricane Irma that struck Cuba in 2017. Such a storm could produce storm surges up to almost 35 feet in the Houston Ship Channel, compared to the less than 13 feet of surge seen in this area during Hurricane Ike. These model simulations also have not incorporated any projected sea level rise. Adding another 2-3 feet to sea level prior to the oncoming hurricane, as projected by the U.S. Army Corps of Engineers, would only increase these estimated surge levels. Rising sea levels will also increase the intensity and strength of future hurricanes that are expected to occur in the Gulf.

The potential damage associated with even the hypothetical small Category 4 storm in the SSPEED models would be substantial and very different from that associated with Harvey. Aside from one major chemical release in northeast Harris County, the chemical and refining community was not physically impacted by Harvey, although significant air emissions occurred during shutdown and start-up events, and many refineries could not operate because workers were unable to drive across flooded streets. However, a 25-foot surge would cause significant flooding to most of the refineries and chemical plants on the ship channel, in the Bayport chemical complex, and even in the Texas City complex, which



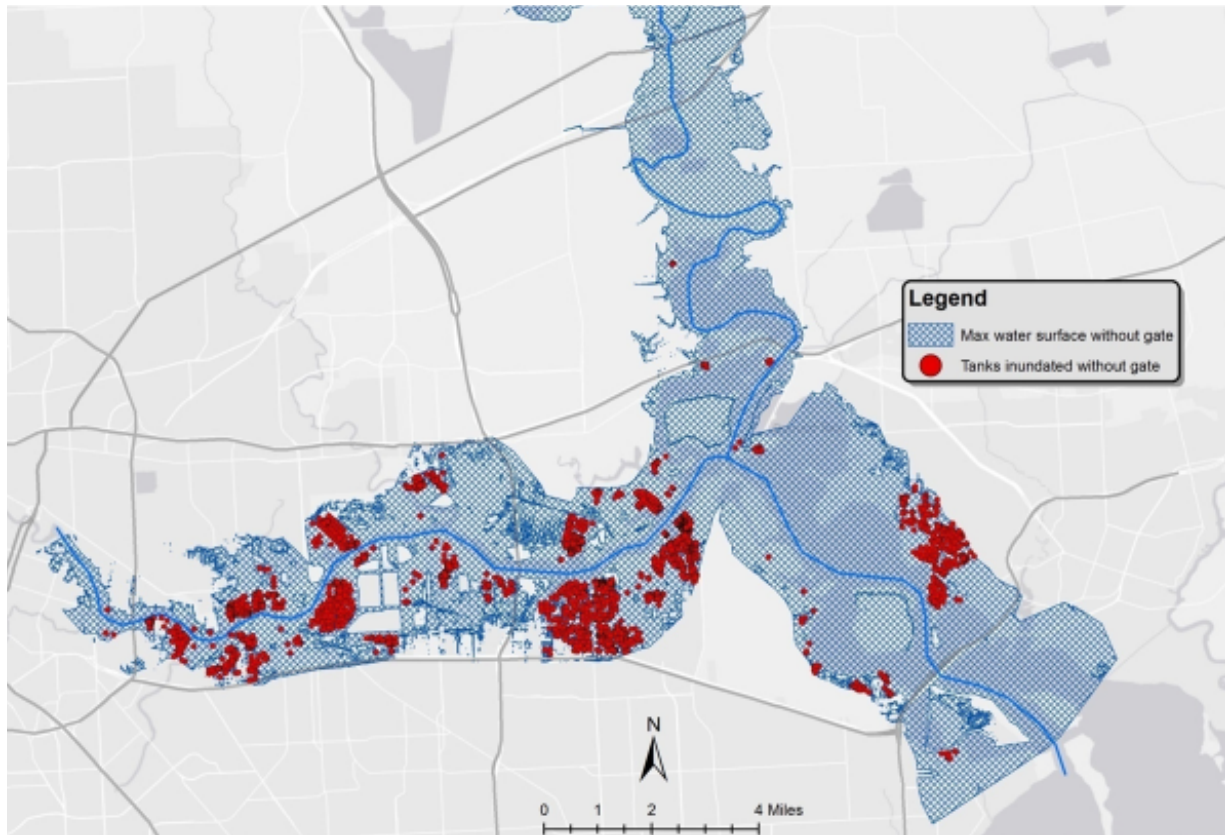
is protected by a dike to about 17 feet, a level barely adequate with Ike and clearly inadequate for the projected surge. Dr. Jamie Padgett of the SSPEED Center has estimated that upwards of 2,200 petroleum and chemical storage tanks would experience some degree of inundation, potentially releasing upwards of 90 million gallons of oil and hazardous substances. In addition, such a storm would likely shut down most of these industries for at least a few months, and many could be crippled for a year or more, affecting United State gasoline and jet fuel supplies. An image depicting the oil and hazardous storage tanks inundated by a 25-foot surge up the channel is shown in Figure 22.

**Figure 21.** Computer Modeling Results for a Small Category 4 storm at the South End of Galveston Island



Source: Analysis by Dr. Clint Dawson for the SSPEED Center. Image prepared by Christina Walsh for the author(s)

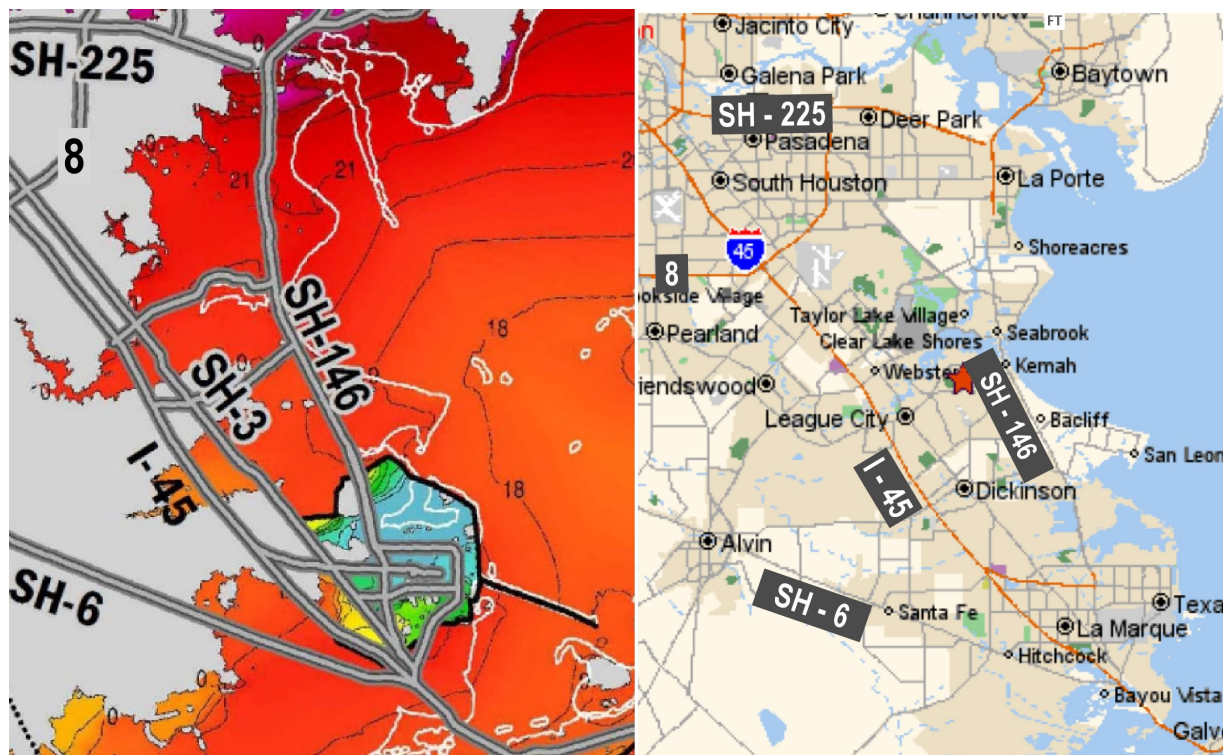
**Figure 22.** Diagram of Oil and Hazardous Substance Tanks Likely to Be Flooded by a 25-foot Storm Surge if No Flood Barriers or Gates are Placed in or around Galveston Bay.



Source: Analysis from Dr. Jamie Pagett, Rice University; graphic courtesy of the SSPEED Center

In addition to this major impact to the chemical and refining industry, the residential community on the west side of Galveston Bay would be devastated by the hypothetical Category 4 storm in the SSPEED model. It is certainly feasible that over 25,000 homes could be destroyed by such a surge and tens of thousands more simply flooded. As can be seen from Figure 23, many of the smaller communities in southeast Harris County are at significant risk, including southeastern Houston and the communities of northern Galveston County. Collectively, over 300,000 people live in these areas, not counting the population in the Clear Lake City area. The area behind the Texas City levee would also be flooded by this storm event. If people in these areas do not heed evacuation warnings, several thousand people could be killed by this surge event.

Figure 23. Map of Storm Surge in the Clear Lake Area



Note: The left side of the image shows the projected inundation area from a storm generating about a 22-23 foot surge in the Clear Lake area. On the right, the various smaller communities that are at risk from such an event are shown.

Source: Image prepared by Christina Walsh for the author(s)

It is also important to note that the city of Galveston would also be at risk from this kind of storm event. The current height of the sea wall is 17 feet, while the height of the surge at the coastline would reach over 20 feet for this modeled storm event. Additionally, Galveston Island is extremely vulnerable to backside flooding where the island is unprotected. When the bay fills up with water, the water elevation simply rises higher than the elevation of northern Galveston (this was the cause of most of the flooding in the city during Ike). In addition, as a storm hits further east, Galveston would also be flooded by the movement of water from north to south within Galveston Bay due to the counter-clockwise circulation in this area. Thus, Galveston is extremely vulnerable to such severe storm events.

## V. Potential Solutions

As can be seen from the previous sections, Houston and Harris County have serious flooding problems. These problems, however, can be addressed, but the solutions need to be realistic, smart, and creative. These flooding problems took over 40 years to develop, and it will take time to fix them. There are no quick or easy solutions other than buyouts, but there are some ideas that make sense in both the long term and the short term.

### *A. An Overall Vision*

It is useful to visualize a long-term solution that would address these problems in a comprehensive yet realistic manner in recognition of the different types of flooding issues in this area. First, consider the Houston region in three zones: the developing areas west of Houston, the already developed areas of Houston and Harris County, and the Galveston Bay and Houston Ship Channel coastal complex (see Figure 23). Each of these three zones requires different types of treatment. It is also important to remember that there are very real financial limits to what can be done, so any plans must be financially responsible as well.

The three major zones for flood planning and management in the Houston region (A, B, and C) are shown in Figure 24. The basic idea in Zones A and B is to manage the stormwater such that flooding is tolerable. Flooding from storms such as Harvey or other severe events cannot be completely eliminated. Local residents can live with these flood events, but that means recognizing the risks, minimizing the damage, and incorporating stormwater and flood management into future designs for these areas.

For Zone A, this means that as new development proceeds through the western prairie area, developers and local governments must ensure that there is no increase in flooding downstream. This may mean less dense development in this area, with significant retention/detention ponds or basins, particularly given the issues with the Addicks and Barker Dams, as well as the noted problems along Cypress and Spring Creeks.

In addition, in Zone B, where extensive development has already occurred, storm and flood waters must be given sufficient space to move through the communities along the various bayous and towards the bay. This can be achieved by physically intervening to increase the carrying capacity of the bayous and constructing retention/detention ponds.

Finally, in Zone C, the major solution is to try to hold back surge along the coast and in the bay through structural intervention to keep damaging waves and high water levels away from vulnerable buildings and other structures. Each of these zones is discussed in the following sections.

### *B. Zone A*

Zone A includes what is generally referred to as the Katy Prairie, although Zone A also extends up beyond the Cypress Creek watershed into the Spring Creek watershed in an



The map shows the Houston area divided into three zones, each outlined with a thick colored line and labeled with a large black text box:

- Zone A (Blue outline):** Located in the northwest, it includes **Spring Creek**, **Little Cypress Creek**, **Addicks Reservoir**, and **Barker Reservoir**. It is bounded by the Brazos River to the west and south.
- Zone B (Yellow outline):** The central area, including **Willow Creek**, **Cypress Creek**, **Greens Bayou**, **White Oak Bayou**, **Carpenters Bayou**, **Hunting Bayou**, **Buffalo Bayou**, **Brays Bayou**, **Sims Bayou**, and **Clear Creek**. It is bounded by the San Jacinto River to the north and east.
- Zone C (Purple outline):** Located in the southeast, it includes **San Jacinto & Galveston Bay**, **Armand Bayou**, and **San Jacinto & Galveston Bay**. It is bounded by the Gulf of Mexico to the south and east.

The map also shows major highways (US Hwy 59, 10, 610, 45, 290, 281, 287, 289, 291, 293, 295, 297, 299, 301, 303, 305, 307, 309, 311, 313, 315, 317, 319, 321, 323, 325, 327, 329, 331, 333, 335, 337, 339, 341, 343, 345, 347, 349, 351, 353, 355, 357, 359, 361, 363, 365, 367, 369, 371, 373, 375, 377, 379, 381, 383, 385, 387, 389, 391, 393, 395, 397, 399, 401, 403, 405, 407, 409, 411, 413, 415, 417, 419, 421, 423, 425, 427, 429, 431, 433, 435, 437, 439, 441, 443, 445, 447, 449, 451, 453, 455, 457, 459, 461, 463, 465, 467, 469, 471, 473, 475, 477, 479, 481, 483, 485, 487, 489, 491, 493, 495, 497, 499, 501, 503, 505, 507, 509, 511, 513, 515, 517, 519, 521, 523, 525, 527, 529, 531, 533, 535, 537, 539, 541, 543, 545, 547, 549, 551, 553, 555, 557, 559, 561, 563, 565, 567, 569, 571, 573, 575, 577, 579, 581, 583, 585, 587, 589, 591, 593, 595, 597, 599, 601, 603, 605, 607, 609, 611, 613, 615, 617, 619, 621, 623, 625, 627, 629, 631, 633, 635, 637, 639, 641, 643, 645, 647, 649, 651, 653, 655, 657, 659, 661, 663, 665, 667, 669, 671, 673, 675, 677, 679, 681, 683, 685, 687, 689, 691, 693, 695, 697, 699, 701, 703, 705, 707, 709, 711, 713, 715, 717, 719, 721, 723, 725, 727, 729, 731, 733, 735, 737, 739, 741, 743, 745, 747, 749, 751, 753, 755, 757, 759, 761, 763, 765, 767, 769, 771, 773, 775, 777, 779, 781, 783, 785, 787, 789, 791, 793, 795, 797, 799, 801, 803, 805, 807, 809, 811, 813, 815, 817, 819, 821, 823, 825, 827, 829, 831, 833, 835, 837, 839, 841, 843, 845, 847, 849, 851, 853, 855, 857, 859, 861, 863, 865, 867, 869, 871, 873, 875, 877, 879, 881, 883, 885, 887, 889, 891, 893, 895, 897, 899, 901, 903, 905, 907, 909, 911, 913, 915, 917, 919, 921, 923, 925, 927, 929, 931, 933, 935, 937, 939, 941, 943, 945, 947, 949, 951, 953, 955, 957, 959, 961, 963, 965, 967, 969, 971, 973, 975, 977, 979, 981, 983, 985, 987, 989, 991, 993, 995, 997, 999, 1001, 1003, 1005, 1007, 1009, 1011, 1013, 1015, 1017, 1019, 1021, 1023, 1025, 1027, 1029, 1031, 1033, 1035, 1037, 1039, 1041, 1043, 1045, 1047, 1049, 1051, 1053, 1055, 1057, 1059, 1061, 1063, 1065, 1067, 1069, 1071, 1073, 1075, 1077, 1079, 1081, 1083, 1085, 1087, 1089, 1091, 1093, 1095, 1097, 1099, 1101, 1103, 1105, 1107, 1109, 1111, 1113, 1115, 1117, 1119, 1121, 1123, 1125, 1127, 1129, 1131, 1133, 1135, 1137, 1139, 1141, 1143, 1145, 1147, 1149, 1151, 1153, 1155, 1157, 1159, 1161, 1163, 1165, 1167, 1169, 1171, 1173, 1175, 1177, 1179, 1181, 1183, 1185, 1187, 1189, 1191, 1193, 1195, 1197, 1199, 1201, 1203, 1205, 1207, 1209, 1211, 1213, 1215, 1217, 1219, 1221, 1223, 1225, 1227, 1229, 1231, 1233, 1235, 1237, 1239, 1241, 1243, 1245, 1247, 1249, 1251, 1253, 1255, 1257, 1259, 1261, 1263, 1265, 1267, 1269, 1271, 1273, 1275, 1277, 1279, 1281, 1283, 1285, 1287, 1289, 1291, 1293, 1295, 1297, 1299, 1301, 1303, 1305, 1307, 1309, 1311, 1313, 1315, 1317, 1319, 1321, 1323, 1325, 1327, 1329, 1331, 1333, 1335, 1337, 1339, 1341, 1343, 1345, 1347, 1349, 1351, 1353, 1355, 1357, 1359, 1361, 1363, 1365, 1367, 1369, 1371, 1373, 1375, 1377, 1379, 1381, 1383, 1385, 1387, 1389, 1391, 1393, 1395, 1397, 1399, 1401, 1403, 1405, 1407, 1409, 1411, 1413, 1415, 1417, 1419, 1421, 1423, 1425, 1427, 1429, 1431, 1433, 1435, 1437, 1439, 1441, 1443, 1445, 1447, 1449, 1451, 1453, 1455, 1457, 1459, 1461, 1463, 1465, 1467, 1469, 1471, 1473, 1475, 1477, 1479, 1481, 1483, 1485, 1487, 1489, 1491, 1493, 1495, 1497, 1499, 1501, 1503, 1505, 1507, 1509, 1511, 1513, 1515, 1517, 1519, 1521, 1523, 1525, 1527, 1529, 1531, 1533, 1535, 1537, 1539, 1541, 1543, 1545, 1547, 1549, 1551, 1553, 1555, 1557, 1559, 1561, 1563, 1565, 1567, 1569, 1571, 1573, 1575, 1577, 1579, 1581, 1583, 1585, 1587, 1589, 1591, 1593, 1595, 1597, 1599, 1601, 1603, 1605, 1607, 1609, 1611, 1613, 1615, 1617, 1619, 1621, 1623, 1625, 1627, 1629, 1631, 1

## 1. Addicks and Barker

38



been fixed due to a lack of interest. Solving the overtopping issues needs to become a number one priority. Until these dams are secure, Houston cannot be safe from either the need to release water from Addicks and Barker or the risk of dam failure.

Second, the feasibility of expanding the storage capacity of Addicks and Barker Reservoirs must be considered. For example, most of the land within the reservoirs is already owned by the federal government, and it can be made to store more water than the current design allows. The first step should be to simply remove any sediment that has built up behind these two dams over the last 60 years of operation. This sediment removal should provide some additional storage. Second, it needs to be determined if Addicks and Barker Reservoirs can be dug out to create additional storage, as has been suggested. Even belowground storage and a set of pumps to remove this water after it rains would be beneficial.

Third, the concept suggested by Fort Bend County should be examined, in which a levee is built along the outer edge of federally owned lands to separate the private lands from the government lands, which would be allowed to flood. Pumps could then protect the low areas upstream of the levee from runoff buildup.

Finally, providing additional storage upstream of these two reservoirs, particularly in the upper Cypress Creek watershed, should be considered to eliminate overflows from that watershed that enter into the Addicks watershed and eventually into the reservoir. This will be further discussed below.

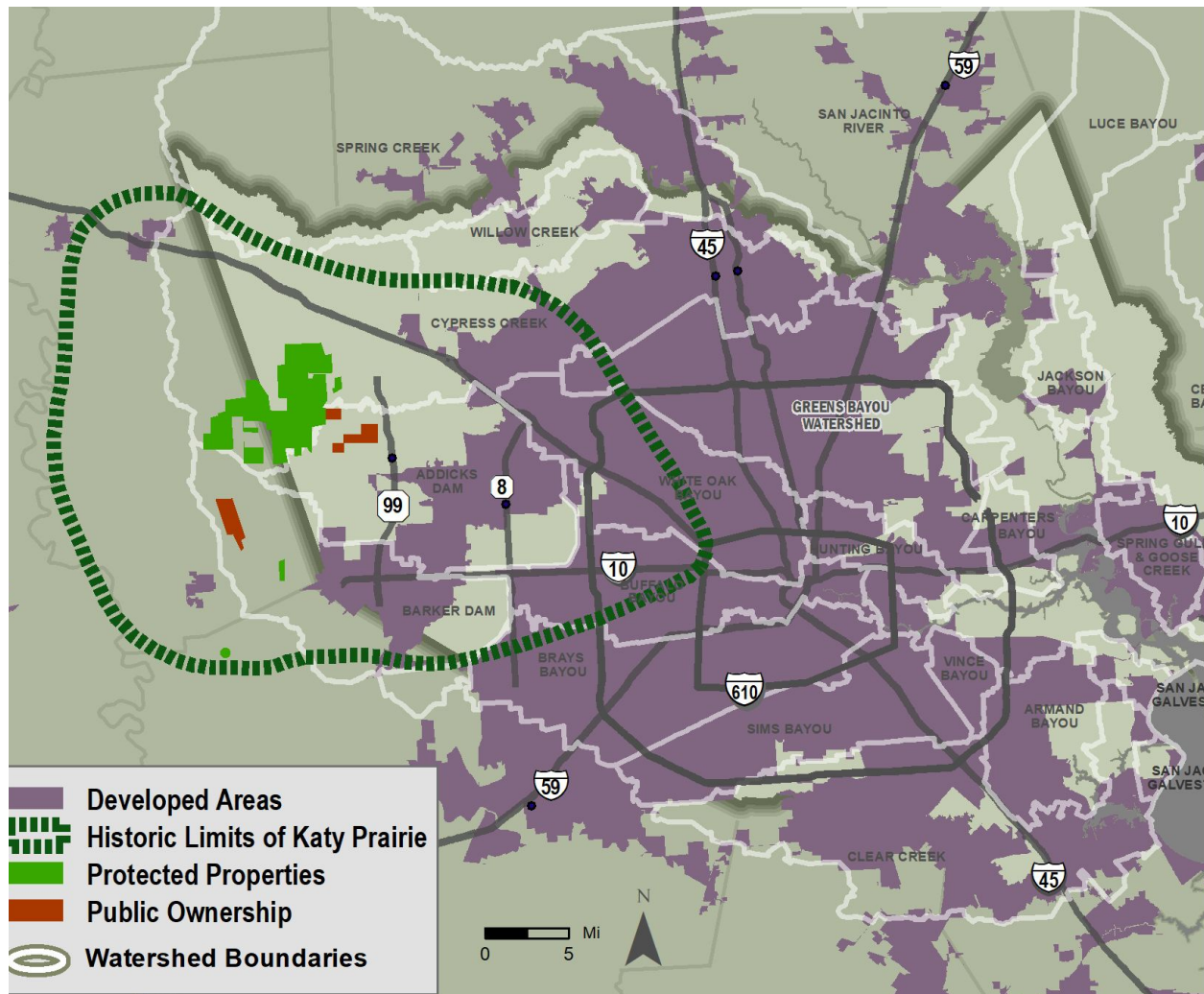
These steps could make Addicks and Barker Dams/Reservoirs much more effective, even without the dams' overflow issues being resolved. However, the U.S Army Corps of Engineers must be funded to do this work as soon as possible, which appears to have occurred to some extent, with HR 1892 and the Corps' authorization of additional work. This repair of Addicks and Barker Dams has to be the highest community priority. Also, a plan must be developed to address the homeowners behind Addicks and Barker Dams that live in the flood pool beyond the limit of government-owned land. For example, the federal government could negotiate a flood easement with these landowners, if not an outright buyout to reduce the upstream impacts of Addicks and Barker Dams. An effective plan on communicating risk to the public, both before and during a major storm event like Harvey, must also be developed. The Corps' knowledge and expertise was not used to their best advantage during Harvey. That cannot be allowed to happen again.

## 2. The Katy Prairie

There are both conventional and creative concepts to solve flooding issues that can be utilized in the Katy Prairie area. The historic boundaries of the "Katy Prairie" area are outlined in green in Figure 25, and they encompass the Addicks and Barker watersheds and the upper Cypress Creek watershed. One of the conventional ideas to help with flooding in this area is to create a third reservoir somewhere in either the Addicks or Cypress Creek watersheds to provide downstream flood relief from Addicks and Barker releases. Such storage was originally proposed by the HCFCD for the Cypress Creek overflow zone in the

Katy Prairie, but because this project was originally conceived to aid developers in building within the overflow zone rather than protect Addicks and Barker, it has been set aside by Harris County, as such relief is apparently not needed or desired at this time. This decision has led to discussion about locating such a third reservoir or multiple smaller storage systems in upper Cypress Creek instead. These projects should be studied regarding effectiveness, cost, and environmental impact on remnant prairie lands, and then compared to other concepts that initially appear to be more attractive, as discussed below.

Figure 25. Map of the Katy Prairie



Note: The historic boundaries of the Katy Prairie are denoted by the dotted green line. The lands protected by the Katy Prairie Conservancy are highlighted in green, and other protected lands are shown in red. The white line crossing the west part of the prairie is the boundary of the watersheds that drain toward the developed area of the city of Houston.

Source: Image prepared by Christina Walsh for the author(s)

One of the best short-term, and potentially even long-term, concepts to solve flooding in the Katy Prairie area is to use the natural capacity of the prairie to hold water. The Katy Prairie Conservancy owns over 13,500 acres, with conservation easements across about 4,500 additional acres. These lands are highlighted in Figure 25. This reserve is an important community resource and should be expanded. These natural prairie lands historically have held tremendous amounts of water, acting as the region's natural sponge for water retention. If the prairie were to be restored, this natural water-holding capacity would also be restored.

The natural capacity of this region to hold water is being lost due to development, yet what remains can be managed to hold even more water than under natural conditions. By restoring native vegetation, the deep root systems of prairie grasses would allow more water to be stored in the soil. Certain areas currently not protected may be suitable for additional storage enhancements such as the creation of a number of small holding dams, much like rice farm levees that have been used for decades. The key here is that private landowners along with non-governmental and governmental organizations could be paid to manage their lands, which are often used as pastures, in a manner such that they hold additional water for a week or two after big rains. As can be seen from Figure 26, the Katy Prairie held tremendous amounts of water during the major flooding events, including the Tax Day Flood of 2016 and Hurricane Harvey. There is no reason why similar water retention could not occur across tens of thousands of acres.

Furthermore, rather than building large storage facilities, Harris County should instead evaluate paying landowners to manage their land to hold stormwater behind multiple mini-dams or small berms. If these landowners restored native prairies, they could enhance the movement of water into the subsurface, thereby reducing the amount of runoff created from rainfall. Landowners could also sell a new agricultural commodity, such as carbon sequestration capacity (Blackburn 2018; Blackburn et al. 2017), in the near future while still running cattle. If for instance a landowner were paid \$100 per acre per year, 50,000 acres could be used for flood storage for \$5 million per year. Over 50 years, this solution would cost about \$250 million, compared to the cost for a large reservoir (about 12,000 acres) of about \$400 million. The government could pay landowners to hold water for 50 years and still come out ahead from a financial standpoint, while simultaneously gaining significantly more holding capacity and respecting private property rights. This of course depends upon landowners wishing to stay in the agricultural business, and there is no doubt that many thousands of acres are tied up by land development speculators.

This idea of selling water storage capacity as a commodity derives from the Texas Coastal Exchange (TCX) concept developed by the SSPEED Center, which proposed creating a transaction system to buy and sell ecological services such as flood and carbon storage. This TCX concept, which has been renamed the Soil Value Exchange (SVX) for prairie carbon transactions, is now in the process of being adapted to create a carbon dioxide transaction system for ranchers from Texas to North Dakota. This is a private sector method of paying landowners to help achieve important social and ecological goals such as storing

floodwaters, sequestering carbon, enhancing water supply, and supporting fish and wildlife. This idea should be seriously considered for the Katy Prairie area before the prairie is removed in favor of increased development.

**Figure 26.** The Katy Prairie after the Tax Day Flood of April 2016



Source: Photo courtesy of Jaime González and the Katy Prairie Conservancy

### *C. Zone B*

Zone B is the heart of the developed area of Houston and Harris County. Here, the solutions are many and varied, ranging from various channelization alternatives to detention ponding to buyouts. These proposed projects have been divided into different categories according to Harris County Flood Control District in anticipation of the upcoming bond election (HCFCD 2018d). Their division of these projects is:

- **Voluntary Home Buyouts:** The purchase of flood-prone structures from willing sellers in areas that are too deep in the floodplain to benefit from structural flood risk reduction projects, or in areas where such projects are not feasible. This process

includes demolishing structures and relocating the original landowner to higher ground.

- **Storm Repair:** Major maintenance projects that restore the designed function and capacity of a channel or stormwater detention basin.
- **Subdivision Drainage Improvement:** Partnership projects with the Harris County Engineering Department and Municipal Utility District to provide drainage improvements to subdivisions in unincorporated Harris County.
- **Partnership Projects:** Flood risk reduction projects such as channel modifications or stormwater detention basin construction using a combination of Harris County Flood Control District funding and funding from local, state, or federal partners such as FEMA.
- **Local Projects:** Flood risk reduction projects such as channel modifications or stormwater detention basin construction using only HCFCD funds.
- **Community Input Projects:** Projects suggested by community members, including during community engagement meetings to be held in each Harris County watershed prior to the August 25, 2018 bond election.
- **Neighborhood Levees with Pump Storage:** An alternative to a complete buyout of an area, but would require some upstream storage for offset.

The Harris County Flood Control District is working to compile a comprehensive list of strategies in each of these categories. As of mid-June, the list included upwards of 100 separate projects among the 22 watersheds and can be found at [www.hcfcd.org/media/2682/2018-bond-proposed-project-list-public-distribution061318.pdf](http://www.hcfcd.org/media/2682/2018-bond-proposed-project-list-public-distribution061318.pdf). This list will change as more projects are identified by the public, reflecting the transparency integrated into the order calling for a bond election on August 25, 2018.

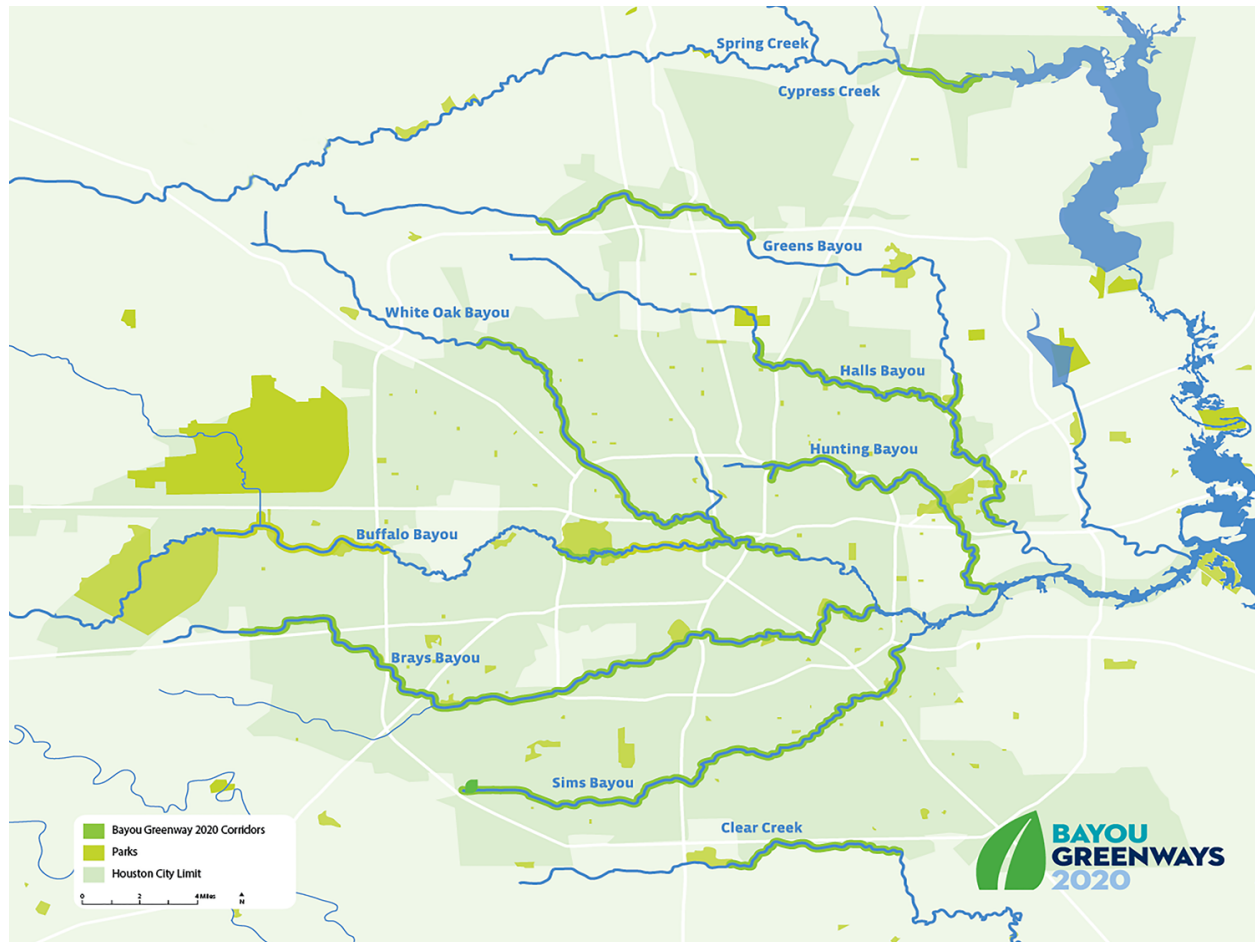
When considering these projects, it is important to keep in mind information about the existing 100-year floodplain map, which is obsolete as previously discussed in Section II of this report. The size of the estimated 100-year floodplain will be adjusted later this year or next, although the full extent is not clear yet. The designs of the federal projects described above are not based upon this revised floodplain and therefore do not fully solve the existing flooding problems. As a result, there will still be homes near creeks and bayous that will remain at risk of flooding even with a lot of money being spent on federal and local improvement projects. This is unfortunately an unavoidable fact.

The challenge going forward is to recognize this reality and structure a program to remove, elevate, or protect as many homes at risk from the residual floodplain as possible. In this manner, we can offer more immediate relief to the most vulnerable homes and families. For those who don't want to be bought out, elevating or flood-proofing may be options. For those areas where buyouts make sense, they will eliminate the risk of flood damage and create an inventory of green space that can be used for channel construction that is wider and more natural than some current bayous. Such a concept would include extensive use of this recovered water space for detention and retention ponding, as well as recreation. Such a concept is compatible with the Houston Bayou Greenways project currently being pursued by the Houston Parks Board, with over \$100 million in bond financing from the city of



Houston, as set out in Figure 27. This Houston Bayou Greenways project implements a concept for linking the bayous throughout the city of Houston through implementation of hike and bike infrastructure, a concept first discussed in the Comey Plan in 1913 (City of Houston 2018). As shown in Figure 27, the Bayou Greenways project proposes the development of an extensive hike and bike trail system along the bayous within Houston that will allow the expanded space to be used for flood management and flood storage.

**Figure 27.** The Houston Bayou Greenways Concept



Note: The Houston Parks Board proposal is only within the boundaries of Houston. This project could also be extended into Harris County and other jurisdictions, which would require separate authorizations. The yellow-green areas are parks and the proposed greenways are shown in darker green.

Source: Graphic courtesy of Houston Parks Board

In many respects, this project would represent a redesign of Houston and Harris County around local water systems, showing both respect for the extensive area covered by water in large storms and also providing a balanced response between engineering, planning, and common sense. If Houston and Harris County were to implement this type of localized

solution, it would catapult the region to the top of innovative thinkers in an era when all major cities, particularly those along the coast, are struggling to respond to increased rainfall amounts. Perhaps most importantly, this approach also offers immediate results through buyout as other various physical improvements are constructed.

It is also important to note that if certain housing is bought out, particularly in low income areas, there must also be plans for locating and constructing the next generation of housing for bought-out homeowners. These new houses could be provided either by the public or private sector, but planning to deliver this housing must be incorporated in any plans from the outset. Previous plans have not coordinated housing and flood management activities, but such coordination is necessary for the long-term success of these kinds of projects.

**Figure 28.** The Clear Lake Sign Erected after Hurricane Ike



Note: This sign was removed after only being in place for a couple of months because it interfered with real estate sales.

Source: Photo from author's collection

In terms of short-term relief, it is also important that an effective system for distributing flood warnings and reliable flood-related information is developed. The public is a partner with the government in dealing with flooding problems. There need to be public signs that identify flood depths during rainfall and hurricane surge events. The sign shown in Figure 28 was erected in the Clear Lake area and then quickly removed because it allegedly interfered with real estate sales. In the past, people seem to have been more concerned about selling homes and real estate rather than protecting the public from flooding. That attitude should change, and it can be done immediately by leadership from the top levels of government. What our leaders say, and what they emphasize to the public, is important for shaping public attitudes.

Finally, as mentioned in Section IIIB, there are some watersheds that need stronger regulations to better protect them from upstream development. These watersheds include Sims Bayou and Cypress and Spring Creeks at a minimum. Additionally, the city of Houston should carefully examine its regulatory system for redevelopment. Many buildings were built before the full impact of urbanization on flooding was understood. We now know that urbanization increases flooding, and redevelopment has the opportunity to lessen the flooding problem in certain areas if detention and retention ponds are incorporated into the redesign. This is an issue worth public discussion. The city is currently considering some new regulations regarding redevelopment.

If the bond issue passes, there will be \$2.5 billion in local money to match the federal projects that could easily bring in several additional billions in project and buyout money. The issue is spending that money wisely, assuming the bond issue passes. If it does not pass, then Houston and Harris County will be left in a situation where the floods will eventually eliminate large developed areas without compassion and hope.

#### *D. Zone C*

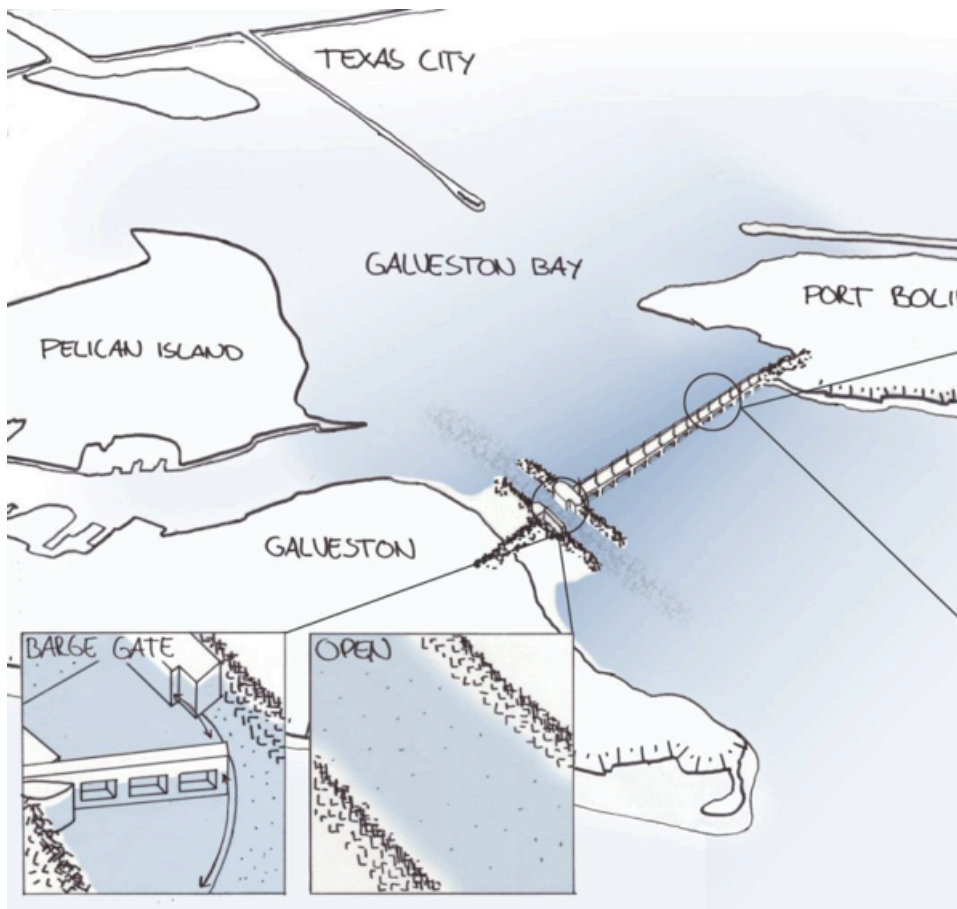
Zone C is the coastal zone that is vulnerable to hurricane surge flooding. This is perhaps the area that is the most exposed and most difficult to address. Here, there are two major alternatives—the Coastal Spine/Ike Dike solution and the Galveston Bay Park/Mid-bay solution—that are also very compatible with one another. The Ike Dike has the political support of most coastal elected politicians, but the mid-bay proposal has many advantages and is much cheaper than the Ike Dike. These two alternatives will be discussed sequentially.

##### 1. The Coastal Spine/Ike Dike

The “Ike Dike” was originally promoted by Dr. William Merrill of Texas A&M University at Galveston in the immediate aftermath of Hurricane Ike, which had caused significant flooding damage to the city of Galveston. The Ike Dike concept subsequently morphed into the coastal spine idea, which would be a system of berms and gates that extends from the northern end of the Bolivar Peninsula southward across the Bolivar Roads pass between Bolivar and Galveston Islands. It would then connect with the existing seawall on Galveston Island and continue down the island to San Luis Pass, where it would terminate. This berm and gate system is proposed to be about 17 feet above sea level in height and

would extend for about 80 miles along the peninsula and the island. The berm portion of this system has independent utility and has also been proposed in association with a gate structure that would cross approximately 10,000 feet of water ranging in depth from 30 to 60 feet where it crosses the Houston Ship Channel. There would be a large navigation gate structure about 1,200 feet long across the channel that would mostly remain open to allow vessels moving in and out of Galveston Bay. There would also be a much longer environmental gate structure with openings to allow circulation between the bay and Gulf waters. Both of these gate structures are immense engineering projects and would be similar to projects constructed in the Netherlands at Rotterdam (the navigation gate) and in Eastern Scheldt (the environmental gate). A diagram of the potential gate structures across Bolivar Roads is shown in Figure 29. A photograph of the Eastern Scheldt environmental gate is shown in Figure 30.

**Figure 29.** The Proposed Gate Structures across Bolivar Roads



Source: Anne Loes Nillesen, Defacto Architecture and Urbanism–Rotterdam,  
<https://repository.tudelft.nl/islandora/object/uuid%3A65b45d61-3453-4c2d-9dcb-d35b83f39542?collection=research>

**Figure 30.** The Environmental Gates of the Eastern Scheldt in the Netherlands

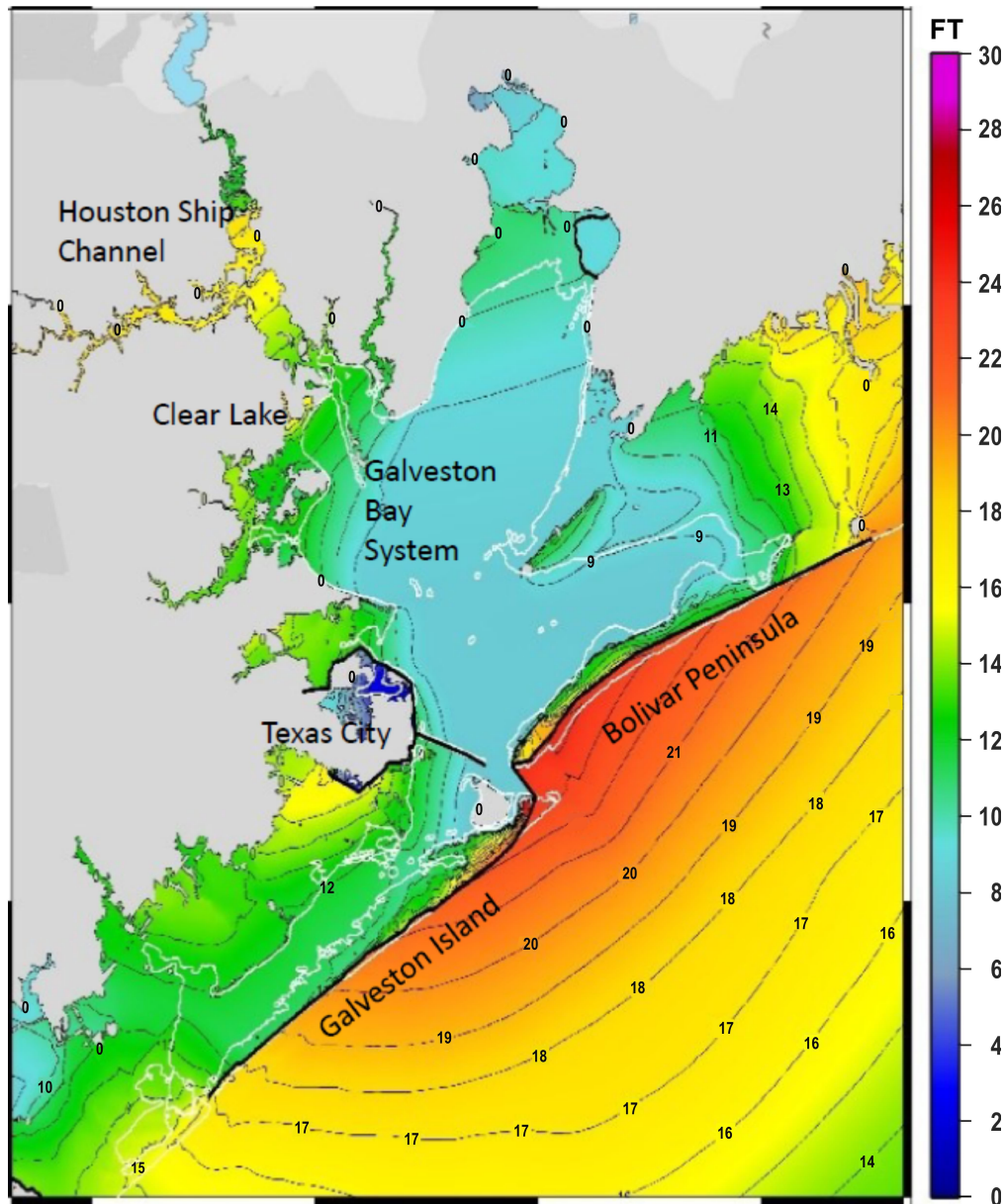


Source: Blackburn (2017)

There is no question that the coastal spine could be very effective in reducing the impact of certain types of hurricane surge. However, the city of Galveston would remain vulnerable on the bay side even with the coastal spine in place, and the western shoreline and the Houston Ship Channel industrial complex would also be at risk to damaging storm surge, although not to the same extent as without the coastal spine. Figure 31 shows the resulting surge from a hypothetical small Category 4 storm after placement of the coastal spine at a height of 17 feet from the south end of Galveston Island to the top of Bolivar Peninsula. While the coastal spine does reduce the vulnerability of west Galveston Island and the Houston Ship Channel to a large extent, there would still be significant surge flooding in these areas due to strong hurricane-force winds pushing floodwaters into the bay. In addition, the city of Galveston would experience significant flooding due to the overtopping of the 17-foot-high seawall from the expected surge height of over 20 feet, as well as backside flooding as the winds shift from heading into the bay to heading out of the bay. Flooding behind this coastal spine would be much greater for larger hurricanes, exposing critical infrastructure and residents to disastrous consequences.



Figure 31. Map Showing the Effectiveness of the Coastal Spine Project



Note: Modeled using the extent of coastal flooding from a small Category 4 storm coming ashore on the south end of Galveston Island.

Source: Analysis by Dr. Clint Dawson for the SSPEED Center

Apart from these gaps in protection, there are two major issues regarding the coastal spine. The first is cost. SSPEED currently estimates that constructing this berm and gate system will cost \$10 billion, and it is possible that this cost could further increase. Given the important refining and chemical industry complexes that would be protected with the coastal spine, as

well as several hundred thousand homes, this project should certainly have a positive benefit-to-cost ratio, meaning that federal financial criteria should be met. However, it is unclear if \$10 billion or more is available to fund this project when there are so many other needs along the Texas coast. Second, there is the issue of environmental impact. This project would cross one of the most important fish and shellfish movement areas in the United States, with Galveston Bay being the second-most productive estuary in the United States. The impact of these gates on fish movement patterns, tidal exchange, and bay circulation will be of great importance in determining the overall feasibility of this project.

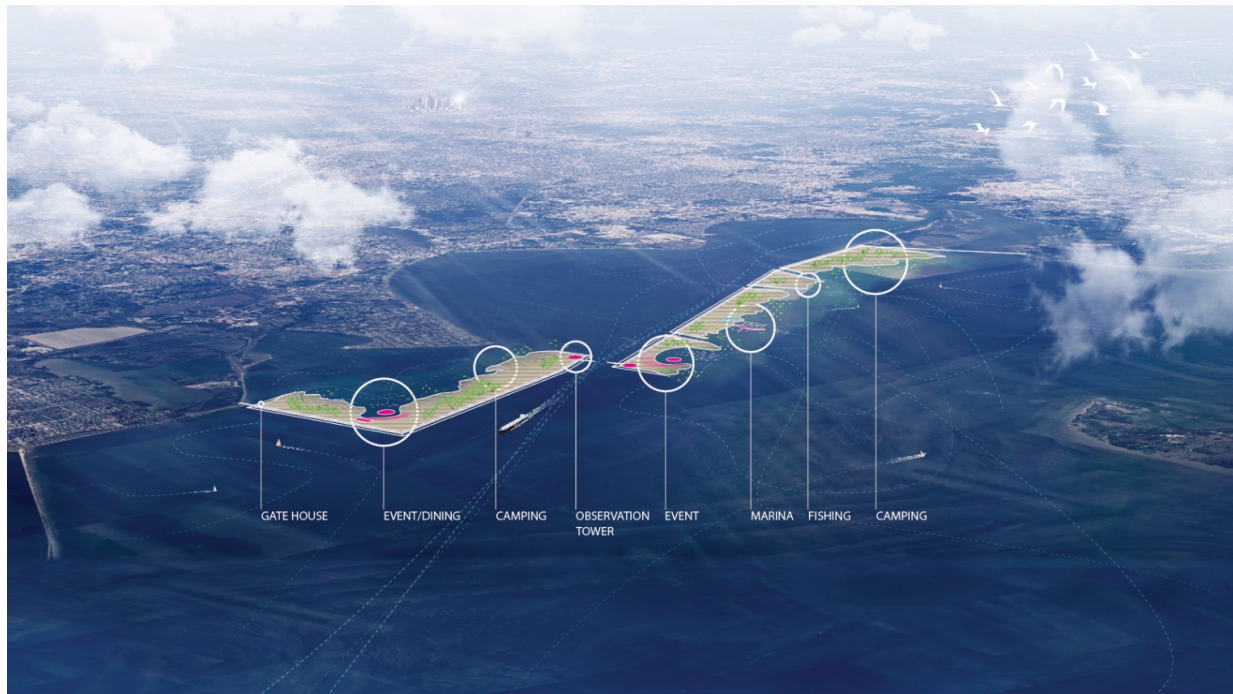
At this time, the environmental impact of the coastal spine is being evaluated by the U.S. Army Corps of Engineers. A Draft Environmental Impact Statement (DEIS) is expected to be released in September 2018, at which time both the Corps' preferred alternative and its environmental impacts will be presented for public review and comment. It is possible that the Corps could recommend only constructing a portion of the coastal spine, or they could recommend constructing the entire proposed concept depending upon the results of their benefit-to-cost assessments, their understanding of the potential recurrence intervals of hurricane surge events, and the results of their environmental impact analysis. One alternative to the full coastal spine project would be to build the berms on Bolivar and Galveston Islands without any gate structures across Bolivar Roads. This would greatly reduce the cost of the coastal spine and the potential environmental impact to the bay system. However, it would also leave the Houston Ship Channel and the west side of Galveston Bay vulnerable to larger storm surge events, such as those modeled by SSPEED.

It should be noted that uncertainty currently exists with regard to the location of the berms on both Bolivar Peninsula and Galveston Island as well as any supplemental berms to protect the western side of Galveston Island and the western shoreline of Galveston Bay. These issues should be set out in the Corps' DEIS forthcoming in September 2018.

## 2. Galveston Bay Park/Mid-Bay Alternative

A second option named the "mid-bay" alternative was initially designed by the SSPEED Center in an attempt to provide alternative approaches to the Ike Dike for solving the surge problem. The concept of the mid-bay alternative is to connect the relatively high land in Chambers County with the Texas City levee system by extending the 25-foot-high berms currently around the upper disposal areas along the Houston Ship Channel southward to a point near Eagle Point (e.g., San Leon). At this point, a navigation gate structure would be placed across the ship channel. The berm would then continue across the bay to intersect with the Texas City levee that currently protects the city and its industries. A series of small craft navigation gates would be interspersed along the in-bay berm system to allow for small boat traffic to traverse across the bay and for water circulation. More recently, the SSPEED Center has proposed turning such an in-bay berm system into a park system, known as the Galveston Bay Park, to provide both recreational and environmental benefits. The general design of the Galveston Bay Park concept is displayed in Figure 32. Note that all in-bay berms are at 25 feet above sea level, including adding additional height to the Texas City levee system to provide a consistent level of protection.

**Figure 32.** The Galveston Bay Park Alternative



Note: The Galveston Bay Park alternative is shown here connecting the Texas City levee system at the bottom left with high land on western shore of Trinity Bay in Chambers County at the upper right. Some recreational concepts are also depicted.

Source: Image and conceptual plan courtesy of Rogers Architects

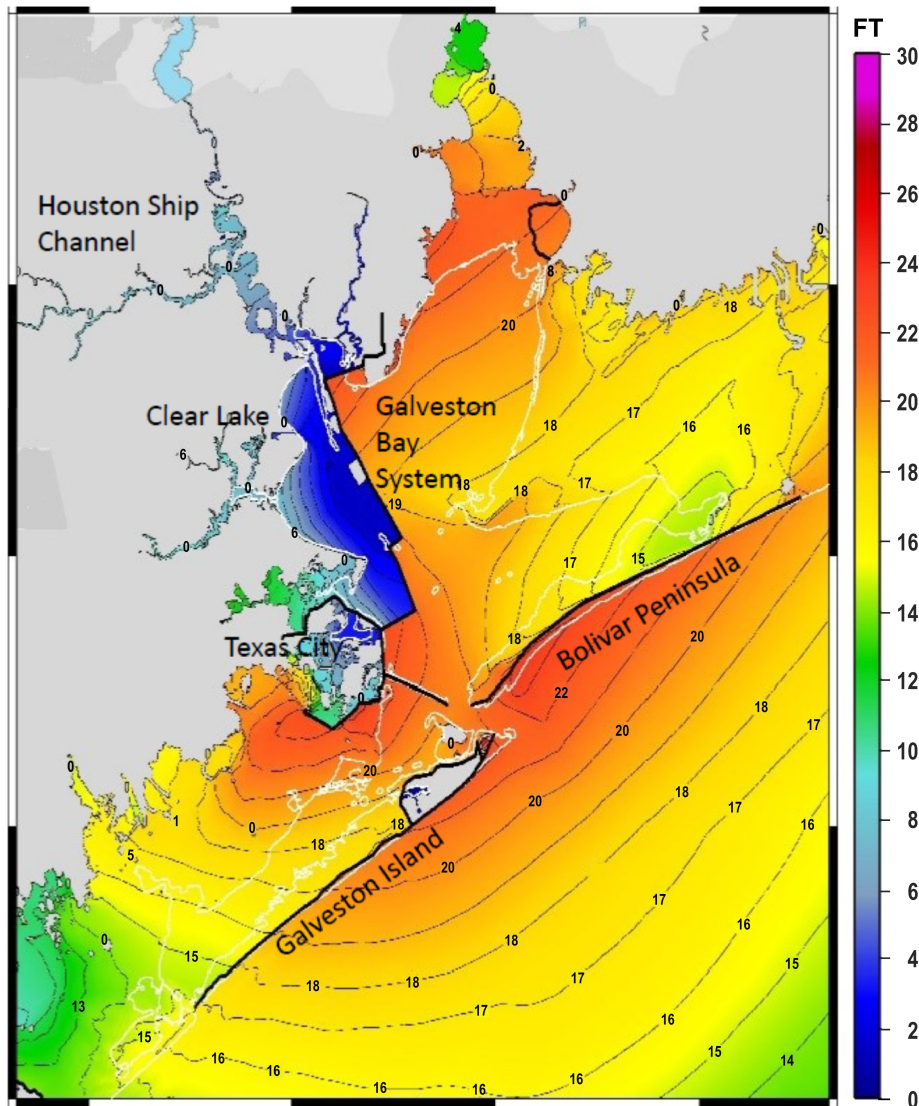
As shown above, the Galveston Bay Park alternative does not protect either Galveston Island or the city of Galveston. However, in addition to this in-bay park/berm system, the SSPEED Center also proposed a levee system to protect the western side of Galveston and an increase to the height of the sea wall by at least an additional three feet (from its current height of 17 feet). Further, SSPEED proposed elevated roads (or berms/dunes) on Bolivar Peninsula and Galveston Island. This configuration would be very successful in protecting the Houston Ship Channel, the west side of Galveston Bay, and the city of Galveston, as shown in Figure 33.

There are many benefits to the Galveston Bay Park approach besides its surge protection features. First, this approach would create in-bay, bermed areas that would support the need for dredge material disposal for ongoing dredging activity along the Houston Ship Channel. This in-bay berm system would therefore create additional disposal capacity and use the dredged material in a beneficial way to create wetland areas and other environmental amenities such as those already implemented by the ship channel dredge disposal program. However, instead of creating land areas within the bay simply for disposal purposes, these land areas could be turned into parks and other recreational features to serve as an attraction to residents and tourists. Another major benefit of this in-



bay alternative is its cost, which is estimated at about \$3 billion and includes constructing the Galveston backside levee and berms on both Bolivar and the western end of Galveston Island. The in-bay system with its one large navigation gate and several smaller gates would likely affect some oyster areas within the bay, but this impact could be mitigated. This project would also have much less impact on bay circulation and would not interfere with the tidal, circulatory, or fishery functions of Bolivar Roads. Thus, there are certainly significant benefits to the Galveston Bay Park solution.

**Figure 33.** Map Showing the Effectiveness of the Mid-bay Alternative



Note: This map shows the placement of the mid-bay alternative, including the Galveston backside levee alignment and elevated roadways along the coast, for a small Category 4 storm coming ashore along the southern end of Galveston Bay and the Houston Ship Channel.

Source: Analysis by Dr. Clint Dawson for the SSPEED Center

The SSPEED Center proposed the in-bay berm solution as a part of a larger coastal protection system that includes some or even all elements of the coastal spine. If the Corps proposes only a coastal spine solution, the Galveston Bay Park alternative could become a viable locally sponsored addition that would further protect the Houston Ship Channel and western shoreline of Galveston Bay. It may be prudent for local governmental entities to seek a permit to construct this in-bay system at this point in time, given that the likely review time for this permit would be at least one to two years. By moving forward right now, it would be possible to utilize the Corps' existing environmental impact review and have this permit potentially processed along with the Corps' decision documents on the coastal spine, ensuring a full range of alternatives are available. This is prudent to the extent that there is no requirement to construct a permitted alternative but an alternative cannot be constructed if not permitted.

## VI. Conclusion

In summary, Houston and Harris County have serious flooding problems to address, but there are very real alternative approaches and concepts that can help solve these issues. As Albert Einstein is reputed to have said, "The world we have created today as a result of our thinking thus far has problems which cannot be solved by thinking the way we thought when we created them." Nothing could be truer about Houston than that summary. We must collectively solicit the best ideas from around the world and be open to doing things differently. We have to think differently than we have in the past. Hopefully, this paper has introduced some new ideas. Our economic future, homes, and lives are at stake.

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