Buffalo Bayou and Tributaries Resiliency Study, Texas

Review of Completed Projects

Interim Feasibility Report

October 2020

Photograph: Record breaking rainfall from Hurricane Harvey in 2017 caused catastrophic flooding in Houston. The above photograph shows a completely submerged Interstate 10 outside of Houston, Texas on August 26th, 2017.

US Army Corps of Engineers®
Galveston District

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DEPARTMENT OF THE ARMY
GALVESTON DISTRICT, CORPS OF ENGINEERS
P. O. BOX 1229
GALVESTON, TEXAS 77553-1229

Buffalo Bayou and Tributaries Resiliency Study, Texas

Combined Feasibility Report and Environmental Impact Statement

Review of Completed Projects

October 2020

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RECORD OF DECISION

Buffalo Bayou and Tributaries Resiliency Study, Texas

Combined Feasibility Report

Review of Completed Projects

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EXECUTIVE SUMMARY

Introduction

The U.S. Army Corps of Engineers (Corps), in partnership with the Harris County Flood Control District (HCFCD), is conducting a feasibility study of the Buffalo Bayou and Tributaries flood risk management system. This interim feasibility report documents initial analyses conducted by the project delivery team (PDT), but does not present final conclusions and recommendations. The report is a mid-point technical document for review prior to recommending a Tentatively Selected Plan (TSP).

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

Study Purpose

The study was initiated in response to several recent flood events in the Houston metro area, including Hurricane Harvey that struck Texas with devastating effects in August 2017. Harvey made landfall on August 25th about 30 miles northeast of Corpus Christi near the communities of Rockport and Fulton. The Category 4 hurricane caused extensive damage as it moved north toward San Antonio and then veered sharply east towards Houston and Louisiana. After stalling, Harvey dropped record rainfall volumes in east Texas causing widespread flooding, and producing record water levels in Addicks and Barker reservoirs and downstream in Buffalo Bayou.

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

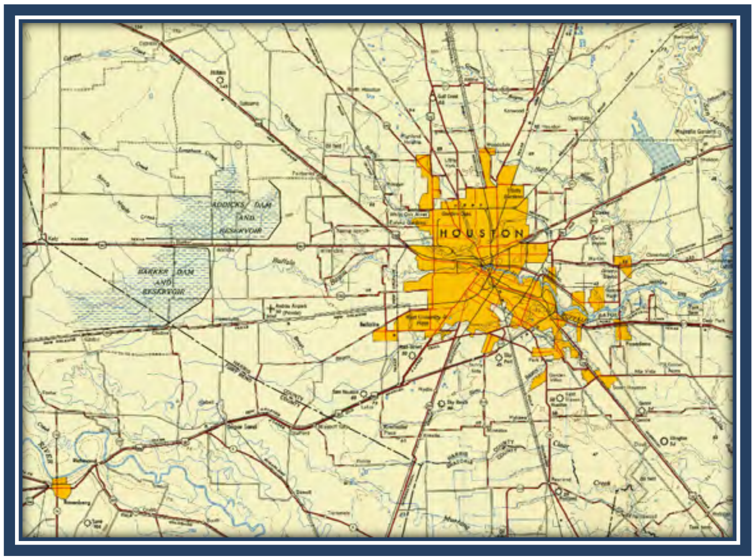
The purpose of the Buffalo Bayou and Tributaries study is to evaluate changed conditions since the projects were constructed. The objective is to identify, evaluate, and recommend actions to address the changed conditions, including potential modifications to the Buffalo Bayou system to reduce flood risks to people, property, and communities.

Changed Conditions

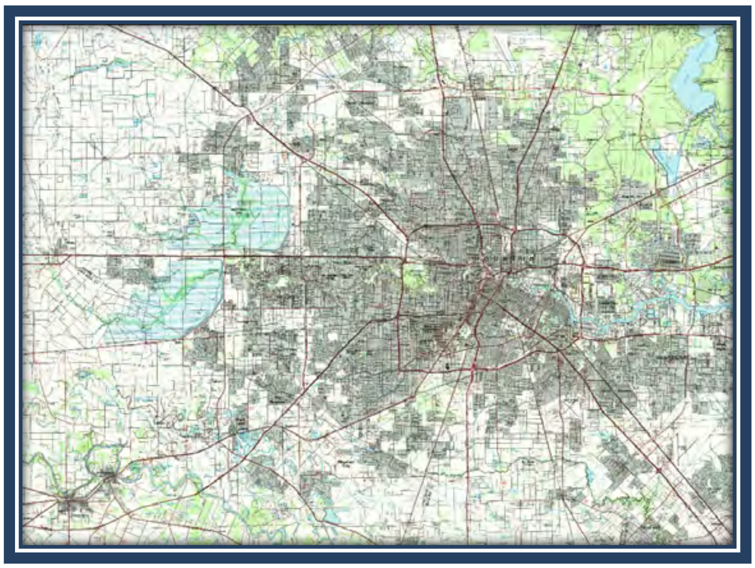
The greatest change in the region has been the growth and expansion of the greater Houston area surrounding the dams and reservoirs. Both dams were originally constructed in what was a rural setting west of Houston. Since then, a strong regional economy has driven population growth to almost 7 million residents, and resulting development has filled the landscape between the dams and downtown Houston, and has continued westward in areas surrounding the reservoirs. Maps and aerials on the next page illustrate the phenomenal growth in the Houston area.

Hurricane Harvey was a near probable maximum precipitation (PMP) event exceeding all previous PMP estimates at several locations in southeast Texas. As a result, reevaluating the PMP estimates for Addicks and Barker Dams was appropriate based on the expected change in conditions. Multiple storms occurring between 1973 and 2018 were analyzed to determine whether original estimates were still indicative of the critical potential for catastrophic rainfall. While precipitation totals from Hurricane Harvey exceeded previous original estimates for durations longer than 48 hours and areas greater than 1,000 square miles, areas and durations less than these, were not exceeded. Since the Addicks and Barker watersheds are less than 200 square miles, the original 72-hour PMP estimates of 48.8 inches are appropriate.

Subsidence has occurred along the dams and at the outlet works since construction. A new outlet structure at Barker Dam was put into operation on 14 February, 2020 as well as a new outlet structure at Addicks Dam on 24 March, 2020. The old outlet structures had a combined maximum design discharge of 16,630 cubic feet per second (CFS). Discharge for the new outlet structures will not exceed the previous maximum discharge.



1950



1992

2016

Maps and aerial imagery from 1950, 1992 and 2016 illustrate rapid growth of the greater Houston area. In 1950, 807,000 people lived in Houston, and today there are nearly 7.1 million people living in the area.

With a gross domestic product (GDP) of nearly $500 billion, Houston is major economic hub for the nation, the fourth largest of any metro in the nation. In terms of GDP Houston's economy is comparable in size to GDP of sovereign nations including Sweden, Belgium and Thailand.

The region is a strategic hub of the U.S. with one the nation's largest deep draft ports, and comprises the largest concentration of petroleum and chemical manufacturing in the world, including for synthetic rubber, insecticides and fertilizers. It is the world's leading center for oilfield equipment construction, with the city of Houston home to more than 3,000 energy-related businesses, including many of the top oil and gas exploration and production firms and petroleum pipeline operators.

In addition to rapid population growth and economic development, precipitation patterns have also changed, and the frequency and intensity of rainfall events has increased. NOAA published the most recent precipitation frequency atlas for Texas in 2018 in Atlas 14 Volume 11 Version 2 (Atlas 14) that incorporates rainfall data from the 1940s through 2017 and includes rainfall associated with Hurricane Harvey. As shown in Table 1, Atlas 14 shows a significant increase in precipitation for each frequency (25 to 50 percent increases in rainfall volume expected for storms of 12 to 72-hour duration for all frequencies).

Table 1. New (NOAA Atlas 14) precipitation-frequency values compared to values from the old version (precipitation in inches)

	Average Recurrence Interval (yrs)													
Duration	2		10		25		50		100		500		1000	
	Old	New	Old	New	Old	New	Old	New	Old	New	Old	New	Old	New
12-hrs	3.4	4.3	5.9	7.2	7.4	9.4	8.7	11.4	10.2	13.7	14.7	20.6	16.8	24.1
24-hrs	4.1	5.0	7.1	8.5	9.0	11.2	10.6	13.7	12.4	16.6	17.7	24.5	20.2	28.5
2-days	4.7	5.8	8.1	10.0	10.8	13.3	12.5	16.5	14.0	20.0	20.0	28.2	23.6	31.8
3-days	5.0	6.3	8.7	10.9	11.5	14.5	13.3	17.9	15.0	21.6	21.5	29.8	25.6	33.3

Source: NOAA National Weather Service, 2018

A combination of development and higher rainfall volumes has led to increased runoff into the reservoirs. Table 2 shows that the two highest pool elevations over the projects' lives occurred in 2016 and 2017, with the 2017 Harvey flood producing the highest recorded floods in both reservoirs and on Buffalo Bayou. Reservoir pools extended beyond government owned lands for the first time in 2016 (the elevation of federal property is 103 feet at Addicks and 95 feet at Barker).[1]

Table 2. Top 5 Historic Peak Stages in Addicks and Barker Reservoirs; High Water Marks on Buffalo Bayou

Addicks		Barker		Buffalo Bayou	
Date	**Elevation**	**Date**	**Elevation**	Date	**Elevation**
Aug-17	109.1	Aug-17	101.6	Aug-17	71.6
Apr-16	102.65	Apr-16	95.22	Apr-09	65.4
Mar-92	97.64	Mar-92	93.6	Apr-16	65.3
Apr-09	97.08	Nov-02	93.24	Mar-92	64.5
Nov-02	96.63	Nov-98	92.31	May-15	62.9

Study Location

Buffalo Bayou watershed is in the San Jacinto River Basin located primarily in Harris and Fort Bend counties in southeast Texas. Barker Dam sits above Buffalo Bayou, and Addicks Dam is

[1] All elevation data is in the North American Vertical Datum of 1988. All elevations are given in feet above mean sea level.

on South Mayde Creek, a tributary of Buffalo Bayou. Both dams are on the northwestern boundaries of the city limits of Houston.

Study Scope

The Buffalo Bayou and Tributaries Resiliency Study evaluates six watersheds (Figure 1):

Upper Cypress Creek (267 square miles),

White Oak Bayou (111 square miles),

Brays Bayou (127 square miles),

Addicks Reservoir (138 square miles),

Barker Reservoir (126 square miles); and,

Buffalo Bayou (102 square miles).

The six watersheds are included in the modeling and technical analyses of flooding, but the primary scope of the study is to reduce flood risk for the Addicks, Barker, and Buffalo Bayou watersheds.

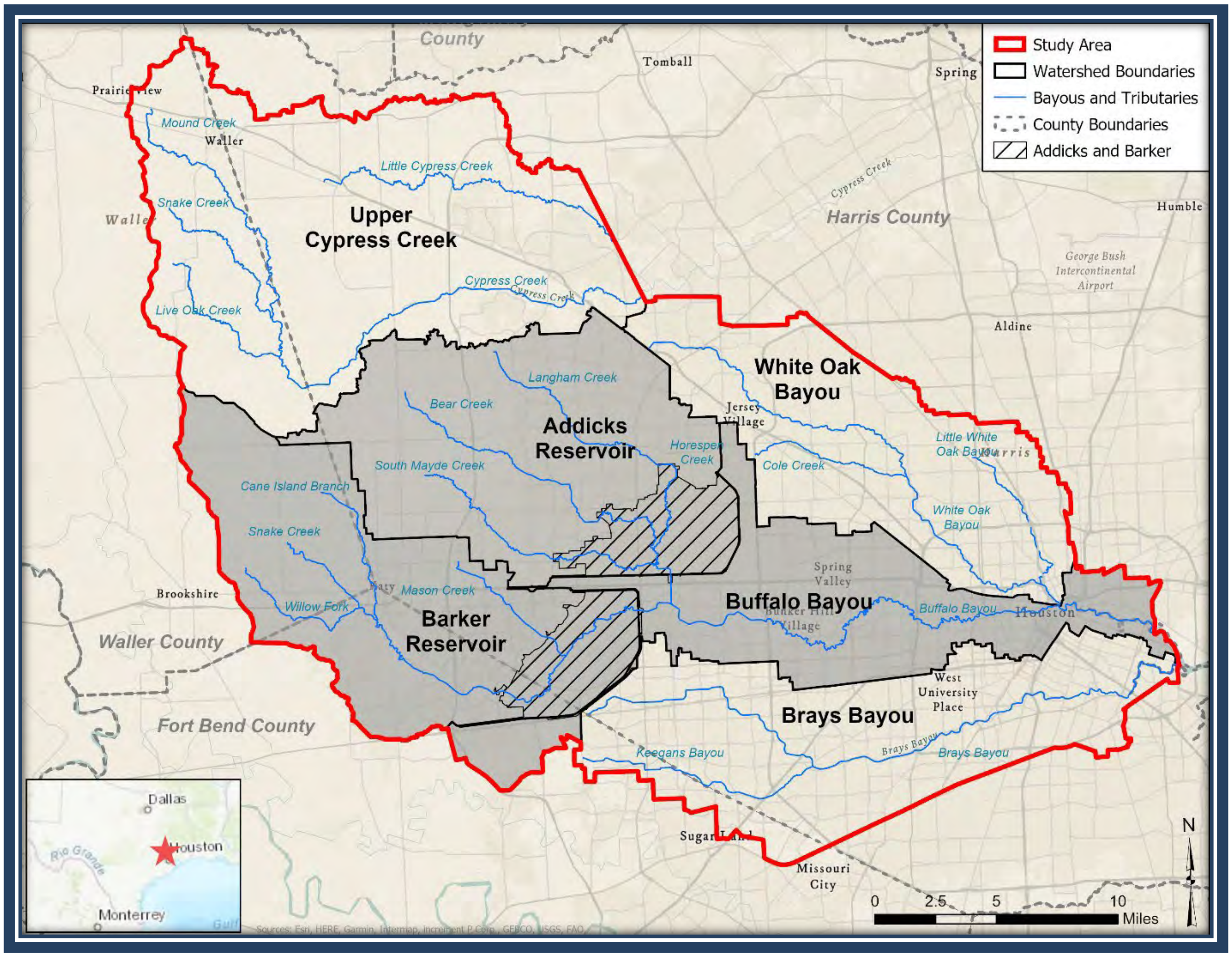


Figure 1. Addicks and Barker Reservoirs and Buffalo Bayou, Texas Study Area Map

Environmental Compliance

An Environmental Impact Statement (EIS) is underway since there are a number of significant environmental resources in the study area, and recommended alternatives could have significant impacts.

Public Coordination

Between April 30 and May 9, 2019, the Corps and the HCFCD hosted five Public Scoping Meetings. Three meetings were held near Buffalo Bayou downstream of Addicks and Barker reservoirs, and two meetings were held upstream. A Public Notice was published on the Galveston District website, and in the Legal Notices section of the Houston Chronicle. Public news releases announcing the scoping period timeframe, public meeting dates, times, and locations, and where to send comments were published in local newspapers, and on the Corps Galveston District and HCFCD websites. Public notices were also distributed to local stakeholders and known interested parties.

Problem Statement and Planning Objectives

The PDT developed brief problem statements and planning objectives used to guide the identification and evaluation of potential solutions. Hurricane Harvey presented an enormous challenge for the region, and demonstrated a need to address changed conditions around the two dams and downstream Buffalo Bayou. Harvey produced record rainfall amounts that accumulated in Addicks and Barker reservoirs resulting in record pool elevations. Flood waters from Harvey flooded homes upstream and put extreme pressure on the two dams; and controlled releases contributed to downstream flows that exceeded the carrying capacity of Buffalo Bayou. Flooding during Harvey revealed several inherent risks in the system: 1) upstream risks when inflows exceed reservoir capacity, 2) dam safety risks if a dam component were to fail during a flood, and 3) downstream risks when flows exceed channel capacity. Problem statements, planning objectives, and constraints are summarized below.

Problems

1) Intense rainfall events cause flooding in the Buffalo Bayou watershed and significant inflows into the Addicks and Barker reservoirs;
2) High water levels in Addicks and Barker reservoirs can extend beyond project lands and pose unacceptable risks to health and human safety, private property, and public infrastructure;
3) Pool releases from Addicks and Barker reservoirs combine with downstream inflows to pose risks to health and human safety, public infrastructure, and private property;
4) Probable maximum flood water elevations for both Addicks and Barker dams have increased as well as the frequencies leading to increased loading on spillways;
5) Spillway protective concrete layers are more than 25 years old and have cracks, separations, and are eroded; and,
6) Land subsidence has lowered spillway elevations.

Objectives and Constraints

Objectives include:

1) Reducing life-safety risks consistent with Corps tolerable risk guidelines;
2) Reducing damages to homes, businesses, and infrastructure in the study area for the 50-year period of analysis (2036 through 2085); and,
3) Supporting community resilience and recovery.

The planning constraint is to avoid increasing flood risk or transferring flood risk to other areas. Transferred risk is defined as a result of an action taken in one region of a system to reduce risk, where that action shifts the risk burden to another region in the system. Any eventual recommendation will avoid increasing or transferring the risk to another area.

Plan Formulation

Plan formulation is the process of building alternative plans that reduce risks and achieve planning objectives while working within the planning constraints.

The following decision criteria with appropriate metrics and data sources are listed as the means of identifying the tentatively selected plan:

- Reduction in Flood Damages
- Depths of flooding
- Impacts to Life Safety
- Costs
- Impacts to Critical Infrastructure
- Required Mitigation
- Impacts to T&E species
- Cultural Impacts
- Resiliency

Alternative Plans

To address study objectives as it relates to flood risk management, the PDT identified alternative plans that could address the problems. Generally, alternatives consider combinations of alternatives that would:

1) Increase system storage via new reservoirs, detention storage, or excavation in Addicks and Barker reservoirs;
2) Increase conveyance with new tunnels or by increasing capacity in existing channels;
3) Divert water away from the reservoirs and Buffalo Bayou;
4) Increase the structural reliability of the dams;
5) Use nonstructural measures to reduce exposure or vulnerability of people, homes and other property in harm's way through measures including property acquisition, flood-proofing or elevating structures in place; or,
6) Combinations of the above actions.

Table 3 summarizes alternatives and the initial screening-level evaluation. The first screening eliminated tunnels and diversions. Tunnels were dropped because they perform the same function as channel improvements (Alternative No. 6), but cost significantly more than other alternatives ($2.2 to $12 billion at July 2019 price levels). Diversions would not be effective because during large flood events, which are the focus of this study, adjacent watersheds would also be at flood stage and their capacity to store flood water from Buffalo Bayou is limited. Diverting water beyond adjacent watersheds would be prohibitively expensive.

Table 3. Initial Evaluation of Alternatives

Alternative Plans	Description	Added Measures	In Focused Array	Notes
Alt 1: No Action	No plan is implemented because of this study	None	Yes	This forms the baseline for costs, benefits, and impact comparison. It aids in understanding how each plan functions compared to the baseline
Alt 2: Cypress Creek Dam and Reservoir	Store water on Cypress Creek by constructing a new dam and reservoir	$2.1 to 2.9 billion	Yes	None
Alt 3: Addicks and Barker Reservoir Excavations	Increase storage capacity within each reservoir by deepening portions of the reservoirs	$1.3 to 1.8 billion	No	This plan provides only localized benefits
Alt 4: Tunnels	Convey up to 20,000 cubic feet per second (cfs) of floodwaters through underground tunnels that would capture water at the dams and empty water into the Houston Ship Channel/Galveston Bay	$6.5 to 12 billion	No	Tunnels provide comparable benefits as other alternatives but at a much higher cost
Alt 5: Diversions	Divert water from the Buffalo Bayou Watershed to Brays and/or the Brazos River	$0.25 to 0.35 billion	No	Diversions present a high risk in long-term operation because Brays and or the Brazos River may already be flooded
Alt 6: Buffalo Bayou Channel Improvements	Widen and deepen Buffalo Bayou from just below Addicks and Barker Dams to convey 15,000 cfs	$1.0 to 1.25 billion	Yes	None
Alt 7: Nonstructural	Large-scale acquisition plan along Buffalo Bayou to convey 15,000 cfs	None	Yes	Mandatory to carry forward
Alt 8: Combined Plan (Alts 2 + 6)	Store water on Cypress Creek by constructing a new dam/reservoir AND widen and deepen Buffalo Bayou from just	$3.0 to 4.25 billion	Yes	None

	below Addicks and Barker Dams to convey 15,000 cfs (Alternatives 2 and 6)

Revised Array of Alternatives

The focused array of alternatives includes the no action plan (baseline for comparison), three structural alternatives, and a nonstructural alternative. Structural alternatives include a new dam and reservoir on upper Cypress Creek, channel improvements on Buffalo Bayou, and a combination of these two. Ancillary measures were added to the anchor measure to broaden each plan’s effectiveness.

Table 4 shows measures included for further evaluation of each alternative, and Tables 5 and 6 briefly describe each alternative. Note that excavation in existing reservoirs does not create enough additional capacity to have a significant effect as a primary anchor measure; however, it was kept as an ancillary or complementary measure that could be used in combination with other alternatives. Similarly, diversions were kept as ancillary measures to optimize reservoir or channel improvement alternatives.

Table 4. Management Measures Comprising the Revised Array of Alternatives

Measures	Alternative Plans				
	No Action	Cypress Creek Reservoir	BB Channel Improvements	Downstream Nonstructural	Combo
Anchor					
Cypress Creek Dam		X			X
Buffalo Bayou Channel Improvement			X		X
Ancillary					
Upper Buffalo Dam		X	X		X
Addicks Reservoir Excavation		X	X		X
Barker Reservoir Excavation		X	X		X
North Canal via Houston Diversion		X	X		X
Barker to Brays Diversion		X			
Cane Island Branch Channel Improvement		X	X		X
Downstream Relocation				X	

Downstream Acquisition	X
Downstream Elevation	X

Alternative Plan 2: Cypress Creek Dam and Reservoir would construct a new 190,000-acre foot reservoir upstream of Addicks in the Cypress watershed. Embankment crowns would be 190 feet with spillways at 187 feet. An emergency operation schedule similar to Addicks and Barker was developed. One overflow spillway discharges into the Cypress Creek watershed, while a second discharges into the Addicks Watershed. The primary control structure releases into Cypress Creek. A downstream control point with a maximum flow of 2,000 cubic feet per second (cfs) would be just upstream of Tomball Parkway. First costs for the Cypress Creek Dam are estimated at $2.14 billion to $2.90 billion. With ancillary measures included, first costs are $4.5 to $6.1 billion.

Table 5. Alternative No. 2 Cypress Creek Dam & Reservoir Specifications

Component	Specification
Elevation (Top of Embankment)	190 feet
Crown	12 feet
Side Slope	1V:3H
Embankment Height	30 feet
Length	55,000
Spillway Elevation	187 feet
Footprint/Right of Way	392 feet
Capacity	190,343 acre-feet
Land Acquisition	22,142 acres

Alternative Plan 6: Buffalo Bayou Channel Improvements involves rehabilitating Buffalo Bayou to improve conveyance up to 15,000 cfs by excavating, widening, and re-grading the existing channel (Table 6 and Figure 2). The centerline of the channel improvement is assumed to be the same as the existing channel. The number and size of storm drains needed to lower the channel invert were roughly estimated as were impacts to existing bridges and may not be completely captured. Average cut depth is estimated at 11.6 feet with a channel bottom width of 70 feet and top of channel width of 230 feet. Slopes would be 1V:4H and the channel would be about 24 miles in length. First costs for the Buffalo Bayou Channel Improvement range from $946 million to $1.23 billion. With ancillary measures included, first costs are $3.1 to $4.1 billion.

Table 6. Alternative Plan No. 6 Buffalo Bayou Channel Improvements Specifications

Component	Specification
Conveyance	15,000 cfs
Average Cut Depth	11.6 feet
Channel Bottom Width	70 feet
Channel Top Width	230 feet
Slope	1V:4H
Approximate Length of Improvements	24 miles

Alternative Plan 7: Downstream Nonstructural would involve acquiring and relocating existing structures downstream of Addicks and Barker dams along Buffalo Bayou. Multiple scales were considered. At the high end, up to 441 structures (including businesses and multi-family structures) would be acquired and relocated at a cost of $2.3 billion.

Alternative Plan 8: Combination of (Alternatives 2 and 6) would merge plans 2 and 6. Costs are estimated at $5.2 to $7.0 billion with ancillary measures included.

Figure 2. Alternative Plan 8 Combined Plan with Buffalo Bayou Channel Improvements (Alternative 6) and Cypress Reservoir (Alternative 2)

Evaluation of Focused Array OF Alternatives

Structural Alternatives

Structural alternatives were evaluated to identify the most cost-effective alternative to address planning objectives, and an alternative's impact on life safety risks. No structural alternatives have a strong benefit-cost ratio (BCR). Alternative 6 (channel improvement) has the lowest cost and highest BCR at 0.3; however, BCRs do not reflect life-safety benefits. As a standalone option, the channel plan would reduce estimated fatalities from 248 to 82 in the daytime scenario. When combined with Alternative 2 (Cypress Creek Reservoir) to form Alternative 8 (Combination Plan), first costs increase by an additional $2 to $3 billion, but would reduce life safety risks by an additional 35 lives at Addicks reservoir, but would have no change in safety risks at Barker.

Table 7. Cost Effective Analysis of Structural Alternatives

Alternative Plan	Project Costs (includes Ancillary Measures)	Benefit Cost Ratio*	Mitigation Acres	Life Safety Annual Life Loss Addicks (Day)	Addicks (Night)	Barker (Day)	Barker (Night)
1. No Action	**None**	None	None	224	123	124	70
2. Cypress Creek Dam & Reservoir	$4.5 to 6.1B	0.1	7,523	22	11	25	18
6. Buffalo Bayou Channel Improvements	$3.1 to 4.1B	0.3	3,093	57	27	25	18
8. Combination (Alt. 2 and Alt. 6)	$5.2 to 7.0B	0.2	7,593	22	11	25	18

October 2019 Price Levels, Costs in $Billions *Based on the high costs

Other considerations include the effectiveness of the alternatives at reducing the peak and duration of high pool elevations during large flood events, and containing reservoir pools on government-owned lands. Figures 3 and 4 show pool elevations during a 0.002 annual exceedance probability (AEP) event at Addicks and Barker, respectively.[2] These results reflect the changed precipitation conditions in the watershed. The horizontal solid black line marks the extent of government owned lands. None of the alternatives reduce the peak of the 0.002 AEP flood below the government boundary at either reservoir. However, alternatives reduce flood duration above government land, which helps reduce recovery time but does not meaningfully reduce property damages and life safety risks.

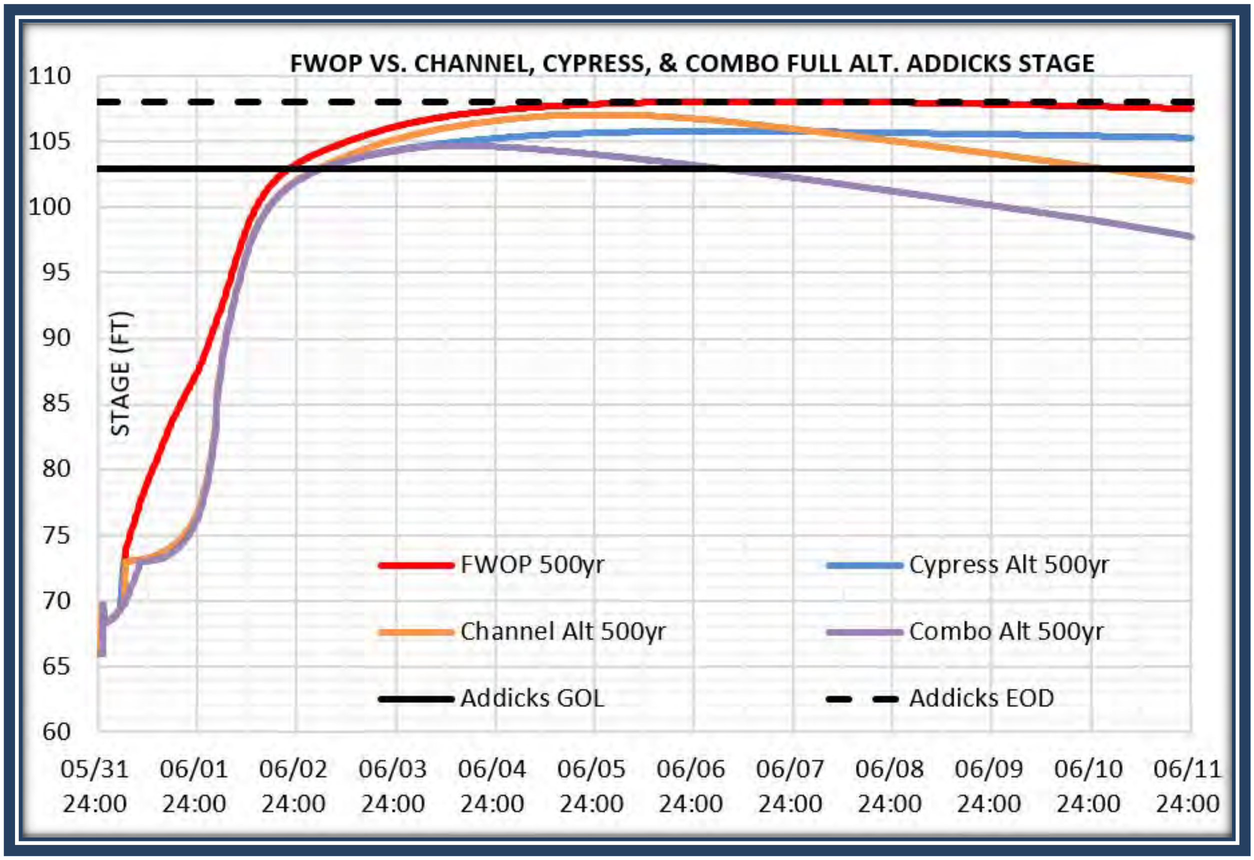


Figure 3. Addicks Reservoir FWOP 0.002 AEP vs Alternative Plans 2, 6, and 8

[2] The 0.002AEP is used for comparison, but it is not the maximum flood possible.

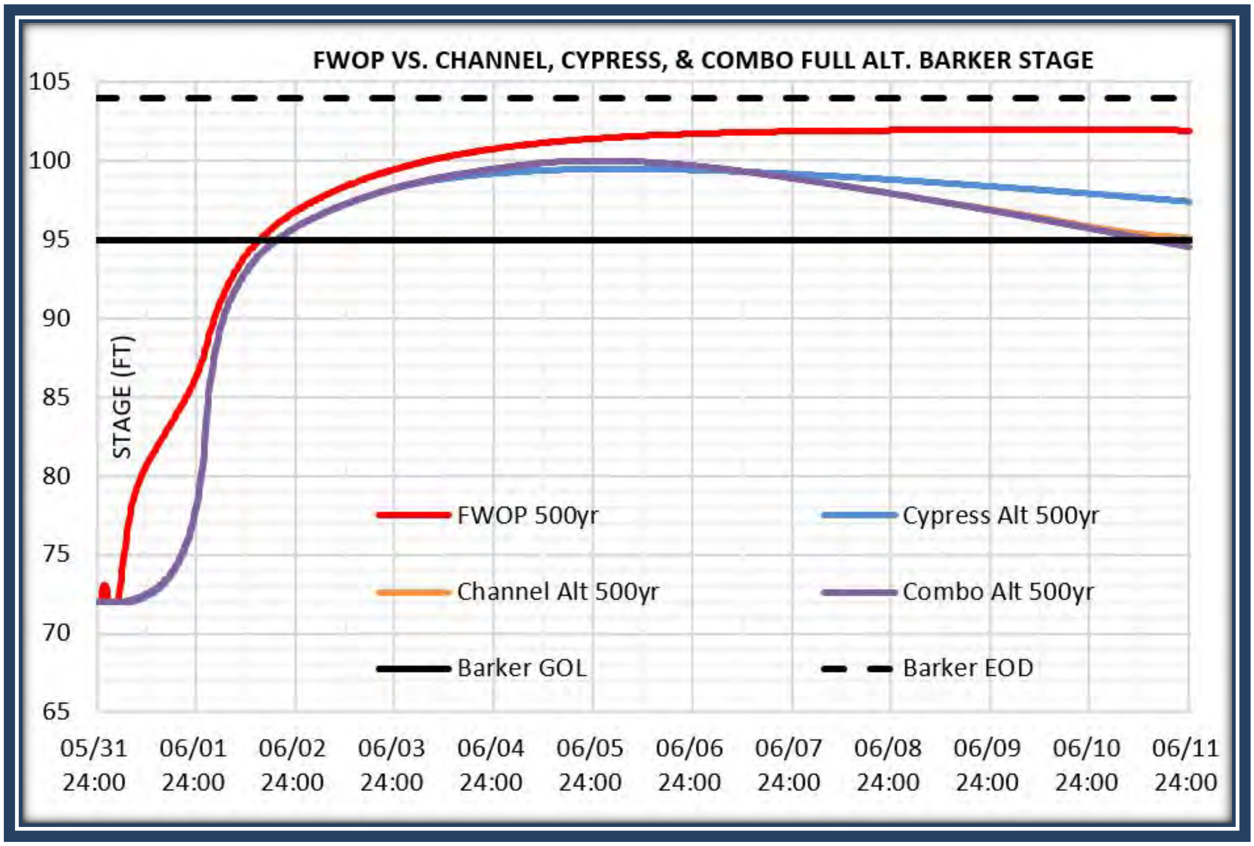


Figure 4. Barker Reservoir FWOP 0.002 AEP vs Alternative Plans 2, 6, and 8

Based on the evaluation, Alternative 6 (Buffalo Bayou Channel Improvement) is the most cost effective structural plan and reduces 76 percent of the life safety risks, while incurring half the environmental impacts of the reservoir and one-third of the combined plan. Addition of the reservoir (Alternative) would further reduce safety risks by 10 percent, but that would increase costs by an additional $2 to $3 billion and impact an additional 7,500 acres of Katy prairie habitat.

Nonstructural Alternatives

To assess the nonstructural alternative, the PDT looked at various scales of downstream acquisitions to allow increased releases from Addicks and Barker reservoirs up to 15,000 cfs (equivalent performance level of the channel improvement plan). Multiple scales were considered (Table 8). The 0.02 AEP plan approximates the amount of land required to convey 15,000 cfs. The 0.02 AEP would require buying 441 structures at an estimated cost of $2.3 billion ($1.0 billion more than the channel improvement plan).

Table 8. Cost Effective Analysis of Nonstructural Alternatives

Alternative Scale	Number of Structures	Expected Annual Benefits	First Cost	Annual Cost	Net Benefits
0.5 AEP	19	$56,000	$204,000	$8,000	$48,000
0.2 AEP	33	$58,000	$264,000	$10,000	$48,000
0.1 AEP	64	$61,000	$438,000	$17,000	$44,000
0.04 AEP	341	$77,000	$1,937,000	$74,000	$4,000
0.02 AEP	441	$79,000	$2,277,000	$87,000	($8,000)

October 2019 Price Levels, Costs in $1,000s

Dam Safety Modification

The third component of plan formulation addresses dam safety. Today, the Corps is in the process of replacing outlet structures at both dams, and the study that recommends replacing the outlets also identified problems with subsidence and cracking of concrete auxiliary spillways. Table 9 describes dam safety alternatives evaluated. Dam removal and replacement were screened from further consideration, and the analysis focused on armoring two of the four spillways or all four the spillways. The focused array is listed below.

Table 9. Focused Array of Dam Safety Alternative Plans

Alternative Plan	Description	In Focused Array	Notes
Alt 1: No Action	No actions are taken to address any of the probable failure modes (PFM).	Yes	Plan does not address the risk nor meet the objectives. Risks above tolerable levels would remain.
Alt 2: Dam Removal	The dam would be removed and not replaced.	No	Both dams are crucial components to preventing major flood damages to property and loss of life within the Buffalo Bayou and surrounding watersheds. Removing the dams would induce unacceptable risk and damages.
Alt 3: Dam Replacement	The dam would be replaced in the same place or a different location and built to meet today's standards.	No	Dam replacement is for the most part being completed with the Phase I actions. The spillways are the only part of the dam that would not be new.

Alternative Plan	Description	In Focused Array	Notes
Alt 4: Tolerable Risk	Armoring of the North Spillways of both dams.	Yes	Actions would reduce the risk below established societal guidelines
Alt 5: Tolerable Risk as Low As Reasonably Practicable	Armoring of both the North and South Spillways of both dams.	Yes	Actions would reduce the risk to the lowest possible while still being cost-effective.

Real Estate Requirements for Systems Operations

A significant effect of the changed conditions in the surrounding watersheds is that government owned lands (GOL) are more likely to be exceeded during large events than when the projects were originally constructed. Federal dams constructed in urban settings today are typically required to own lands at least to the standard project flood (SPF) elevation. At dams with a high-level spillway like Addicks and Barker, GOL should be equal to the spillway crest elevation. At Addicks and Barker, the SPF elevation is approximately four and a half feet higher than the current GOL elevation, and the spillway crests are four to six feet higher than the SPF. Table 11 shows pertinent elevations and Figure 6 maps key elevation boundaries. To address changed conditions and ensure continued safe operations of the dams, the Corps may acquire properties to the end of dam elevation, 108 feet and 104 feet, and possibly up to the spillway crest elevation, 111.5 feet and 105 feet at Addicks and Barker respectively.

In the original design, the land acquisition flood was determined as the 1935 storm centered over each watershed. The original real estate acquisition plan called for an additional three feet of freeboard above the land acquisition flood. Three feet of freeboard applied to the current SPFs would produce elevations of 110.5 feet NAVD88 in Addicks and 102 feet NAVD in Barker.

Table 10. Elevation Details for Addicks and Barker Dam (elevations in feet, NAVD88)

	Addicks Dam	Barker Dam
Spillway Design Flood	116.0	109.9
Approx. Spillway Crest	111.5	105.0
Harvey Peak Pool Level	109.1	101.6
Top of Surcharge Envelope	108.8	103.7
Elevation at the end of dams	108.0	104.0
Standard Project Flood	107.5*	99.0*
First Home Flooded	103.4	97.1
Government Owned Land (GOL)	103.0	95.0
First Street Flooded outside of GOL	101.2	94.9

*These are in the process of being updated

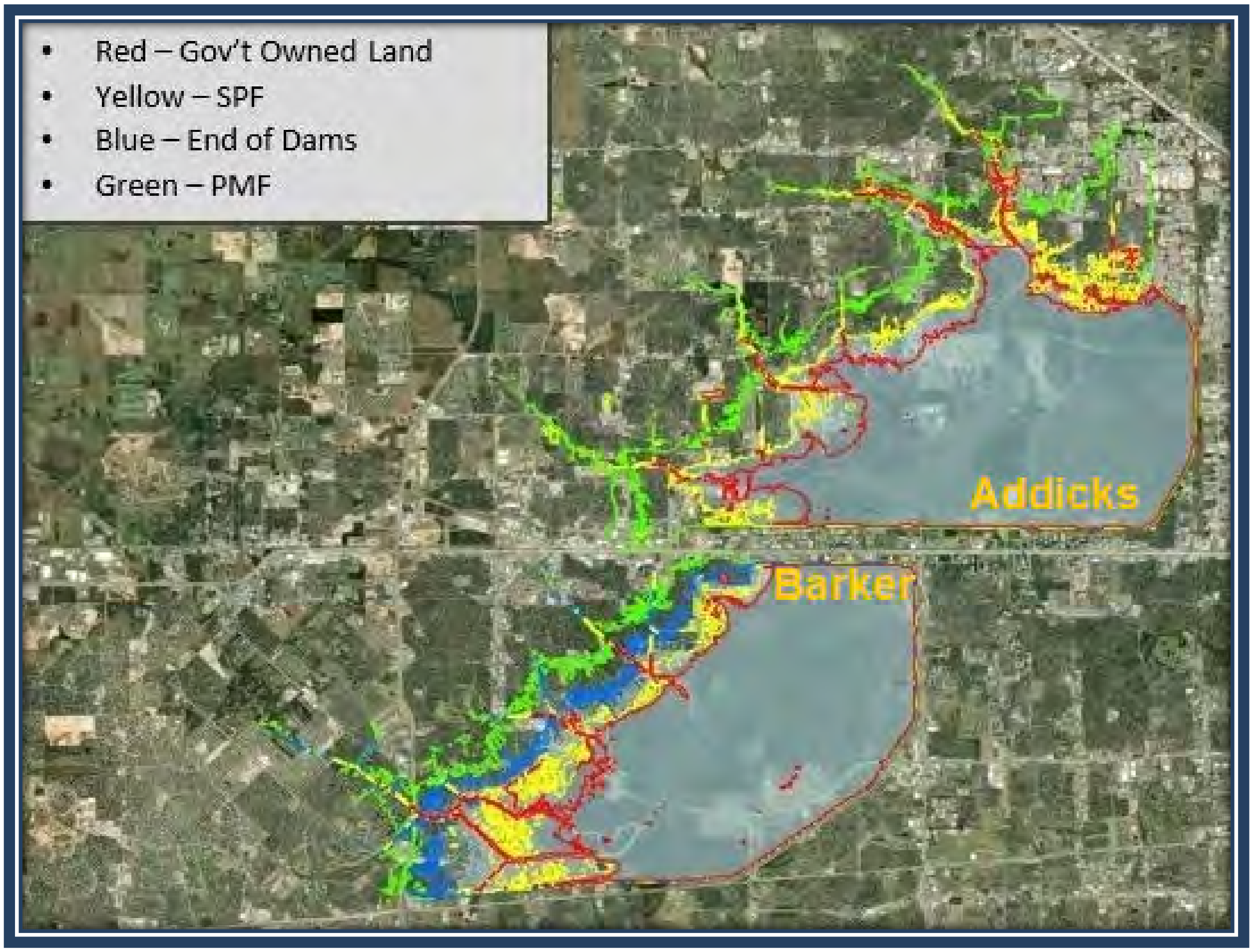


Figure 5. Map Showing Various Elevations at Addicks and Barker Reservoirs

The lands adjacent to the GOL are almost fully developed with neighborhoods of relatively high-density and high-value properties, infrastructure, and commercial business ventures. There are more than 20,000 homes and 24,000 parcels on the adjacent lands that are at or below the spillway crest elevation, 111.5 feet and 105 feet, at Addicks and Barker respectively. The total acquisition cost to acquire to the spillway elevations would be approximately $10 billion, and would have significant impacts to the people, businesses, and neighborhoods in the area and to the local tax base.

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1 General Information

The U.S. Army Corps of Engineers (Corps) in partnership with the Harris County Flood Control District (HCFCD), is conducting a feasibility study of the Buffalo Bayou and Tributaries flood risk management system. HCFCD, Harris County, Texas, sent a letter of intent to the Commander of the Galveston District on 13 February 2018. The letter expressed HCFCD's desire to begin a study partnership to address flood risk management upstream and downstream of the Addicks and Barker dams west of Houston, Texas. A Feasibility Cost Share Agreement was signed between the Corps and the Harris County Flood Control District on 10 October 2019.

This interim feasibility report documents initial analyses conducted by the project delivery team (PDT), but does not present final conclusions, recommendations, or compliance with the National Environmental Policy Act. This does not constitute a "decision document", but rather presents data from analyses conducted to date as well as the best professional judgment of the PDT for the alternatives analyzed to date. Comments received on this interim report will be used to inform additional technical analyses and evaluations to be conducted prior to release of a draft report containing a Tentatively Selected Plan.

When released, the draft report and environmental impact statement (EIS) will undergo review by the public, resource agencies, and technical & policy staff at the Corps and HCFCD. Comments received at that time will be used to inform whether the TSP should become the agency's Recommended Plan in the final report, or whether a different plan or modified version of the TSP should be recommended. Following the draft report, additional technical analyses will be conducted on the recommended plan in order to refine the design and develop a reasonable cost estimate before seeking authorization from Congress to design and construct the recommended plan. It is important to note that a local sponsor is required to share in the cost of design and implementation of the recommended plan (typically responsible for 35 percent of the project cost) and ultimately this sponsor is responsible for the operations and maintenance (O&M) of any projects that are constructed. If there is no cost-shared sponsor willing to share in the design and construction, and assume responsibility for O&M of the recommended plan, it would not be implemented unless a solution is specifically authorized.

The study was initiated in response to several recent flood events in the Houston metro area, including Hurricane Harvey. Hurricane Harvey struck Texas with devastating effect in August 2017. The hurricane made landfall on August 25th about 30 miles northeast of Corpus Christi, Texas, near the communities of Rockport and Fulton. The Category 4 hurricane caused extensive damage as it moved north toward San Antonio and then east towards Houston and Louisiana. The storm dropped record rainfall volumes on east Texas, causing widespread flooding, and producing record water levels in Addicks and Barker reservoirs and downstream on Buffalo Bayou.

Addicks and Barker Dams were constructed in the 1940s in response to damaging floods on Buffalo Bayou that struck Houston in 1929 and 1935. The dams have performed well over their

70+ years in operation, preventing loss of life and billions of dollars in damage along Buffalo Bayou. Trends suggest an increasing frequency of high-rainfall storms that will load the dams.

The purpose of the Buffalo Bayou and Tributaries Resiliency Study, Texas, Feasibility Report and Combined EIS, Review of Completed Projects study, hereafter called "the BB&T study", is to evaluate conditions that have changed since the projects were constructed. The specific objective is to identify, evaluate, and recommend actions, including potential modifications to the Buffalo Bayou system, to reduce further flood risks to people, property, communities, and businesses.

Flood risk-management is considered an appropriate Federal activity since addressing this is in the interest of the public's general welfare. The Buffalo Bayou and Tributaries Resiliency Study looked at both structural [dams, levees, channels, tunnels, diversions] and nonstructural [dry- and wet-floodproofing, relocations] measures to reduce the public's flood risks. The study looked at the extent of the flood risk based upon different precipitation events, how each of the various measures would perform alone or in combination, the costs, and how they compare to each other.

The Corps periodically examines each of their dams to ensure dam integrity, capability, and to make sure dams do not provide unacceptable risks to the public, to property, or to the environment. The study's dam safety portion looked at the ungated spillways at both Addicks and Barker dams to assess the risks associated with the possibility that the spillways could fail due to erosion, or that they could be breached. The dam safety study evaluated the chances of the spillways failing, how each of the measures would perform alone or in combination, the costs, and how much each alternative plan bought down risk.

As part of operations and maintenance, the Corps continues to assess the operational needs of its projects. Since construction of Addicks and Barker reservoirs, changed conditions within the system have led to increased runoff and larger storms. As evidenced in 2017, pools under large-scale flooding events can exceed the area currently owned by the Corps. This study evaluated options to expand the surcharge area of these reservoirs to accommodate current and future operational needs within Corps regulations..

Study Authorization

Public Law 91-611; Title I - River and Harbor Act, Section 216, dated 31 December 1970, 33 USC. § 549a[3], states:

> *"The Secretary of the Army, acting through the Chief of Engineers, is authorized to review the operation of projects the construction of which has been completed and which were constructed by the Corps of Engineers in the interest of navigation, flood control, water supply, and related purposes, when found advisable due to significantly*

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[3] https://planning.erdc.dren.mil/toolbox/library/PL/RHA1970.pdf

changed physical or economic conditions, and to report thereon to Congress with recommendations on the advisability of modifying the structures or their operation, and for improving the quality of the environment in the overall public interest."

Section 216 of the Rivers and Harbors Act of 1970, Public Law 91-611, authorizes the Secretary of the Army to review existing Corps' completed projects due to changes in physical and/or economic conditions. The Corps then reports to Congress with recommendations on the advisability of modifying the project, or how it is operated, and for improving environmental quality in the public interest.

After the initial appraisal, the Section 216 study process is the same as that for normal General Investigations studies.

1.1 Study Purpose and Need

The purpose of this Section 216 study is to identify and analyze comprehensive plans that efficiently and effectively reduce the flood risks that the Buffalo Bayou and its tributaries pose to Harris County and the surrounding areas over the 50-year period of analysis, while simultaneously mitigating dam safety concerns. The need is driven by residual flood risks in the project area that remain following the construction and ongoing operation and maintenance of Addicks and Barker Reservoirs, which are exacerbated by urbanization and increased frequency of large-scale flooding events. While these two flood risk management projects provide a level of protection from frequently occurring flooding events, recent large-scale events have demonstrated that residual risks remain both adjacent to the pools and downstream of the reservoirs.

The most recent example, Hurricane Harvey, made landfall on 25 August 2017 near Rockport, Texas, as a Category 4 hurricane with wind gusts exceeding 150 miles per hour and is the wettest tropical cyclone on record. Harvey's inland stall caused heavy rainfall across Harris and surrounding counties over four-day period from 26 to 29 August with nearly 50 inches total. HCFCD estimates that nearly 70 percent of the county was covered with up to 1.5 feet of water, flooding nearly 136,000 structures. Over those four days, Harris County received 68 percent of its annual rainfall. Pools behind Addicks and Barker reservoirs began rising on 25 August due to rainfall in the upstream watersheds. Reservoir gates were opened on 28 August releasing stormwater into Buffalo Bayou. Pools continued to rise due to the tremendous inflow rates from bayous draining into the reservoir. Pools in both reservoirs were at or near their peaks as of 30 August. This leads to flooding of streets and homes downstream of the reservoirs; when the combined release rate from the reservoirs exceeds approximately 4,000 cubic feet per second (cfs).

Hurricane Harvey Impacts at Addicks and Barker Reservoirs

Addicks Reservoir peaked at a record elevation of 109.10 feet on August 30th surpassing the previous 2016 "Tax Day" Flood record of 103 by 6.5 feet. At maximum pool the reservoir was impounding 217,726 acre feet of water and reached an elevation of 108.0 feet on August 29th

resulting in uncontrolled flow around the end of the north spillway for the first time ever. These elevations are displayed in Figure 1 along with the observed elevation for the “Tax Day” Flood. These events are shown in relation to the current 0.002 AEP event (500-year), based on current effective flows from FEMA and not updated to NOAA Atlas 14, and the current 0.01 AEP event (100-year). Additionally, these events are shown in relation the government-owned land (GOL) at Addicks at the elevation 103 feet which was exceeded by just over six feet. This flow impacted several subdivisions and businesses on either side of Tanner Road from Eldridge Pkwy to Brittmore Park Drive. The pool elevation fell to 108 feet on September 1st sending the flow around the north end spillway. The pool elevation did not exceed the elevation of the south spillway. A maximum inflow of 72,200 cfs entered Addicks Reservoir on the morning of August 28th from Bear, Langham, and South Mayde Creeks including a peak flow of 41,000 cfs from Bear Creek. Harvey exceeded the previous maximum inflows recorded during last year’s Tax Day flood by 31,300 cfs. The flow in Bear Creek alone exceeded the entire combined peak inflow from the 2016 Tax Day flood.

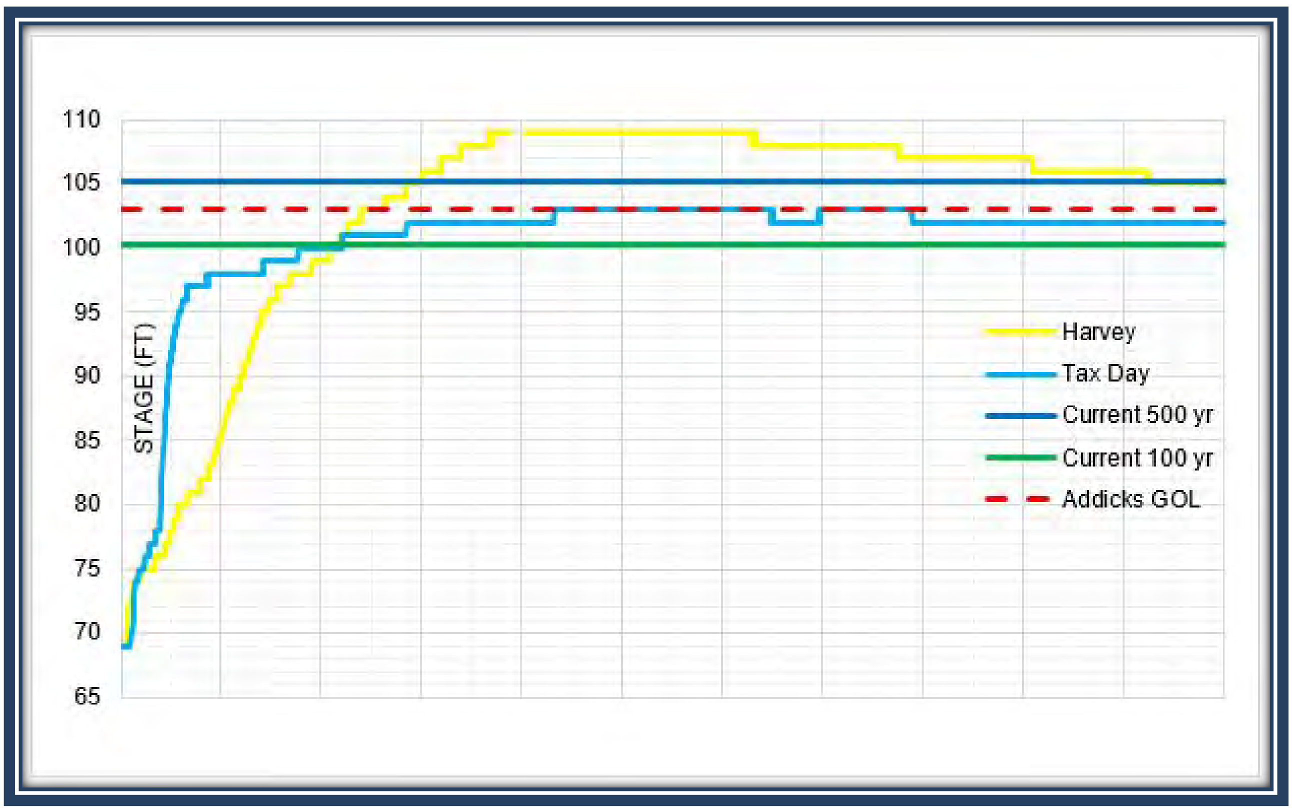

Figure 1. Observed Elevation of Hurricane Harvey at Addicks Dam

Barker Reservoir reached a peak pool elevation of 101.6 feet on August 30th impounding 171,000 acre-feet. Barker Reservoir exceeded its previous record pool of 95 feet during the 2016 Tax Day flood by 6.3 feet. Flows did not go around the north or south spillways. This elevation is displayed in Figure 2 along with the observed elevation for the “Tax Day” Flood just as in the figure for Addicks. These events are shown in relation to the current 0.002 AEP event (500-year) and the current 0.01 AEP event (100-year). Additionally, these events are shown in relation the government-owned land (GOL) at Addicks at the elevation 95 feet which was exceeded by almost seven feet.

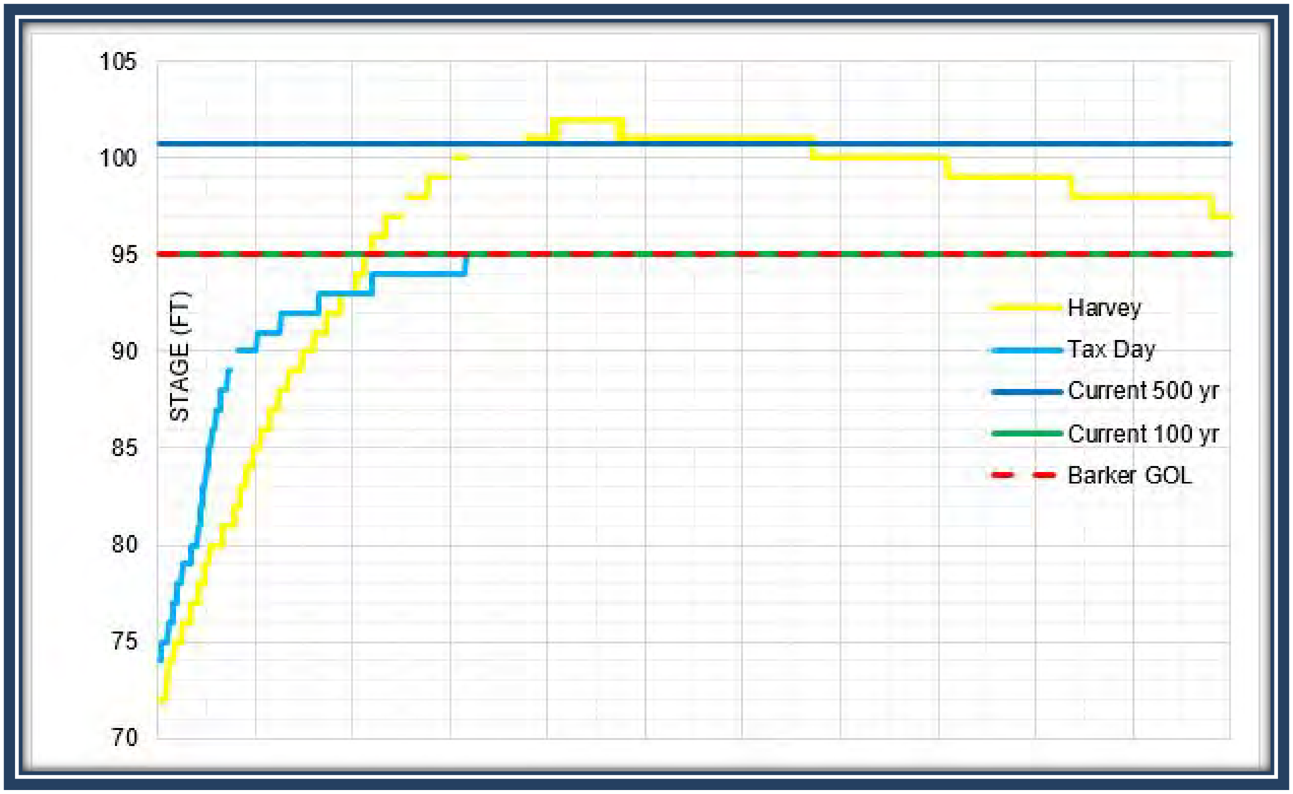

Figure 2. Observed Elevation of Hurricane Harvey at Barker Dam

Both reservoirs combined impounded 388,726 acre-feet of water at peak pool elevations. That is 126 billion gallons of water which is about 2.4 times bigger than the normal storage of Lake Houston and would fill NRG Stadium 187 times. Widespread flooding of homes and streets occurred within the pools upstream of Addicks and Barker Reservoirs as well as flooding of major roadways within the reservoirs. Flooding from the north spillway of Addicks was the first time homes had ever flooded from the pools at either reservoir. Only a few minor rainstorms occurred after Harvey allowing the reservoir water levels to drop below these critical elevations and releases were slowed in a relatively short amount of time. Volumes from Harvey were finally drained from the reservoirs by mid-October 2017.

The table below lists the top five costliest tropical cyclone impacts in US history adjusted for inflation.

Table 1. Top Five Costliest Tropical Cyclone Impacts in US History

Storm	Damage	Year	Category
Katrina	$160,000,000,000	2005	3
Harvey	$125,000,000,000	2017	4
Sandy	$70,200,000,000	2012	1

Irma	$50,000,000,000	2017	4
Andrew	$47,790,000,000	1992	5

Source: HCFCD

The following figures, derived from the HCFCD, depict the two- and four-day peak rainfall frequencies for Harris County during Hurricane Harvey. While areas in the southeastern part of the county saw the most intense rainfall during the event, the area primarily associated with study saw intensities ranging in the 0.0005 to 0.0002 annual exceedance probability (2,000- to 5,000-year event) during the peak two-day period and intensifying to the 0.0002 to 0.00005 AEP (5,000- to 20,000-year event) over the four-day peak rainfall period.

Hurricane Harvey Impacts on Buffalo Bayou

The record flooding that occurred along Buffalo Bayou exceeded previous floods of record from Tax Day 2016, March 1992, and Tropical Storm Allison (2001). Water levels in downtown Houston exceeded the previous record from Tropical Storm Allison by five to seven feet. From downtown west to the 610 West Loop water levels exceeded Allison by two to four feet and the March 1992 flooding by four to six feet. West of the 610 West Loop water levels exceeded the previous record from Tax Day 2016 by five to eight feet. Water levels were generally above the 0.002 (500-yr) annual exceedance probabilities (AEP) from HWY 6 downstream to Farther Point and between the 0.01 (100-yr) and 0.002 AEP downstream of Farther Point to east of downtown Houston.

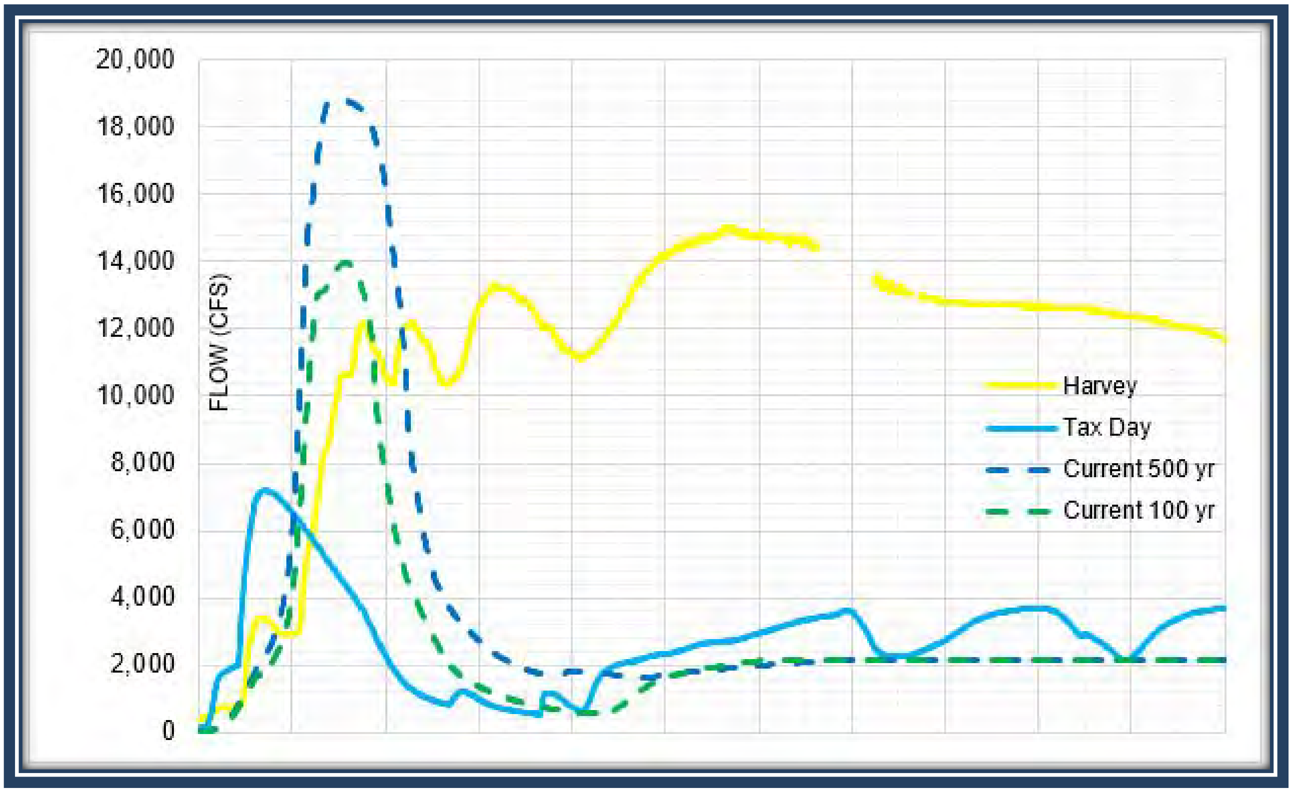

Figure 3. Hurricane Harvey Flow on Buffalo Bayou at Piney Point

Water levels recorded at the Houston Ship Channel Turning Basin were five feet above the 2016 Tax Day flooding, and only three feet lower than levels recorded during Hurricane Ike.

Water level elevations and duration were influenced by emergency releases during the extreme rainfall and the subsequent releases to empty the Addicks and Barker Reservoirs.

Downstream of Barker on Buffalo Bayou, Harvey produced a peak flow at the USGS Piney Point gage of about 12,200 cfs on the 28th. Due to the severity rainfall upstream, a combined 16,000 cfs of water was released based on the reservoirs' Water Control Plan; the highest release rate since the outlets were fully gated in 1963. These flows are depicted in Figure 3 long with the flows for the "Tax Day" flood and the current 0.002 AEP (500-year) and 0.01 AEP (100-year) events.

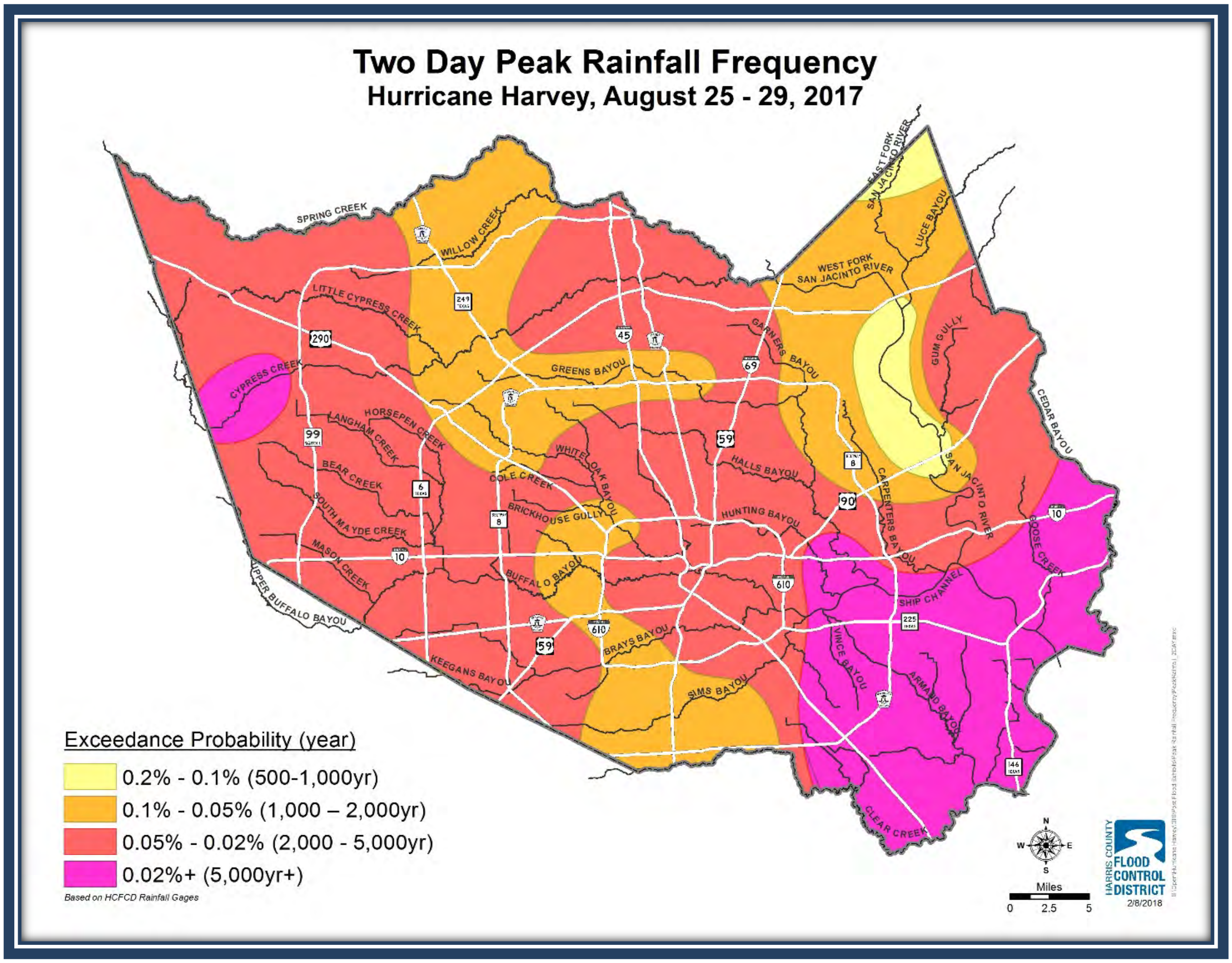

Figure 4. Harvey Two-Day Peak Rainfall Frequency

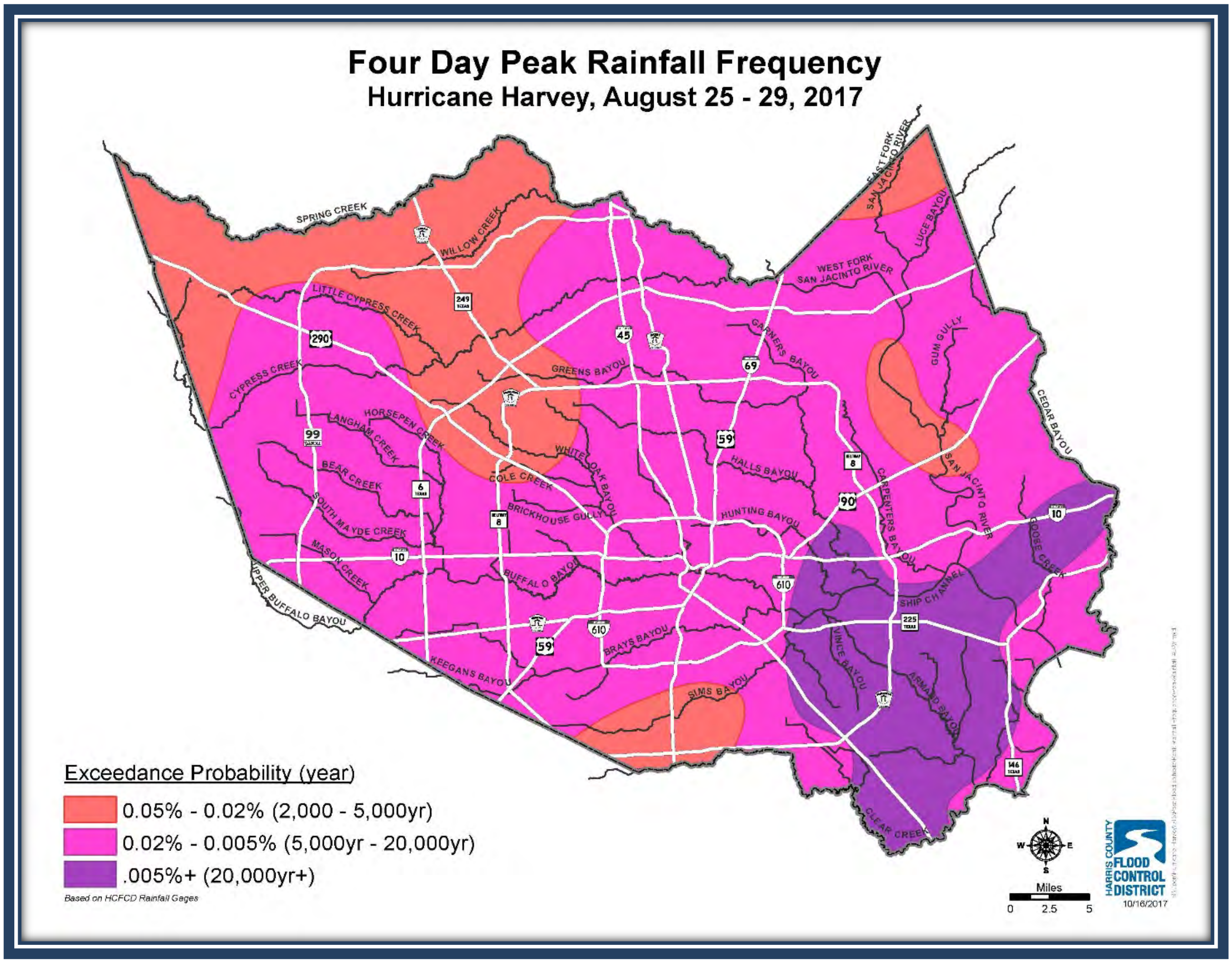

Figure 5. Harvey Four-Day Peak Rainfall Frequency

Addicks and Barker Dam and Reservoirs, both Corps' flood risk-management projects, reduce downstream flood risks for most precipitation events. Recent large-scale events have shown that flood risks remain. Hurricane Harvey in 2017 showed that large-scale events flood structures upstream of both reservoirs, as well as downstream along Buffalo Bayou. Hurricane Harvey was a Category 4 storm and caused heavy rains of up to 50 inches in parts of Harris and surrounding counties over a four-day period.

Harris County Flood Control District estimated that almost 70 percent of the county had up to 1.5 feet of water and flooded almost 136,000 structures. Even with the gates of both Addicks and Barker Dams releasing an amount of water into an already flooded Buffalo Bayou, reservoir levels rose and flooded structures upstream as well.

In 2009 and 2010, a dam safety study was performed that looked at potential failure modes for both Addicks and Barker dams. This dam safety study is a continuation of that study.

Due to land subsidence, the northeast spillway at Addicks Dam is now three feet lower than the southwest spillway, and would allow water to pour quickly over a single spillway. In addition, the concrete covering the spillways at both dams has deteriorated and there is risk that they could fail.

1.2 Federal Interest

Federal interest in water resources development is established by law. Section 1 of the Flood Control Act of 1936 declared flood control to be a proper Federal activity since improvements for flood control purposes are in the interest of the general welfare of the public. The Act also stipulated that for Federal involvement to be justified, "…the benefits to whomsoever they may accrue [must be] in excess of the estimated costs, and the lives and social security of people [must be] otherwise adversely affected."

Approximately 586,000 people live in the six watersheds comprising the study area with approximately 138,000 of those living in the three primary watersheds of Addicks, Barker, and Buffalo Bayou. Expected annual damages for the future without project damages are estimated $192 million with $122 million being within the three watersheds of Addicks, Barker, and Buffalo Bayou. Within the study area is Houston's Energy Corridor; home to corporate and regional offices of area's many energy sector companies and the second-largest employment center in the region. The corridor experienced extensive flooding during Hurricane Harvey. The study area is also the location of the city's Texas Medical Center district, the largest medical center in the world, located in Brays Bayou. The district has over sixty medical institutions including M.D. Anderson Cancer Center, Texas Children's Hospital, the Texas Heart Institute, as well as Baylor College of Medicine and Methodist Hospital.

Two Federal projects are currently under construction within the Brays and White Oak Bayous watersheds. The final authorized reports are listed in Section 1.5. The reports were completed in 2008 (Brays) and 2013 (White Oak) and both projects are expected to be completed in CY 2021.

1.3 Study Area

The Buffalo Bayou watershed is within the San Jacinto River Basin, and lies primarily in Harris and Fort Bent Counties in Southeast Texas. Harris County is located along the Texas Gulf Coast upstream of Galveston Bay (Figure 6).

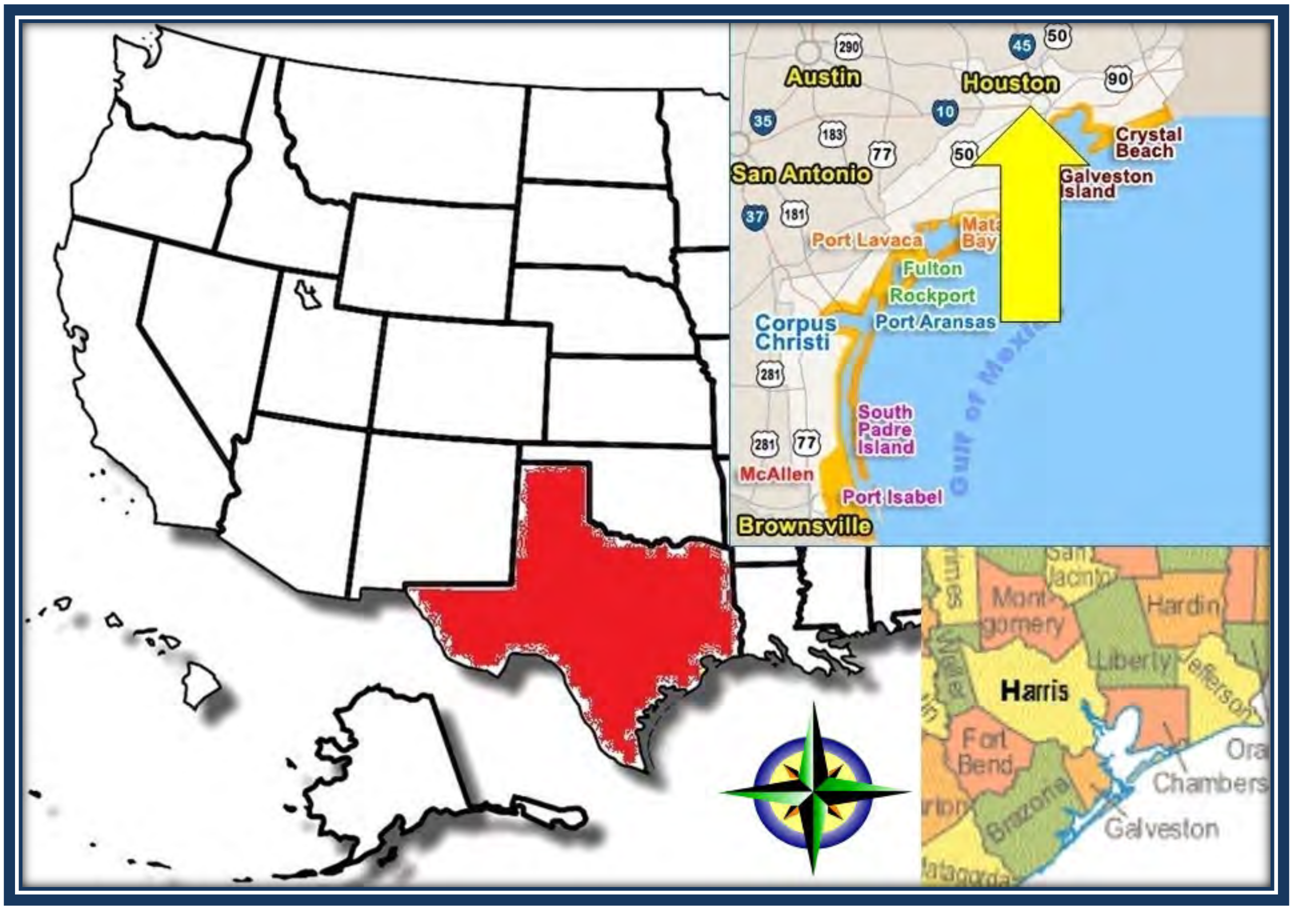

Figure 6. Buffalo Bayou & Tributaries Study Area

1.3.1 Harris County

Harris County was once known as Harrisburg County. The town of Harrisburg was first surveyed and laid out around 1826 and named after John R. Harris. The town of Harrisburg was not officially recognized until after the Texas independence and the first provisional government was formed in 1835. Harrisburg was the temporary capital of Texas from March 17, 1836 until April 14, 1836.

On 22 December 1836, Houston was made the county seat of Harrisburg County. On 28 December 1836, Harrisburg's name was changed to Harris, and the single county was split into four counties: Galveston, Fort Bend, Waller, and Harris.

Waller County is located to the northwest, Montgomery County to the north, Chambers and Liberty counties to the east, Fort Bend to the southwest, and Brazoria and Galveston counties to the south (Figure 6).

There are 1,778 square miles in Harris County and an estimated 4,713,325 people as of 1 July 2019[4], and about 2,400 people per square mile. The county slopes from sea level at Galveston Bay to a little over 200 feet above sea mean level, at the border with Montgomery County.

Barker Dam is located on Buffalo Bayou, and Addicks Dam is located on South Mayde Creek, a tributary of Buffalo Bayou. Both dams are located on the northwestern boundaries of the city limits of Houston, TX (Figure 7)

According to the 2010 Census, the population of Harris County was 4,092,459 or 16 percent of Texas' total population. Harris County is the most populous county in Texas and the third most populous county in the United States. The county seat is Houston and is the main city of the Greater Houston metropolitan area with a population estimated at 2.3 million. Greater Houston contains Houston, The Woodlands, and Sugar Land spread out over nine counties. Greater Houston is the fifth populous metropolitan area in the United States and the second largest in Texas with an estimated 2018 population 6,997,384. For this study, the term "Houston" will refer to the county seat.

Addicks and Barker Dams and Reservoirs

The Buffalo Bayou and Tributaries Resiliency Study is evaluating these six watersheds:

Upper Cypress Creek – 267 square miles

White Oak Bayou – 111 square miles

Brays Bayou – 127 square miles

Addicks Reservoir – 138 square miles

Barker Reservoir – 126 square miles

Buffalo Bayou – 102 square miles

The six watersheds are included in the modeling and technical analyses of flooding, but the primary scope of the Buffalo Bayou and Tributaries Resiliency Study is to reduce flood risk within the Addicks, Barker, and Buffalo Bayou watersheds (Figure 7).

The Corps is the regulating agency for Addicks and Barker Reservoirs. The Addicks and Barker Reservoirs are part of the Buffalo Bayou and Tributaries, Texas flood risk-management system located on the west side of Houston, Texas. Addicks and Barker Dams were completed in the mid-1940s. These reservoirs provide flood risk-management benefits for the City of Houston, and for the Port of Houston and the Houston Ship Channel, which is formed from the lower end

[4] https://www.census.gov/quickfacts/fact/table/harriscountytexas/PST045219

of Buffalo Bayou. Over 4 million people live and work in and transit through the Buffalo Bayou watershed. Industrial, commercial, and residential development is located throughout the Buffalo Bayou corridor. In addition to commercial and residential structures, this development includes hospitals, highways, roads and utilities, oil industry infrastructure, and water and sewerage treatment facilities.

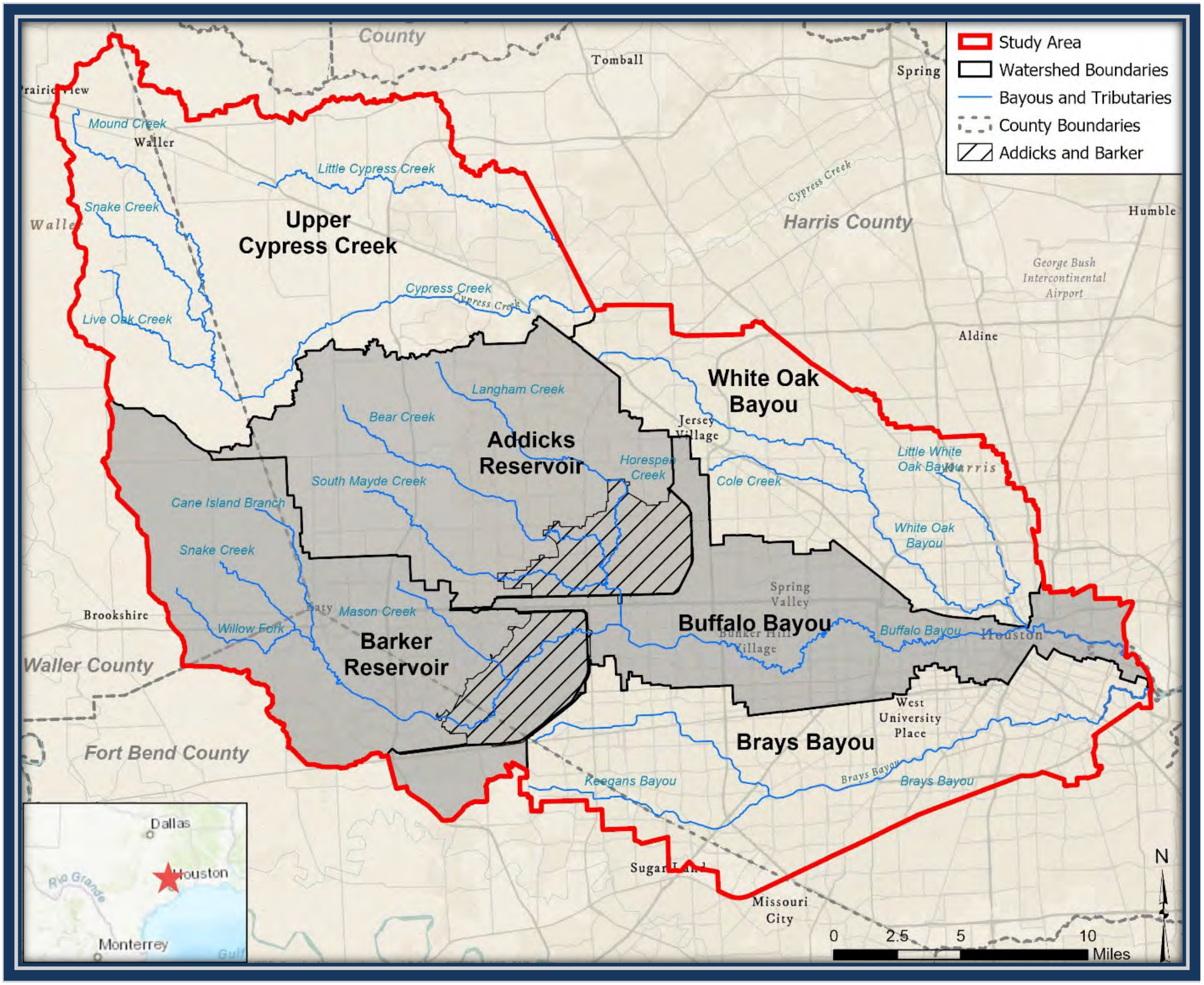

Figure 7. Addicks and Barker Reservoirs and Buffalo Bayou, Texas Study Area Map

Addicks and Barker Reservoirs were originally designed and constructed to reduce the peaks of flood hydrographs by extending the duration flow. Outlet gates were added incrementally, and the reservoirs were fully gated by the 1960s.

The Addicks Reservoir project features include an earthen dam, concrete outlet works, and uncontrolled auxiliary spillways. The earthen dam consists of a random fill embankment that is 61,166 feet long and 48.5 feet above the original streambed. Both ends of the dam are armored with roller compacted concrete that serve as uncontrolled auxiliary spillways. Existing ground at the north end of Addicks Dam is at elevation 108 feet above mean sea level and ties into the auxiliary spillway crest at 112.5 feet. The existing ground at the south end is at elevation 111.0 feet and ties into the auxiliary spillway crest at 115.5 feet.

The Barker Dam and Reservoir project features include an earthen dam, concrete outlet works, and uncontrolled auxiliary spillways. The earthen dam consists of a random fill embankment that is 71,900 feet long with a maximum height of 42.9 feet at the outlet works. Both ends of the dam are armored with roller-compacted concrete that serve as uncontrolled auxiliary spillways. Existing ground at both ends of Barker Dam is at elevation 104.0 feet. The auxiliary spillway crest at the north end is at elevation 105.5 feet and the south end is at 106.7 feet.

The Hydrology and Hydraulics/Water Management Branch in the Galveston District Office is responsible for determining pool limits, setting water control standards and objectives, making hydrologic forecasts, and coordinating overall water management operations (Appendix A – Hydrology, Hydraulics, and Climate, Section 1.5.3).

What Has Changed Since The Dams Were Built?

In the 1940s and 1950s, agricultural land made up a much larger percentage of the study area (Figure 8). Population centers were concentrated into fewer, separated towns with open spaces in between. The population for Harris County was 528,961 in 1940 and 802,102 in 1950[5]. When floods came, most of the land under water was fields or pastures, with many fewer structures damaged when compared to today.

Because the population in Harris County has multiplied by almost 9 times since the 1940 census to approximately 4.7 million (Table 4), the number of structures (houses, apartments, mobile homes, schools, churches, hospitals, doctor’s offices, government buildings, retail stores, distribution centers, restaurants, bridges, interstates, surface roads, etc.) within the floodplain has also increased (Figure 9). Depending upon location, and the size of the flood event, many of these structures and building contents, are damaged when floods occur.

Hurricane Harvey was a near probable maximum precipitation (PMP) event exceeding all previous PMP estimates at several locations in southeast Texas. The original PMP estimates for Addicks and Barker Dams were developed using Hydrometeorology Report 51 (HMR 51), “Probable Maximum Precipitation Estimates, United States East of the 105th Meridian”, dated 1978. As a result of Harvey, reevaluating the PMP estimates for Addicks and Barker Dams was appropriate based on the expected change in conditions. A study was conducted to determine whether the general HMR 51 PMP estimates were still indicative of the critical potential for catastrophic rainfall using multiple storms that occurred between 1973 and 2018. While precipitation totals from Hurricane Harvey exceeded previous HMR 51 estimates for durations longer than 48 hours and areas greater than 1,000 square miles, areas and durations less than

[5] https://www2.census.gov/library/publications/decennial/1950/pc-02/pc-2-43.pdf

these, were not exceeded. Since the Addicks and Barker watersheds are less than 200 square miles, the general HMR 51, 72-hour PMP estimate of 48.8 inches are appropriate.

Subsidence has occurred along the dams and at the outlet works since construction. A new outlet structure at Barker Dam was put into operation on 14 February, 2020 as well as a new outlet structure at Addicks Dam on 24 March, 2020. The old outlet structures had a combined maximum design discharge of 16,630 cubic feet per second (CFS). Discharge for the new outlet structures will not exceed the previous maximum discharge.

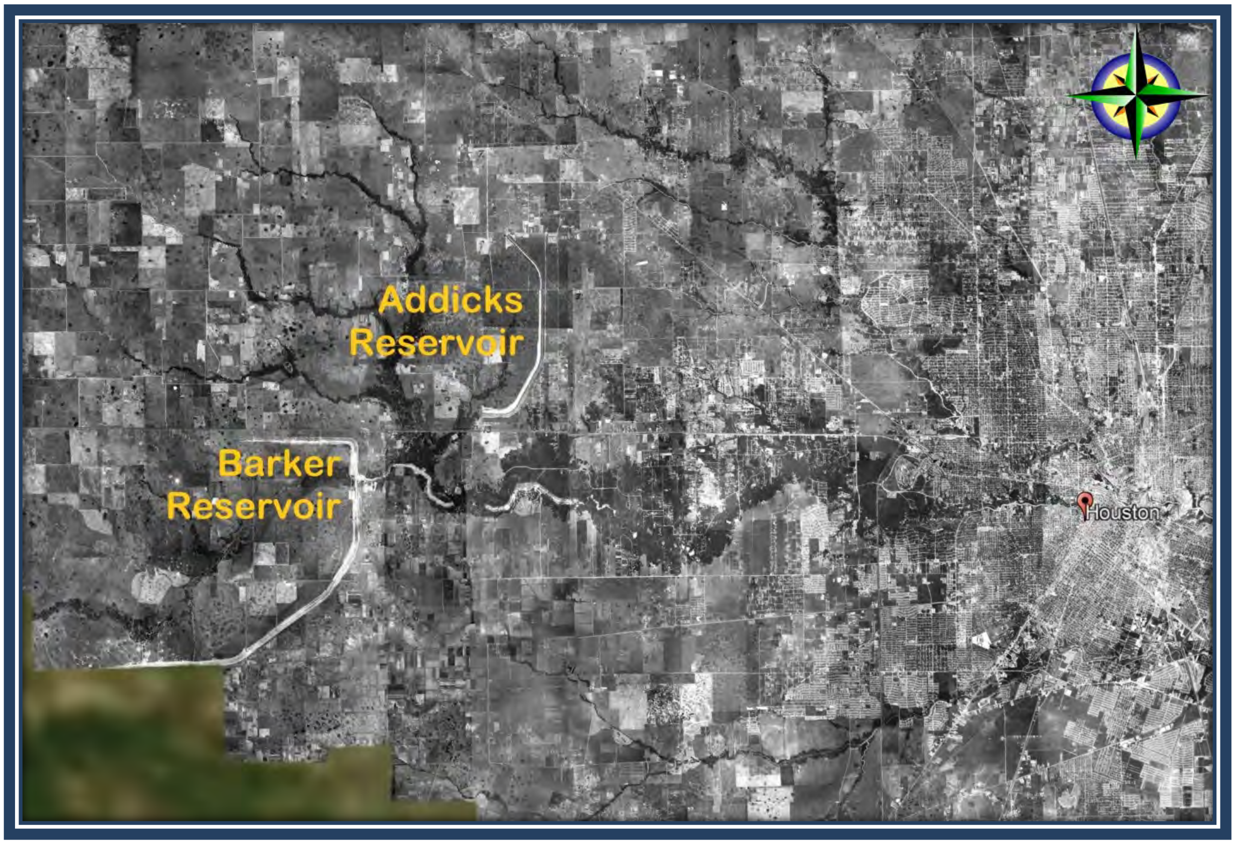

Figure 8. Study Area in 1953 (Google Earth Image)

Figure 9. Study Area in 2020 (Google Earth Image)

1.3.2 Non-Federal Sponsors

Harris County Flood Control District, Texas[6]

1.3.3 Congressional Representatives

Representatives to Congress from the Study Area/Project Area are:

Texas State Senator John Cornyn

Texas State Senator Ted Cruz

Texas State Representative, 2nd District, Dan Crenshaw

Texas State Representative, 7th District, Lizzie Fletcher

Texas State Representative, 9th District, Al Green

[6] https://www.Harris County Flood Control District.org/

Texas State Representative, 10th District, Michael McCaul

Texas State Representative, 18th District, Sheila Jackson Lee

Texas State Representative, 29th District, Sylvia Garcia

Texas State Representative, 36th District, Brian Babin

1.4 Problem Statement

The PDT developed brief problem statements and planning objectives that were used to guide the identification and evaluation of potential solutions. Hurricane Harvey presented an enormous challenge for the region. It also demonstrated the need to address the changed conditions around the two dams and downstream Buffalo Bayou. The storm produced record rainfall amounts that accumulated in Addicks and Barker reservoirs resulting in record pool elevations. Flood waters from Harvey flooded homes upstream and put extreme pressure on the two dams; and controlled releases contributed to downstream flows that exceeded the carrying capacity of Buffalo Bayou. This flood event illustrates problems in three categories – upstream risks when inflows exceed reservoir capacity, dam safety risks if a dam component were to fail during a flood, and downstream risks when flows exceed channel capacity. The PDT formulated, compared and evaluated alternatives to address these problems in this study and can be found in more detail throughout Chapter 4.

1.5 Prior Studies and Reports

The PDT utilized prior studies and reports in formulation of the existing conditions, which are discussed in further detail in Chapter 2. Some of these reports for Buffalo Bayou and Tributaries, Texas, include:

US Army Corps of Engineers. 1940. *Definite Project Report; Buffalo Bayou, Texas*[7]. Galveston District.

US Army Corps of Engineers. 1978. *Brays Bayou and Tributaries, Texas, Addicks and Barker Dams, Letter Report for Spillways*. Galveston District.

US Army Corps of Engineers. 1984. *Buffalo Bayou and Tributaries, Texas, Addicks and Barker Dams, Dam Safety Assurance General Design Memorandum*. Galveston District.

[7] https://riparianhouston.com/2017/10/09/the-1940-definite-plan/

US Army Corps of Engineers. 1995. *Buffalo Bayou and Tributaries, Texas, Reconnaissance Report, Section 216 Study Addicks and Barker Reservoirs, Houston, Texas*. Galveston District.

Costello, Inc. 2000. *Feasibility Study for Improvements to Addicks and Barker Reservoirs.*

US Army Corps of Engineers. 2008. *Brays Bayou Federal Flood Control Project, Harris County, Texas, Alternative to the Diversion Separable Element, General Reevaluation Report and Environmental Assessment*. Galveston District.

US Army Corps of Engineers. 2012. *Water Control Manual: Addicks and Barker, Buffalo Bayou and Tributaries, Jan Jacinto River Basin, TX*. Galveston District.

US Army Corps of Engineers. 2013. *Addicks and Barker Dam Safety Modification Report, Buffalo Bayou & Tributaries, Houston, Texas*. Galveston District.

US Army Corps of Engineers. 2013. *White Oak Bayou Federal Flood Control Project, Harris County, Texas, General Reevaluation Report and Environmental Assessment*. Galveston District.

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2 Existing Conditions

The second step of plan formulation, and the starting point in any the Corps' analysis, is to develop an accurate picture of the existing conditions (Chapter 2) and future-without-project conditions (Chapter 3). Existing conditions are defined as conditions that currently exist in the study area. The term baseline is also often used occasionally throughout the report to refer to existing conditions at the time of a measurement, observation, or calculation. Existing conditions are described both quantitatively and qualitatively.

Resources discussed include:

1. Hydrology, hydraulics, and climate,
2. Economics,
3. Environmental resources (affected environment),
4. Cultural resources,
5. Environmental engineering,
6. Geology and structural setting,
7. Real estate; and,
8. Socioeconomics.

Additional detail regarding each resource is available in relevant appendices and the Environmental Impact Statement.

2.1 Hydrology, Hydraulics, and Climate

2.1.1 Hydrology

Hydrology involves determining how much water there is, where water is found, how water moves, and the properties of water. Hydrology studies water's relationship with the environment during the hydrologic cycle: the continuous process of water being purified by evaporation, transported from the earth's surface into the atmosphere (transpiration), and then water returning to the land and oceans (precipitation as rain, sleet, hail, or snow). It also includes studying how water on the earth's surface moves into the ground (infiltration) and how it moves vertically and horizontally while underground. For the purpose of the Buffalo Bayou and Tributaries Resiliency study, hydrology focuses on precipitation (where and when does it fall, and how much), and then how the water moves once it is on the ground.[8]

TERMINOLOGY

Many people are familiar with how the Federal Emergency Management Agency (FEMA) names different flood events, with the most familiar event being the 100-year flood. Instead of using the

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[8] For more information see: https://www.usgs.gov/special-topic/water-science-school/science/what-hydrology

term “100-year event”, hydrologists describe this as having a 1 percent chance of happening in any given year, or as having a 0.01 Annual Exceedance Probability (AEP). AEP for a particular location (usually a gaging station) is the probability of water flows being equaled or exceeded during any given year. Therefore, an AEP of 0.01 means there is a 1 percent (AEP ×100) chance that a specific high-water flow will in a given year. The term AEP also refers to different intervals ranging from a 2-year (0.5 AEP) event to a 1,000-year event (0.001 AEP). Table 2 shows common ranges of AEP designation.

Table 2. Flood Event Terminology for Various Precipitation Events

FEMA Year Event	2	5	10	25	50	100	250	500	1,000
AEP	0.5	0.2	0.1	0.04	0.02	0.01	0.004	0.002	0.001

THE ADDICKS WATERSHED

The Addicks Watershed has four streams: Bear Creek, Horsepen Creek, Langham Creek, and South Mayde Creek (Figure 10). During certain flood events, water will overflow into the Addicks Watershed from the Upper Cypress Creek Watershed (Figure 7). Drainage from the four tributaries, and sometimes from Upper Cypress Creek, gathers in the Addicks Reservoir and empties into Buffalo Bayou. The upper Addicks Watershed has historically been agricultural land with most of the residential and commercial development mainly around the Addicks Reservoir. Given the high density of development immediately upstream of the reservoir, immediately downstream of the spillways, and along Buffalo Bayou, water management operations of the Addicks Reservoir is a difficult process.

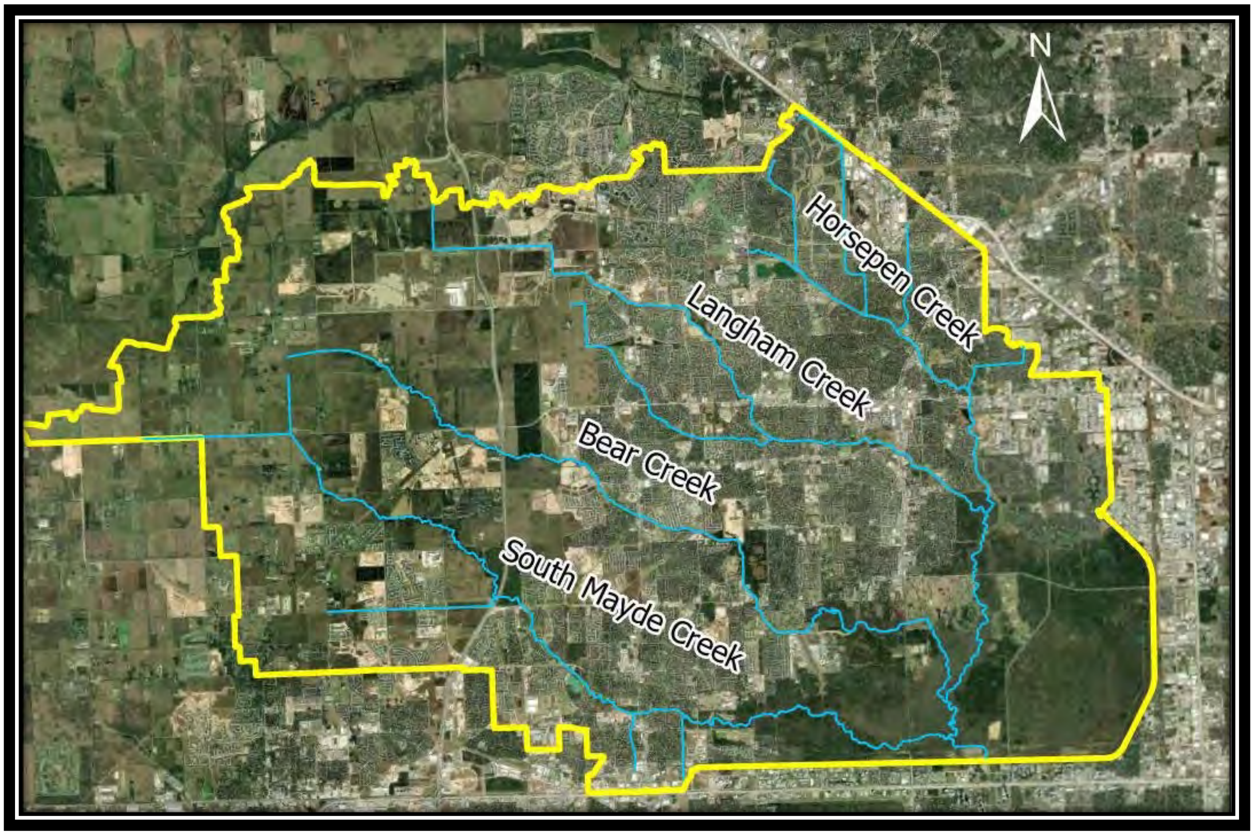

Figure 10. Addicks Watershed Map with Outline and Creeks

THE BARKER WATERSHED

The Barker Watershed has two primary streams: Mason Creek and Upper Buffalo Bayou (Figure 11). T. Upstream portions of the watershed are in the eastern corners of Waller and Fort Bend counties. Drainage from the Barker Watershed flows into Barker Reservoir, which then empties into to Buffalo Bayou. Similar to the Addicks Watershed, upper portions of the watershed are primarily agricultural with most of residential and commercial development concentrated around the reservoir. Given the high density of development immediately upstream of the reservoir, immediately downstream of the spillways, and along Buffalo Bayou, water management operations of Barker Reservoir is also a difficult process.

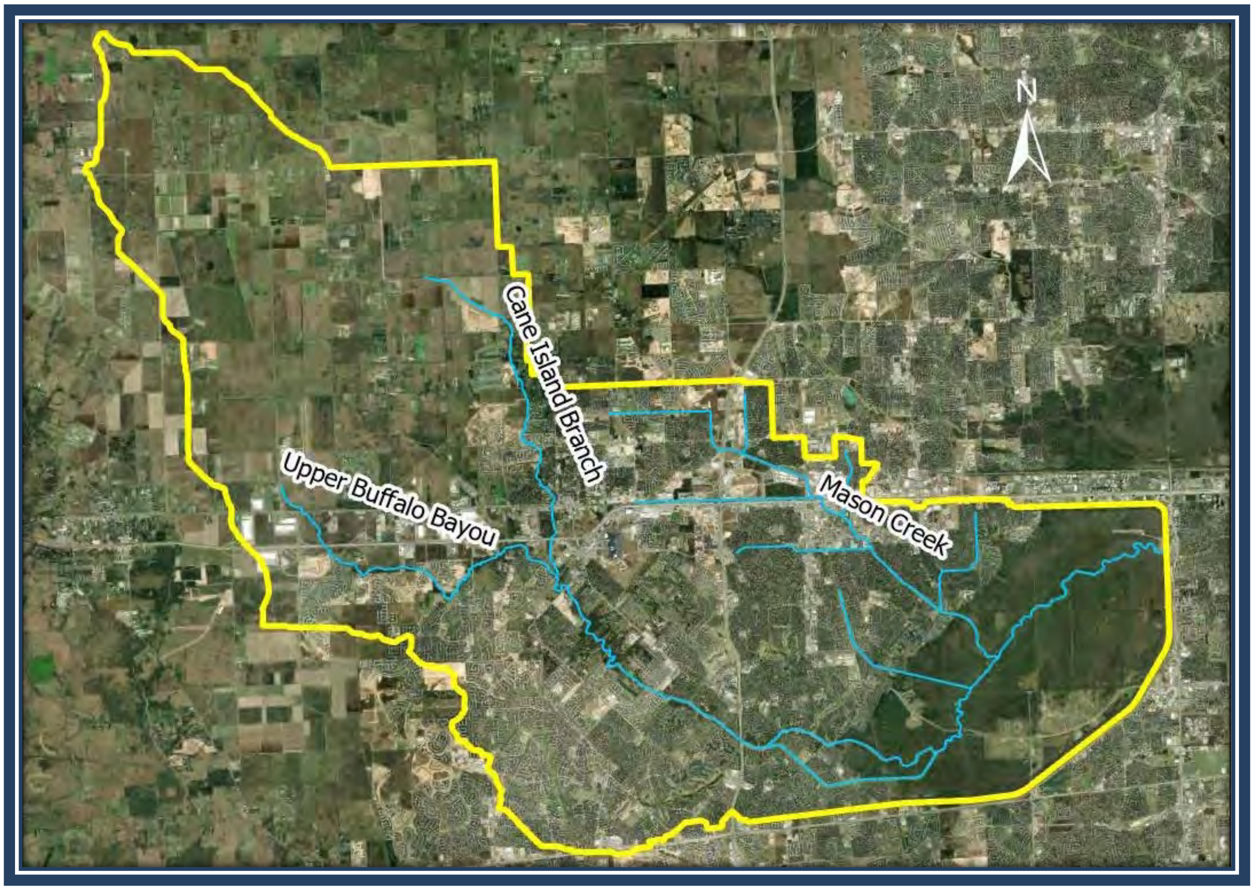

Figure 11. Barker Watershed Map with Outline and Waterways

THE BUFFALO BAYOU WATERSHED

The Buffalo Bayou watershed (Figure 7 and Figure 12) is mainly located in west-central Harris County with a small portion crossing into Fort Bend County. Rainfall within the 102 square miles of the Buffalo Bayou watershed drains into the watershed's primary waterway, Buffalo Bayou. Buffalo Bayou travels through heavily wooded residential areas, and much of the bayou remains in a natural state. Near downtown Houston, White Oak Bayou flows into Buffalo Bayou.[9] Just east of downtown Houston near the Turning Basin, Buffalo Bayou becomes the Houston Ship Channel. There are 106 miles of open waterways in the Buffalo Bayou watershed, including Buffalo Bayou and its major tributaries such as Rummel Creek, Soldiers Creek, Spring Branch, and Turkey Creek.

[9] https://www.Harris County Flood Control District.org/Find-Your-Watershed/Buffalo-Bayou

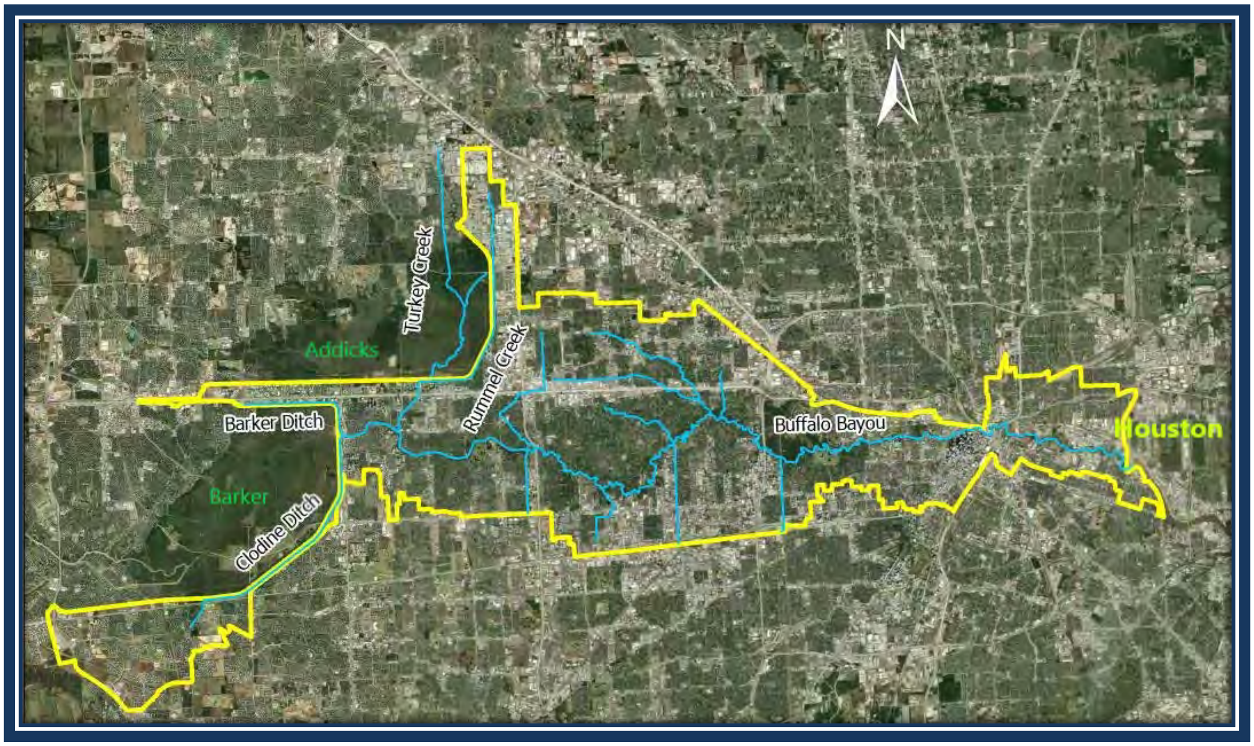

Figure 12. Buffalo Bayou Watershed

2.1.2 Hydraulics

Hydraulics is a branch of science that deals with practical applications such as the transmission of energy, or the effects of flow of liquid (such as water) in motion.[10] Hydraulic engineers in this study looked at the flow of water under different events in the study area (Figure 6) and how it affects, or is affected by dams and levees, stream volumes and paths, tunnels and diversions, how much vegetation or other obstructions are inside the channel, bridges and culverts etc. Collected data was used in models that estimate likely scenarios of what the water will do, where it will go, how fast it will flow, and how deep it will be for different precipitation events.

INLAND FLOODPLAIN MAPPING

Figure 13 through Figure 16 display maps for Addicks Dam and Reservoir watershed, Barker Dam and Reservoir Watershed, and Buffalo Bayou from Barker Dam to the periphery of downtown Houston. These figures represent inundation patterns for various events under existing conditions. Maps show where the water will go after four different AEP events: 0.1, 0.02, 0.01, and 0.002 AEP (10-year, 50-year, 100-year, and 500-year events) based on current topography and land use. Maps show the distribution of flows but not depths.

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[10] https://www.merriam-webster.com/dictionary/hydraulics

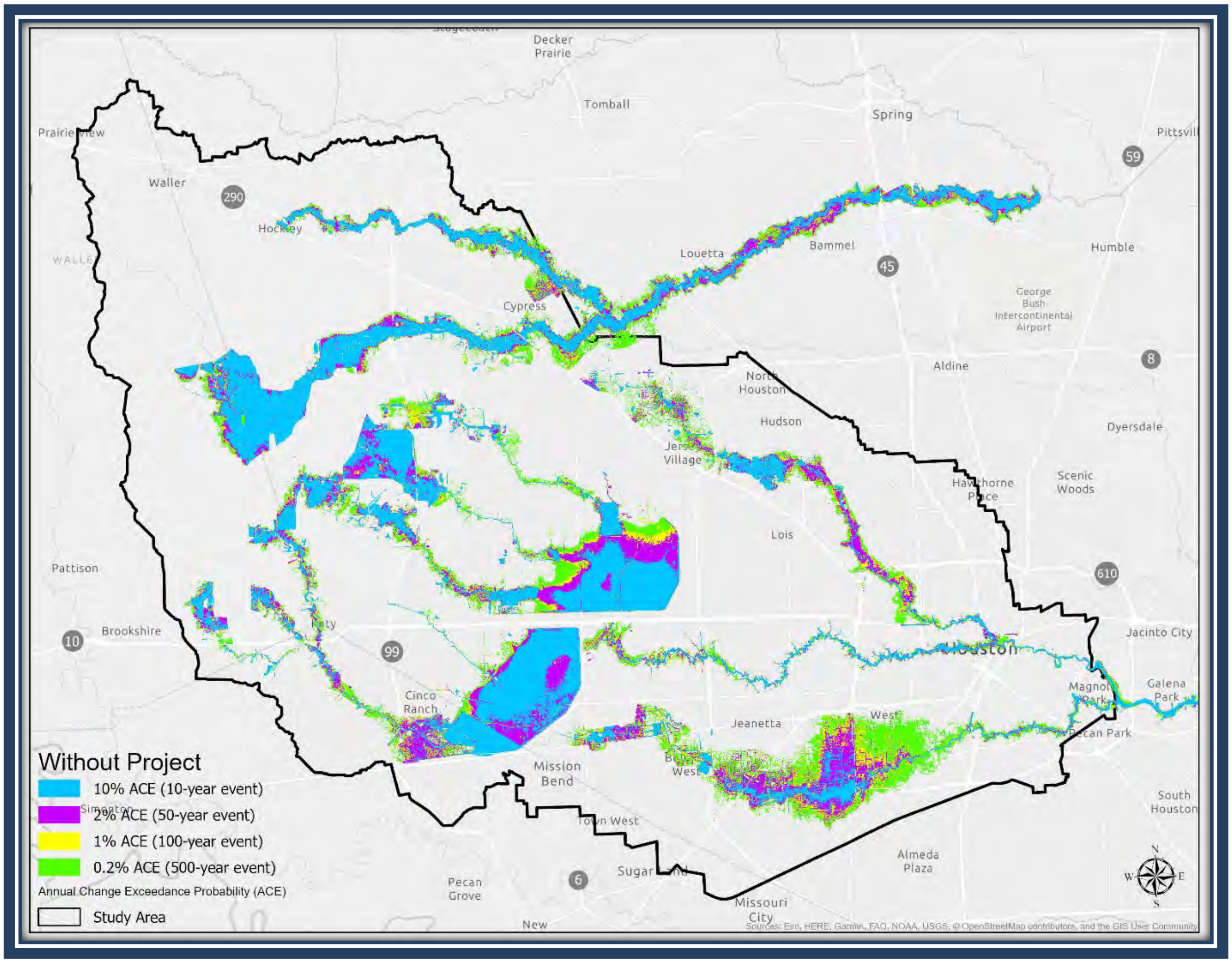

Figure 13. Study Area 2 Map Showing the 2020 0.1, 0.02, 0.01, and 0.002 AEP

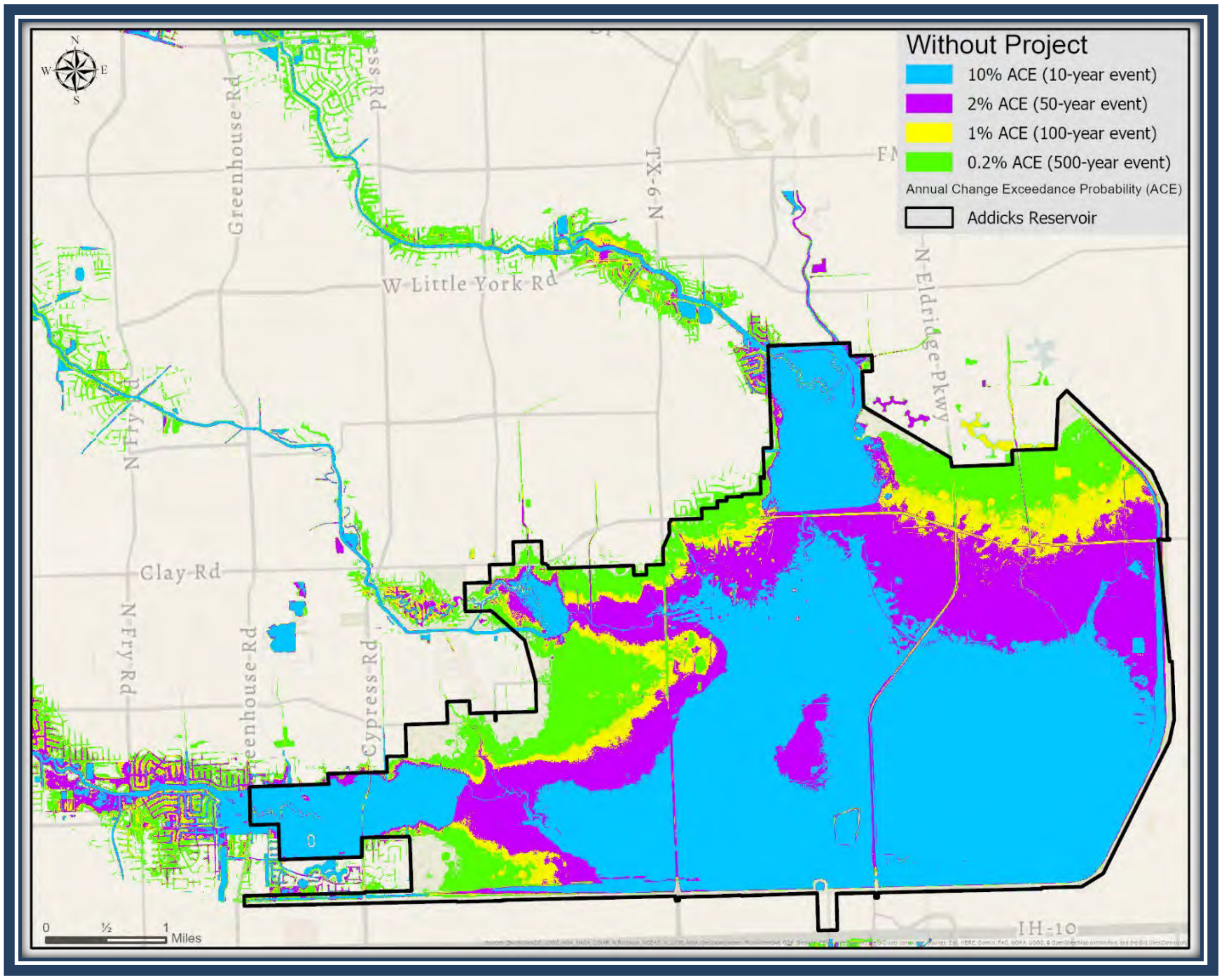

Figure 14. Addicks Dam and Reservoir Map Showing the 2020 0.1, 0.02, 0.01, and 0.002 AEP

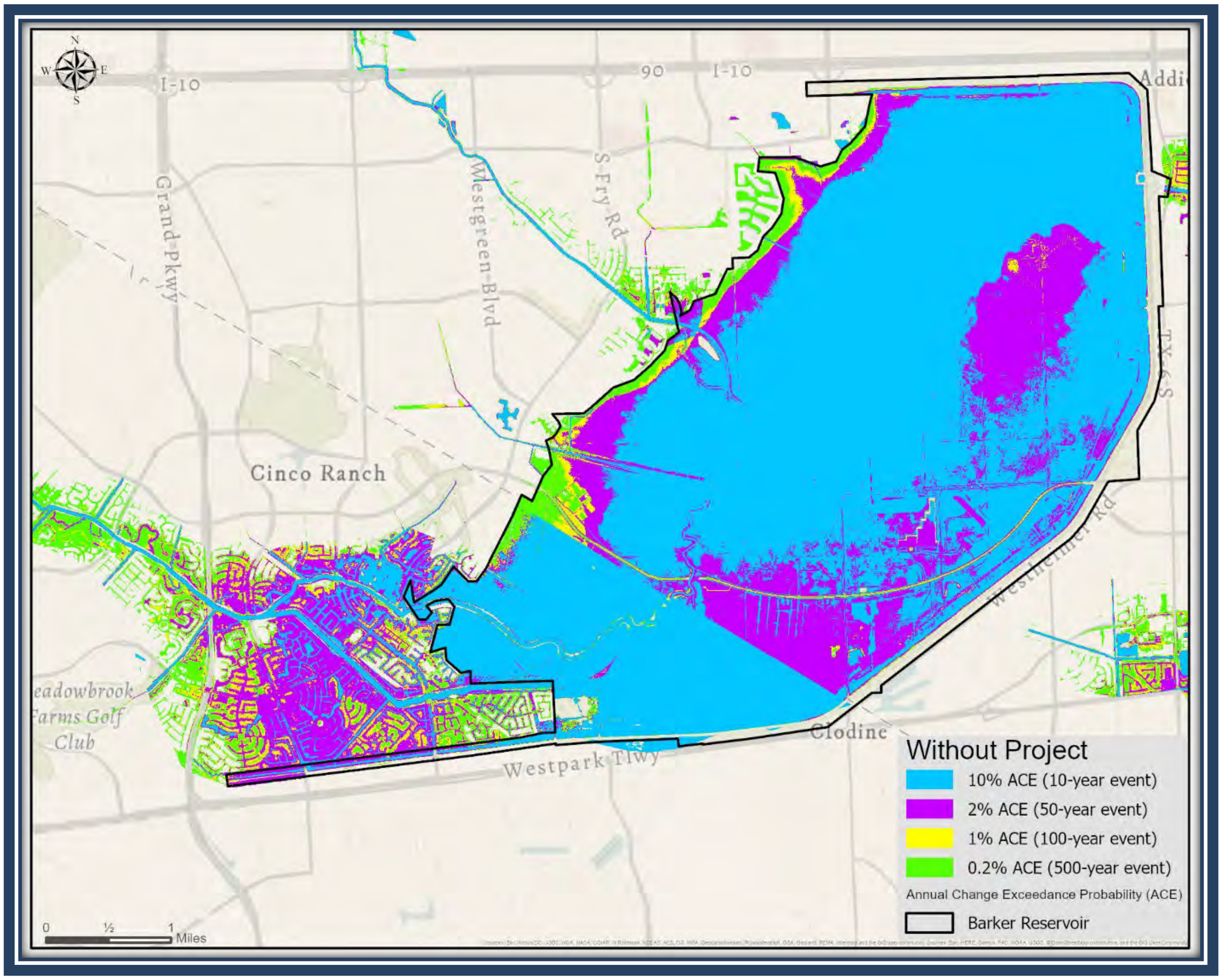

Figure 15. Barker Dam and Reservoir Map Showing the 2020 0.1, 0.02, 0.01, and 0.002 AEP

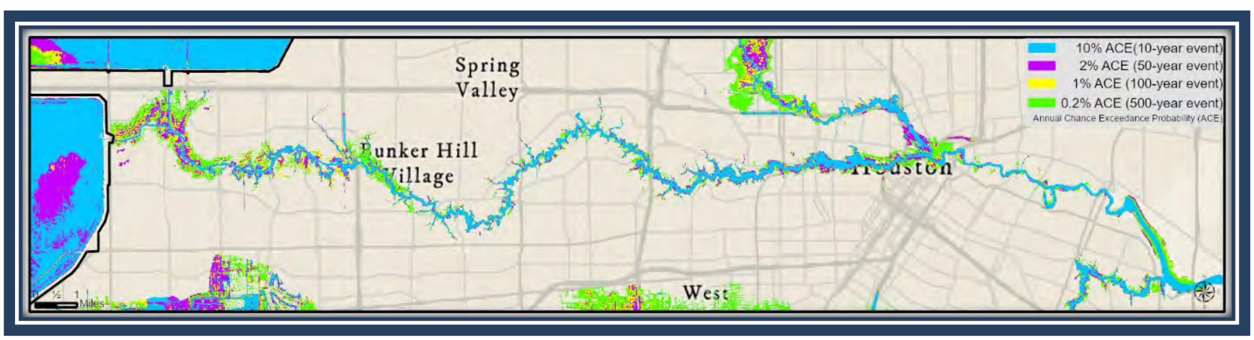

Figure 16. Buffalo Bayou Map Showing the 2020 0.1, 0.02, 0.01, and 0.002 AEP

TIDES AND MEAN HIGHER HIGH WATER

Buffalo Bayou, like most of the main streams White Oak and Brays, is tidal through the city of Houston, meaning that at very high tides the flow can stop and even reverse. Buffalo Bayou is considered tidal to about 440 yards west of the Shepherd Drive Bridge. Today, the Mean Higher High Water (tide), which is the 19-year average calculated by the National Ocean Service (NOS), in Buffalo Bayou reaches just past the Eastex Freeway (U.S Highway 59). This is shown in Figure 17.

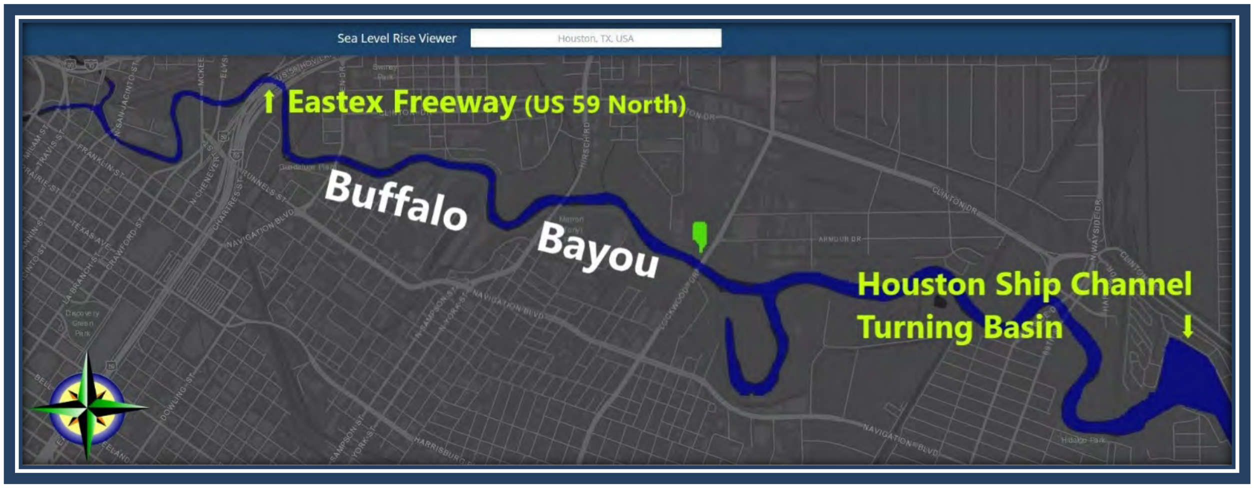

Figure 17. Buffalo Bayou Map Showing the 2020 High Tide[11]

2.1.3 Climate

The average annual high temperature for the Houston area is 78 degrees Fahrenheit (F) and the average annual low temperature is 60 degrees F. The warmest months are usually July (92 degrees) and August (93 degrees), and the coolest months are December (45 degrees) and January (44 degrees).[12]

2.1.3.1 Precipitation

Average annual precipitation for the Houston area is 45.3 inches. The wettest months are usually May (4.5 inches) and July (5.2 inches), and the driest are February (3.2 inches) and March (2.4 inches). Annual precipitation is usually well distributed throughout the year; however, the area can be affected by torrential rainfall associated with hurricanes and other tropical storms.

In 2018, the National Oceanic and Atmospheric Administration (NOAA) published the most recent precipitation-frequency atlas for Texas titled *Atlas 14 Volume 11 Version 2* (Atlas 14).[13] This document supersedes previous reports and for the Houston area it incorporates rainfall data from the 1930s through the 1940s to Hurricane Harvey in late 2017. Table 3 compares

[11] https://coast.noaa.gov/slr/#/layer/slr/0/-10613161.392868461/3472795.867956687/15/streets/none/0.8/2050/interHigh/midAccretion

[12] https://www.usclimatedata.com/climate/houston/texas/united-states/ustx0617

[13] https://www.noaa.gov/media-release/noaa-updates-texas-rainfall-frequency-values

2018 precipitation-frequencies to frequencies from the 1960s and 1970s. According to Atlas 14: "The new values are more accurate than estimates developed 40 to 50 years ago due to decades of additional rainfall data, an increase in the amount of available data, both in the number of stations and their record lengths, and improved methods used in the analysis." For example, for a 12 hour 25-year event, the old atlas estimated 7.4 inches of precipitation. In contrast, Atlas 14 estimates 9.43 inches of precipitation for the same event.

Table 3. Atlas 14 Precipitation-Frequency Compared to Old Version

	Average Recurrence Interval (yrs)													
Duration	2		10		25		50		100		500		1000	
	Old	New	Old	New	Old	New	Old	New	Old	New	Old	New	Old	New
12-hrs	3.4	4.3	5.9	7.2	7.4	9.4	8.7	11.4	10.2	13.7	14.7	20.6	16.8	24.1
24-hrs	4.1	5.0	7.1	8.5	9.0	11.2	10.6	13.7	12.4	16.6	17.7	24.5	20.2	28.5
2-days	4.7	5.8	8.1	10.0	10.8	13.3	12.5	16.5	14.0	20.0	20.0	28.2	23.6	31.8
3-days	5.0	6.3	8.7	10.9	11.5	14.5	13.3	17.9	15.0	21.6	21.5	29.8	25.6	33.3

2.2 Economy

Most land along Buffalo Bayou is developed with both residential and commercial areas along with dozens of schools, churches, hospitals, water treatment facilities, police and fire departments, international consulates, and public parks. There are also large concentrations of industrial facilities downstream of both Addicks and Barker, many of which are suppliers to regional petrochemical refineries. According to the Bureau of Economic Analysis, real gross domestic product (GDP) of the Greater Houston Metropolitan Statistical Area (MSA) is nearly $500 billion (29 percent of Texas GDP and seventh largest Metropolitan Statistical Area in the US). Based on GDP, the economy of the Houston MSA area is approximately the same size as the nation of Sweden and has an economy bigger than 36 states. Harris County has an annual payroll of $130 billion with over 2 million paid workers. Trade and transportation are the largest sector by payroll in Harris County. Other key regional industries include Education and Health Services and Government.

2.3 Environmental Resources – Affected Environment

The Houston Metropolitan Area is a highly urbanized area and the natural environment has been altered significantly over the years. Natural resources in the study area are limited to a few undeveloped areas near main water channels, tributaries, parks, and the Addicks and Barker reservoirs. Addicks and Barker are the largest natural environments, both of which support thousands of acres of productive wetland/bottomland and upland communities. Open, grassland environments adjacent to the reservoirs provide habitat for the largest population of Texas Prairie Dawn Flower, a Federally-listed Endangered species.

The undeveloped areas along Buffalo Bayou provide habitat for a variety of land and aquatic species including the largest known breeding population of Alligator Snapping Turtles (State Listed Threatened) in Texas and possibly the US. Bayous without artificial bottoms provide better physical stream habitat quality, when compared to other urban stream areas, resulting in suitable stopover habitat for migratory birds, a resource of increasing national importance.

In the far west part of the study area, more space that is open exists; however, modifications to the natural resources have occurred through agriculture (Figure 18). Despite agricultural modifications, the land still has the characteristic features of historic Katy Prairie. This Katy Prairie is the last of the historic coastal prairie that once sprawled throughout the study area to the coast. The Katy Prairie Conservancy, a non-profit organization, has established conservation lands to protect this remaining area, most of which is at or near the headwaters of Cypress Creek. As a result, this constrains siting measures that are located along these bayous, the naturalized tributaries that drain into them, and in the Katy Prairie area.

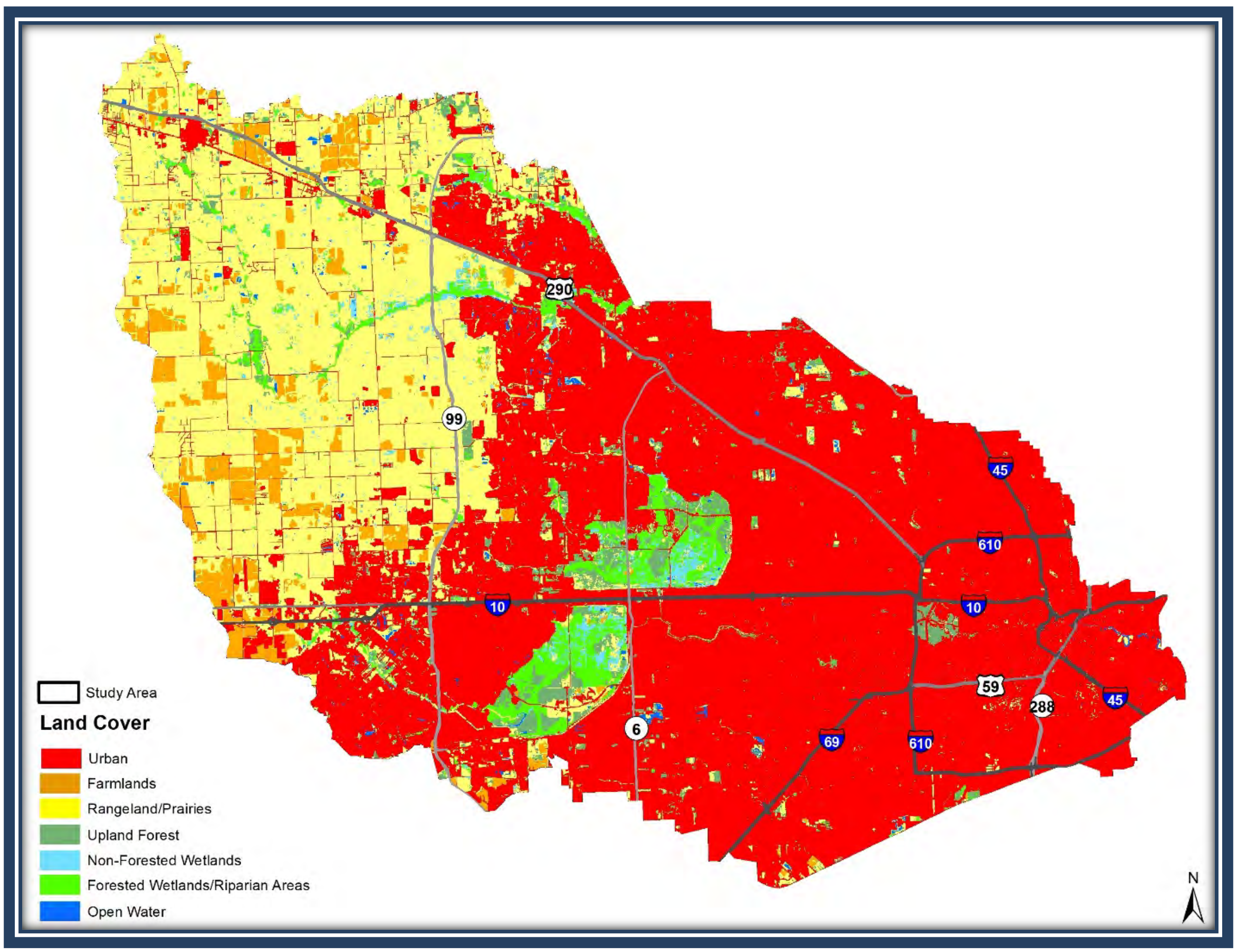

Figure 18. Land Cover Types (USGS National Land Cover Database 2016)

The incised nature of Buffalo Bayou has created a floodplain that significantly differs from historic conditions, and the combined impact of urbanization has reduced natural floodplains and wetlands. Urbanization in the drainage basin and concrete lining in parts of the channels has accelerated runoff and reduced overbanking, both of which contribute to a smaller natural floodplain. Buffalo Bayou has visible erosion in all reaches, and channel widening is occurring due to severe bank failures. These failures are mostly in curving and unarmored stream segments. There is less erosion where channel straightening and concrete lining has occurred.

2.4 Cultural Resources

Cultural resources are found along most of bayous and in the Addicks and Barker reservoirs. There is a high potential for encountering historic age archeological sites and cemeteries, as well as historic age structures and buildings across the entire project area. In non-urbanized areas, the reservoirs and in undeveloped potions along streams and bayous the potential for encountering prehistoric archeological sites is moderate to high. Finally, there is moderate potential for encountering submerged prehistoric and historic resources within Buffalo Bayou.

2.5 Environmental Engineering

Water quality in the bayous has improved since the 1980s, but still suffers from continuing problems associated with fecal bacterial and pollution. Due to urbanization, most stormwater runoff flows into streets and storm sewer networks with little surface flow over natural undeveloped areas or through wetlands, which probably contributes to water quality problems. Dry weather water flows are dominated by wastewater treatment plant effluent. Past industrial land uses in the eastern portion of the study area have either been cleaned up, still require remedial action, or have potentially contributed to water quality problems related to industrial activities (e.g., coolant fluids, petroleum).

2.6 Geology and Structural Setting

Harris County is within the Gulf Coastal Prairies Province, which is characterized as a broad band paralleling the Gulf of Mexico coastline and with the land surface dipping gently southwest towards the Gulf at less than one foot per mile. The land surface is supported by sediments dipping towards the gulf at a rate slightly greater than the land surface so that progressively younger strata are exposed towards the gulf. The oldest of these sediments are Upper Cretaceous marine shales and marls that outcrop along the northwestern boundary of the province and the youngest sediments are the recent coastal silts and beach sands that occur along the present shoreline. Deltaic sands, silts, and clays have eroded to nearly flat grasslands that form almost imperceptible slopes to the southeast. Minor steeper slopes, from 1 foot to as much as 9 feet high, result from subsidence of deltaic sediments along faults.

The geology of Harris County, Texas, is mostly the Lissie and Beaumont formations. Isolated zones of Alluvium and Fill and Spoil are present along portions of the Houston Ship Channel. Alluvium is also present on either side of the San Jacinto River as it extends south from Lake Houston and intersects the Houston Ship Channel. Pockets of the Deweyville Formation exist adjacent to the Alluvium along the San Jacinto River. The Willis Formation is present in the far northwest portion of Harris County and also generally parallels the Gulf Coast of Texas.

The Beaumont Formation consists of Pleistocene Age deposits of mostly clay, silt, and sand, including stream channel, point-bar, natural levee, backswamp, coastal marsh, and mud-flat deposits. Beaumont clays are typically stiff to hard consistency with undrained shear strengths ranging from about 1,000 psf to over 5,000 psf. The clays are overconsolidated with an overconsolidation ratio range of 2 to 8. The clays have joints and fissures, randomly oriented, sometimes containing sand and/or silts which occur as thin seams. Unfilled fissures can be slickensided. The clays have a moderate to high potential for shrink/swell. The Beaumont Formation is poorly drained with a slow permeability.

The Lissie Formation is mid-Pleistocene Age, deposited in shallow coastal river channels and flood plains. It is about 200 feet thick, heterogeneous, and interbedded. The soils are sand, silt, clay, and a minor amount of gravel. Iron oxide and iron-manganese nodules are common in the weathering zone. The surface is fairly flat and featureless except for many shallow depressions and small mounds.

There are several geologic consideration in Harris County such as faults, salt domes, sinkholes, seismicity and subsidence.

There are several salt domes in Harris County. A salt dome is a geologic formation created when lighter materials force their way up through denser ones. Salts and other evaporated minerals are generally lighter than the sedimentary rock that surrounds them; and as a result, salt has a tendency to well up, creating a visible bulge in the surface of the earth. Salt is also an extremely stable storage medium, leading some companies to use salt domes to store deposits of fuel and natural gas. The number of salt domes used for storage here is a result of their role in oil and gas production.

Subsidence is the gradual lowering of the ground’s surface because of groundwater withdrawals for domestic, industrial, and agricultural uses over many decades. Long-term pumping has caused groundwater levels to drop. To meet the growing demands for water, and comply with the groundwater reduction requirements, the region is in the process of switching its water supply from groundwater to surface water sources such as Lake Houston. According to Harris County Subsidence District charts, the majority of subsidence in Harris County area has occurred in the east and northeast of Addicks Reservoir within the past 20 years. According to these charts, portions of the Addicks Reservoir has subsided 2 to 3 inches and parts Barker Reservoir has subsided by about 1.0 to 1.5 feet over the last 20 years (Figure 19). There is an approximately three feet difference in the North and South ends of the Addicks embankment, with the North end at about Elevation 108 feet and the South end at about 111.5 feet.

Natural ground elevations in the Addicks and Barker Reservoir watersheds vary from approximately 200 feet at the upstream to about 68 feet at Addicks Dam and 70 feet at Barker Dam. Natural stream flow gradients in the basin are consistent at about five feet per mile sloping in a southeasterly direction. Harris County is within the Gulf Coastal Prairies Province15 that is a broad swath of land paralleling the Gulf of Mexico coastline with a land surface dropping southwest towards the Gulf. There are no reported active earthquake capable faults in the Texas Gulf Coast region.

According to the Addicks and Barker Dam Safety Modification Report (DSMR, 2013), groundwater is present at depths ranging from 15 to 19 feet below natural ground at Addicks Reservoir and 12 to 15 feet below natural ground at Barker Reservoir. Underground site conditions of Buffalo Bayou is similar to those at the outlet works of Barker Dam; the Buffalo Bayou channel is immediately east of the outlet works of Barker Dam.

The upper layer of stiff sandy, silty, low flexibility clay extends to about 10 to 15 feet and lies above a layer of low flexibility clay, silt, and fine sands. Erodible fine sand, silty fine sand, sandy silt, and silt occurs in several layers and pockets. This easy to break down layer extends to a depth of about 30 feet and lies on top of highly flexible clay.

Natural ground elevations in the Addicks and Barker Reservoir watersheds vary from approximately 200 feet at the upstream to about 68 feet at Addicks Dam and 70 feet at Barker Dam. Natural stream flow gradients in the basin are consistent at about five feet per mile sloping in a southeasterly direction. Harris County is within the Gulf Coastal Prairies Province[14] that is a broad swath of land paralleling the Gulf of Mexico coastline with a land surface dropping southwest towards the Gulf. There are no reported active earthquake capable faults in the Texas Gulf Coast region.

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[14] https://legacy.lib.utexas.edu/geo/fieldguides/physiography_print.html

[15] https://www.wisegeek.com/what-is-a-salt-dome.htm

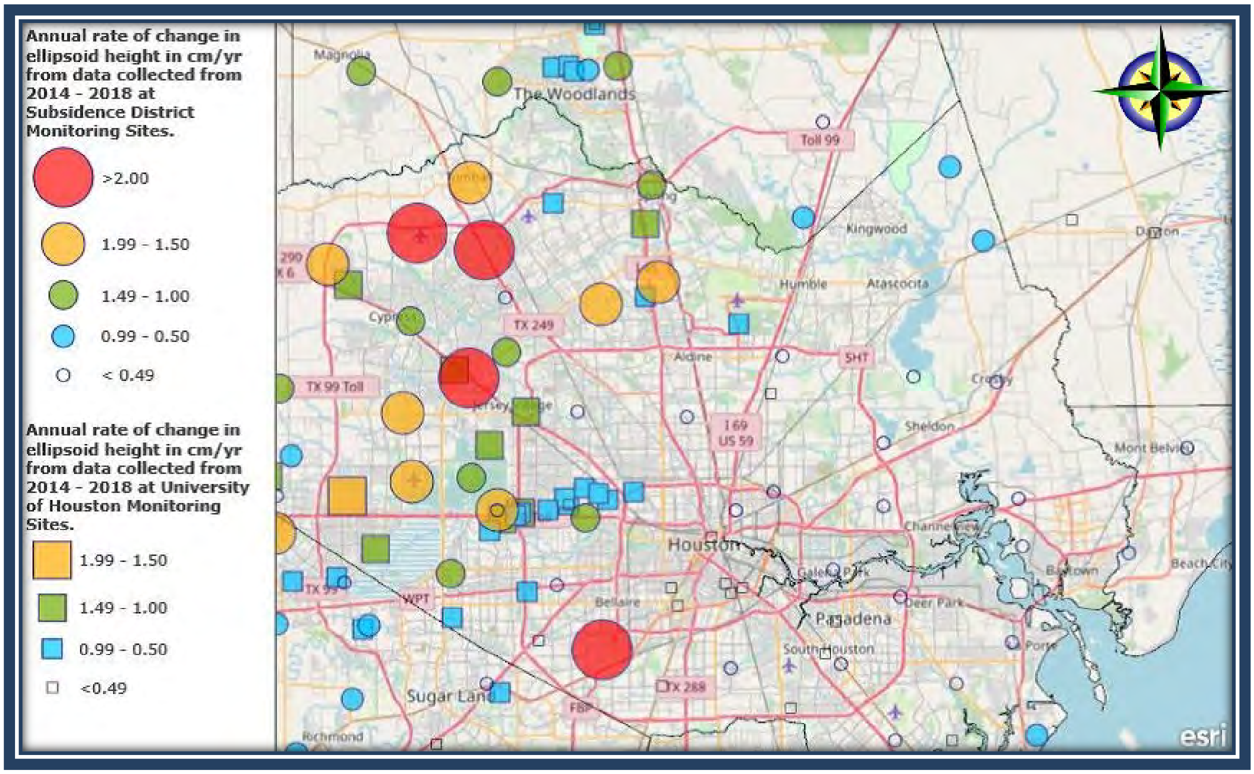


Figure 19. Subsidence Rates in Harris and Surrounding Counties in Centimeters per Year (0.394 cm = 1 inch)

2.7 Real Estate

2.7.1 Addicks and Barker Reservoirs

When Addicks and Barker reservoirs were built, the Federal government bought land to support operations based on historic storm data found for multiple events prior to 1948. At the time, the reservoirs were in a relatively undeveloped area approximately 20 miles to the west of downtown Houston in far western Harris and eastern Fort Bend counties. Since their construction, urbanization has brought development around nearly all edges of the dams. Addicks is located entirely within the boundaries of Harris County, and consists of 160 tracts totaling 13,814 acres with Government interest. Barker is located in Harris and Fort Bend counties, and has 100 tracts totaling 12,586 acres with Government interest. Both reservoirs are popular recreation areas when dry. For instance, the Federal government has issued outgrants at Addicks Reservoir for a rifle range, hiking and biking trails, the Bear Creek Pioneers Park (3,080 acres), and Cullen Park (9,269 acres). Barker Reservoir outgrants include: Cinco Ranch Park (1,961 acres) and George Bush Park (7,800 acres). Several roads run through the reservoirs.

2.7.2 Buffalo Bayou

Today, HCFCD maintains Buffalo Bayou. The Corps disposed any interests along Buffalo Bayou in 1965 to HCFCD, which holds 132 easements and owns 95 tracts in fee within and or intersecting the bayou totaling more than 11,221 acres.

2.8 Socioeconomics

Socioeconomics focuses on relationships between social behavior and economics, and examines how social norms, ethics, emerging popular sentiments, and other social philosophies influence consumer behavior and shape public buying trends. Socioeconomics incorporates history, current events, politics, and social sciences to predict potential results from changes to society or the economy. A group with similar characteristics is a socioeconomic class. Characteristics can include social and economic standing, education level, profession, ethnicity, and heritage.

2.8.1 Population

As is shown in Table 4, growth over the period from 2000 to 2018 in the city of Houston and Harris County has been substantial. Harris County has matched the growth rate for the state of Texas over the same period which has outpaced US growth by 20 percentage points. The city of Houston is expected to overtake the city of Chicago as the nation's third-largest city by the second half of the decade of the 2020s (https://www.houstontx.gov/abouthouston/houstonfacts.html).

Table 4. Population for Houston, Harris County, Texas and the U.S. (2000 through 2018)

Place	2000	2010	2018	Percent Change (2000-2018)
Houston City	1,980,578	2,093,615	2,325,502	19%
Harris County	3,400,578	4,093,188	4,698,619	38%
Texas	20,851,028	25,146,114	28,701,845	38%
United States	281,421,906	308,758,105	327,167,434	18%

Additional analysis was done by watershed utilizing ESRI's Community Analyst tool and displayed in Table 5 based on information derived from the Census Bureau's 2018 American Community Service. As the table suggests, no one group makes up more than 50 percent of the racial makeup. While this data is aggregated by watershed, analysis of this supposition of individual census blocks generally held.

Table 5. Gender and Race by Watershed

	Addicks	Barker	Buffalo	Cypress	Brays	White Oak	Total
Total Population	297,584	299,610	189,615	299,769	413,400	230,001	1,729,979

Gender							
Male	49.1%	48.9%	52.6%	49.0%	49.9%	49.9%	49.7%
Female	50.9%	51.1%	47.4%	51.0%	50.1%	50.1%	50.3%
Race							
White	28.0%	42.8%	48.1%	49.1%	24.9%	32.7%	36.3%
Hispanic	44.3%	25.1%	27.9%	26.2%	42.7%	40.6%	35.2%
Black/African American	15.5%	12.1%	12.8%	14.5%	17.7%	15.6%	15.0%
Asian	9.8%	17.1%	8.9%	7.6%	12.6%	8.9%	11.1%
Multiple Races	2.0%	2.3%	1.7%	2.0%	1.7%	1.7%	1.9%
Other Race	0.2%	0.3%	0.4%	0.2%	0.2%	0.2%	0.2%
American Indian/Alaska Native	0.2%	0.3%	0.2%	0.3%	0.1%	0.2%	0.2%
Pacific Islander	0.1%	0.1%	0.0%	0.1%	0.0%	0.0%	0.1%

Source: ESRI's Community Analyst and Census Bureau American Community Service (2018)

2.8.2 Income

With the exception of median household and per capita income in Cinco Ranch that are both significantly higher than other areas, income metrics, both per capita and median, are similar on a regional, state and national level (Figure 20). Median household incomes range from a high of $65,394 in the Houston MSA to a low of $60,232 for Harris County as a whole.

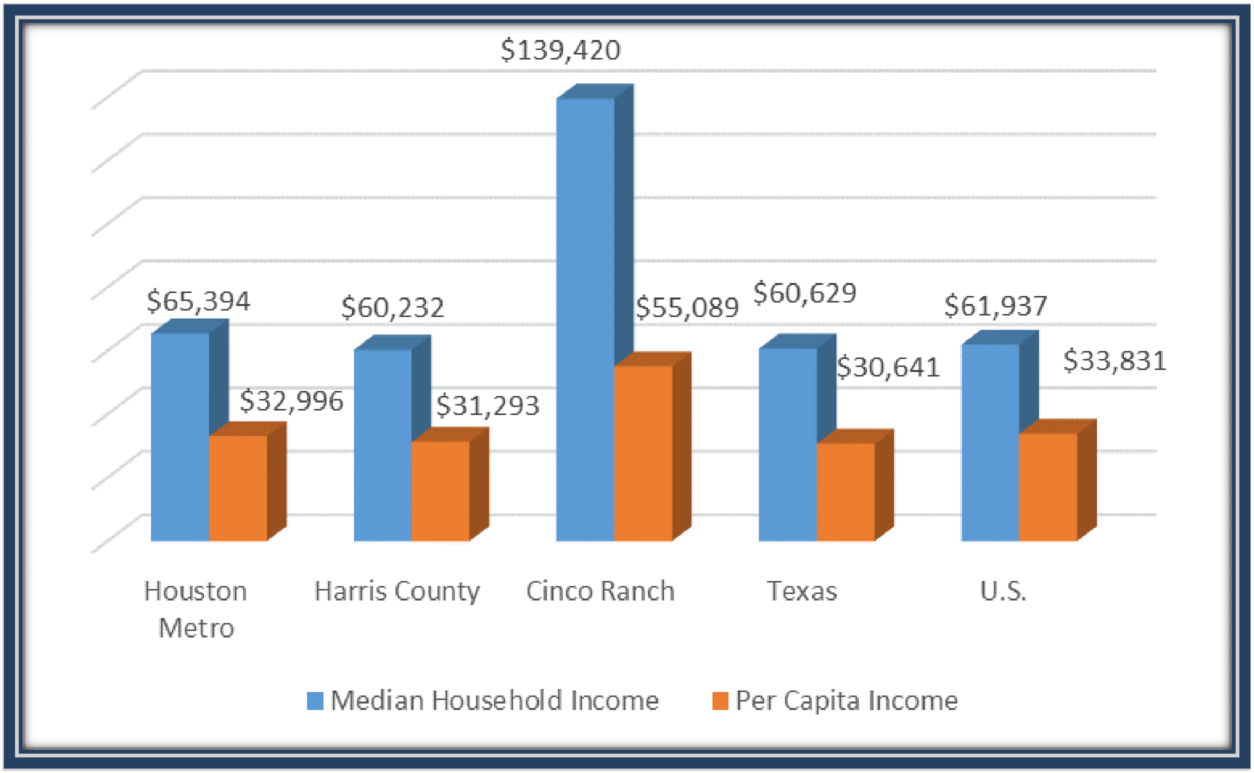


Figure 20. Median Household and Per Capita Income

The same watershed analysis used for the gender and racial makeup was also applied to for a breakdown of median household income. This data is displayed below. Median income for each of the watersheds is well above the poverty threshold of $19,985 for a family of three (based on poverty thresholds for 2018 and 2019 population estimates for Harris County of 2.88 persons per household).

Table 6. Median Household Income by Watershed

	Addicks	Barker	Buffalo	Cypress	Brays	White Oak
Median Household Income	$69,998	$134,480	$102,275	$91,800	$54,670	$66,968

2.8.3 Education Levels Achieved

Table 7. Education Levels Achieved by Percentage for Ages 25 Years and Over

Place	No High School	High School No Diploma	High School Graduate	Associate's Degree	Bachelor's Degree	Graduate Or Professional Degree
Houston City	12.8	8.9	22.7	5.3	19.5	12.6
Harris County	10.4	8.2	23.4	6.7	19.9	11.7

Cinco Ranch	0.9	0.9	8.5	4.3	37.6	25.1
Texas	8.5	8.3	25.0	7.1	19.1	10.2
U.S.	5.3	7.1	27.1	8.4	19.4	12.1

https://data.census.gov/cedsci/table?layer=VT_2018_050_00_PY_D1&table=DP05&t=Educational%20Attainment&tid=ACSST5Y2018.S1501&hidePreview=true&vintage=2018&cid=S1501_C01_001E

2.8.4 Race and Hispanic Origin

Table 8. Race and Hispanic Origin by Percentage for 2018

Race/Ethnicity	Houston	Harris County	Cinco Ranch	Texas	US
White (alone not Hispanic)	24.6	29.1	76.2	41.5	60.4
Black (alone)	22.5	19.9	5.1	12.8	13.4
American Indian and Alaskan Native	0.3	1.1	0.0	1.0	1.3
Asian (alone)	6.9	7.4	15.8	5.2	5.9
Native Hawaiian or Pacific Islander	0.1	0.1	0.0	0.1	0.2
Two or More Races	2.1	1.9	2.3	2.0	2.7
Hispanic	44.8	43.3	15.7	39.6	18.3

Source: Census.gov QuickFacts v2018 [Cinco Ranch, Fort Bend County v2019]

2.8.5 Demographic Indicators for Environmental Justice

Executive Order 12898 – *Federal Actions to Address Environmental Justice in Minority Populations and Low Income Populations*, speaks to inconsistent human health and environmental impacts that a project or plan may have on minority or low-income communities. Thus, the environmental effects of a plan on such communities, including Native American populations, must be disclosed and agencies must evaluate projects to ensure that proposed actions do not disproportionally affect minority or low-income communities. If such impacts are identified, appropriate mitigation measures must be implemented.

Based on the information provided above regarding the racial makeup of the study area and relative comparison with data from cities such as Houston, the State of Texas, and the US, the study area and Harris County reflect a population that does not have one racial group making up more than 50 percent of the population. Additionally, median household income is well above any estimates of the current poverty threshold. Considering these, any disproportionate impacts on these potentially protected populations are not anticipated. NEPA scoping did not identify any potential issues with regard to race and income. The study will continue to evaluate any disproportionate impacts that may occur to potentially protected populations.

(NOTE: This page intentionally left blank.)

3 Future without Project Condition

Future without project conditions (FWOP) are conditions expected to exist in the study area during the 50-year period of analysis (2036 through 2085) in the absence of a proposed water resources project. The FWOP is the same as the "No Action" alternative plan. Forecasts (qualitative and quantitative) extend from the base year (year when the proposed project is expected to be operational) to the end of the period of analysis. The FWOP forms the basis against which alternative plans are developed, evaluated, and compared. Proper definition and forecasting of the FWOP are critical to the success of plan formulation.

Hydrology and Hydraulic modeling continue to be updated to better determine the current and future flood risk within the study area. Updates include those to flood frequencies, inundation, loading, as well to the probable maximum flood and the standard project flood. Accurate analyses are essential to other disciplines as they continue to update project designs for Alternative Analysis, environmental modeling, and Benefit-Cost Analysis for potential alternatives. These updates will be reflected in future releases of the draft report and accompanying appendices as well as other venues for the public's awareness.

3.1 Hydrology, Hydraulics, and Climate

3.1.1 Hydrology

3.1.1.1 Impervious Ground Surfaces

When it rains, or snows, in areas covered with asphalt, concrete, shingles, metal roofs, water does not have a chance to soak into the ground (infiltrate), as it does in areas that are more rural or natural. Instead, water quickly runs off heading for the lowest areas, which in urban areas are streets, drains, and in the study area, bayous, creeks, rills, and Addicks and Barker reservoirs. The more impervious the ground is to precipitation, the faster the water moves from high ground to lower ground, and the less time one has to prepare for floods. By 2085, (the end of this project's life expectancy), it is anticipated that impervious areas will increase (Table 9).

Table 9. Average Impervious Area by Percent

Year	Watershed		
	Addicks	Barker	Buffalo Bayou
2016	27.10	24.96	55.29
2085	38.30	36.78	57.24
% Change	+41.33	+47.36	+3.53

3.1.2 Hydraulics

With the study area continuing to grow in population, and with less open ground over time, the same rain event in 2020 will have larger effects in the future unless addressed.

Figure 21 displays maps for Addicks Dam and Reservoir watershed, Barker Dam and Reservoir Watershed, and Buffalo Bayou from Barker Dam to the periphery of downtown Houston representing inundation patterns for various events under the future without project condition. Maps show where the water will go after four different AEP events: 0.1, 0.02, 0.01, and 0.002 AEP (10-year, 50-year, 100-year, and 500-year events) based on current topography and land use. Like previous figures, these maps show the distribution of flows but not depths.

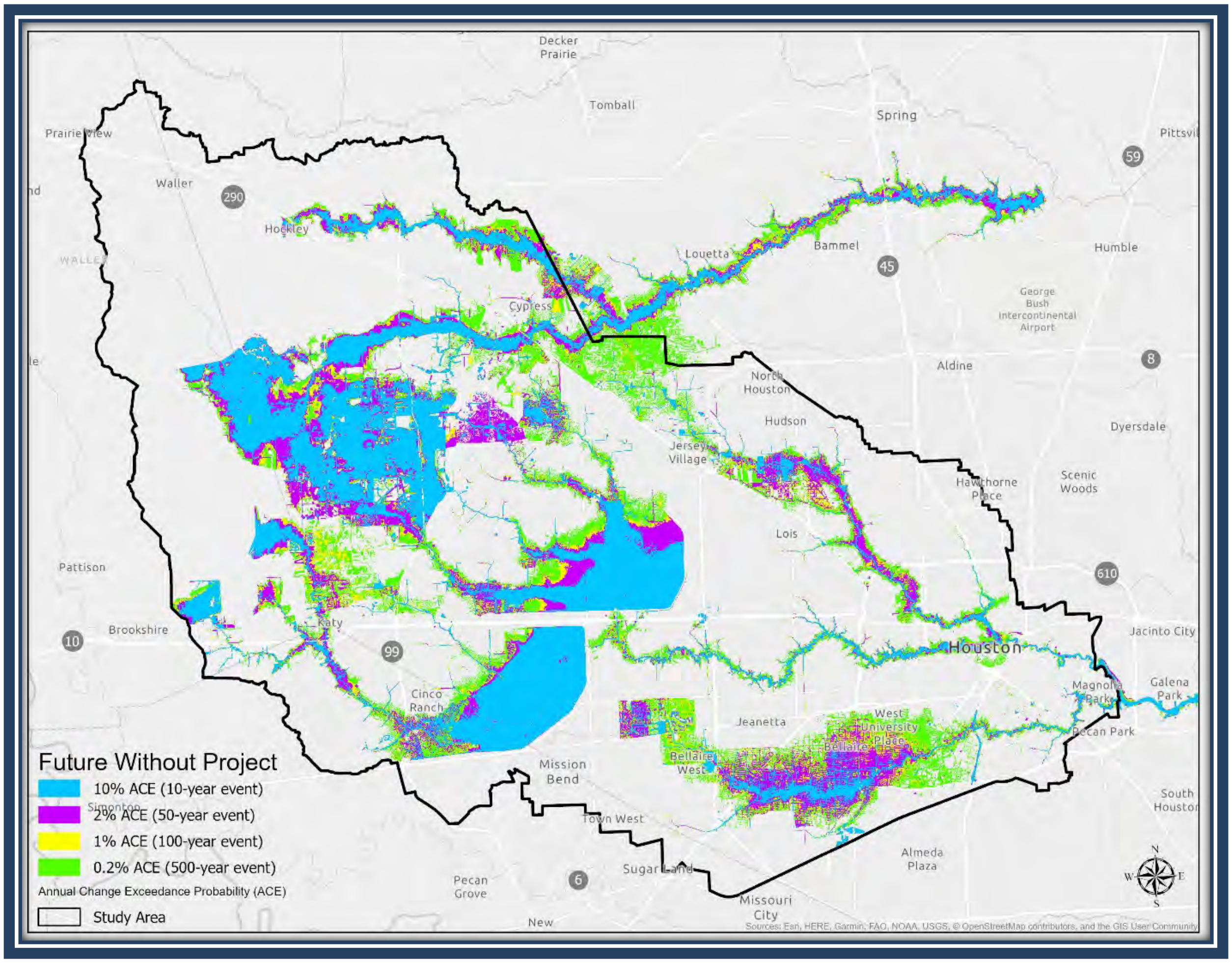


Figure 21. Study Area 2 Map Showing the FWOP 0.1, 0.02, 0.01, and 0.002 AEP

The following figures (Figure 22 through Figure 24) show the comparisons between the existing conditions from Chapter 2, to the Future Without-Project Conditions in this chapter.

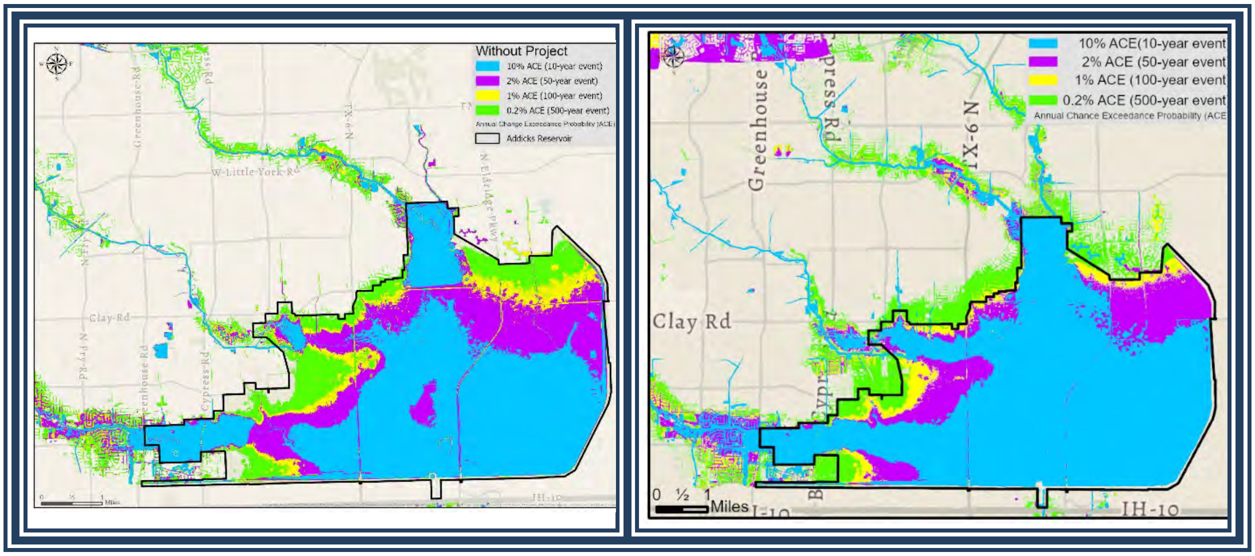


Figure 22. Addicks Reservoir Maps Showing Existing vs. Future Without-Project Conditions

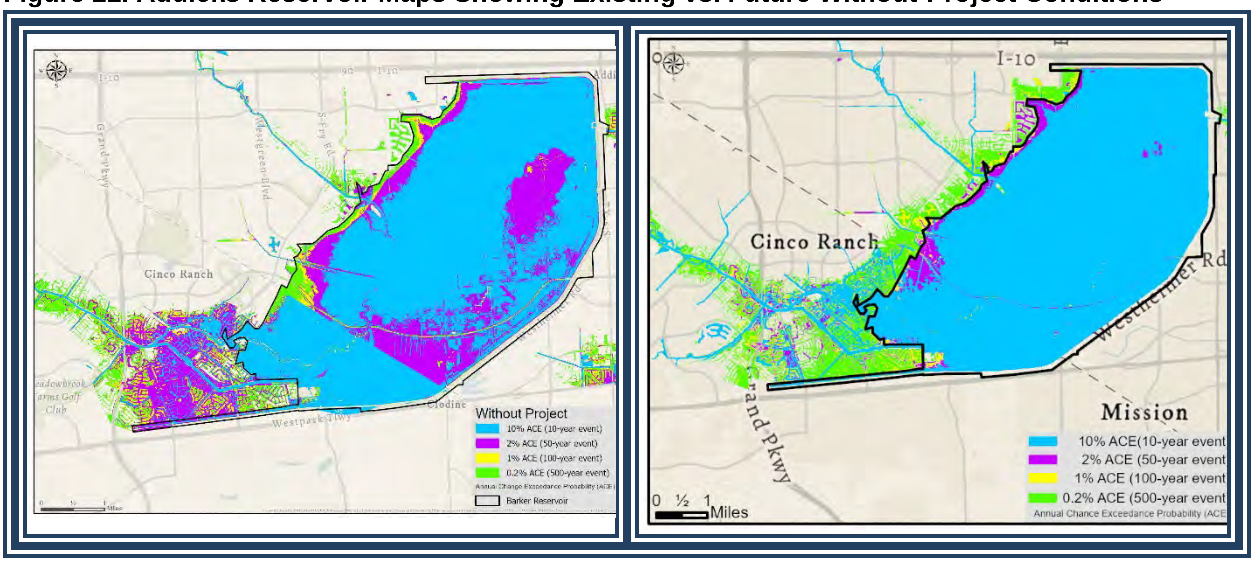
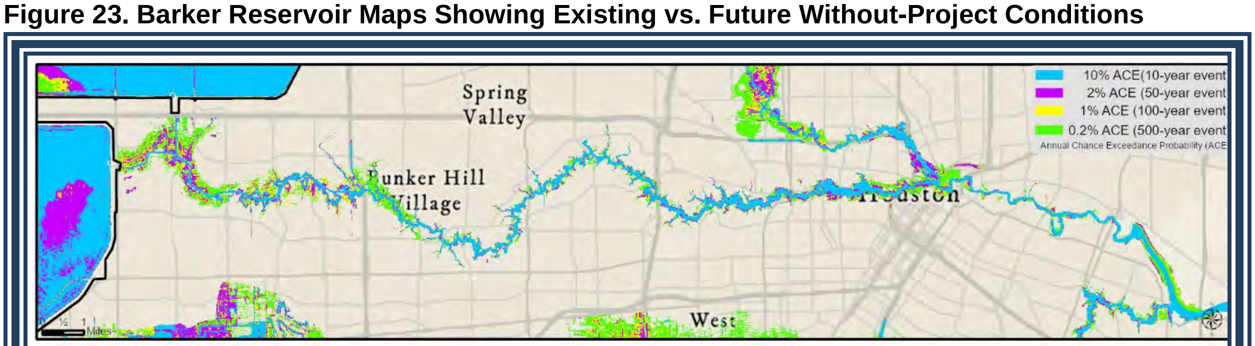
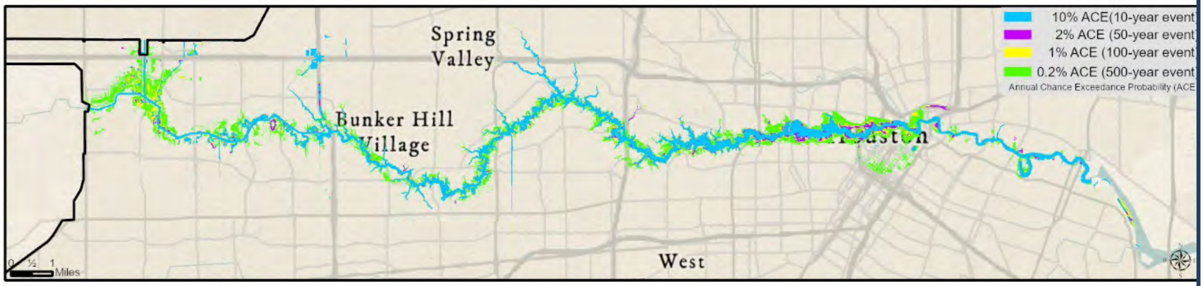


Figure 23. Barker Reservoir Maps Showing Existing vs. Future Without-Project Conditions



Buffalo Bayou Existing Conditions



Buffalo Bayou Future Without-Project Conditions

Figure 24. Buffalo Bayou Maps Showing Existing vs. Future Without-Project Conditions

3.1.3 Climate

Relatively recent evidence, climate models, and studies imply a changing climate. Fixed climate baselines with a small range of changeability may no longer be appropriate for long-term flood risk-management projects. Long-term, natural or human-driven, climate change can alter regional thermal, hydrologic, and environmental patterns. The purpose of this study's climate change analysis is to textually show how hydrologic variables may have reacted to the climate in the past, may react in the future, and to assess climate change (Appendix A – Hydrology, Hydraulics, and Climate Section 5.1 provides additional detail regarding climate change analysis).

3.1.3.1 Temperature

Climate change is expected to lead to an increase in average temperatures as well as frequency, duration, and intensity of extreme heat events with a reduction in extreme cold events. The US National Climate Assessment[16] annual average temperature projections show an increase of 3.6° to 5.1°F by the mid-21st century and by 4.4° to 8.4°F by the late 21st century, compared to the annual average temperature for 1976 through 2005. The mean daily maximum temperature in the study area would be expected to increase from approximately 80°F in 2016 to approximately 88°F in 2099.

By the late 21st century, under the low scenario the study area is projected to experience up to an additional 20 days per year in which temperatures exceed 100° as compared to current conditions (about 5 days per year), while the high scenario projects an additional 30 to 40 days per year above 100°F. NOAA's Climate Explorer Tool[17] indicates that beginning in the year 2090, the number of days could reach as many as 65 days per year (an increase of up to 60

[16] https://nca2014.globalchange.gov/

[17] https://toolkit.climate.gov/#climate-explorer

days per year when compared to NOAA's high scenario). An increase in extreme heat events would likely increase drought and wildfire risk.

3.1.3.2 Precipitation

Climate change and greenhouse gas (GHG) emissions are expected to alter future weather patterns including precipitation. Most climate models suggest average annual precipitation changes would be minimal, with slightly wetter winters and drier summers. The Climate Explorer shows an annual average increase of 0.5 percent to 1.5 percent in the number of days with more than three inches of precipitation under the low and high scenarios, while there would be an average increase of 10 percent to 15 percent in the number of days with less than one inch of precipitation.

The frequency and intensity of heavy precipitation are anticipated to increase as well, particularly under higher GHG scenarios and later in the 21st century. Expected increases in precipitation intensity implies fewer soaking rains with more time to dry out between events. In the National Climate Assessment high scenario, the number of extreme extents (greater than a 0.2 AEP or 5-year event) increases by 200 percent to 300 percent of the historical average by the end of the 21st century. Under the low scenario, increases are 50 percent to 100 percent. Projections of changes in the 0.05 AEP (20-year event) for daily precipitation shows an increase of around 10 percent to 14 percent for the low scenario and approximately 20 percent for the high scenario by the end of the 21st century. The increases in extreme precipitation tend to increase with return interval, such that increases for the 0.01 AEP (100-year event) are about 30 percent by the end of the century under the higher scenario.

3.1.3.3 Relative Sea Level Rise

The relative sea level trend as observed at the Galveston Pier 21 gauge is 6.55 mm (or about 0.26 inches) per year with a 95 percent confidence interval of +/- 0.22 mm/yr based on monthly mean sea level data from 1904 to 2019. [18] This equivalent to a change of 2.15 feet in 100 years. Projected trends show that sea level rise can be between 2.14 feet and 9.12 feet over the 100 years between the years 2036 and 2136 depending on the sea level rise scenario (Low, intermediate, or high). Table 10 shows three sea level change scenarios for Pier 21 on Galveston Island using the Corps' Sea Level Change Curve Calculator. Figure 25 graphically shows these scenarios over the same time period. [19] Figure 26 shows where the head of tides may be expected to appear in the 2085 and 2100.

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[18] https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8771450

[19] http://corpsmapu.usace.army.mil/rccinfo/slc/slcc_calc.html

Table 10. Sea Level Rise Scenarios for Pier 21, Galveston, Texas in Feet

Datum	MHHW	MSL	MLLW
1992 feet	1.21	0.61	-0.1
2036 Low	2.16	1.56	0.85
2036 Int	2.33	1.73	1.02
2036 High	2.87	2.27	1.56
2085 Low	3.21	2.61	1.9
2085 Int	3.98	3.38	2.67
2085 High	6.42	5.82	5.11
2100 Low	3.53	2.93	2.22
2100 Int	4.57	3.97	3.26
2100 High	7.86	7.26	6.55
2136 Low	4.3	3.7	2.99
2136 Int	6.15	5.55	4.84
2136 High	11.99	11.39	10.68

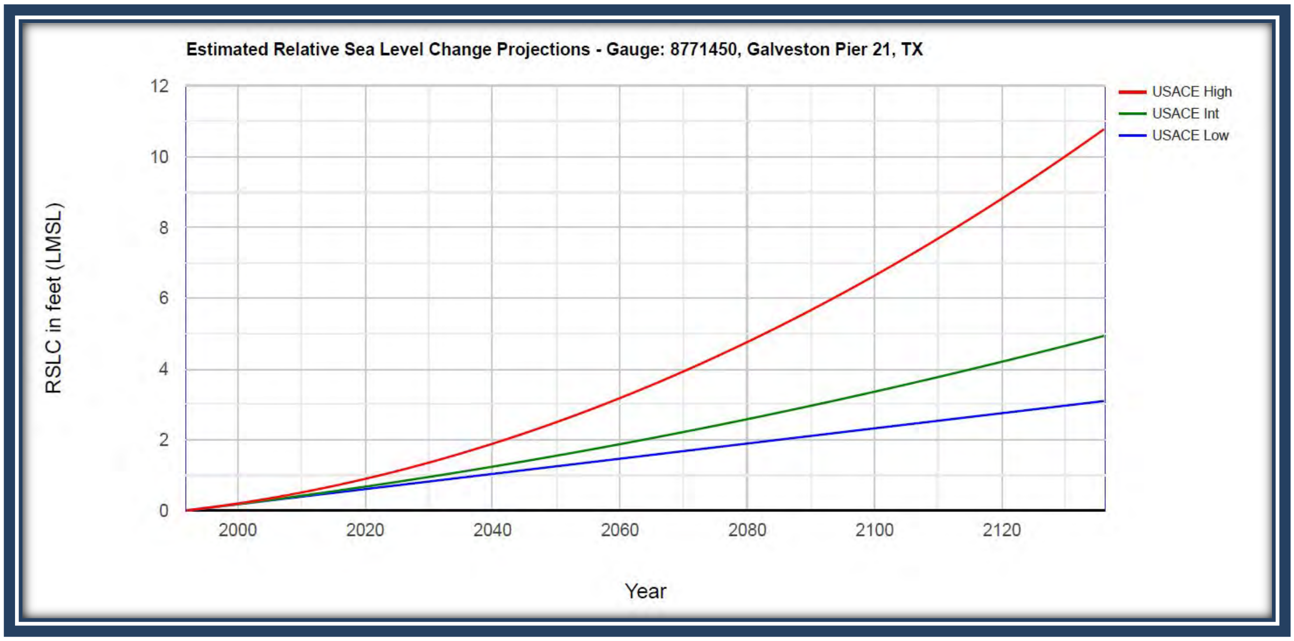

Figure 25. Graph Showing Possible Relative Sea Level Change at Galveston's Pier 21

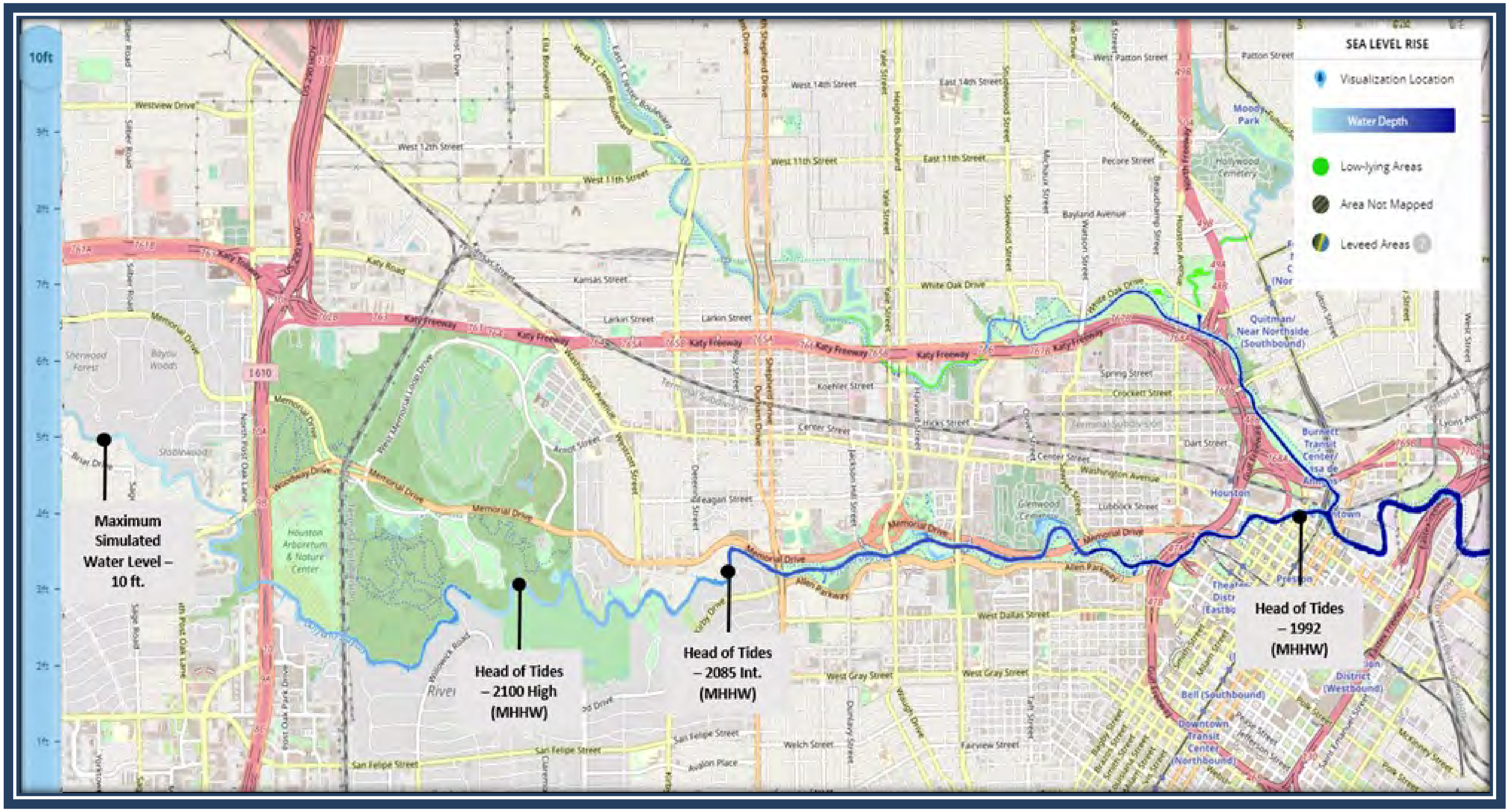

Figure 26 - Expected Location of Head of Tides in 2085 and 2100

3.2 Environmental Resources Affected Environment

The Buffalo Bayou watershed below Addicks and Barker dams is almost entirely urbanized, and is undergoing redevelopment in many areas. New mid-rise and high-rise multifamily residential construction is occurring more frequently and farther outside of the Houston City center. Revitalization and redevelopment are occurring. It is expected that through the period of analysis (2036 through 2085), the few remaining large tracts of undeveloped vacant land will be developed with office buildings, high-density residential areas, and commercial centers. This would result in the loss of a significant portion of the remaining riparian habitat outside of parks, floodways, and residential areas upstream on Buffalo Bayou. The only places expected to keep natural riparian habitat is along a very narrow and scarce swath lining the banks. In the future, suitable habitat for wildlife will decline and open spaces for recreation will be limited to designated parks and the floodway. Erosion is expected to continue along Buffalo Bayou, with channel widening expected to produce the biggest changes. Widening is expected to be greatest along steep banks with deep, sandy layers where large slopes failures would occur.

3.3 Cultural Resources

Environmental and socioeconomic trends affecting cultural resources in the project area will continue, and the main threat to cultural resources is the lack of city-wide comprehensive zoning within the city of Houston directing commercial, industrial, and residential development. Cultural resources are also threatened by flooding including shoreline erosion, structural damage, and displacement. These practices may result in partial or total loss of historic properties.

3.4 Geology and the Structural Setting

The FWOP is not likely to change in any significant way either in terms of geology or structural setting.

3.5 Real Estate

3.5.1 Addicks and Barker Operations

When Addicks and Barker Dams were originally built, the federal government bought land for the reservoirs up to 103 feet in elevation (Addicks) and 95 feet (Barker). Since then, changed conditions in the system have led to more runoff for the same precipitation events. In addition, Corps of Engineers Engineering Manual 1110-2-1420 *Hydrologic Engineering Requirements for Reservoirs* dated 24 Sep 2018, and other guidance, specify the land acquisition flood that would apply if constructing the reservoirs today. Additional higher elevations could be either the standard project flood (SPF)[20], the lower ends of the dam where spilling would begin plus approximately 3 feet of freeboard, or the probable maximum flood (PMF). (Table 11).

Table 11. Dam Design Project Elevation Data (feet)

Elevations	Standard Project Flood	End of Dam	Probable Maximum Flood
Addicks Reservoir	107.6	108.0	115
Barker Reservoir	98.3	104.0	108

Source: 2012 Water Control Manual

3.6 Socioeconomics

Under the No Action Plan, the study area will likely continue on its present course of population growth trends, economic development, and residential and commercial development patterns. The demand for community facilities, services, and housing will continue to increase due to population growth. Future economic damages from flooding are likely. Damages would affect individuals through loss of property, and the economic cost of restoring property or relocating. Property taxes are the most significant source of public revenue that could be impacted by flooding, which can affect property values and therefore decrease revenue.

3.6.1 Population Projections

At the state and county level, population projections indicate robust growth for the period of analysis; however, depending upon source and the methodology used, projections vary. According to the Texas Demographic Center, the number of people living in Harris County is expected to grow from 4.97 million in 2020 to 7.9 million in 2050. Texas's population will reach 29.7 million in 2020, and top 47.3 million by 2050 (Table 12). The Texas Water Development Board[21] estimates that the number of people living in Harris County will grow from roughly 4.7 million in 2020 to 6.3 million in 2070. Texas's population as a whole will reach 29.7 million in 2020, and top 51.5 million by 2070 (Table 13 and Figure 27). According to the Houston government, the number of people living in the City of Houston is expected to grow from roughly 2.5 million in 2020 to 3.6 million in 2060. The number of people living in Harris County is expected to grow from roughly 4.5 million in 2020 to 6.7 million in 2060, and Texas's population will reach 29.1 million by 2020, and top 45.5 million by 2060 (Table 14). The reason why there are multiple population forecasts is that it depends upon the modeler’s data source and model used. Forecasting future populations is not an exact science.

[20] 2012 USACE Addicks and Barker Reservoirs Water Control Manual

[21] https://www3.twdb.texas.gov/apps/reports/Projections/2022%20Reports/pop_region

Table 12. Population Projections for Harris County and the State of Texas

Place	2020	2030	2040	2050
Harris	4,978,845	5,924,750	6,901,842	7,933,397
Texas	29,677,668	34,894,452	40,686,496	47,342,105

https://demographics.texas.gov/Data/TPEPP/Projections/

Table 13. Population Projections for Harris County and the State of Texas

County	2020	2030	2040	2050	2060	2070
Fort Bend	881,966	1,095,123	1,259,307	1,421,933	1,583,782	1,755,164
Harris	4,707,870	5,058,144	5,376,099	5,678,242	5,974,068	6,272,346
Waller	52,538	63,443	75,535	88,736	103,314	119,122
Texas	29,695,345	33,913,233	38,063,056	42,294,281	46,763,473	51,486,113

https://www3.twdb.texas.gov/apps/reports/Projections/2022%20Reports/pop_region

Table 14. Population Projections for Harris County and the State of Texas

Place	2020	2030	2040	2050	2060
Houston City	2,520,926	2,798,278	3,073,268	3,349,540	3,626,591
Harris County	4,502,786	5,053,890	5,604,994	6,156,098	6,707,202
Texas	29,108,012	33,040,035	36,877,046	41,054,973	45,533,734

https://www.houstontx.gov/planning/Demographics/demograph_docs/PopProjections.htm

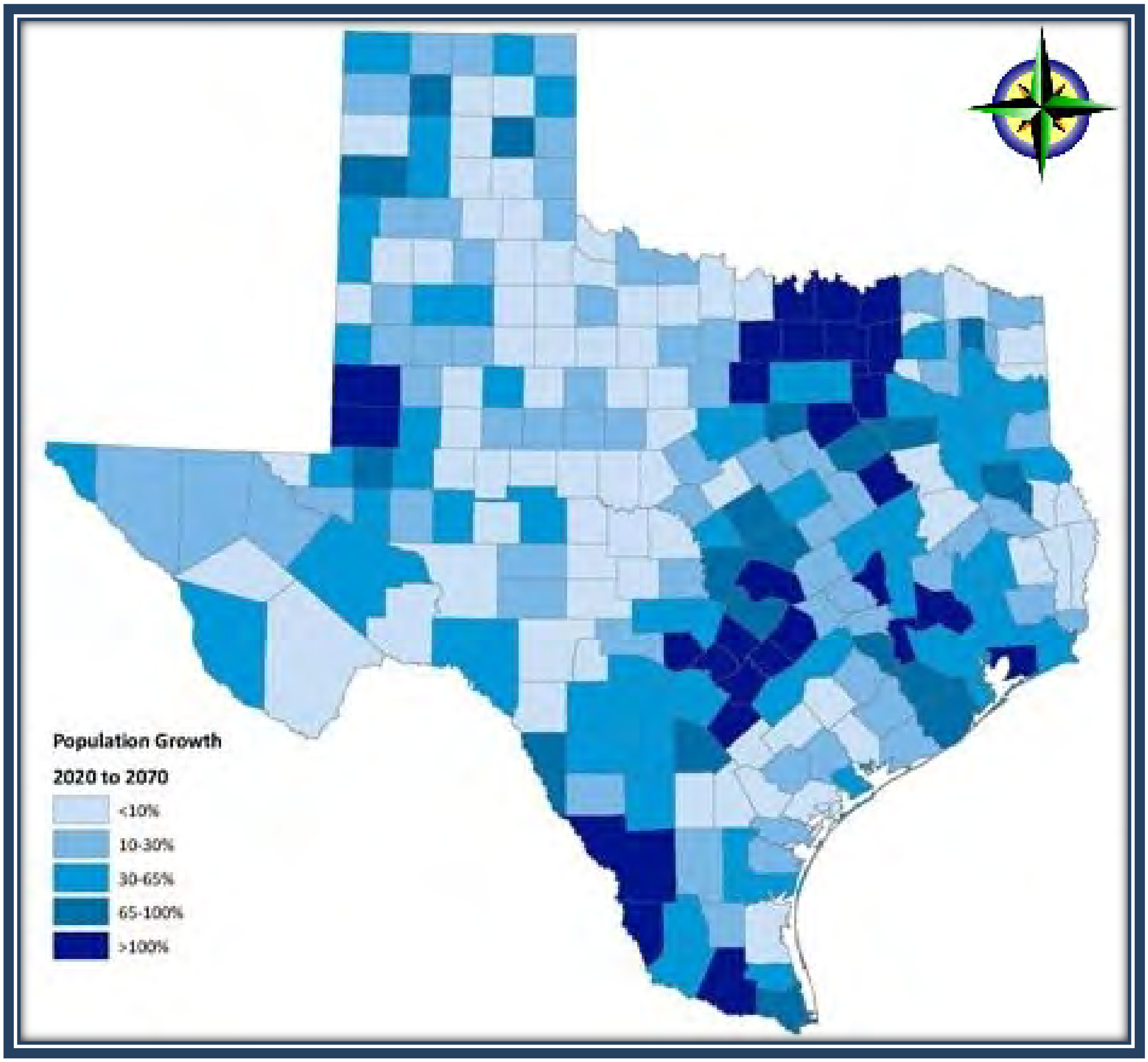

Figure 27. Projected Population Growth by County 2020 - 2070[22]

[22] https://www.twdb.texas.gov/waterplanning/data/projections/2022/popproj.asp

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4 Plan Formulation

The Corps' plan formulation process, as laid out in Engineering Regulation 1105-2-100 *Planning Guidance Notebook*, was used to develop measures for problem solving and identifying opportunities, and to develop an array of comprehensive alternative plans from which a single plan is recommended.

This section describes the first five steps in the Corps' six-step planning process that the PDT used to develop, evaluate, and compare the management measures and alternative plans. The Corps' six steps process is as follows:

1. **Identifying Problems and Opportunities:** The specific problems and opportunities to be addressed in the study are identified, and the causes of the problems are discussed and documented. Planning goals are set, objectives are established, and constraints (limitations) are identified.
2. **Inventorying and Forecasting Resources:** Existing and future-without-project (No Federal Action) conditions are identified, analyzed, and estimated for a 50-year period of analysis. The existing condition resources, problems, and opportunities critical to plan formulation, impact assessment, and evaluation are characterized and documented.
3. **Formulating Alternative Plans:** Alternative plans are created that address the planning objectives. An initial set of alternative plans are developed and evaluated at a preliminary level of detail, and are subsequently screened into a final selection of alternative plans. Each plan is evaluated for its costs, potential effects, potential benefits, and is then compared with the No Action Plan for the 50-year period of analysis.
4. **Evaluating Alternative Plans:** Alternative plans are evaluated for their potential to meet specific objectives and constraints, effectiveness, efficiency, completeness, and acceptability. The impacts of alternative plans are evaluated using the system of accounts framework National Economic Development, Environmental Quality, Regional Economic Development, and Other Social Effects specified in the Corps' *Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies* and in Engineering Regulation 1105-2-100 *Planning Guidance Notebook*.
5. **Comparing Alternative Plans:** Alternative plans are compared to each other and to the No Action Plan. Results are presented (e.g., benefits and costs, potential environmental effects, trade-offs, risks and uncertainties) to prioritize and rank alternative plans.
6. **Selecting the Tentatively Selected Plan:** A plan is selected for recommendation, and related responsibilities and cost allocations are identified for project approval and implementation.

Per ER 1105-2-100 *Planning Guidance Notebook*, as amended, "Various alternative plans are to be formulated in a systematic manner to ensure that all reasonable alternatives are evaluated." For Flood Risk Management studies, "A plan that reasonably maximizes net national economic development benefits, consistent with the Federal objective, is to be formulated." This plan is to be identified as the NED plan.

4.1 Problems and Opportunities

Water resources projects are planned and carried out to solve problems and grasp opportunities. In alternative planning, a problem can be thought of as an undesirable condition, such as flooding. An opportunity offers a chance for improvement of the situation. The identification and documentation of problems and opportunities gives focus to the planning effort and aids in the development of specific planning objectives. Problems and opportunities can also be thought of as local and regional resource conditions that could be changed in response to public concerns. This section identifies the problems and opportunities within the Buffalo Bayou watershed based on the evaluation of existing and expected future-without-project conditions.

The study team developed brief problem statements and planning objectives that were used to guide the identification and evaluation of potential solutions. Hurricane Harvey presented an enormous challenge for the region. It also demonstrated the need to address the changed conditions around the two dams and downstream Buffalo Bayou. The storm produced record rainfall amounts that accumulated in Addicks and Barker reservoirs resulting in record pool elevations. Flood waters from Harvey flooded homes upstream and put extreme pressure on the two dams; and controlled releases contributed to downstream flows that exceeded the carrying capacity of Buffalo Bayou. This flood event illustrates problems in three categories – upstream risks when inflows exceed reservoir capacity, dam safety risks if a dam component were to fail during a flood, and downstream risks when flows exceed channel capacity. The problem statements, planning objectives, and constraints are summarized as:

Problem Statements

Intense rainfall events cause flooding in the Buffalo Bayou watershed and significant inflows into the Addicks and Barker reservoirs

High water levels in Addicks and Barker reservoirs can extend beyond project lands and pose unacceptable risks to health and human safety, private property, and public infrastructure

Pool releases from Addicks and Barker reservoirs combine with downstream inflows to pose risks to health and human safety, public infrastructure, and private property

Probable maximum flood water elevations for both Addicks and Barker dams have increased as well as the frequencies leading to increased loading on spillways

Spillway protective concrete layers are 25+ years old and have cracks, separations, and erosion

Land subsidence has lowered the spillway elevations

Opportunities Statements

An opportunity exists to address flood damages within the Buffalo Bayou watershed for future high precipitation events.

An opportunity exists to ensure the safety and operability of the Addicks and Barker spillways.

An opportunity exists to address upstream flood damages resulting from high water levels in the Addicks and Barker reservoirs under emergency operations.

4.2 Planning Objectives and Constraints

An objective is a statement of the intended purposes of the planning process; it is a statement of what an alternative plan should try to achieve. More specific than goals, a set of objectives represents the mission statement of the Federal/sponsor planning partnership.

Our planning partnerships exist in a world of scarceness where it is not possible to do everything. Our choices are limited by a number of factors. Planning is no exception. A critical element of any planning study is the set of constraints challenging the planners. A constraint is a restriction that limits the planning process. Constraints, like objectives, are unique to each planning study.

Planning Objectives

Reduce life-safety risks consistent with Corps tolerable risk guidelines

Reduce damages to homes, businesses, and infrastructure in the study area for the 50-year period of analysis (2036 – 2085)

Support community resilience and recovery

Federal Goals

The Federal objective of water and related land resources project planning is to contribute to National Economic Development in harmony with protecting the Nation’s environment, following national environmental laws, applicable executive orders, and other Federal planning requirements. Water and related land resources project plans shall be formulated to lessen problems and take advantage of opportunities in ways that add to this objective.

The use of the term objective should be separated from specific study planning objectives, which are more precise in terms of expected or desired outputs. The Federal objective may be considered more of a National goal.

Planning Constraints

Plans should avoid increasing flood risk or transferring flood risk to other areas. Transferred risk is defined as a result of an action taken in one region of a system to reduce risk, where that action shifts the risk burden to another region in the system. Any eventual recommendation will avoid increasing or transferring the risk to another area.

Plan formulation is the process of building Plans that meet planning objectives, and avoid planning constraints. The PDT defines the combination of management measures that comprise a plan in sufficient detail that realistic evaluation and comparison of the plan's contributions to the planning objectives and other effects can be identified, measured, and considered. This process requires the views of stakeholders and others in agencies and groups outside the Corps to temper the process with different perspectives. Plan formulation capitalizes on imagination and creativity wherever it is found, across technical backgrounds and group affiliations.

Alternatives, sometimes known as alternative plans or just plans, are formulated to address the planning objectives. Combinations of management measures make up these plans, and are defined in sufficient detail, so that realistic evaluation and comparison of each plan’s contributions to the objectives, and effects, can be identified, measured, and considered. Usually multiple alternatives meet planning objectives. Good planning eliminates the least suitable alternatives while refining the remaining alternatives fairly and comprehensively.

Sometimes, the formulation process emphasizes structural details, costs, project outputs, safety, reliability, and other technical matters. Plan formulation must be balanced with environmental, institutional, and other information that is less quantifiable, such as other social effects.

This is a multi-objective study which was formulated to address problems in three specific components:

1) Flood Risk Management;
2) Dam Safety; and
3) System Operational Changes.

4.3 Flood Risk Management Formulation

Specific Flood Risk Management Problems, Opportunity, Objectives and Constraint

Flood Risk Management Problems

- Intense rainfall events cause flooding in the Buffalo Bayou watershed and significant inflows into the Addicks and Barker reservoirs

- High water levels in Addicks and Barker reservoirs can extend beyond project lands and pose unacceptable risks to health and human safety, private property, and public infrastructure
- Pool releases from Addicks and Barker reservoirs combine with downstream inflows to pose risks to health and human safety, public infrastructure, and private property

Specific Flood Risk Management Opportunity Statement

An opportunity exists to address flood damages within the Buffalo Bayou watershed for future high precipitation events.

Specific Flood Risk Management Planning Objectives

- Reduce life-safety risks consistent with Corps tolerable risk guidelines
- Reduce damages to homes, businesses, and infrastructure in the study area for the 50-year period of analysis (2036 – 2085)
- Support community resilience and recovery

Specific Flood Risk Management Planning Constraints

- Plans should avoid increasing flood risk or transferring flood risk to other areas

One of the primary challenges facing this study has been formulating a recommendation that is compliant with traditional Corps policy, specifically a recommendation that would generate positive net benefits in accordance with the National Economic Development objective. A number of both Federal and local flood risk projects have been constructed in the last few decades that addressed the vast majority of the smaller events (2-year to 25-year events) including the Addicks and Barker dams as well as a number conveyance and detention projects both existing and those under construction. However, the system as a whole is susceptible to large events like Hurricane Harvey in 2017.

Three primary strategies can be implemented to address flood risks associated with Addicks and Barker reservoirs during these large-scale events:

1) Increase the amount of storage within the system
2) Increase conveyance of water out of the system
3) Limit the exposure and vulnerability of people, homes, and other property in harm’s way

While the first two strategies apply directly to those measures developed for flood risk management, the third strategy can be accomplished through measures developed to address dam safety concerns at both Addicks and Barker. The analyses have looked at the tradeoffs between performance and the relative cost of the measures. In addition, analysis of the potential for reducing life loss has been evaluated, as has the potential for reducing the number of homes unable to recover in a sufficiently acceptable timeframe based on an analysis of what the potential impacts to resiliency due to the socioeconomic characteristics of an area.

4.4 Preliminary Flood Risk Management Measures

After defining the problems, opportunities, objectives, and constraints, the PDT began formulating structural and nonstructural management measures to address the specific problems with FRM.

A measure is defined as a means to an end; an act, step, or procedure designed for the accomplishment of an objective. In other words, a measure is a feature (structure), or an activity, that can be implemented at a specific geographic site to address one or more planning objectives. Measures are the building blocks of Plans and are categorized as structural and nonstructural. Equal consideration was given to these two categories of measures during the Planning process.

As discussed above, the team formulated for the 3 primary strategies for addressing FRM and then classified those measures within each strategy as either “Anchor Measures” or “Ancillary Measures”. These classifications are defined as:

Anchor measures were those identified as being able to reduce lots of flood risk.

Ancillary measures were identified as being best able to reduce remaining residual risks after one or more Anchor Measures were implemented.

Anchor measures placed in two categories; 1) storage – how a measure could increase the amount of storage within the system; and 2) conveyance – how a measure that would effectively move water. The following describes the anchor measures developed to meet these two strategies (Figure 28 and Figure 29).

Structural Measures to Increase Storage within the System

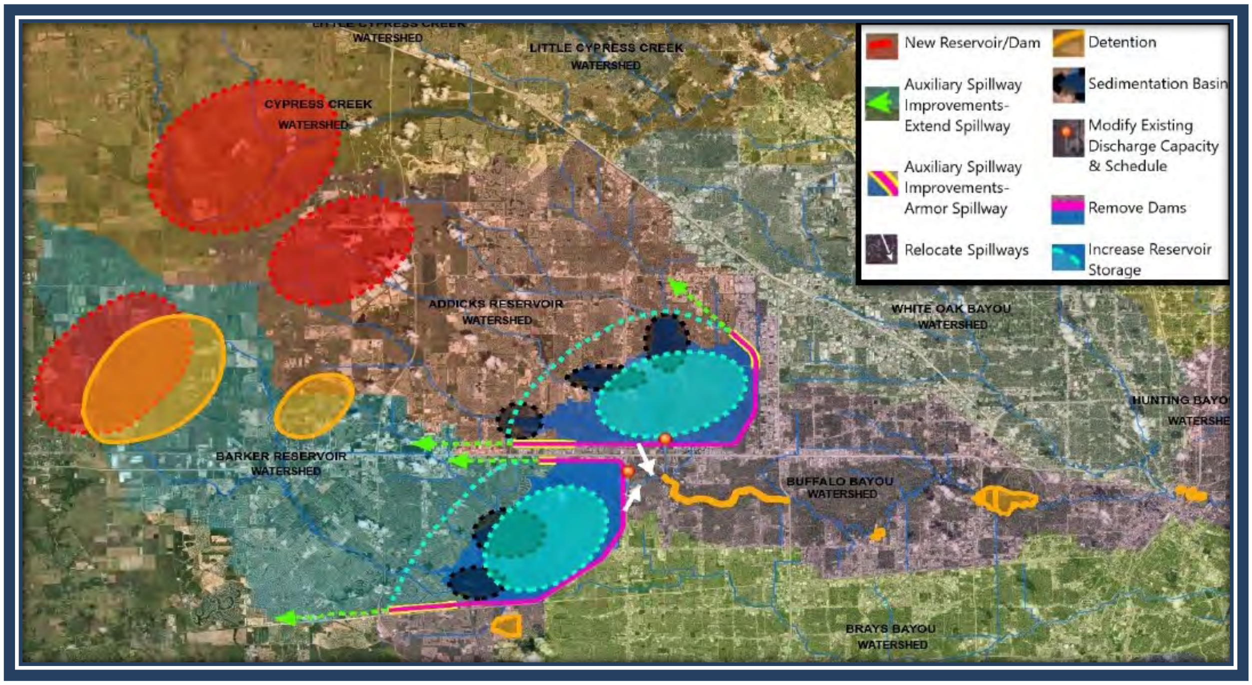

Figure 28. Structural Measures to Increase Storage within the System

Structural Measures to Increase Conveyance out of the System

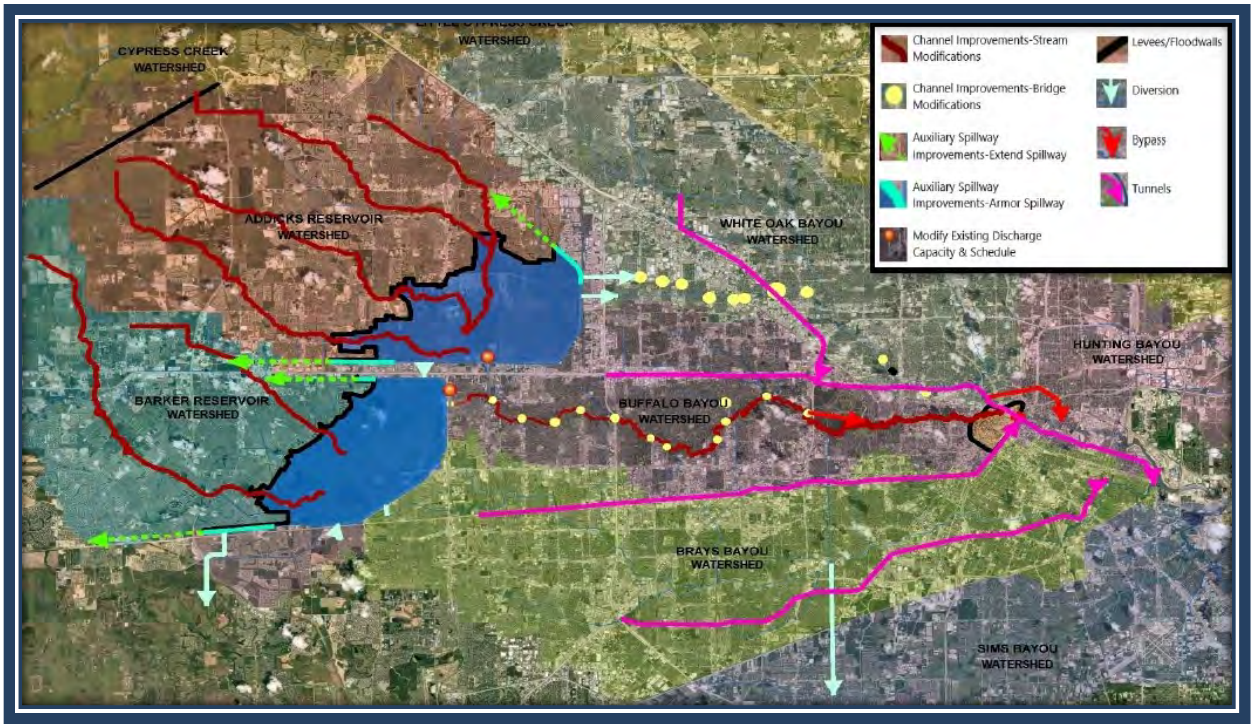

Figure 29. Structural Measures to Increase Conveyance out of the System

4.5 Anchor Measures

Anchor measures were those identified as those that could achieve the largest potential for reducing flood risk.

4.5.1 Storage Measures

4.5.1.1 Cypress Creek Dam

This measure would construct a new reservoir/dam upstream of Addicks in Cypress watershed with top of reservoir embankment elevation of 190 feet (configuration Res2a). It would control runoff from about one-third of the Cypress Creek watershed located above U.S. Hwy 290 into Addicks. It would have the capacity of approximately 190,343 acre-ft. The embankment top or crown width would be 12 feet with a side slopes of 1V:3H. The spillway elevation would be 187 feet, three feet below the top of the embankment elevation. The height of the embankment is approximately 30 feet with an embankment length of approximately 55,000 feet tied to natural high ground at elevation 190 feet. The spillway would be located north of Cypress Creek allowing for the return of uncontrolled flows back to Cypress Creek. The spillway would be constructed of 4,000 psi reinforced concrete with a minimum thickness of ten inches with a cutoff wall on the downstream side of the spillway to prevent internal erosion and undermining from flows across the spillway. The spillway length would be approximately 1,000 feet. The permanent footprint for the embankment would include a width of 100 feet on either side of the toe of the embankment for an approximate right-of-way width of 400 feet.

Estimated flows from the outlet structure would be 2,000 cfs, like the new outlet structure just completed at Addicks, with the exception of two ten foot diameter steel encased conduits as opposed to the three just completed conduits at Addicks. The new approach channel and outlet channel would be constructed such that flows return back into Cypress Creek. Embankment data is shown below. The overflow of the Cypress Creek watershed into the Addicks reservoir would be reduced somewhat but would need to work with other measures (such as channel improvements) to become effective system-wide.

Additionally a reservoir height of 25 feet with an embankment elevation of 180 feet and spillway length of 500 feet was analyzed. A typical embankment section is shown in Figure 31. Embankment data for two configurations (Res2a and Res2c) is shown in the table below.

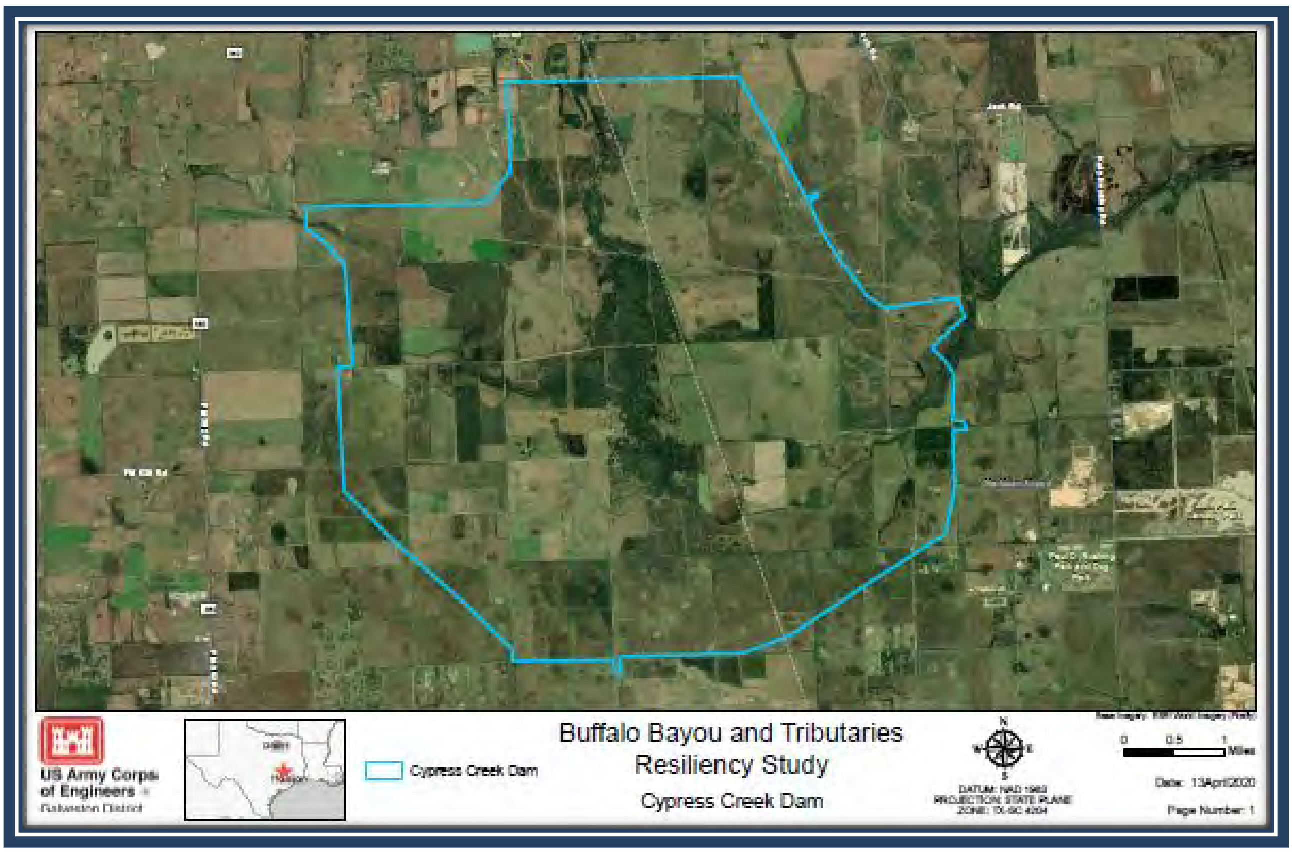

Figure 30. Cypress Creek Reservoir Storage Area

Table 15. Cypress Creek Dam Dimensions

ID	Cypress Creek Dam						Spillway	
	Length (ft)	Elevation (ft)	Crown Width (ft)	Side Slopes	Av. Height (ft)	Fill (CY)	Length (ft)	Elevation (ft)
Res2a	55,000	190	12	1V:3H	30	6,234,000	1,000	187
Res2c	50,160	180	12	1V:3H	25	5,685,000	500	177

Typical embankment sections for Res2a and Res2C is shown below.

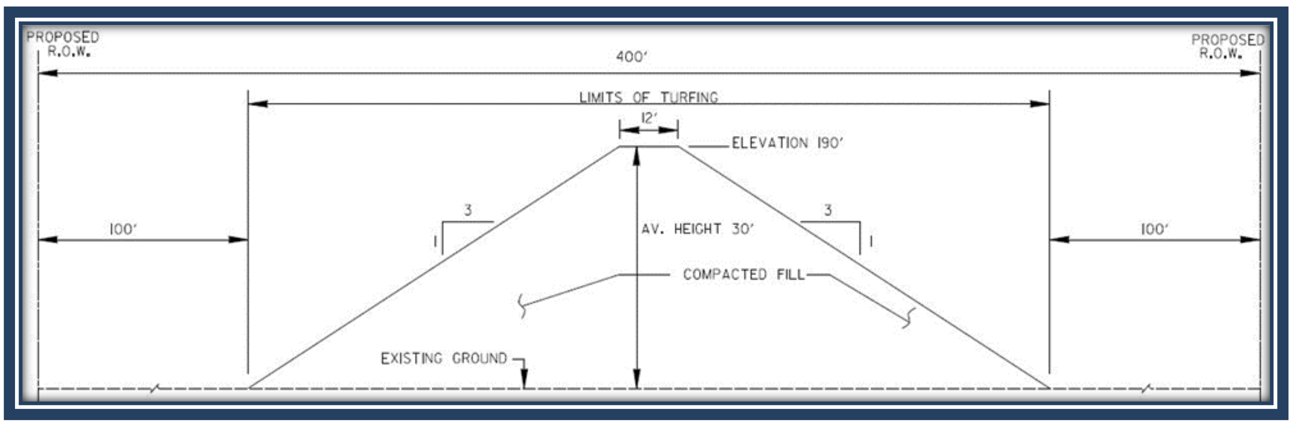

Figure 31. Typical Embankment Section (Res2a)

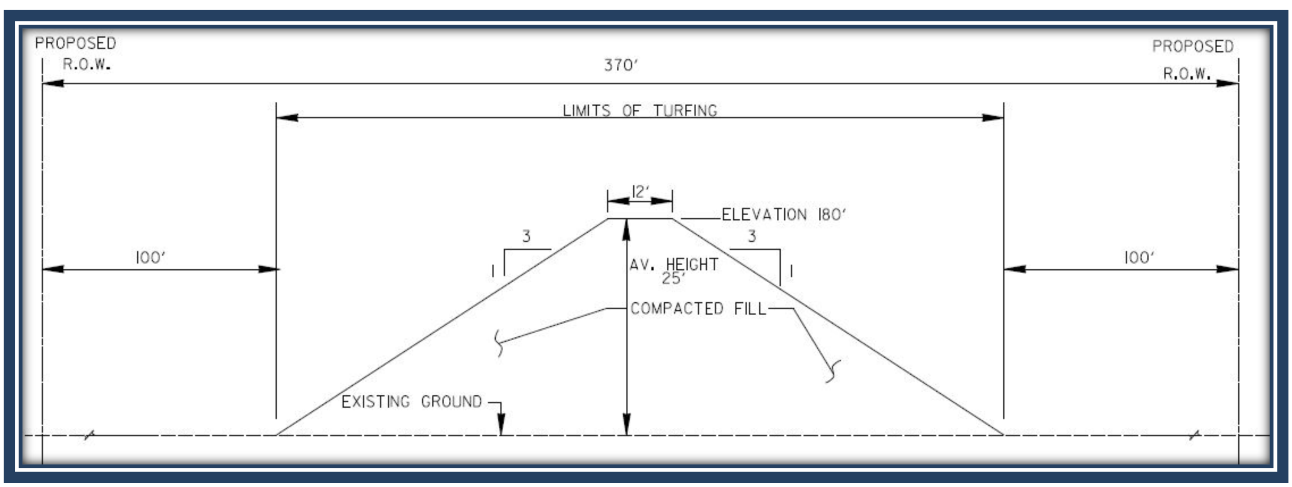

Figure 32. Typical Embankment Section (Res2c)

4.5.1.2 Upper Buffalo Bayou Dam, Ungated

A detention basin would be constructed upstream of Barker reservoir north of Highway 90 bounded on the east by Cardiff Road and on the west of Neuman Road (Figure 33) and would capture sheet flow upstream of Barker. The embankment will be approximately ten feet high with side slopes of 1V:3H. The top of embankment elevation would be 170 feet with a crown width of 12 feet. Figure 34 below is a typical cross section for the proposed detention embankment. The spillway would be at an elevation of 167 feet and approximately 500 feet long. Right-of-way width for the footprint is approximately 275 foot. Borrow material for construction of the embankment would be expected to be taken from within the reservoir, avoiding numerous utilities and pipelines within the reservoir at an excavation depth of ten feet. No excavation would be allowed within 1,100 feet of interior embankment toe. The outfall structure would be ungated consisting of two 36-inch concrete pipes or box culverts. The structure concept is similar to the existing outlet structure at Brays Detention Basin shown in Figure 35.

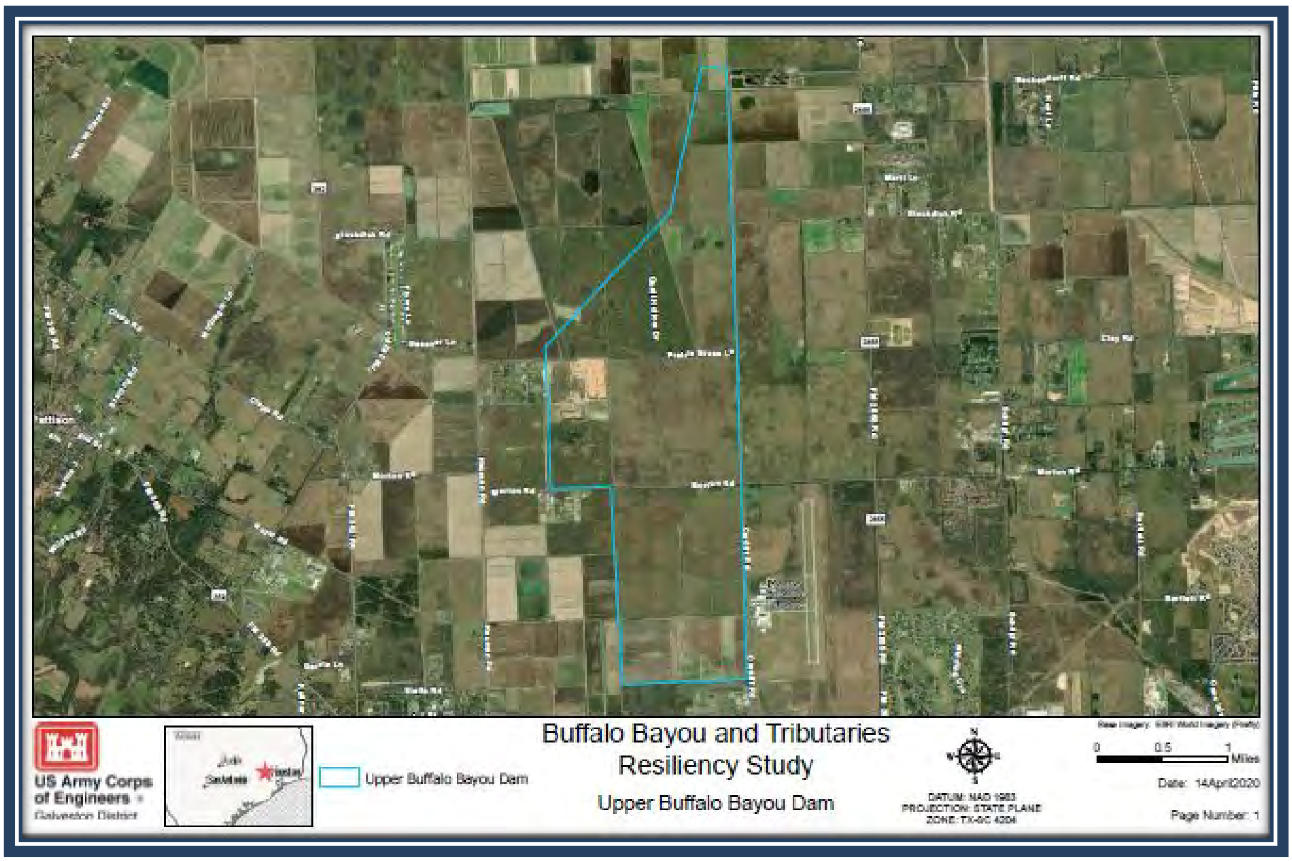

Figure 33. Upper Buffalo Bayou Dam Site

Table 16. Upper Buffalo Detention Data

Length (ft)	Elevation (ft)	Crown Width (ft)	Side Slopes
45,390	170	12	1V:3H
Av. Height (ft)	**Fill (CY)**	**Spillway Length (ft)**	**Spillway Elevation (ft)**
10	70,6100	500	167

Typical embankment section for Res3a is shown below.

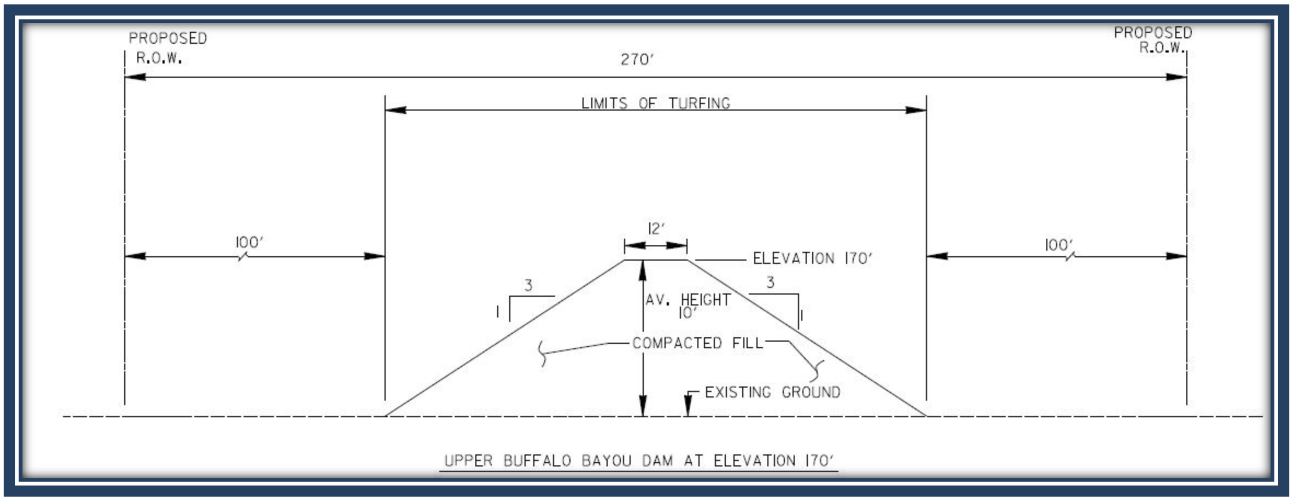

Figure 34. Typical Upper Buffalo Cross Section (Res3a)

Figure 35. Existing Outfall Structure at Brays Detention at Hwy 6

4.5.1.3 Extending Existing Spillways

This would increase storage within both Addicks and Barker reservoirs by extending the existing spillways at their current elevation to an existing matching ground elevation. Embankment material would excavated from within the reservoir to construct 3,750 feet of new embankment for the Addicks North spillway and 400 feet of new embankment for Addicks South spillway. Barker would require 1,600 feet of new embankment for the south spillway and 520 feet of new embankment for the north spillway. The extended spillway would be lined with 4,000 psi reinforced concrete with a minimum thickness of ten inches. Additionally the existing Roller Compacted Concrete (RCC) lining the spillways would be removed and replaced with reinforced concrete lining to address current dam safety issues with the existing RCC. Figure 36 and

Figure 37 below show the extension of the existing spillway for Addicks and Barker reservoirs. The Addicks North spillway extension will require additional real estate to accommodate the footprint.

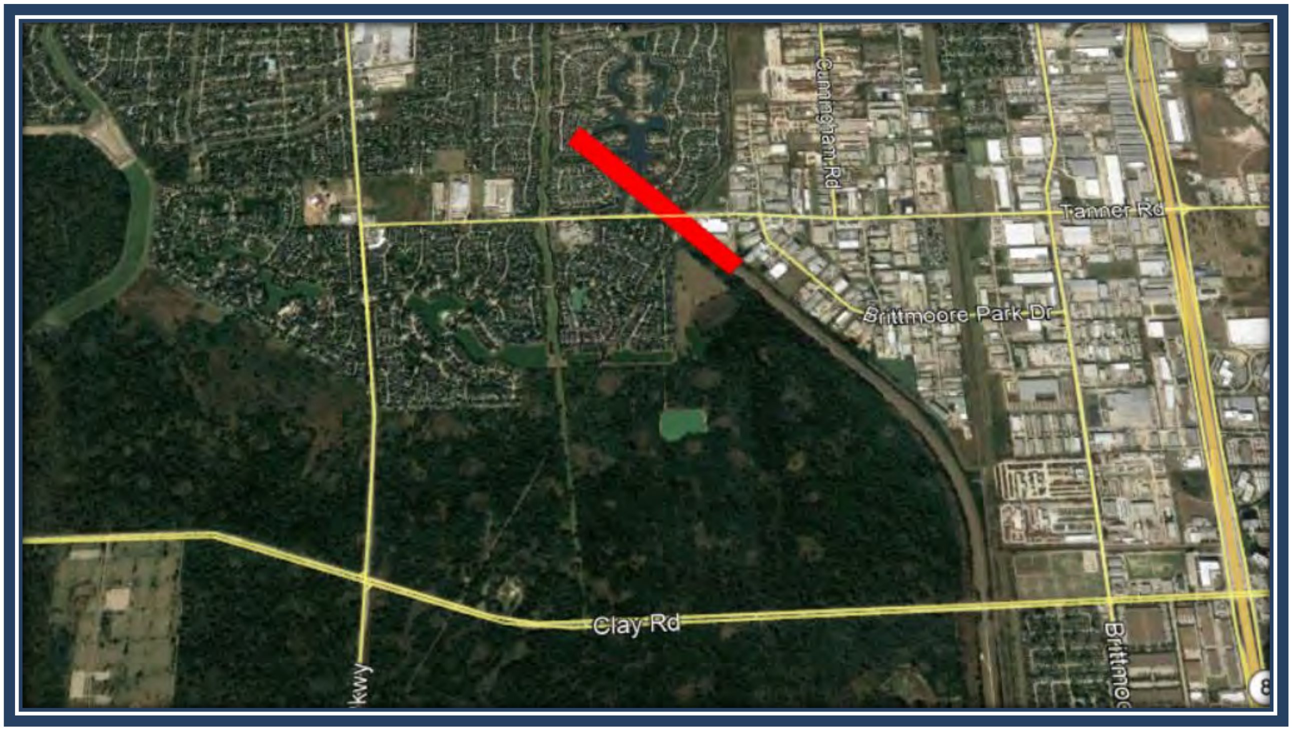

Figure 36. Addicks North Spillway Extension

Table 17. Design Data for Spillway Extension

	Existing Spillway Length (ft)	Average Elevation (ft)	Extended Length (ft)
Addicks North Spillway	8,525	113	3,750
Addicks South Spillway	10,550	113	400
Barker South Spillway	11,700	108	1,600
Barker North Spillway	3,000	106	520

Figure 37. Barker South Spillway Extension

4.5.1.4 Raise Embankment (Stor1b)

This would increase storage within both Addicks and Barker reservoirs by raising the existing dam embankment and spillway embankment height by two feet and extending the spillways to an existing matching ground elevation**.** Figure 38 to Figure 41 below show the extended length of the spillway if it were raised. The existing RCC would be removed from the spillways allowing raising and placement of concrete lining along the length of the spillways. Addicks is at approximately elevation 112 feet, however the proposed spillway will be at elevation 114 feet. Similarly, the spillway for Barker is approximately 105 feet and the proposed elevation is expected to be at elevation 107 feet. Raising the existing dam embankment did not account for adjustments that would have to occur at the new outlet works currently being constructed.

Figure 38. Addicks North Raise 2 Feet and Extend

Table 18. Design Data for Embankment and Spillway Raise

	Existing Spillway Length (ft)	Average Elevation (ft)	Extended Length (ft)
Addicks North Spillway	8,525	115	3,750
Addicks South Spillway	10,550	115	400
Barker South Spillway	11,700	110	1,600
Barker North Spillway	3,000	108	520

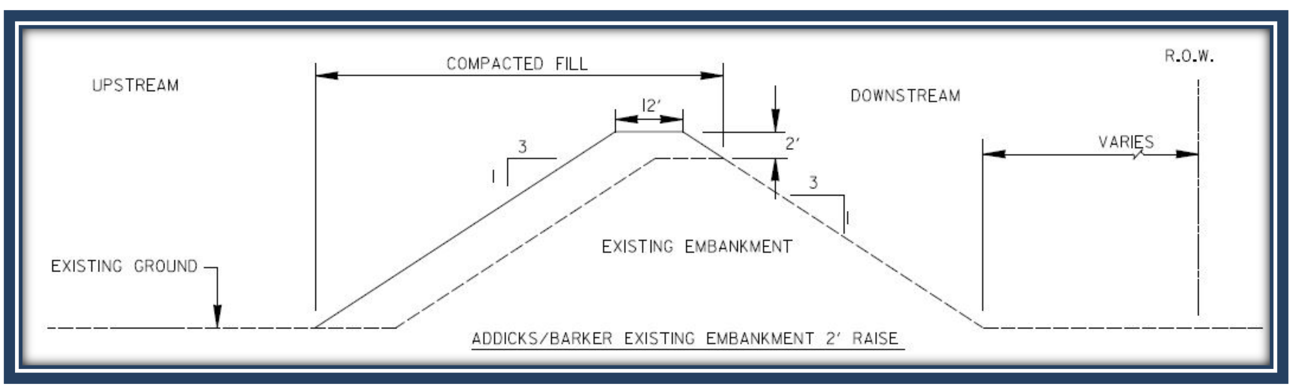

Figure 39. Typical Embankment Raise

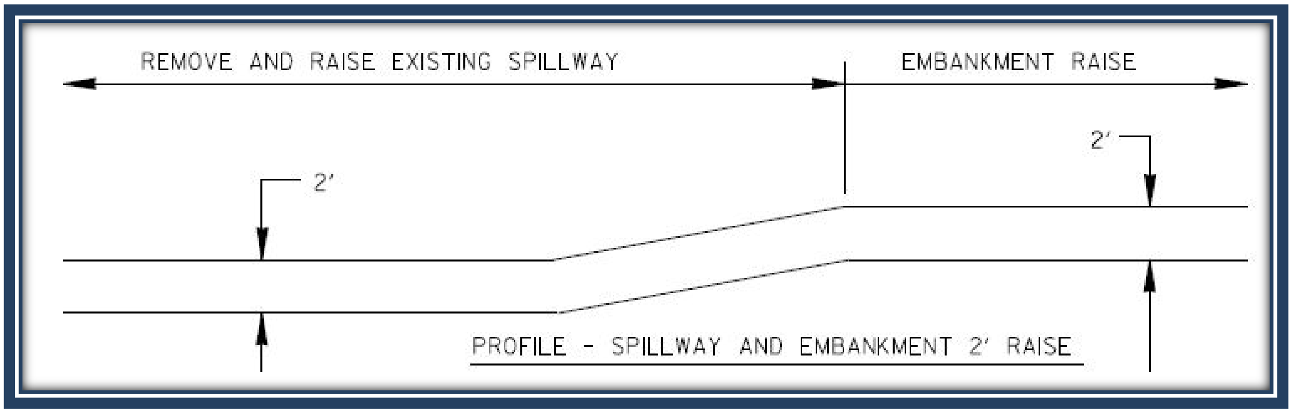

Figure 40. Profile – Spillway and Embankment Raise

Figure 41. Barker North 2 Feet Raise and Extension

4.5.1.5 Reservoir Excavation

Soil would be excavated from Government Own Land (GOL) within the existing reservoirs to increase the total storage capacity. Existing capacity at Addicks is approximately 113 acre-ft. while Barker is 83 acre-ft. Capacity would be expected to increase by either five and fifteen percent in both Addicks and Barker. This increase should also increase the level of protection and help reduce and delay impacts of flooding beyond GOL. The basin would be dry and the bottom elevation would not be lower than the approach channel elevation of 65 feet for Addicks and 67.5 feet for Barker. The five percent storage increase assumed the same four-foot excavation depth based on borrow excavation currently being untaken for outlet improvements at Addicks and Barker in order to avoid groundwater.

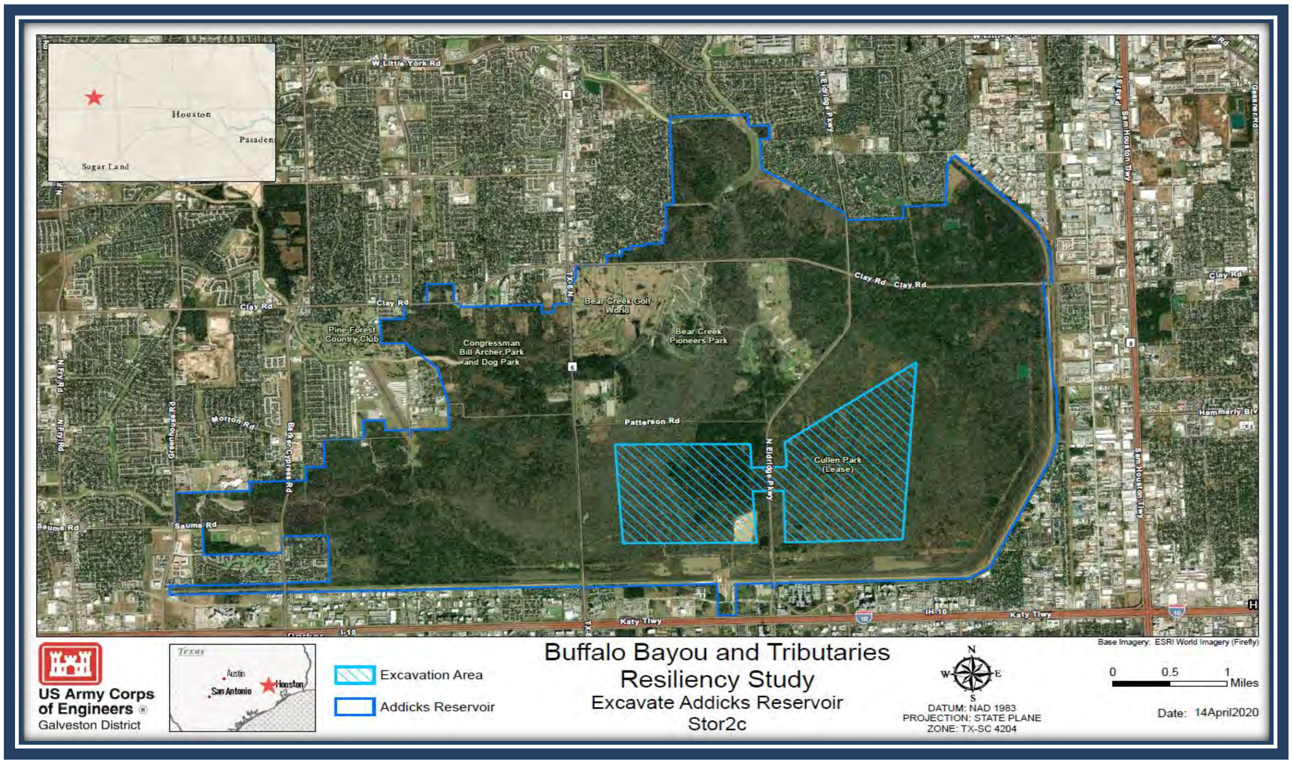

Figure 42. Addicks Reservoir 15% Excavation

Groundwater is estimated to be at depths five to fifteen feet within the silty clay material. Similarly, the fifteen percent storage increase assumed ten feet excavation depth to avoid potential groundwater intrusion. Excavated material would be disposed offsite in accordance with local, state, and federal regulations. Costs for removal of excavated material could be high if the material is required to be hauled a great distance. Figure 42 shows the footprint of the Addicks excavation. The excavated areas would be sloped to drain towards the existing approach channel for the outlet structure which is approximately at elevation 65.0 for Addicks and 67.5 for Barker. Excavations quantities are in Table 19.

Table 19. Excavation Quantities

Increase Reservoir Storage	Existing Storage (ac-ft.)	Increased Storage (ac-ft.)	Excavation (CY)
Addicks Reservoir (5%)	113,263	5,663	9,136,600
Barker Reservoir (5%)	83,410	4,171	6,728,400
Addicks Reservoir (15%)	113,263	16,989	27,409,646
Barker Reservoir (15%)	83,410	12,512	20,185,220

4.5.2 Conveyance

4.5.2.1 Proposed River Tunnels - Tun1d, Tun1e, and Tun1f

Construction of a tunnel would increase conveyance from Barker to the Houston Ship Channel or Galveston Bay and serve as an alternative discharge outlet alleviating pressure on Buffalo Bayou. The proposed design would follow the approximate alignment of Buffalo Bayou at a depth of approximately 150 feet below ground with an approximate length of 23 miles to the ship canal and 34 miles to Galveston Bay. The tunnel will consist of five (5) large drop shafts along the alignment of Buffalo Bayou as (Figure 43). The diameter of the tunnel increases as it moves from the reservoir eastwards from 31 feet to 47.5 feet for the large tunnel (Tun1f), 28.5 feet to 38.5 feet for medium tunnel (Tun1e) and 23 to 32.5 feet for the small tunnel (Tun1d) configuration. For simplicity, the largest diameters were used to estimate the 1.5x diameter for needed right-of-way. Ground surface elevation varies from approximately 85 feet to 23 feet to -1 foot at the outfall from the Barker reservoir to the Houston Ship Channel. The tunnels would cross several channels as well as utilities such as roads, railways, pipelines, and other existing infrastructure. Tunnels are assumed to be operated as gravity flow with at least one pump for dewatering purposes. The proposed design would allow downstream runoff and local flood waters to flow towards the drop shafts along the tunnel, thereby resulting in the reduction of flooding downstream and downtown. The wall thickness of the drop shaft was assumed to be constructed of three foot reinforced concrete with a diameter from 33.5 feet to 46 feet. Construction would be done using specialized tunneling techniques. Below shows a concept of how a proposed tunnel inlet construction would look like.

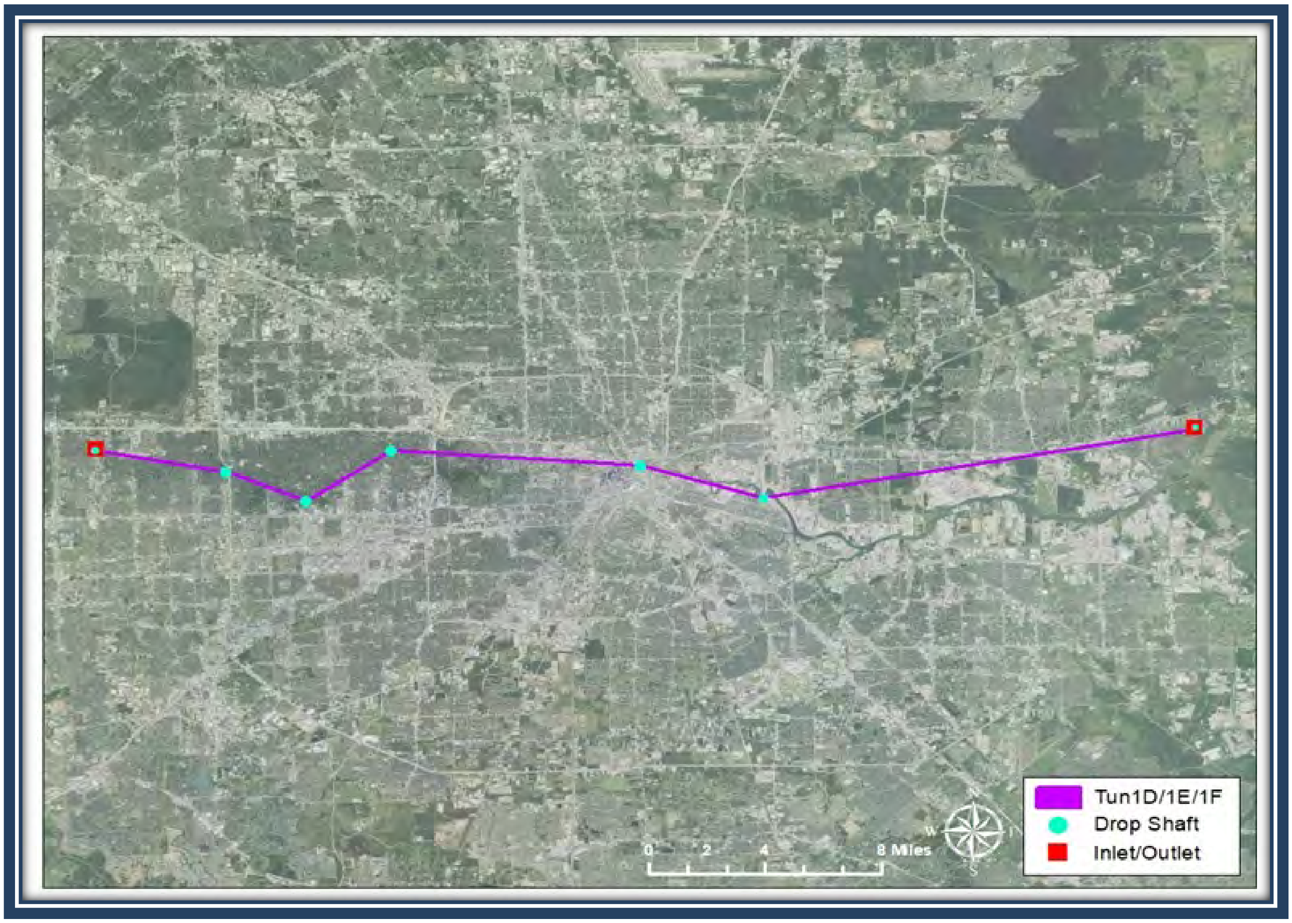

Figure 43. River Tunnel to the Bay

Figure 44. Waller Creek Inlet Construction

4.5.2.2 Proposed Reservoir Tunnels – Tun2a, Tun2b, Tun2c, and Tun2d

Construction of a tunnel would increase conveyance from Barker to the Houston Ship Channel or Galveston Bay and serve as an alternative discharge outlet also alleviating pressure on the Buffalo Bayou. The proposed design is a straight tunnel from West to Eastwards at a depth of approximately 150 feet below ground and approximately 22 miles in length for outfall into the Houston Ship Channel and 35 miles for outfall at Galveston Bay. The tunnels will consist of an inlet and an outlet without drop shafts. The diameter of the tunnel ranges from 33 feet to 47 feet. The small diameter tunnel is 33 feet, medium is 43 feet, and the largest is 47 feet. For simplicity the largest diameters were used for the alignment with a 1.5x diameter for right-of-way. Ground surface elevation varies from 93 feet to 0 feet from Barker to the Houston Ship Channel. The tunnels would cross several channels and utilities such as roads, railways, pipelines, and other infrastructure. The tunnels would operate as gravity flow with at least one pump for dewatering purposes. The thickness of the inlet and outlet would be three feet of reinforced concrete and a diameter of 33 feet. The construction of the tunnels will be done using specialized tunneling techniques.

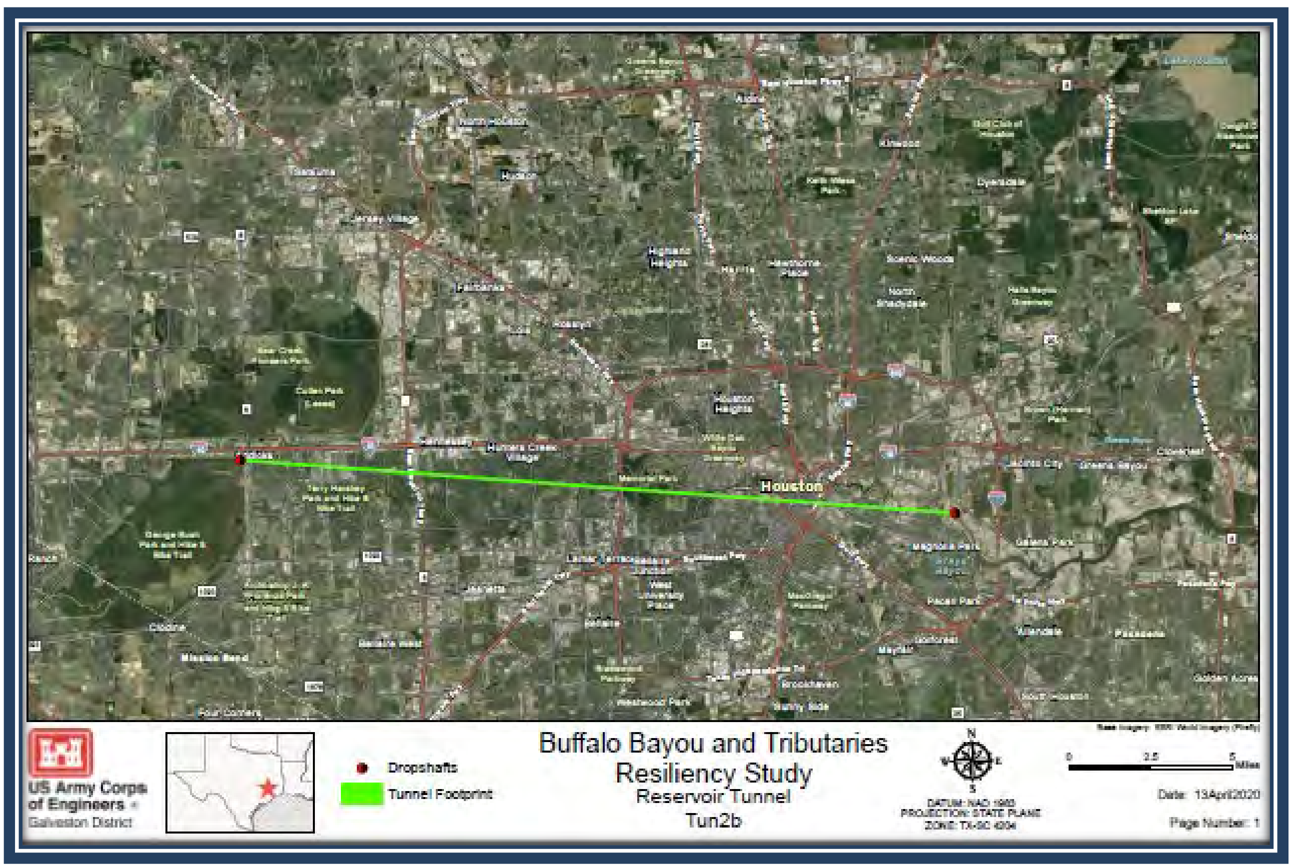

Figure 45. Reservoir Tunnel to Houston Ship Channel

4.5.2.3 Brazos Tunnels – Tun3a, Tun3b

Construction of a tunnel from the southwest Barker reservoir to the Brazos River, Figure 46, would increase discharge and serve as additional alternative conveyance. This additional outflow would bypass Buffalo Bayou and discharge into the Brazos River. The tunnels would have an inlet and an outlet without drop shafts along the alignment at a depth of 150 feet with diameters of 31 feet to 41 feet. For simplicity the largest diameters were used for the alignment with a 1.5x diameter for right-of-way. The tunnel would cross several channels and utilities such as roads, railways, pipelines and other infrastructure. The tunnels would operate as gravity flow with at least one pump for dewatering purposes. Surface elevation varies from 94 feet to 73 feet from the southwest area of Barker to the Brazos. The thickness of the inlet and outlet would be three feet reinforced and a diameter of 31 feet. The construction of the tunnels would be done using specialized tunneling techniques.

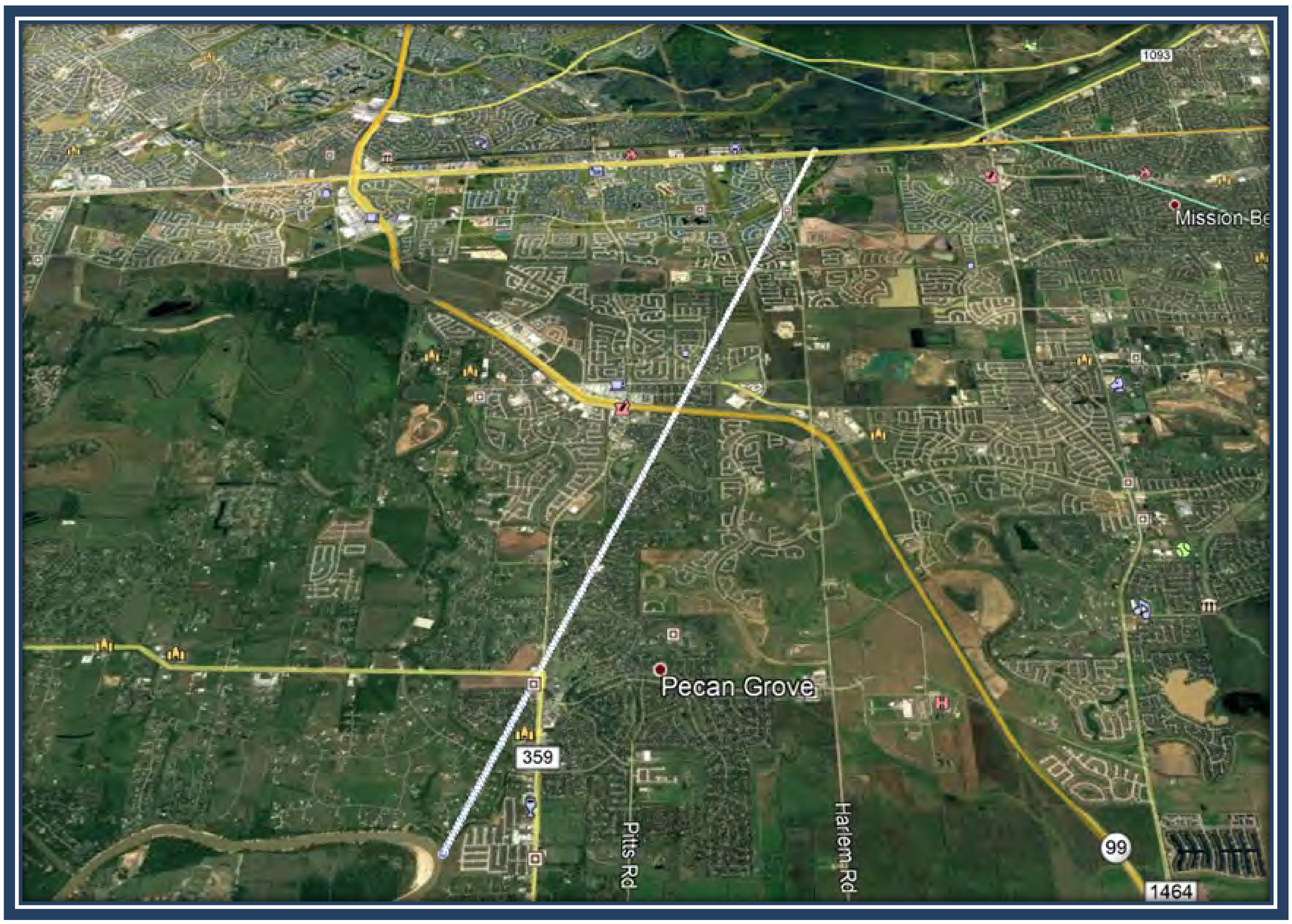

Figure 46. Tunnel from Barker South to Brazos River

4.5.2.4 Diversions – Barker to Brays, Gated (Div 1b)

This would divert Barker storage flows via the construction of a tunnel to an existing detention basin for Brays Bayou as shown above in Figure 47**.** The existing detention basin is located east of Hwy 6 where Brays Bayou crosses Hwy 6. The tunnel inlet would be gated and constructed within Barker reservoir on GOL and would outfall within the existing detention basin just east of Hwy 6 and south of McClendon to Bishop Fiorenza Road. The tunnel would have a diameter of approximately 20 feet and a length of 7,900 feet. The tunnel would be at least 50 feet below ground and would gravity drain into the existing detention basin. Ground surface elevation varies from 91 feet within the reservoir, 112 feet at the dam embankment to 82 feet at the Brays detention basin. The tunnel easement width was estimated to be 1.5x the tunnel diameter over the length of the tunnel for a width of 60 feet.

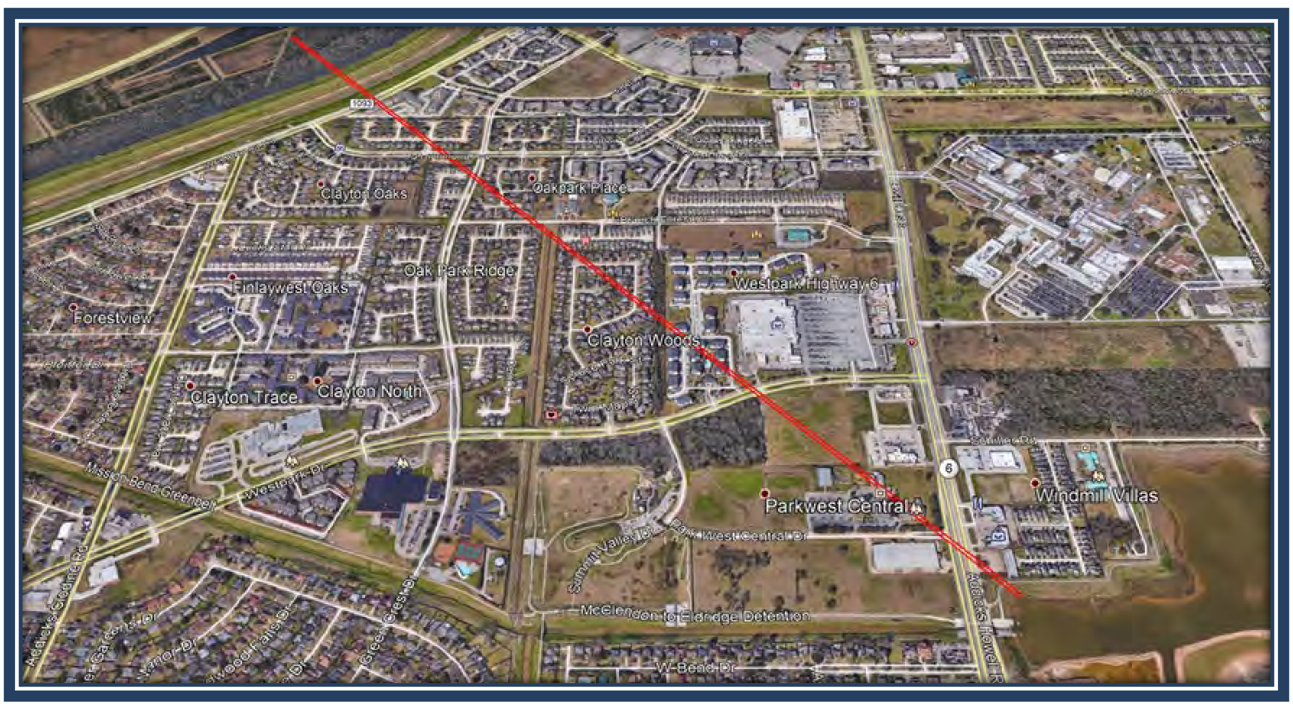

Figure 47. Barker to Brays Diversion

4.5.2.5 Channel Improvements – Buffalo Bayou Channel Improvement (Cha1 and Cha3)

This measure consists of approximately 22 miles (117,500 LF) of channel improvements in the existing Buffalo Bayou starting approximately 1,500 feet downstream of Studemont Street in the Allen Parkway area and continuing upstream to State Highway 6 located downstream of the Baker outfall structure. (Figure 48). These improvements would increase Buffalo Bayou conveyance up to 6,000 cfs and 15,000 cfs (Cha1 and Cha3) respectively. Each would increase the existing channel depth and widen it for additional conveyance. Figure 49 shows a typical section. The 15,000 cfs configuration (Cha3) would be a trapezoidal channel which means widening the existing channel bottom to 70 feet and deepening/cutting the existing bottom grade to an average depth of approximately 11.6 feet. The side slope would be 1V:4H to 1V:3H and the existing centerline would be maintained. Additional analysis will be conducted to shift the existing channel centerline to the center of the existing HCFCD right-of-way to convey design flows and minimize real estate costs. The channel will consist of a low flow of about three to five feet. Existing storm drains would be modified to the lower channel invert. Impacts to existing bridges were roughly estimated so additional analysis will be conducted to ensure all impacts have been captured. The footprint of this measure was estimated to be approximately 230 feet wide at the top while maintaining the existing centerline.

The 6,000 cfs configuration (Cha1) would have a bottom width of 50 feet and deepening/cutting the existing bottom grade to an average depth of approximately 8.4 feet with side slopes of 1V:3H. The average top width would be 180 feet including 30 feet of additional width on either side of the top cut to account for backslope drainage for sheetflow and localized drainage. The alignment would be along the existing centerline.

In some locations the bottom width and side lopes may be adequate. However, several crossings along the Buffalo Bayou such as bridges and utilities exist and a detailed inventory would be conducted to capture existing infrastructure and impacts to channel improvements. Estimates for the number and size of storm drains to be modified for the lowering of the channel invert were made and some may have been captured. Impacts to existing bridges were roughly estimated so additional analysis will be conducted to ensure all impacts have been captured. Channel configurations would be lined with opened cell Articulated Circulated Blocks (ACB) allowing for the establishment of turf within the blocks cells to increase stability and creating a more environmentally acceptable environmental appearance. The ACB blocks would be designed to meet design channel velocities and areas of critical shear stress.

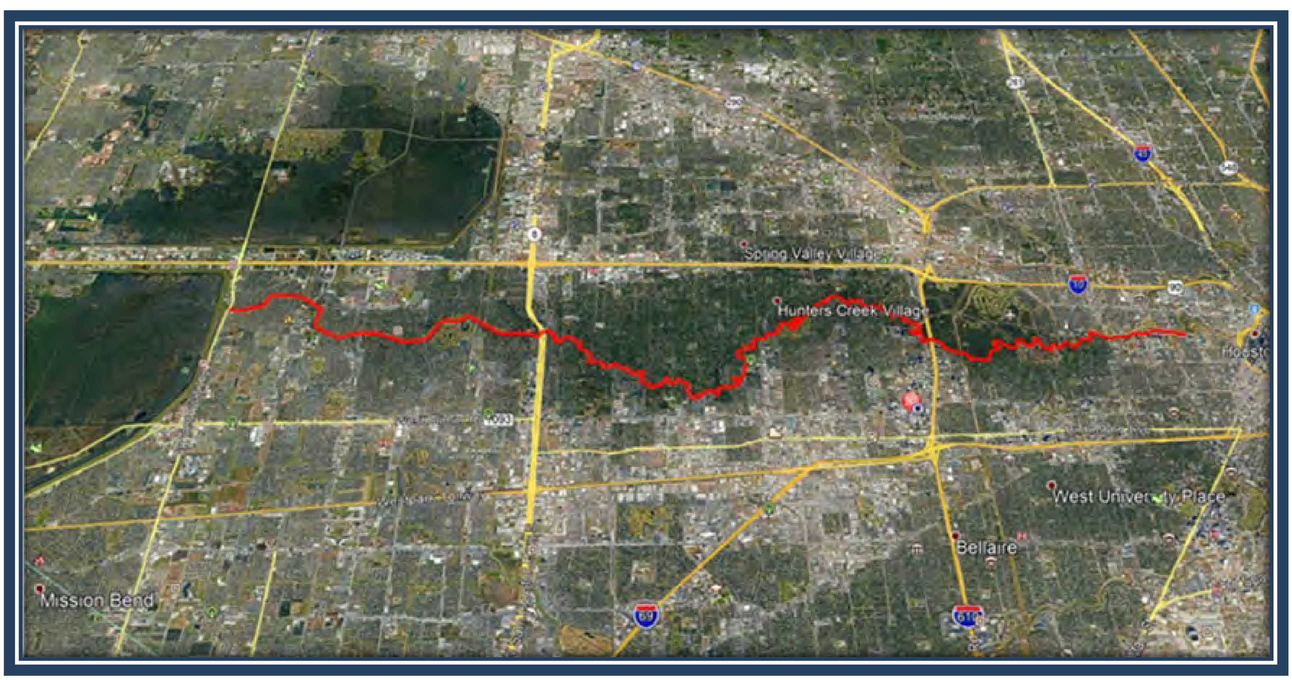

Figure 48. Buffalo Bayou Channel Improvement

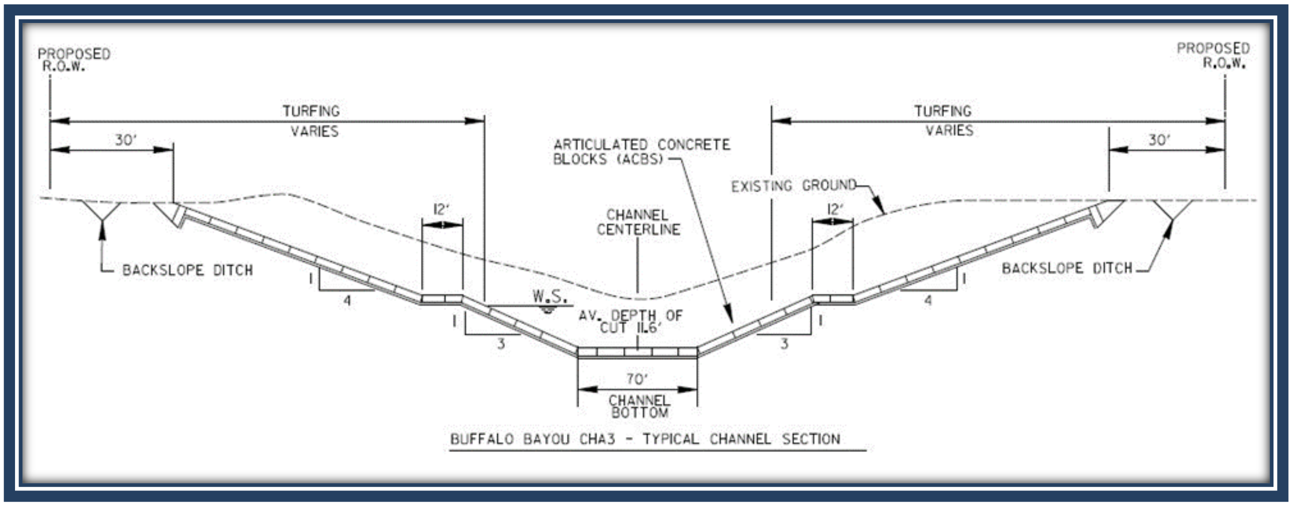

Figure 49. Cross Section of Buffalo Bayou Channel Improvement

Table 20. Channel Improvement Quantities

ID	Length of Improvement (LF)	Average Cut Depth (ft)	Channel Excavation (CY)
Cha1	117,500	8.4	3,098,300
Cha3	117,500	11.6	6,837,850

Costs

The following table displays the costs for the anchor measures initially under consideration.

Table 21. Anchor Structural Measure Costs ($1,000s, Oct. 2019 Price Level)

Anchor Measure	Measure		Measure Configuration	Cost (Low)	Cost (High)
Storage Measures					
New Reservoir	Cypress Creek Dam		Res2c	$1,624,158	$2,192,613
	Upper Buffalo Bayou Dam		Res3a	$397,683	$536,872
Increased Storage	Raise Dam/Extend Spillway*		Stor1a	-	-
			Stor1b	-	-
	Excavate Reservoirs		Sto2a	$1,056,554	$1,426,348
			Sto2c	$1,311,042	$1,769,907
Conveyance Measures					
Tunnels	River Tunnels		Tun1d	$6,524,832	$8,808,523
			Tun1f	$8,935,156	$12,062,461
	Reservoir Tunnels		Tun2a	$4,521,315	$6,103,775
			Tun2b	$5,808,286	$7,841,186
	Brazos Tunnels		Tun3a	$2,238,708	$3,022,256
			Tun3b	$2,869,740	$3,874,149

Diversions	Barker to Brays, Gated		Div1b	$243,095	$328,178
	Addicks/Barker Diversion*		Div3	-	-
Channel Improvements	Increase Channel Capacity		Cha1	$250,980	$338,823
			Cha3	$488,774	$659,845

***These measures were qualitatively screened early and not costed out.**

A number of other measures were considered but were screened early for various reasons. These include the following;

Pumping Stations

Pumping stations were determined to not be feasible or cost effective. Pump stations by themselves would not be efficient since there is insufficient ground slope in the waterways for gravity. Pump stations would be a large upfront cost and also have substantial long-term operation and maintenance.

Injection Wells

Injection wells were determined to not be effective at reducing the flood risk. USACE policy (CR 1130-2-14) prohibits construction of injection wells on GOLs, so wells would have to be constructed outside the reservoirs requiring construction of some form of conveyance (channels, pipes, etc.) and pumping stations to transport water to the well sites and substantial real estate that would be removed from other valuable (ecological and economic) uses. Issues also exist with injecting contaminated stormwater into aquifers.

Restoration and Preservation of Coastal Prairies and Wetlands

Natural and agricultural features provide natural attenuation and relief to downstream flowrates, thereby providing flood benefits to the downstream watershed. Native prairie grasses are known to develop deep and robust root systems that open up the notoriously poorly draining clay soil characteristics of the Texas coastal plain, and substantially increase the ability of the soil to absorb runoff.

The Cypress Creek Overflow Plan, developed by HCFCD, investigated the concept of restoring native prairies to decrease the net volume of runoff. While the plan found that restoring prairies is an effective measure in reducing the volume to Addicks Reservoir, along with a slight reduction in flow and overflow during large rainfall events, the number of acres needed would be substantial to make a significant difference in the flood risk. The plan would capture virtually all runoff from smaller, relatively frequent events and would reduce runoff by up to 55 percent for large events. Restoration of one acre of prairie would offset the impact of two acres of single-family land use or an acre of commercial development. (TWDB 2015).

Other studies have investigated the benefits of habitat restoration on floodwater detention. The EPA estimates that one acre of wetlands can store between 1.0 to 1.5 million gallons of water

(EPA 2002), significantly higher than prairie retention. However, wetlands restoration is challenging given the extent of potential watershed and channel modifications. Prairie and wetland restoration measures are efficient and effective at storing water at a local scale and should be a consideration by others as a means to contribute to flood risk reduction in the study area. For this study however, land required for prairie and wetland restoration is outside the authorized study area.

The following table summarizes the structural measures along with the location of where these are to be assessed and the intended purpose of each.

Table 22. Measures Summary

Structural Measures	Location/Components	Purpose
No Action		Leaves reservoirs discharge (2,000 cfs) and dam structures as is
Dams & Reservoirs	*Upper Cypress Creek* *Addicks Watershed* *Barker Watershed*	Provides additional storage upstream and stores/reduces overflow from Cypress Creek to Addicks watershed Provides additional storage upstream and stores overflow from Cypress Creek. Provides additional storage upstream
Reservoir Excavation	*Excavation of the reservoir interior* *Raise dam embankment*	Additional storage to the existing reservoirs. Increases level of flood protection
Detention	*Detention storage Upstream/Downstream*	To reduce inflows and flood damages downstream.
Dam Raising	*Addicks* *Barker*	Raising the crest of the dam by placing additional material on top of the existing dam crests and on the upstream side of the dams to retain slope
Tunnels	*Network of Tunnels*	Increase conveyance/discharge away from the two reservoirs
Bypass	*White Oak/Buffalo Confluence* *Buffalo Bayou near I-610*	The measure is to increase conveyance along Buffalo Bayou
Diversion	*Clodine Ditch to Brays Bayou* *Barker to Brays Bayou* *Barker to Oyster/Brazos* *Addicks to White Oak* *Addicks Reservoir to Barker Reservoir* *Addicks Reservoir to Cole Creek*	Increases conveyance in Buffalo Bayou. Increases Addicks capacity

Channel Improvements	*Buffalo Bayou (Bridge Modifications)* *Buffalo Bayou (Bank Stabilization)* *Buffalo Bayou* *White Oak Bayou*	Improves conveyance of water underneath bridges, reduces localized flooding
Levees/Floodwalls	*Cypress Creek/Addicks Watershed* *Ring Levee around Downtown Houston* *Backside of Addicks and Barker* *White Oak/Addicks watersheds*	Reduces overflow from Cypress Creek watershed. Reduces overflow to downtown. Reduces overflow from watershed from the reservoirs. Reduce overflow from White Oak watershed.

4.6 Nonstructural Measures

Analysis of the potential of nonstructural measures consisted of those two primary areas, downstream of Barker Dam along Buffalo Bayou and upstream of both Addicks and Barker Dams in the Addicks and Barker watersheds. While a number of various nonstructural measures are mentioned earlier in this report (acquisitions, elevation, wet and dry floodproofing, etc.) initial analysis looked at the more consequential measure of acquisition for a broad-based perspective on its relative feasibility. The downstream analysis was done in more policy-compliant, NED-type of analysis determining the relative cost effectiveness of acquiring structures based on the event structures may be in. The area upstream of Addicks and Barker was looked at from a systems operations perspective at Addicks and Barker due to changed conditions based on changes in climate and increased development.

- Elevation – Lifts an existing structure to an elevation, which is at least equal to or greater than the 0.01 annual exceedance flood elevation
- Relocation – Requires physically moving the at-risk structure and buying the land upon which the structure is located

- Acquisitions – Buying the structure and land. The structure could be demolished or sold to others and relocated to a site external to the floodplain. It is required for the relocation measure.
- Dry Floodproofing – Prevents water from entering the structure
- Wet Floodproofing – Allows water to enter and exit the structure
- Flood Warning Preparedness – Includes a Flood Warning System in conjunction with Flood Emergency Preparedness Plans. Flood Warning Systems rely upon stream gage, rain gages, and hydrologic computer modeling to determine the impacts of flooding for areas of potential flood risk. Plans should incorporate the community’s response to flooding, location of evacuation centers, primary evacuation routes, and post flood recovery processes

- Zoning Changes - Land use regulations would identify where future development can and cannot occur, or to what elevation structures should locate their lowest habitable floor
- Reservoir Operations Changes – Modify Addicks and Barker water control operations and update the Water Control Plan

4.6.1 Buffalo Bayou

Any potential acquisition plans for Buffalo Bayou, downstream of the two reservoirs were evaluated for all eight events in the three upstream reaches. The most downstream reach was not evaluated given the commercial and industrial structure inventory in the reach. The PDT deemed that buying out commercial and industrial structures was not viable due to costs involved and the difficulty of relocating these businesses. Table 23 summarizes the number of structures, expected annual damages (EAD), costs, net benefits and BCRs for each plan. The number of structures ranged from 19 in the 2-year event plan with an acquisition cost of $204 million to 4,140 in the 500-year event plan with an acquisition cost of almost $10 billion. For the 2, 5, 10 and 25-year events, BCRs were greater than 1.0, and therefore economically justified. For the 50-year event, the BCR was 0.91, and for remaining plans, BCRs are well below 1.0. A detailed accounting of benefits and costs by plan and reach is shown in Table 23 to Table 31. Buffalo Bayou reach 4 includes mostly industrial structures and would not be included in the acquisition plan.

Table 23. Summary of Buffalo Bayou Acquisition Plans ($1,000, Oct 2019 Prices, 2.75% Interest Rate)

Plan	# of Struc.	EAD	First Cost	Annual Cost	Net Benefits	BCR
2 Year	19	$55,678	$203,742	$7,754	$47,924	7.18
5 Year	33	58,046	264,326	10,062	47,984	5.77
10 Year	64	60,532	437,659	16,659	43,873	3.63
25 Year	341	77,425	1,937,351	73,744	3,681	1.05
50 Year	441	78,789	2,276,649	86,659	-7,870	0.91
100 Year	825	82,892	3,213,387	122,315	-39,423	0.68
200 Year	1,737	86,854	5,309,698	202,110	-115,256	0.43
500 Year	4,140	$91,043	$9,784,192	$372,427	-$281,384	0.24

Table 24. Buffalo Bayou 2 Year Acquisition Plan ($1,000 Oct 2019 Prices, 2.75% Interest Rate)

Reach	No. of Structs	EAD	Real Estate Acq.	Real Estate Cont.	Demo.	Const. Cont.	PED	Const. Mgmt.	First Cost	Annual Cost	Net Benefit s	BCR
Reach 1	1	$293	$462	$92	$60	$18	$95	$95	$823	$31	$262	9.44
Reach 2	12	2,478	39,730	7,946	720	216	7,292	7,292	63,195	2,405	73	1.03
Reach 3	6	52,907	89,177	17,835	360	108	16,122	16,122	139,724	5,318	47,589	9.95
Total	19	$55,678	$129,369	$25,874	$1,140	$342	$23,509	$23,509	$203,742	$7,754	$47,924	7.18

Table 25. Buffalo Bayou 5 Year Acquisition Plan ($1,000 Oct 2019 Prices, 2.75% Interest Rate)

Reach	No. of Structs	EAD	Real Estate Acq.	Real Estate Cont.	Demo.	Const. Cont.	PED	Const. Mgmt.	First Cost	Annual Cost	Net Benefit s	BCR
Reach 1	1	$293	$462	$92	$60	$18	$95	$95	$823	$31	$262	9.44
Reach 2	23	3,108	49,744	9,949	1,380	414	9,223	9,223	79,932	3,043	65	1.02
Reach 3	9	54,646	117,089	23,418	540	162	21,181	21,181	183,572	6,988	47,658	7.82
Total	33	$58,046	$167,295	$33,459	$1,980	$594	$30,499	$30,499	$264,326	$10,062	$47,984	5.77

Table 26. Buffalo Bayou 10 Year Acquisition Plan ($1,000 Oct 2019 Prices, 2.75% Interest Rate)

Reach	No. of Structs	EAD	Real Estate Acq.	Real Estate Cont.	Demo.	Const. Cont.	PED	Const. Mgmt.	First Cost	Annual Cost	Net Benefit s	BCR
Reach 1	2	$325	$1,033	$207	$120	$36	$209	$209	$1,814	$69	$256	4.71
Reach 2	37	5,162	128,067	25,613	2,220	666	23,485	23,485	203,536	7,747	-2,585	0.67
Reach 3	25	55,045	147,290	29,458	1,500	450	26,805	26,805	232,308	8,843	46,202	6.22
Total	64	$60,532	$276,390	$55,278	$3,840	$1,152	$50,499	$50,499	$437,659	$16,659	$43,873	3.63

Table 27: Buffalo Bayou 25 Year Acquisition Plan ($1,000 Oct 2019 Prices, 2.75% Interest Rate)

Reach	No. of Structs	EAD	Real Estate Acq.	Real Estate Cont.	Demo.	Const. Cont.	PED	Const. Mgmt.	First Cost	Annual Cost	Net Benefits	BCR
Reach 1	5	$342	$2,404	$481	$300	$90	$491	$491	$4,258	$162	$180	2.11
Reach 2	181	13,748	489,068	97,814	10,860	3,258	90,150	90,150	781,300	29,740	-15,992	0.46
Reach 3	155	63,335	728,254	145,651	9,300	2,790	132,899	132,899	1,151,793	43,842	19,493	1.44

Total	341	$77,425	$1,219,727	$243,945	$20,460	$6,138	$223,541	$223,541	$1,937,351	$73,744	$3,681	1.05

Table 28: Buffalo Bayou 50 Year Acquisition Plan ($1,000 Oct 2019 Prices, 2.75% Interest Rate)

Reach	No. of Structs	EAD	Real Estate Acq.	Real Estate Cont.	Demo.	Const. Cont.	PED	Const. Mgmt.	First Cost	Annual Cost	Net Benefits	BCR
Reach 1	10	$433	$12,615	$2,523	$600	$180	$2,388	$2,388	$20,694	$788	-$355	0.55
Reach 2	208	14,080	546,605	109,321	12,480	3,744	100,822	100,822	873,794	33,260	-19,180	0.42
Reach 3	223	64,276	871,506	174,301	13,380	4,014	159,480	159,480	1,382,161	52,611	11,665	1.22
Total	441	$78,789	$1,430,726	$286,145	$26,460	$7,938	$262,690	$262,690	$2,276,649	$86,659	-$7,870	0.91

Table 29: Buffalo Bayou 100 Year Acquisition Plan ($1,000 Oct 2019 Prices, 2.75% Interest Rate)

Reach	No. of Structs	EAD	Real Estate Acq.	Real Estate Cont.	Demo.	Const. Cont.	PED	Const. Mgmt.	First Cost	Annual Cost	Net Benefits	BCR
Reach 1	114	$611	$56,683	$11,337	$6,840	$2,052	$11,537	$11,537	$99,985	$3,806	-$3,195	0.16
Reach 2	329	14,961	697,648	139,530	19,740	5,922	129,426	129,426	1,121,692	42,696	-27,735	0.35
Reach 3	382	67,320	1,251,907	250,381	22,920	6,876	229,813	229,813	1,991,710	75,813	-8,493	0.89
Total	825	$82,892	$2,006,239	$401,248	$49,500	$14,850	$370,775	$370,775	$3,213,387	$122,315	-$39,423	0.68

Table 30: Buffalo Bayou 200 Year Acquisition Plan ($1,000 Oct 2019 Prices, 2.75% Interest Rate)

Reach	No. of Structs	EAD	Real Estate Acq.	Real Estate Cont.	Demo.	Const. Cont.	PED	Const. Mgmt.	First Cost	Annual Cost	Net Benefits	BCR
Reach 1	437	$1,177	$299,021	$59,804	$26,220	$7,866	$58,937	$58,937	$510,784	$19,443	-$18,266	0.06
Reach 2	498	15,855	973,644	194,729	29,880	8,964	181,082	181,082	1,569,382	59,737	-43,882	0.27
Reach 3	802	69,823	2,018,083	403,617	48,120	14,436	372,638	372,638	3,229,532	122,930	-53,107	0.57
Total	1,737	$86,854	$3,290,747	$658,149	$104,220	$31,266	$612,657	$612,657	$5,309,698	$202,110	-$115,256	0.43

Table 31: Buffalo Bayou 500 Year Acquisition Plan ($1,000 Oct 2019 Prices, 2.75% Interest Rate)

Reach	No. of Structs	EAD	Real Estate Acq.	Real Estate Cont.	Demo.	Const. Cont.	PED	Const. Mgmt.	First Cost	Annual Cost	Net Benefits	BCR
Reach 1	1,071	$2,106	$1,015,162	$203,032	$64,260	$19,278	$195,260	$195,260	$1,692,252	$64,414	-$62,308	0.03
Reach 2	1,559	17,004	1,622,292	324,458	93,540	28,062	310,253	310,253	2,688,858	102,349	-85,345	0.17
Reach 3	1,510	71,933	3,365,364	673,073	90,600	27,180	623,433	623,433	5,403,082	205,664	-133,731	0.35
Total	4,140	$91,043	$6,002,818	$1,200,564	$248,400	$74,520	$1,128,945	$1,128,945	$9,784,192	$372,427	-$281,384	0.24

The only non-structural plans that are economically justified are the 2, 5 10, 25 and possibly 50-year event plans along Buffalo Bayou. Among these, the 5-year event provides the greatest net benefits, and is the national economic development (NED) plan based on existing information.

4.6.2 Real Estate Required for Systems Operations

When Addicks and Barker Dams were originally constructed, real estate interests were acquired to support operations based on historic storm data for multiple events prior to 1948. Large flood events in 1899 (Hearne, Texas Storm), 1921 (Taylor, Texas Storm), and 1935 were the basis for the standard project flood and spillway design floods for the original design analysis for Addicks and Barker in the late 1930s and early 1940s. Since that time, changed conditions within the system have led to increased runoff and larger storms. As evidenced in 2017, pools under large-scale flooding events can exceed the area currently owned by the Corps. In addition, Corps guidance (EM 1110-2-1420, Hydrologic Engineering Requirements for Reservoirs dated 24 Sep 2018) indicates that, if the projects were built today, the Corps would acquire the higher of either the standard project flood, or the lower end of the dam where spilling starts, as well as some freeboard allowance (~3 feet). The SPF elevation for Addicks is stated as 107.6 feet NAVD 88 and Barker is 98.3 feet NAVD 88.

Discussed earlier, transferred risk is defined as a result of an action taken in one region of a system to reduce risk, where that action shifts the risk burden to another region in the system. Changed conditions have led to a transference of risk to properties outside, particularly upstream, of GOL due to changes in climate that have resulted in the increased recurrence of large events leading to higher pool elevations at both Addicks and Barker as well as increases to the frequencies. Development has also increased over time thereby subjecting more people and property to a higher risk of flooding especially during large events such as Harvey as inflows become greater than what the reservoirs can release. During a 0.002 AEP event (500-year) inflows at Addicks can reach 100K cfs under the future without project condition and 70K cfs at Barker.

The Addicks and Barker dams operate in such a way as to impound upper watershed runoff before it can flood downtown Houston. Impounded waters are released in accordance with a water control manual to minimize downstream flood impacts. In heavy precipitation events, impounded waters may extend above Government Owned Land. Alternatives were formulated to address these operational risks at Addicks and Barker reservoirs which would involve expansion of GOL.

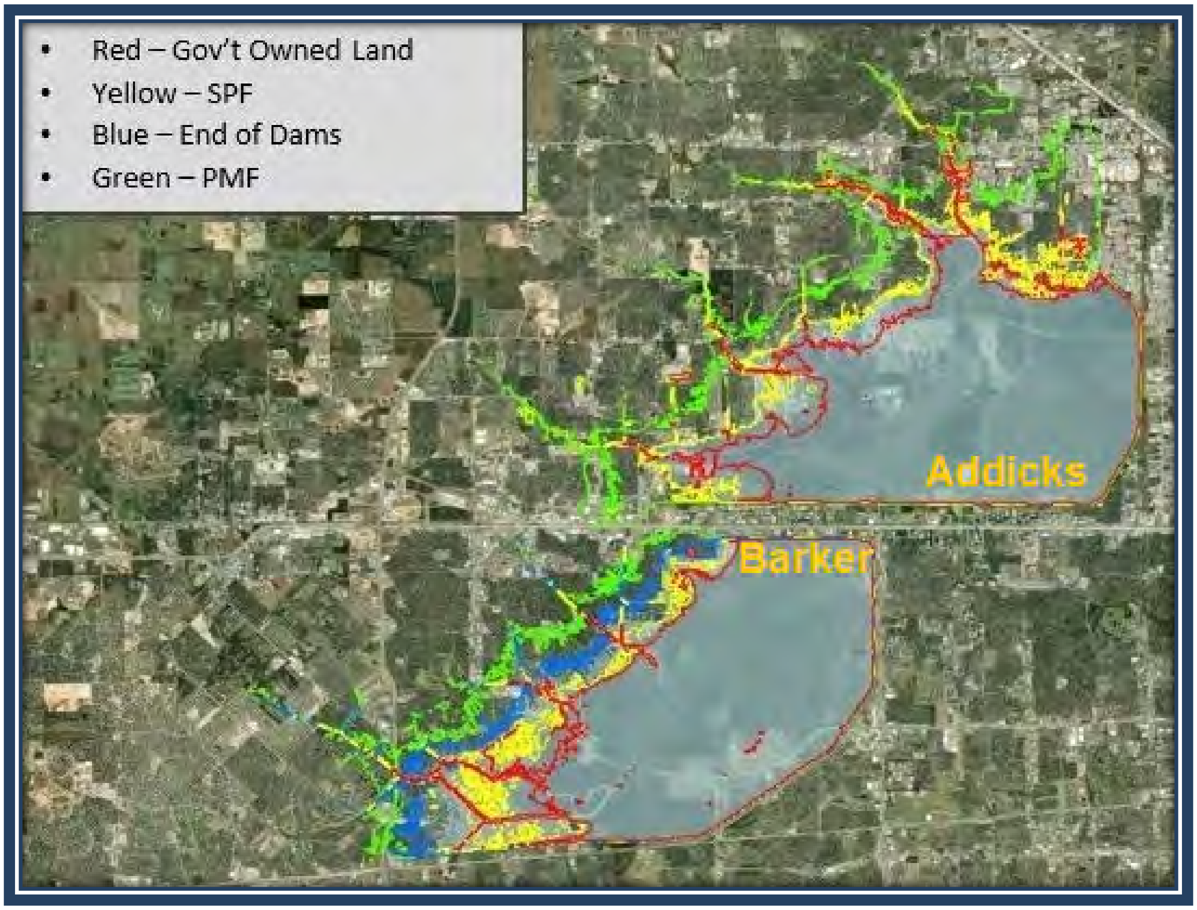

Figure 50. Addicks and Barker Guidance Reference Elevations

The following shows the relevant reservoir pool elevations. In the original design, the land acquisition flood (LAF) was specified as the 1935 storm centered over each watershed (USACE, 1940). The original acquisition plan called for an additional 3 feet of freeboard above that LAF. If 3 feet of freeboard were applied to the current SPF an elevation of 110.5 feet NAVD in Addicks and 102 feet NAVD in Barker would be the acquisition guide contour. The guidance for high level spillways would also apply to the Addicks and Barker reservoirs and could be interpreted to mean the end of the dams (108 at Addicks and 104 at Barker) or the average spillway elevations (111.5 at Addicks and 105.0 at Barker). Figure 50 displays graphical representation of where these delineations lie in relation to each other.

Table 32. Reservoir pool elevations.

	Addicks Dam, ft. NAVD	Barker Dam, ft. NAVD
Spillway Design Flood	116.0	109.9
Approx. Spillway Crest	111.5	105.0
Harvey Peak Pool Level	109.1	101.6
Top of Surcharge Envelope	108.8	103.7
Elevation at the end of dams	108.0	104.0
Standard Project Flood	107.5*	99.0*
Govt. Owned Land	103.0	95.0

*These are in the process of being updated

The following graphs illustrate the frequencies (defined as annual exceedance probabilities or ACE) and their associated stages at both Addicks and Barker. This analysis is based on current modeling and includes the most recent significant events including Hurricane Harvey. Figure 51 and Figure 52 show the pool frequency for the Addicks and Barker reservoirs respectively. Each is labeled with relevant information including approximate spillway crest, Harvey peak pool level, the SPF, elevation of the first home flooded, and GOL.

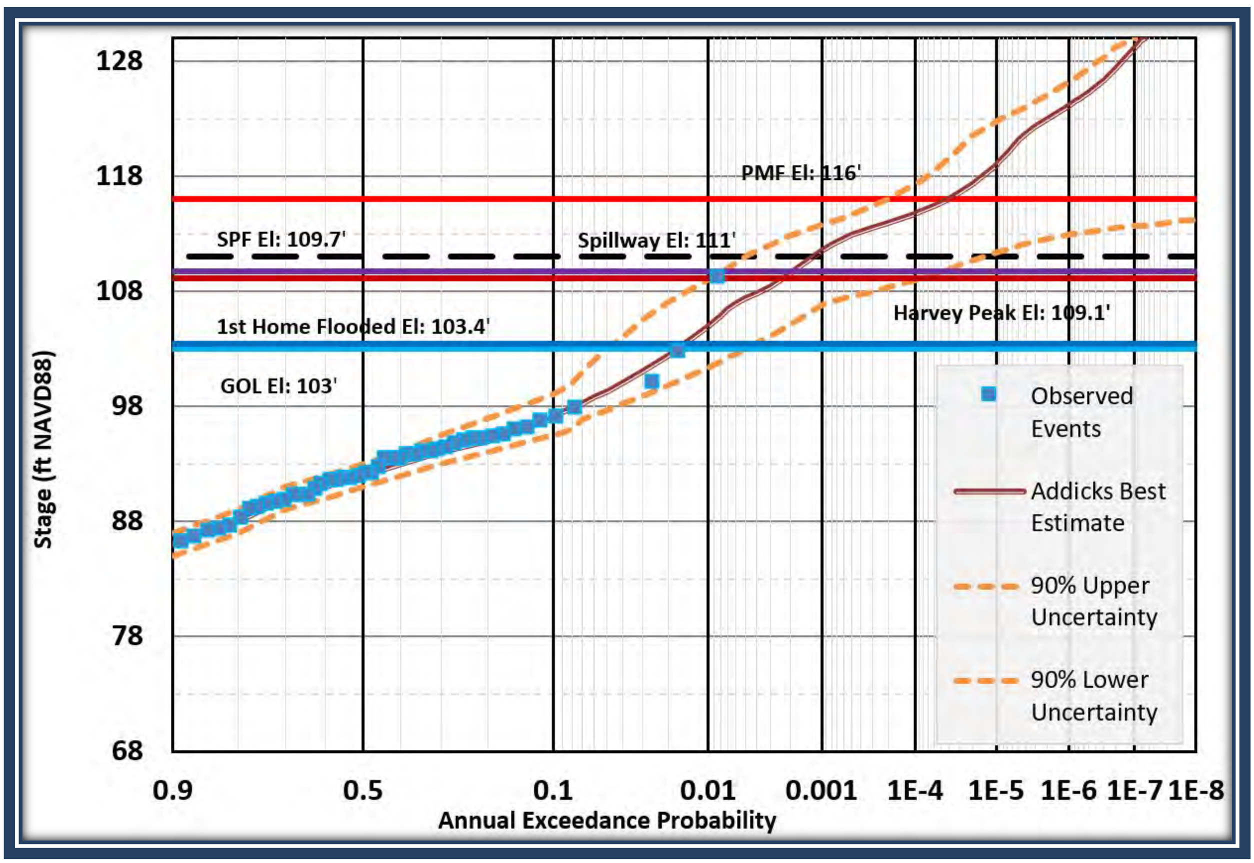

Figure 51. Addicks Pool Frequency Curve (USACE 2020)

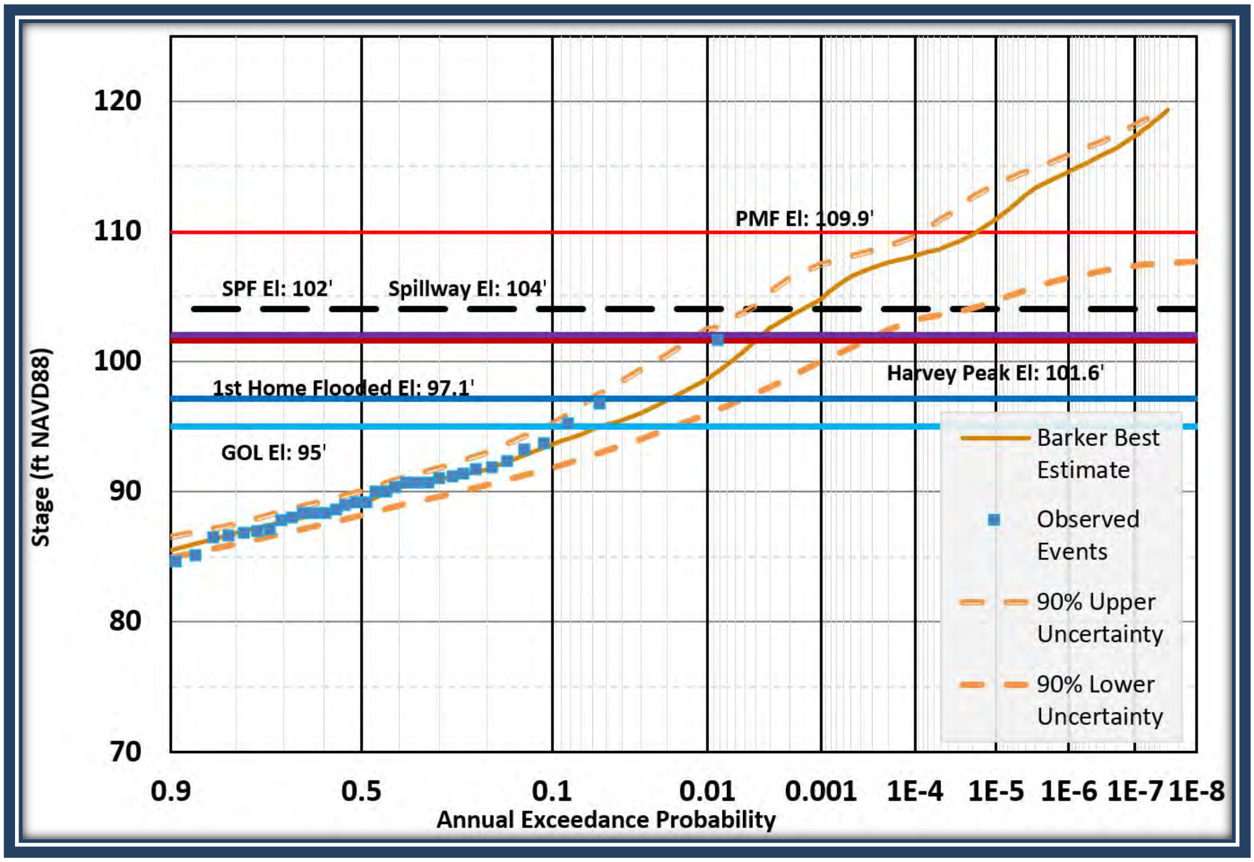

Figure 52. Barker Pool Frequency Curve (USACE 2020)

The figures above show that, for the average water level, GOL extends to approximately the 1/50 ACE pool level at Addicks and approximately the 1/50 ACE pool level at Barker. Applying the extreme bound of the confidence limits shown in the figures, Addicks pool levels could exceed GOL prior to the 1/100 ACE and Barker could exceed GOL at close to the 1/100 AEP.

Current Corps policy (EM 1110-2-1420) indicates that a “land acquisition flood” is to be used to determine the amount of land to acquire at a reservoir to minimize the impact during flood operations and to establish a reasonable surcharge allowance above the top of the flood pool elevation. However, the regulations are not prescriptive in which land acquisition flood should be used; rather it is determined on a case-by-case basis. At this point in the study, various estates are being considered including acquisition and flowage easements as a means of expanding the current surcharge storage area, however, additional analyses are needed to determine the target elevation. As such, a range of potential elevations is provided with a higher and lower level for each reservoir, along with a discussion of the estimated costs and impacts associated with expansion within these ranges. For the purposes of this document, the cost is estimated as in fee purchase, but acquisition of flowage easements is also being considered. The cost and impacts presented represent the highest possible within the range of elevations.

Table 33. Recurrence Interval by Elevation

Elevation	Annual Exceedance Probability	Return Interval (Year)
	Addicks	
108	0.0045	224
111	0.0014	722
112	0.0010	1,036
	Barker	
102	0.0035	285
104	0.0014	704
105	0.0009	1,071

Elevations in feet above mean sea level

An analysis identified all the parcels between the delineations identified in Table 33 and government owned land at both Addicks and Barker. The following table shows the elevations with the number of residential or commercial relocations along with the total number of parcels at each elevation. It should be noted that the total number of parcels is not the sum of residential and commercial relocations as this number takes into account vacant parcels at each elevation. Costs at each elevation include estimates for lands, easements, rights-of-way, relocations and disposal (LERRD) and estimates for both residential and commercial relocations. Cost estimates for the lowest elevations at both Addicks and Barker (108 feet and 102 feet respectively) are estimated at $6,827 million. Cost estimates for the medium elevations (111 feet and 104 feet) are estimated at $11 billion while the estimates at the highest elevations (112 feet and 105 feet) are $13 billion.

Table 34. Proposed Reservoir Elevations, Potential Number of Relocations, First and First Costs of Each

	Elevation	Residential Relocations	Commercial Relocations	Number of Tracts	First Cost ($1,000)
			Addicks @ Three Scales		
No Action	103	-	-	-	-
End of Dams	108 feet	4,435	186	5,083	$2,774,432
Spillway Crest -0.5 feet	111 feet	10,099	313	11,198	$5,569,255
Spillway Crest +0.5 feet	112 feet	11,279	379	13,049	$6,562,135
			Barker @ Two Scales		
No Action	95	-	-	-	-
End of Dams	104 feet	8,338	104	9,785	$5,472,156

Spillway Crest	105 feet	10,023	113	11,658	$6,553,077

October 2019 Price Levels

4.7 Ancillary Measures

Ancillary measures were identified as those that would allow better performance and function of the anchor measures and that could provide additional benefits.

Addicks and Barker Reservoir Excavations

Soils would be removed from government owned lands within the Addicks and Barker reservoirs in order to increase holding capacity by 15 percent.

At Addicks, excavation would capture and detain flows from South Mayde and Langham Creeks and would require bridge improvements on Groeschke, Barker Cypress and Highways 6 to convey and capture flows into the reservoir. Major construction activities include clearing, grubbing, stripping, and excavation and would occur on GOL to a depth of ten feet below existing ground. An additional storage of 16,989 acre-ft would be provided requiring a footprint of 1,700 acres. Side slopes of 1V:3H are assumed for the excavated area.

At Barker, the footprint for the excavation is sited near the Cinco Ranch development to capture and detain flows coming into the reservoir and would require new bridges along the Northbound and Southbound lanes of Westheimer Parkway to convey channel flows towards the Barker outlet structure. Major construction activities include clearing, grubbing, stripping, and excavation and would occur on GOL to a depth of ten feet below existing ground. An additional storage of 12,512 acre-ft would be provided requiring a footprint of 1,300 acres. Side slopes of 1V:3H re assumed for the excavated area.

Figure 53. Addicks Reservoir Excavation

Figure 54. Barker Reservoir Excavation

Diversion from Barker Reservoir to Brays Bayou

Originally considered as an anchor measure but ruled out due lack of system-wide benefits, this would construct a tunnel to divert flows through a tunnel from Barker to a detention basin for Brays Bayou. Flows from the Cinco Ranch area would be diverted to the tunnel inlet structure constructed on GOL. The tunnel would be approximately 20 feet in diameter, 7,900 feet in length, and about 50 feet below the ground surface. The tunnel will be gated at the outlet location and an inlet structure would be constructed within Barker reservoir. Right-of-way was estimated to be 1.5 times the tunnel diameter over its length. The tunnel alignment is shown in Figure 55.

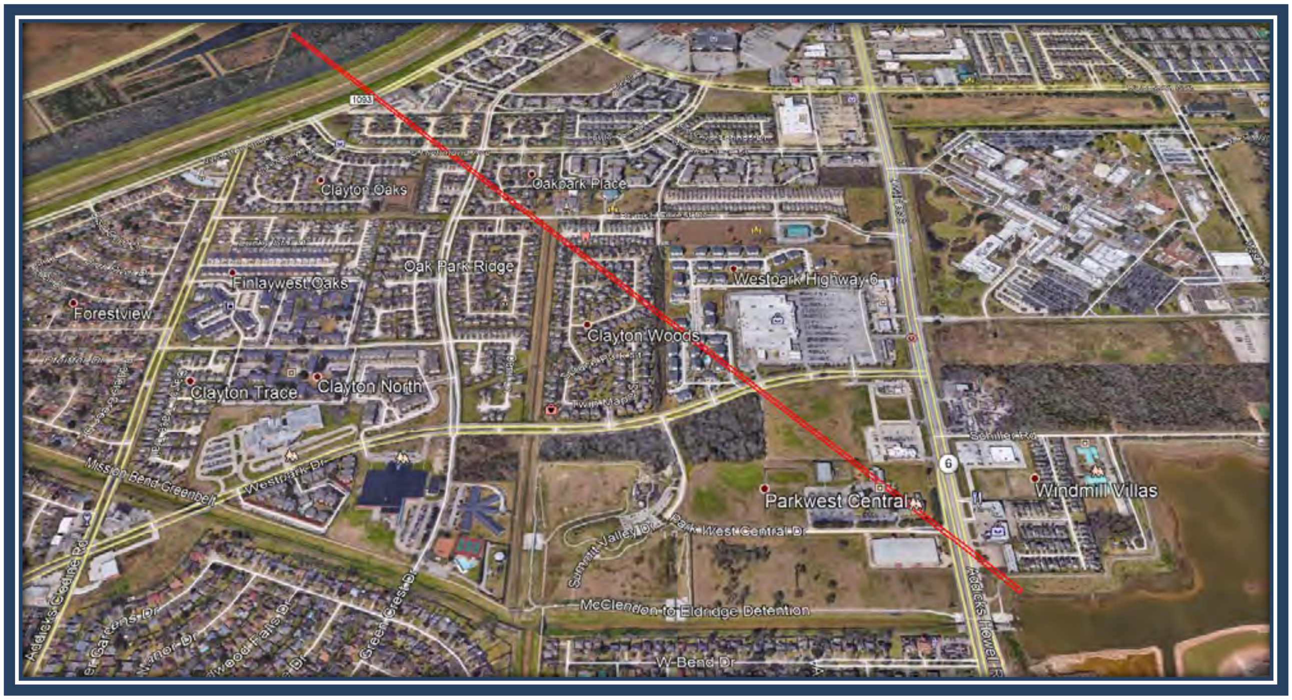

Figure 55. Tunnel from Barker Reservoir to Brays Bayou

4.7.1 Upper Buffalo Bayou Dam

Also originally considered as an anchor, a detention basin would be constructed upstream of Barker reservoir north of Highway 90 bounded on the east by Cardiff Road and on the west of Neuman Road (Figure 56) and would capture sheet flow upstream of Barker. The embankment will be approximately ten feet high with side slopes of 1V:3H. The top of embankment elevation would be 170 feet with a crown width of 12 feet. The spillway would be at an elevation of 167 feet and approximately 500 feet long. Right-of-way width for the footprint is approximately 275 feet. Borrow material for construction of the embankment are expected to be taken from within the reservoir, avoiding numerous utilities pipelines within the reservoir with an excavation depth of ten feet. No excavation would be allowed within 1,100 feet of interior embankment toe.

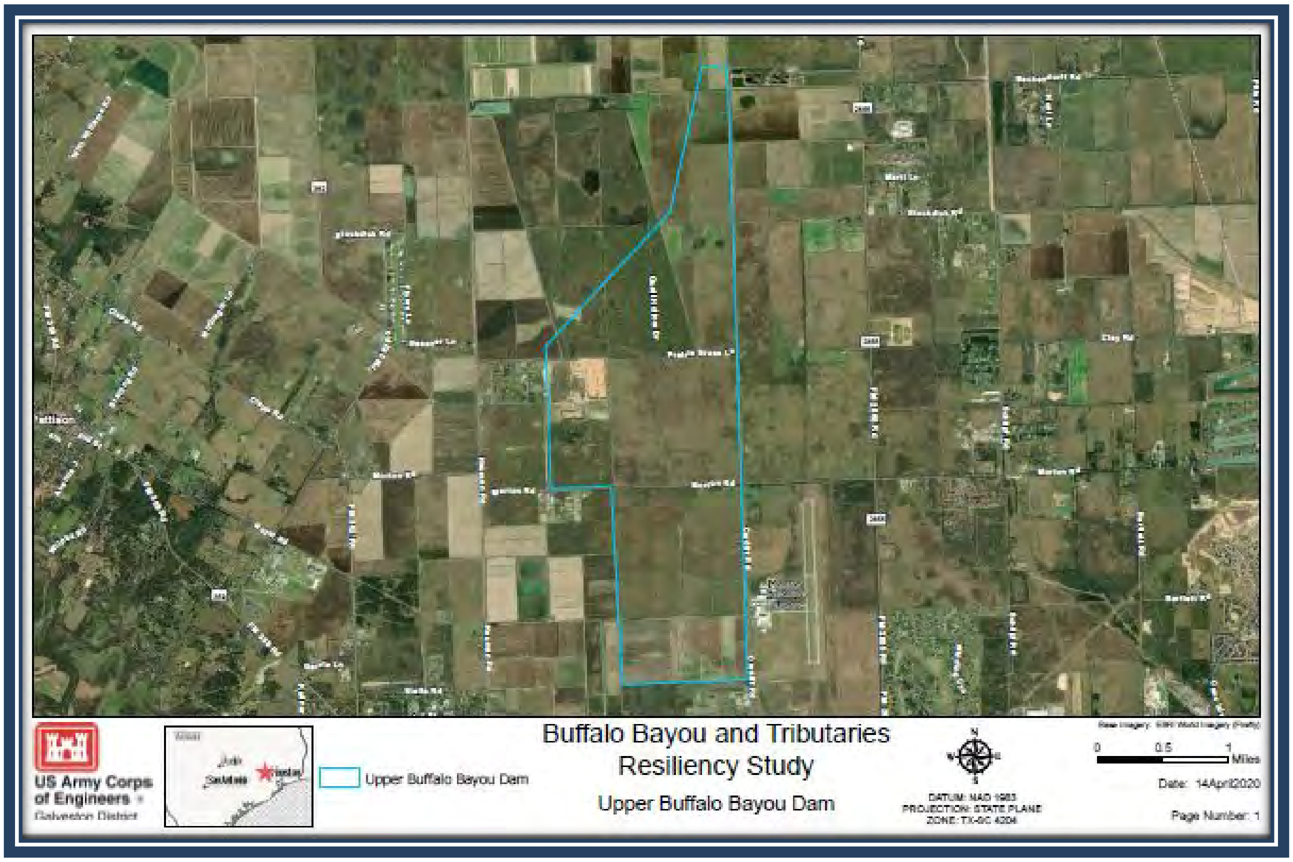

Figure 56. Upper Buffalo Bayou Dam Site

4.7.1.1 Cane Island Branch Channel Improvement

The Cane Island Branch channel improvement would widen and deepen the existing channel from the confluence of Cane Island Branch and Buffalo Bayou just upstream of Kingland Blvd and continue upstream for approximately seven miles to the intersection of Stockdiek and Schlipf Roads. Figure 57 below shows the extent of the channel improvements. Average depth of cut below the existing channel is estimated to be three feet. The proposed channel would have a 30-foot bottom width and 1V:3.5H side slopes lined with articulated concrete block along the bottom and side slopes to the top of bank. The open cells of the block would be filled with topsoil and turfed. A 30-foot width between the top of bank and right-of way would be maintained to allow for channel maintenance and to capture sheet flow runoff. Major construction activities would include excavation, stripping clearing and grubbing and modifications to existing storm drains to lower the pipe outfall to the new channel invert. Bridge replacements would be required to accommodate this improved channel template.

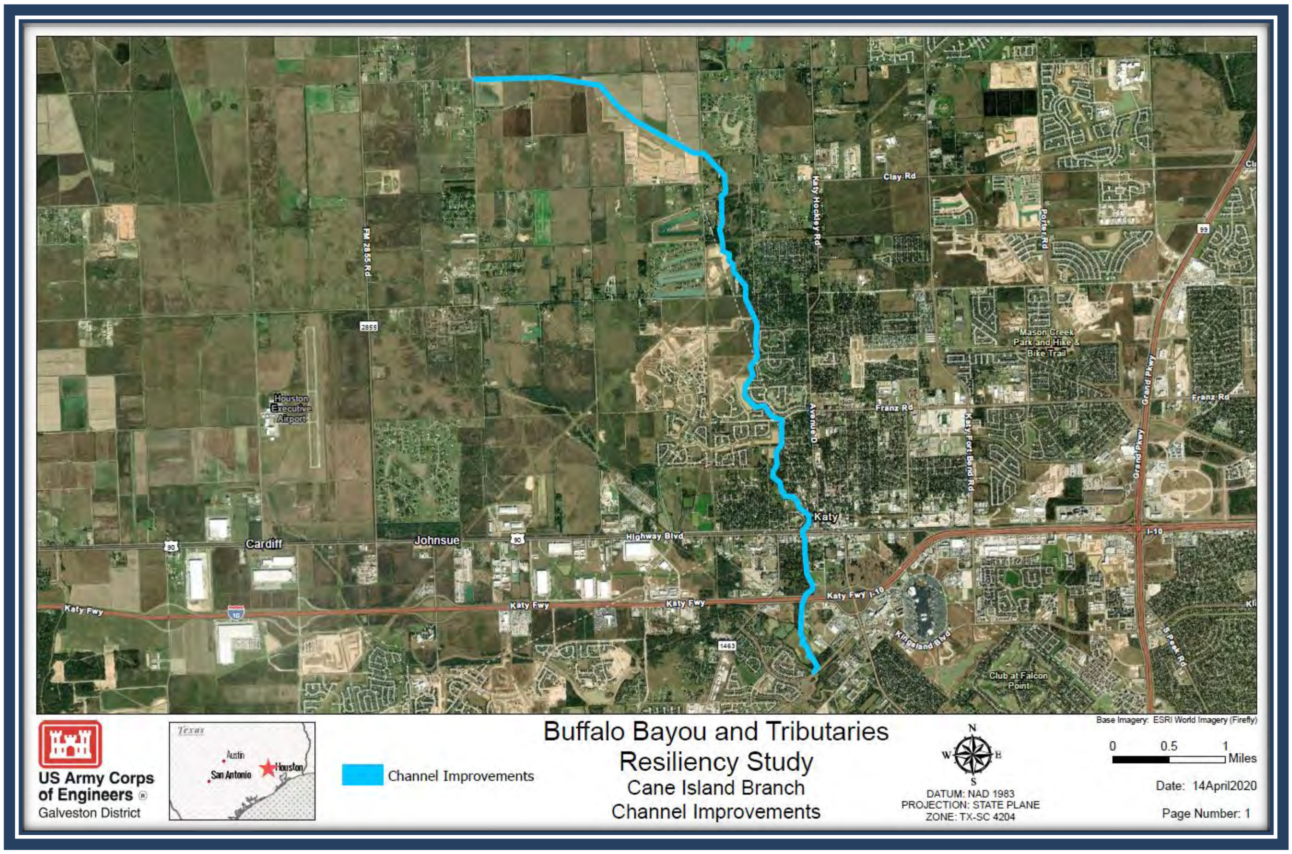

Figure 57. Cane Creek Branch Channel Improvements

4.7.1.2 North Canal at White Oak (Buffalo Bayou)

This canal would divert flow from White Oak Bayou around a portion of Buffalo Bayou having numerous flow constrictions (Figure 58) and consist of a stepped vertical side slope section. The horizontal portions of the section would be grass lined with the vertical portion being concrete. New bridges would be required at San Jacinto Street and the existing rail line that crosses the proposed alignment. Bridge modifications would be required consisting of a higher low chord elevation and higher roadway approaches. The channel modification would lay back the existing channel slope along Commerce Street reducing the channel bend on the north side of Buffalo Bayou. A top of bank width is approximately 160 feet with a 30-foot depth from top of bank to the channel invert. The measure is currently under consideration by the City of Houston.

The table below lists the rough order of magnitude cost estimates, both low and high, for the ancillary measures.

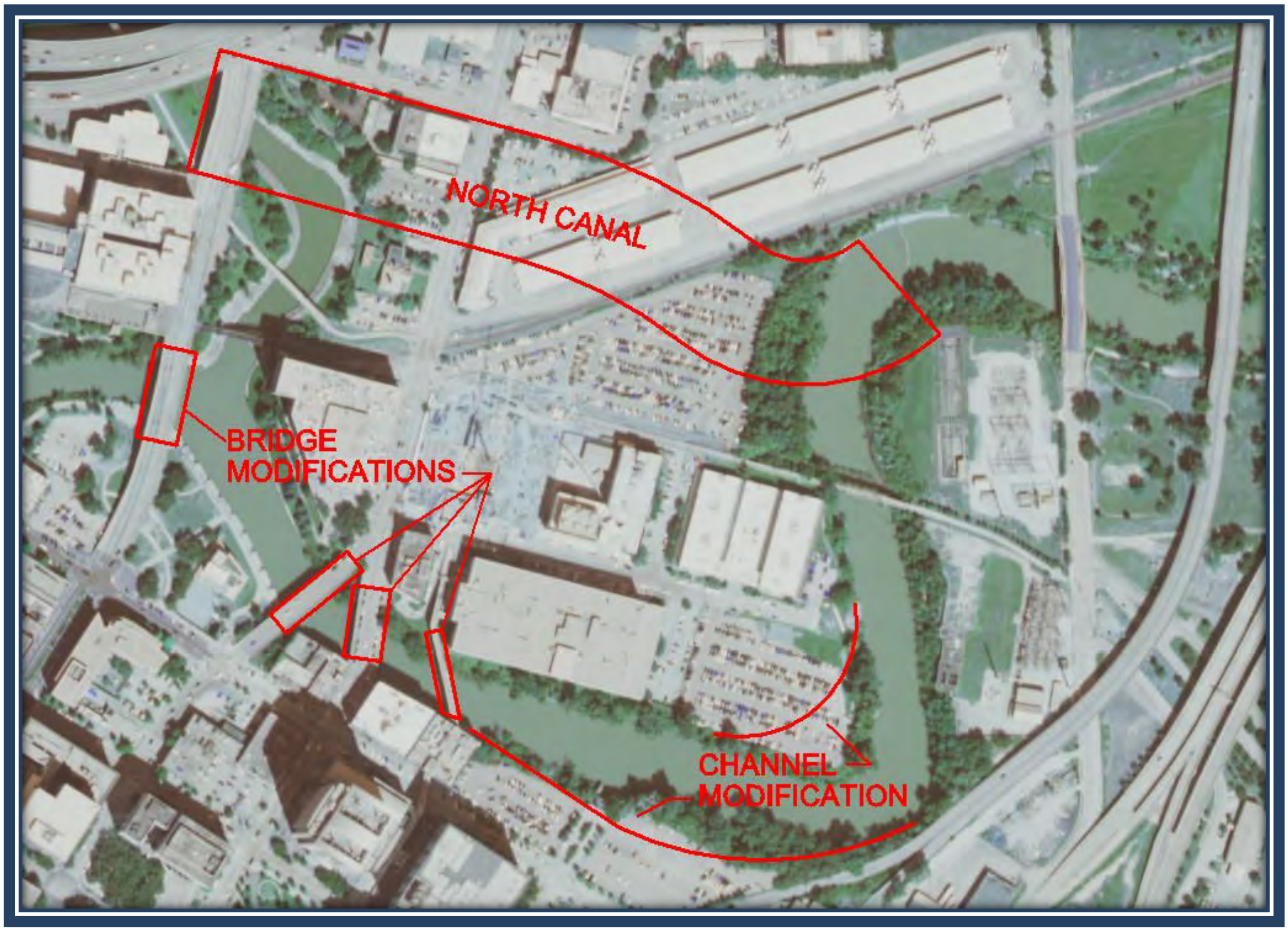

Figure 58. North Canal from White Oak to Buffalo Bayou

Table 35. Ancillary Cost Estimates (Oct. 2019 price level)

Measure	Low Estimate	High Estimate
Addicks Reservoir Excavation	$693,026,000	$935,585,000
Barker Reservoir Excavation	$666,948,000	$900,380,000
Diversion from Barker Reservoir to Brays Bayou	$245,077,000	$330,854,000
Cane Island Branch Channel Improvement	$224,224,000	$302,702,000
Upper Buffalo Bayou Dam	$397,683,000	$536,872,000
North Canal at White Oak (Buffalo Bayou)	$133,358,000	$180,033,000

4.8 Evaluation of Preliminary FRM Measures

The following represents the initial assembly of alternatives based on these strategies. Alternatives 2 and 3 are consistent with the storage strategy while alternatives 4, 5, and 6 are consistent with the conveyance strategy. Alternative 7 follows the dam safety strategy and includes those alternatives required by ER 1110-2-1156. It also includes those measures that might be considered as a stand-alone in the absence of any other action in the study area. Alternative 8 would be assembled out of the “optimally” performing alternatives under the storage and conveyance strategies as the most comprehensive alternative. Alternative 9 would consider nonstructural and will be analyzed for their potential to perform as stand-alone alternatives and to be competitive from a net benefits perspective with structural alternatives. They will also be analyzed for their potential to reduce risk as ancillary measures. The following table displays this array of alternatives. This array is depicted in Table 36.

Table 37 and Table 38 display and summarize the early qualitative screening of the structural measures under consideration while also adding alternatives for dam safety and a large-scale nonstructural. A number of criteria were used to screen the measures under consideration. Table 37 shows a more quantitative assessment as a means of determining what structural measures should be carried forward. The criteria were used to evaluate these structural measures. These include:

- Rough order of Magnitude costs (high, medium or low)
- Potential for System Wide Impacts (best professional judgment based on engineering, H&H)
- Potential Impacts to Critical Infrastructure (number of critical facilities that may be protected along with the number of roads that may be saved from impact)
- Required Mitigation (defined as the potential number of acres that may be required and categorized and from high to low)
- Potential Impacts to T&E species (defined as yes or no)
- Impacts to Potential EJ Populations (defined as yes or no)

Table 36. Initial Array of Alternatives

Storage			Conveyance			Dam Safety	Comprehensive	Nonstructural
Alt #1	**Alt #2 S1**	**Alt #3 S2**	**Alt #4 C1**	**Alt #5 C2**	**Alt #6 C3**	**Alt #7 Dam Safety**	**Alt #8**	**Alt #9**
No Action	**New Reservoir/ Dam**	**Increase Reservoir Storage**	**Tunnels**	**Diversion**	**Channel Improvements**	7.a Meeting full tolerable risk guidelines using ALARP	Best of S1 & S2	**Nonstructural**
	Detention	*Detention*	*Diversion*	*Bypass*	*Bypass*	7.b Achieving only tolerable risk limit for life-safety	Best of C1, C2, and C3	Modify discharge schedule or capacity
	Channel Improvements	*Channel Improvements*	*Channel Improvements*	*Levees/Flood walls*	*Levees/Floodwalls*	7.c Remove structure		
	Modify discharge schedule or capacity	*Modify discharge schedule or capacity*	*Modify discharge schedule or capacity*	*Modify discharge schedule or capacity*	*Modify discharge schedule or capacity*	7.d Replace structure		
	Auxiliary Spillway Improvements	*Auxiliary Spillway Improvements*	*Auxiliary Spillway Improvements*	*Auxiliary Spillway Improvements*	*Auxiliary Spillway Improvements*	7.e No Action		
		Sediment Sump	*Bypass*	*Channel Improvements*	*Diversion*	Auxiliary Spillway Improvements		
	Nonstructural	*Nonstructural*	*Nonstructural*	*Nonstructural*	*Nonstructural*	Relocate Auxiliary Spillway		
						Modify discharge schedule or capacity		

Table 37. Initial Assessment of Measures

Anchor Measure	Name	Costs	Potential for System Wide Impacts	Potential Impacts to Critical Infrastructure	Required Mitigation	Potential Impacts to T&E Species	Impacts to Potential EJ Populations
Storage							
New Reservoir	Cypress Creek Dam	H	✓	Minor	M	Low	No
	Upper Buffalo Bayou Dam	M		Minor	M	Low	No
	Cypress Creek Dam, Gated and Upper Buffalo Bayou Dam	H	✓	Minor	H	Low	No
Increased Storage	Raise Dam	H		Minor	L	Moderate	No
	Excavate Reservoirs	H		Minor	H	High	No
Conveyance							
Tunnels	River Tunnels	H	✓	Minor	L	Moderate	No
	Reservoir Tunnels	H	✓	Minor	L	Low	No
	Brazos Tunnels	H	✓	Minor	L	Low	No
Diversions	Barker to Brays, Gated	L		Minor	L	Low	No
	Addicks/Barker Diversion	L		Minor	L	Low	No
Channel Improvements	Increase Channel Capacity	L	✓	Minor	L	Moderate	No

Table 38. Screening Structural Measures

Anchor Measure	Name	Screened ?	Justification
Storage			
New Reservoir	Cypress Creek Dam	No	Benefits impact Cypress, Addicks and downstream BB. More System wide benefits.
	Upper Buffalo Bayou Dam	Yes	Benefits Katy primarily but also minor benefits to Barker. BB kept as an ancillary
	Cypress Creek Dam, Gated and Upper Buffalo Bayou Dam	Yes	Additional cost of combining reservoirs does not provide commensurate benefits
Increased Storage	Raise Dam	Yes	Other measures can provide same level of benefit for less cost. Substantial real estate investment within the footprint.
	Excavate Reservoirs	Yes	**Ruled out as an anchor due to no system wide impacts** but could still be considered as an ancillary measure; disposal and haul routes costs are significant.
Conveyance			
Tunnels	River Tunnels	Yes	Cost prohibitive and include significant challenges in construction and performance and **other measures can achieve similar benefits at a lower cost**
	Reservoir Tunnels	Yes	Cost prohibitive and include significant challenges in construction and performance and **other measures can achieve similar benefits at a lower cost**
	Brazos Tunnels	Yes	Cost prohibitive and include significant challenges in construction and performance and **other measures can achieve similar benefits at a lower cost**. Diversion to Brazos may not be available.
Diversions	Barker to Brays, Gated	Yes	Screened as an anchor but will be considered as an ancillary. Public opposition and can conveyance if included as an ancillary. **Cannot handle the capacity to be an anchor.** Could still be used as ancillary. No system wide benefits.
	Addicks/Barker Diversion	Yes	Screened as an anchor but diversion component will be considered as an ancillary. Capacity to Brazos may not available when needed.
Channel Improvements	Increase Channel Capacity	No	**Cost-effective in comparison to tunnels and diversions**. Better chance of keeping water on GOL and higher system wide impacts.

Based on the assessment shown in Table 37 the overriding criteria advancing these measures for further consideration is a measure's ability to have system-wide impacts. While some measures may have considerable costs, their potential for significant system-wide impacts warranted them further scrutiny. Among the reservoir measures being considered, only the Cypress Creek Dam remained after the initial round of screening. Upper Buffalo Bayou Dam was deemed only to have relatively minor benefits, primarily to the Katy area. A combination reservoir measure was considered with both Cypress Creek and the Upper Buffalo Bayou Dam but considering the additional cost of Upper Buffalo Bayou Dam with only relatively localized benefits, this reservoir measure was also screened. The other storage measure under consideration included raising the dam which was screened early in the process due primarily to the significant real estate investment that would result from the increase in each of the dams' footprint. The remaining storage measure that was evaluated was excavation at both Addicks and Barker. This measure was screened as an anchor since benefits are essentially localized around the area of the dams themselves. This measure would however be considered as an ancillary primarily for its potential to enhance operations at the existing reservoirs.

4.8.1 Initial FRM Alternative Plans

The following represents the alternatives carried forward for further evaluation following the initial screening of measures. A description of each along with considerations associated with each alternative follows.

Alternative 1: No Action

The Council on Environmental Quality's regulation (40 CFR 1500–1508) for implementing NEPA do not define the "No Action Alternative," stating only that NEPA analyses shall "include the alternative of No Action" (40 CFR 1502.14).

For purposes of this report, under the No Action Alternative, the Corps would implement no Flood Risk Management plan. The Future Without-Project conditions are expected.

Initial screening level estimates for expected annual damages utilizing the Corps' HEC-FIA model are estimated at $18.3 million for the study area. Updated estimates using the Corps' HEC-FDA will be presented later in the report.

Alternative 2: Cypress Creek Dam & Reservoir (also includes Addicks and Barker Reservoir Excavations, Barker to Brays Bayou Diversion, Upper Buffalo Bayou Dam, Cane Island Branch Channel Improvement, and the North Canal)

This alternative is a new reservoir upstream of Addicks Reservoir in the Upper Cypress Creek watershed. The top of the embankments would be 190 feet and spillways at 187 feet. An emergency operation schedule similar to Addicks and Barker would be developed. The primary overflow spillway would empty into the Cypress Creek watershed and a second into the Addicks Watershed. A downstream control point with a max flow of 2,000 cfs would be just upstream of Tomball Parkway. First costs are estimated to be between $2,135,000 and $2,883,000. Initial screening level estimates for expected annual damages utilizing HEC-FIA are reduced by just under $1 million in the study area.

Cypress Creek Reservoir would be placed within a flat open expanse of rangelands and farmlands containing scattered tall-grass coastal prairie remnants and prairie pothole wetlands known as the Katy Prairie.

Alternative 3: Addicks and Barker Reservoir Excavations

Soils would be removed from government owned lands within the Addicks and Barker reservoirs in order to increase holding capacity by 15 percent. Groundwater is estimated to be at depths 5 to 15 feet within the silty clay material. The alternative assumed 10 feet of excavation depth to avoid potential groundwater intrusion. It was assumed that excavated material would become the property of the Contractor and disposed of offsite in accordance with local, state, and federal regulations. Initial screening level estimates for expected annual damages utilizing HEC-FIA are reduced by $1.6 million in the study area. This alternative would increase the storage capacity of both reservoirs by 15 percent. However, this alternative would remove 1,300 acres of quality bottomland hardwood and wetland environments, including the rare and unique Plannartree swamps, in Barker Reservoir through excavation activities. An additional 1,754 acres of mixed habitats including degraded prairie systems, wetlands, bottomlands, and upland pine forest would be removed with this plan. It is anticipated that these habitats would not return due to the loss of productive top soils and change in elevation and hydrologic regimes. The removal of 10 feet of sediment, including all productive layers, is expected to drastically change the existing vegetation communities from dominance in trees and shrubs to herbs composed of species tolerant of low nutrient disturbed soils, many of which are expected to be non-native or invasive. The loss of existing habitats would result in loss of suitable habitat for numerous terrestrial and aquatic species dependent on these areas. Without this habitat, local populations would decrease in numbers and diversity, which could also affect regional populations in the future because of the scarcity of available habitat throughout Harris County.

This vegetation change would substantially reduce water quality filtering abilities of the area as compared to the existing condition. The rich natural diversity of plants in bottomland hardwood and wetland communities act as filtering systems, removing sediment, nutrients and pollutants from water. These communities also assist in removing harmful bacteria, are important in the management of urban effluent and stormwater runoff, and regulate temperatures in the bayous. Increased water temperatures and decreased dissolved oxygen would be expected within the reservoir and in Buffalo Bayou downstream of the dams because of the lack of vegetation to shade and cool the water.

As well, the conversion of habitats is expected to increase the long-term erosion potential, which would release sediments into nearby bayous. The designed side slopes (1V:3H) of the excavation area are considered moderately steep and would likely be susceptible to erosion even after vegetation is established. Over the long-term, the slopes would be subjected to sheet erosion with every precipitation event. During temporary retention events, the excavation areas would be expected to fill with water first, essentially creating a reservoir within a reservoir. Each time the water elevation is raised the side slopes would be deposited with fine-sediments, but upon drawdown, the side slopes would be exposed to wave action generated by wind and flows, which would erode the newly deposited finer-sediments and any exposed soils. This would resuspend the sediments in the water column and move them to lower areas eventually settling out into the bottom of the excavation areas or in the bayous. Long-term sedimentation would further degrade stream habitats and could affect the overall long-term performance of the excavation. No modeling has been done to show the sedimentation rate of the reservoir area or how long the designed depth would be maintained.

Alternative 4: Tunnels Only – This alternative included the River Tunnels, Reservoir Tunnels, and the Brazos Tunnel

River Tunnels

These tunnels would move water from just downstream of the reservoirs to the Houston Ship Channel or Galveston Bay. They would serve as an alternative discharge outlet and reduce the amount of water released into Buffalo Bayou. The tunnels would approximate the Buffalo Bayou channel about 150 feet below the ground's surface for either 23 miles to the ship canal or 34 miles to Galveston Bay. Initial screening level estimates for expected annual damages utilizing HEC-FIA are reduced by $5 to $5.3 million in the study area.

Reservoir Tunnels

These tunnels would move water from just downstream of the reservoirs to the Houston Ship Channel or Galveston Bay. They would serve as an alternative discharge outlet and reduce the amount of water released into Buffalo Bayou. The tunnels would approximate the Buffalo Bayou channel about 150 feet below the ground's surface for either 23 miles to the ship canal or 34 miles to Galveston Bay. Initial screening level estimates for expected annual damages utilizing HEC-FIA are reduced by $2.8 million in the study area.

Brazos Tunnel

The tunnel would move water from the southwest section of Barker reservoir to the Brazos River. It would increase discharge and serve as additional alternative conveyance. The tunnel would bypass Buffalo Bayou and discharge into the Brazos River. Initial screening level estimates for expected annual damages utilizing HEC-FIA are reduced by $2.8 million in the study area.

Alternative 5: Diversion Only

This alternative diverts Barker reservoir storage flows via the construction of a tunnel to an existing detention basin at Brays Bayou. The detention basin is east of Highway 6 where it crosses Brays Bayou. The tunnel would be approximately 7,900 long and be about 50 feet below ground. Initial screening level estimates for expected annual damages utilizing HEC-FIA are reduced by $2.8 million in the study area.

Alternative 6: Channel Improvements to Buffalo Bayou (also includes Addicks and Barker Reservoir Excavations, Barker to Brays Bayou Diversion, Upper Buffalo Bayou Dam, Cane Island Branch Channel Improvement, and the North Canal) – This alternative is modifying Buffalo Bayou to increase water capacity up to 15,000 cfs by excavating, widening, and sloping the banks of the existing channel. The centerline for the channel improvement would be the same. The average cut depth is estimated to be 11.6 feet with a channel bottom width of 70 feet and top of channel width of 230 feet. Slopes would 1V:4H and the channel would be 49.4 miles in length. First costs for are estimated at $946 to $1,277 million.

With ancillary measures included, first costs for this alternative are estimated at $3,061 to $4,132 million. Initial screening level estimates for expected annual damages utilizing HEC-FIA are reduced by $2.8 million in the study area.

In areas of high erosion, the channel bottom and sides would be articulated concrete block mats.

In areas of reduced erosion, the channel bottom and sides would be modified with stepped vegetation.

The intent of this alternative is to increase the conveyance capacity in Buffalo Bayou, while preserving the natural integrity of the bayou. This would be done by terracing the bayou to create benches that would support riparian vegetation commensurate with the hydrologic frequency of that bench. This would in the long-term create wider and higher quality riparian zone than currently exists. As part of this plan, a low flow channel would be maintained which would mimic as closely as possible the depths and bank slopes (from below the water to the surface) that is currently inundated with permanent flows and maintaining at a minimum existing aquatic habitat quality. As well, in-stream structures and riffle-run complexes would be constructed to modify the overall stream structure and function more similar to unmodified streams; thereby increasing overall aquatic habitat quality and diversity. In the short-term there would be significant adverse effects from construction actions; however, as vegetation matures, it is anticipated that the bayou would maintain more acres of riparian zone and would support a higher diversity of aquatic and terrestrial species.

Alternative 7: Nonstructural Measures Only – Acquisitions and Relocation along Buffalo Bayou (also includes acquisitions and relocation upstream of both Addicks and Barker Dams & Reservoirs) – This alternative would involve primarily acquisition and relocation of existing structures downstream of Addicks and Barker dams along Buffalo Bayou. Multiple scales of this measure were considered. At the high end, up to 441 structures (including businesses and multi-family structures) would be acquired and/or relocated at a cost of approximately $2,277 million. A somewhat more refined estimates for reduction in expected annual damages showed that it could be as much as $500 million. A more appropriate comparison with the focused array of structural alternative is done later in the report.

Alternative 8: Combo Plan (Alternative 2: Cypress Creek Dam & Reservoir + Alternative 6: Channel Improvements to Buffalo Bayou) – This alternative would combine plans 2 and 6. Costs are estimated at $5,196 to $7,015 million. Annual costs for the Cypress Creek Dam are estimated at $231 million while annual costs for the channel improvements are estimated at $157 million. Annual costs for the combination are $267 million.

4.8.2 Screening of Initial FRM Alternatives

Alternative 1: No Action

Alternative 2: Cypress Creek Dam & Reservoir – (includes Addicks and Barker Reservoir Excavations, Barker to Brays Bayou Diversion, Upper Buffalo Bayou Dam, Cane Island Branch Channel Improvement, and the North Canal).

Alternative 3: Addicks and Barker Reservoir Excavations – Surface to groundwater depths within the existing reservoirs range between five and 15 feet depending upon location. Excavation depths were estimated to up to 10 feet deep and costs up to ~$900 million per reservoir. Previous analysis has shown costs to be high relative to potential benefits. This would also involve significant increases in operations and maintenance costs due to sedimentation. While this was removed as an anchor, excavation would be considered as ancillary since it is determined that smaller scale excavations could potentially be optimized to provide reasonable benefits due to its ability to enhance the operations of the existing reservoirs.

Alternative 4: Tunnels Only – Tunnels were dropped from consideration due to a large percentage of the same function could be obtained with Channel Improvements to Buffalo Bayou (Alt 6) with less cost. Initial analysis looked at tunnels that could convey up to 20K cfs and channel improvements that could convey up to 15K cfs. Initial cost estimates ranged from $2.2 to $12 billion (July 2019 price levels) while cost estimates for channel improvements ranged from $251 million to $660 million. While tunnels may be an effective and viable long-term option, cost effectiveness, constructability and the continued operations and maintenance remain as challenges. The feasibility of tunnels is currently being investigated by the HCFCD, the non-federal sponsor, which has recently completed a beginning study phase to study tunnel feasibility based on local geological conditions such as fault lines and soil. Subsequent phases will analyze potential locations and potentially viable alignments.

Alternative 5: Diversions Only – Other conveyance measures performed better, particularly channel improvements. This alternative does not move a sufficient amount of water out of the system to be considered an effective anchor. While this stand-alone alternative was removed, the measures associated with it were retained for initial consideration as ancillary measures, as it was determined that smaller scale channel improvements could potentially be optimized to provide reasonable benefits. North Canal through Downtown Houston bypass was dropped from consideration due to the City of Houston pursuing this on their own. Cost estimates for diversions ranged from $243,000,000 to $328,000,000.

Alternative 6: Channel Improvements to Buffalo Bayou Alone – (includes Addicks and Barker Reservoir Excavations, Barker to Brays Bayou Diversion, Upper Buffalo Bayou Dam, Cane Island Branch Channel Improvement, and the North Canal).

Alternative 7: Nonstructural Measures Only – Acquisition of properties along Buffalo Bayou downstream of Barker Dam.

Alternative 8: Combo Plan – Combination alternative consisting of Alternative 2: Cypress Creek Dam & Reservoir and Alternative 6: Channel Improvements to Buffalo Bayou Alone (includes Addicks and Barker Reservoir Excavations, Barker to Brays Bayou Diversion, Upper Buffalo Bayou Dam, Cane Island Branch Channel Improvement, and the North Canal)

Table 39. Focused Array of Alternative Plans

Alternative Plans	Description	Added Measures	In Focused Array	Notes
Alt 1: No Action	No plan is implemented because of this study.		**YES**	This forms the baseline for costs, benefits, and impact comparison. It aids in understanding how each plan functions compared to the baseline.
Alt 2: Cypress Creek Dam & Reservoir	Store water on Cypress Creek by constructing a new dam/reservoir.	Addicks and Barker Reservoir Excavations, Barker to Brays Bayou Diversion, Upper Buffalo Bayou Dam, Cane Island Branch Channel Improvement, North Canal	**YES**	
Alt 3: Addicks and Barker Reservoir Excavations	Increase storage capacity within each reservoir by deepening portions of the reservoirs.		No	This plan provides only localized benefits.
Alt 4: Tunnels Only	Convey up to 20,000 cfs of floodwaters through underground tunnels that would capture water at the dams and empty water into the Houston Ship Channel/Galveston Bay		No	Tunnels provide comparable benefits as other alternatives but at a much higher cost.
Alt 5: Diversions Only	Divert water from the Buffalo Bayou Watershed to Brays and/or the Brazos River		No	Diversions present a high risk in long-term operation because Brays and/or the Brazos River may already be flooded.
Alt 6: Buffalo Bayou Channel Improvements	Widen and deepen Buffalo Bayou from just below Addicks and Barker Dams to convey 15,000 cfs	Addicks and Barker Reservoir Excavations, Barker to Brays Bayou Diversion, Upper Buffalo Bayou Dam, Cane Island Branch Channel Improvement, North Canal	**YES**	
Alt 7: Nonstructural Only	Large-scale acquisition plan along Buffalo Bayou to convey 15,000 cfs		**YES**	

Alt 8: Combo Plan	Store water on Cypress Creek by constructing a new dam/reservoir AND widen and deepen Buffalo Bayou from just below Addicks and Barker Dams to convey 15,000 cfs (Alt 2 + 6)	Addicks and Barker Reservoir Excavations, Barker to Brays Bayou Diversion, Upper Buffalo Bayou Dam, Cane Island Branch Channel Improvement, North Canal	**YES**

Table 40. Revised Array of Alternatives

No Action	Alternative 2 S1	Alternative 6 C3	Alternative 8	Alternative 7	Alternative 9
	Cypress Creek Reservoir	**Channel Improvements (15K cfs)**	**New Reservoir/Channel Improvements (Combo)**	**Dam Safety**	**Nonstructural**
	Addicks Excavation	Addicks Excavation	Addicks Excavation	Step RCC Armor	Step RCC Armor
	Barker Excavation	Barker Excavation	Barker Excavation		
	Brays Diversion	Upper Buffalo Bayou Dam	Upper Buffalo Bayou Dam		
	Upper Buffalo Bayou Dam	Katy Channel Improvement (Cane Island Branch)	Katy Channel Improvement (Cane Island Branch)		
	Katy Channel Improvement (Cane Island Branch)	North Canal	North Canal		
	North Canal	Step RCC Armor	Step RCC Armor		
	Step RCC Armor				

The remaining FRM alternatives, as reflected in Table 40 with the appropriate ancillary measures were evaluated under three of the four accounts established in the Principles and Guidelines. The account not evaluated was Regional Economic Development (RED) due to it not being a decision driver.

1. National Economic Development - Changes in the economic value of the national output of goods and services, as damages prevented based expected annual damages and rough order of magnitude cost.
2. Environmental Quality - non-monetary effects on significant natural and cultural resources as mitigation acres required for each alternative.
3. Other Social Effects - impacts from perspectives that might be relevant to the planning process but are not reflected in the other three accounts, such as life safety as modeled under the "non-fail" scenario with the dams operating as intended.

The following evaluates the alternatives utilizing the P&G accounts based on impacts to the primary watersheds of Addicks, Barker, and Buffalo Bayou.

4.8.3 National Economic Development (NED)

As displayed in Table 41 below, annual costs for the Cypress Creek Dam are estimated at $225 million while annual costs for the channel improvements are estimated at $153 million. Annual costs for the combination are $260 million. All show negative net benefits from $97 million for the channel improvements to $202 million for the combination alternative of a new reservoir and channel improvements.

Table 41. National Economic Development Alternative Comparison

Alternative Plans	Structural Damages		Annual Costs	Net Benefits
	$$ Damages (FDA)	Benefits		
Alt 1: No Action	$122,000	-	-	-
Alt 2: Cypress Creek Dam	$85,000	$37,000	$225,000	-$188,000
Alt 6: Buffalo Bayou Channel Improvements	$66,000	$56,000	$153,000	-$97,000
Alt 8: Combination (2 + 6)	$64,000	$58,000	$260,000	-$202,000

October 2019 Price Levels, Costs in $1,000s

Nonstructural

For Alternative 7, multiple scales were considered as indicated in the table below. The National Economic Development plan appears to maximize at the 0.2 AEP event, which would involve the relocation of 33 structures (including businesses and multi-family structures) at a first cost of $264 million.

A total 441 structures were identified representing those that are in the 0.02 AEP event. This would facilitate roughly 15K cfs of conveyance along Buffalo Bayou. Of the 441 structures, 48 have been identified as commercial with the remaining 393 being residential. Additionally, a nonstructural acquisition at the 0.04 AEP event would accommodate 6-8K of conveyance. Of the 341 structures identified in that scenario, 40 are commercial and 301 are residential. The identification of these structures and those upstream of Addicks and Barker hinges on a couple of assumptions, 1) that first-floor corrections are 1.5 feet and 2) structures are removed once their associated parcels start being inundated. The benefit-to cost ratio for the 0.02 AEP scenario is 0.9 with net benefits of -$8 million. The 0.04 AEP scenario has a benefit-to cost of 1.0 with $4 million in net benefits.

Table 42. Alt Plan 7 - Nonstructural Scale and Data

Alt Plan 7	Number	EAB	First Cost	Annual Cost	Net Benefits
0.5 AEP	19	$56,000	$204,000	$8,000	$48,000
0.2 AEP	33	$58,000	$264,000	$10,000	$48,000
0.1 AEP	64	$61,000	$438,000	$17,000	$44,000
0.04 AEP	341	$77,000	$1,937,000	$74,000	$4,000
0.02 AEP	441	$79,000	$2,277,000	$87,000	-$8,000

October 2019 Price Levels, Costs in $1,000s

Alternative Plan 6 comes the closest to achieving a cost-effective solution among the remaining structural alternatives. First costs are estimated at $3,061 to $4,133 million. First costs for Alternative Plan 2 are $4,496 to $6,069 million and $5,197 to $7,015 million if both the reservoir and channel improvements are implemented. While net benefits are negative for all alternatives in the table, Alternative Plan 6 shows better economic performance among the structural alternatives.

The tunnels anchor measure was screened during initial evaluations in favor of the Buffalo Bayou channel improvement anchor measure (on which Alternative 6 is based) due primarily to costs and the construction complexity associated with them. Stated earlier, HCFCD has recently completed a beginning study phase analyzing the basic feasibility based on local geological conditions such as fault lines and soil. Subsequent phases will analyze potential locations and potentially viable alignments. HCFCD has considered tunnels since the 1990s. Only after Hurricane Harvey have plans advanced to anything substantive. A third phase would include a geotechnical analysis to evaluate construction challenges. Construction timelines are complex and lengthy since they are typically are built in sections. Tunnels of relatively shorter lengths constructed in San Antonio have taken anywhere from 10 to 12 years to construct. The San Pedro Creek flood diversion tunnel is approximately 6,000 feet long and was constructed between 1987 and 1997. The San Antonio River tunnel was built between 1987 and 1999 and is approximately 16,200 feet long. The longest configurations evaluated for this study is 183,610 feet long.

The initial configurations of the tunnels assessed in the early stages would convey as much as 20,000 cfs (TUN2B) while the largest channel improvement configuration would convey up 15,000 cfs so these two measures would not be conveying the same amount of water. Costs developed during the initial phase of the study ranged from $489 million to $660 million for the largest channel improvement configuration while the initial costs for the longer tunnel measure configurations ranged from $8,935 million to $12,062 million for potentially 25 percent more stormwater conveyance. Initial rough estimates of benefits showed that Buffalo Bayou channel improvements could provide as much as 85 to 90 percent of the tunnels' benefits.

Alternative Plan 7 was included for comparison with two scales; a larger scale representing the 0.02 AEP acquisition which would allow for the conveyance of 15K cfs similar to the Buffalo Bayou channel improvement; and a smaller scale representing the 5-year acquisition (0.2AEP) which would be an alternative that reasonably maximizes net benefits and would therefore be considered the "NED Plan." The smaller scale has an estimated first cost of $264 million making it the most cost-effective plan, but would not achieve comparable benefits. The larger scale has an estimated first cost of $2,277 million and would generate benefits similar to the channel improvement along Buffalo Bayou. Table 45 displays a snapshot of the analyses done to this point. While initial analysis shows overall damages being reduced by a greater amount with the 0.2 and 0.002 AEP acquisitions, the larger scale acquisition could potentially be less cost effective relative to the channel improvement and the smaller scale acquisition, while more cost effective has relatively small regionalized benefits conflicting with the overall goal of providing broad-based benefits. Additionally, the smaller scale acquisition does little to alleviate loading during large events within the existing Addicks and Barker reservoir.

4.8.4 Environmental Quality (EQ)

Table 43 lists the number of mitigation acres that may be required should this measure be implemented. As noted in the table, the numbers represent the estimated area that would be regularly impacted by more frequent events. Habitat that would be impacted is mostly low quality and most areas have been modified. Areas of higher quality habitat would be designed in such a way to reduce the overall impact. Table 43 represents the potential mitigation acreage required for each FRM alternative.

Table 43. Mitigation Acres by Alternative Plan

Alternative Plans	Mitigation Acres*	Notes
Alt 1: No Action	0	
Alt 2: Cypress Creek Dam	7,523	Reservoir location would be sited over the last remaining Katy Prairie Habitat in Texas. Resource Agency concern over how the spillway would affect flows to habitats inside and outside the reservoir footprint.
Alt 6: Buffalo Bayou Channel Improvements	3,093	Riparian Habitat
Alt 7: Nonstructural	0	
Alt 8: Combination (2 + 6)	7,593	Katy Prairie & Riparian Habitats

*** Mitigation estimates were based upon desktop analyses and not field collected data or model runs. It is also an estimate of area that would be regularly impacted by more frequent events and where habitat would be converted to spillway and associated right-of-way.**

4.8.5 Other Social Effects

Table 44 shows what the expected loss of life would be under existing conditions for current loading conditions for the non-fail scenario. Each alternative is compared to the baseline condition at each dam displaying its impact on the loading. For these comparisons, dam safety measures are not in place. At Addicks, life loss can be expected to be 224 during the day and 123 at night under the baseline condition. At Barker, life loss is estimated at 124 during the day and 70 at night. Measures representing the reservoir and the combination alternatives show slightly better performance from a life loss perspective than does the alternative representing the channel improvement. An increment of 35 fewer lives lost during the day and 11 at night at Addicks would be expected for those alternatives that include a reservoir. No increment exists in expected life loss between the alternatives at Barker. While the increment in life loss represents a 61 and 59 percent reduction between day and night respectively, it does come at the additional expense of $1.2 to $1.6 billion.

Table 44. Existing Condition Non-Fail Life Loss Estimates

Addicks			
Alternative Plans	**Loading**	**Night**	**Day**
Alt 1: No Action	115.4	123	224
Alt 2: Cypress Creek Dam	112.5	11	22
6: Buffalo Bayou Channel Improvements	113.1	27	57
Alt 8: Alts 2 & 6	112.5	11	22
Barker			
Alternative Plans	**Loading**	**Night**	**Day**
Alt 1: No Action	109.2	70	124
Alt 2: Cypress Creek Dam	107.2	18	25

6: Buffalo Bayou Channel Improvements	107.2	18	25
Alt 8: Alts 2 & 6	107.2	18	25

Table 45. Flood Risk Management Alternatives Principles and Guidelines Account Data

Alternative Plans	NED			EQ	OSE Life Safety - Annual Life Loss			
	Damages Prevented	Annual Costs	Net Benefits	Mitigation acres	Addicks (Day)	Addicks (Night)	Barker (Day)	Barker (Night)
1: No Action	$122,000	-	-	-	224	123	124	70
2: Cypress Creek Dam	$37,000	$225,000	-$188,000	7,523	22	27	25	18
6: Buffalo Bayou Channel Improvements	$56,000	$153,000	-$97,000	3,093	57	11	25	18
7: Nonstructural (0.02 AEP)	$79,000	$87,000	-$8,000	0	-	-	-	-
7: Nonstructural (0.2 AEP)	$58,000	$10,000	$48,000	0	-	-	-	-
8: Alts 2 & 6	$58,000	$260,000	-$202,000	7,593	22	11	25	18

October 2019 Price Levels, Costs in $1,000s

The downstream nonstructural plan (Alternative 7) is the only plan with positive net benefits. While net economic benefits are negative for all structural alternatives, channel improvements show better economic performance among the structural alternatives.

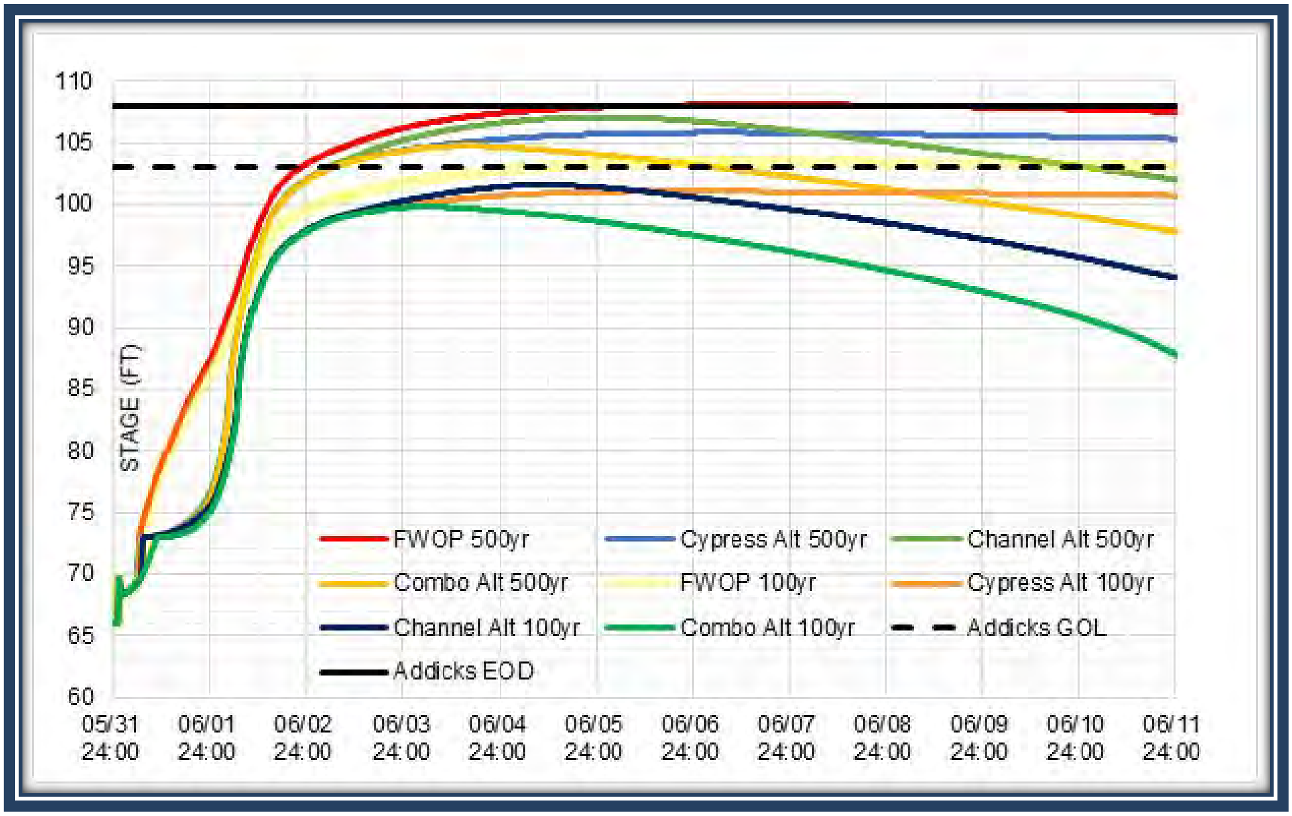

Figure 59. Addicks 500-Year Stages for FWOP and Structural Alternatives

The graph above displays the stages at Addicks for the FWOP and the FWP for the Cypress reservoir, the channel improvement along Buffalo Bayou, and the combination alternatives. As these graphs show, the FWOP 500-year stage can exceed the elevation of government owned land (103 feet NAVD 88) by five feet. The three structural alternatives exceed government owned land at the 500-year event by 1.7 to 4.1 feet. At the 100-year event, the FWOP stage exceeds GOL by 0.4 feet while the three alternatives stay within GOL.

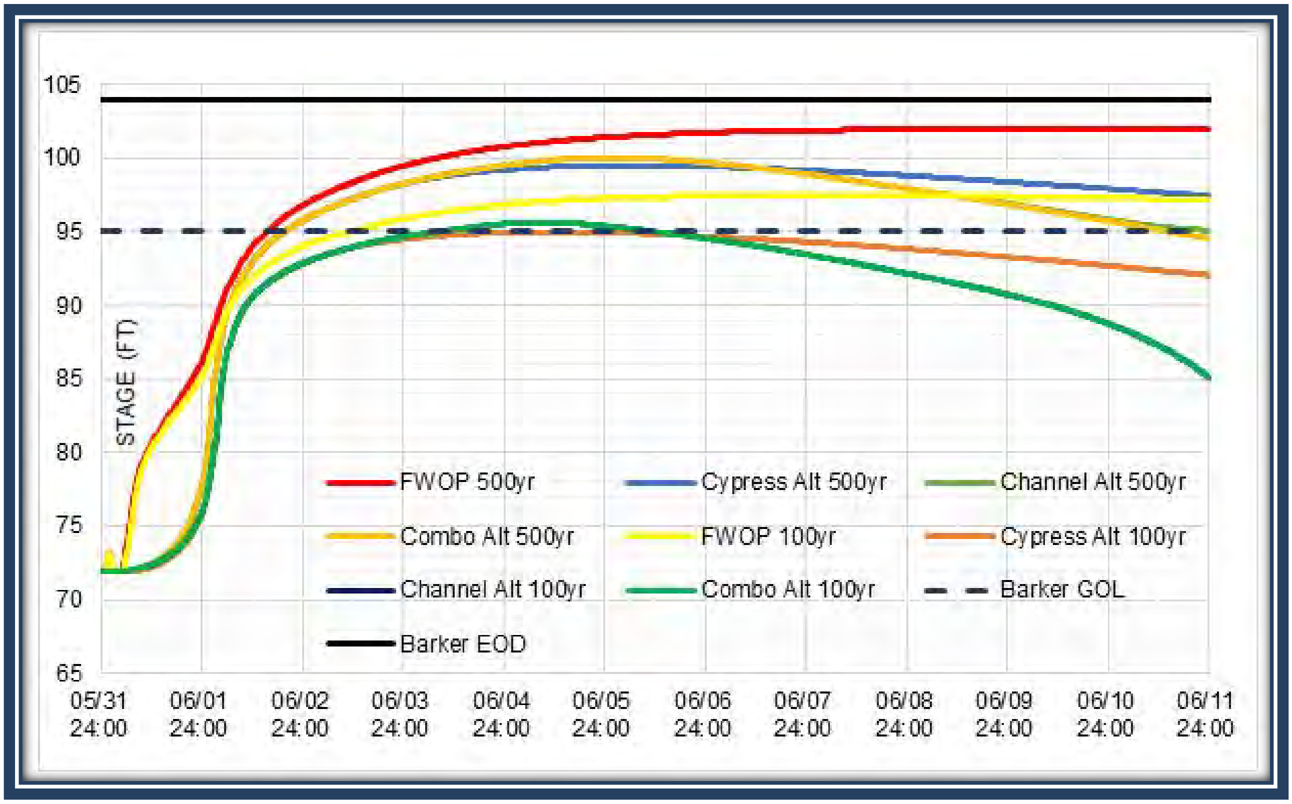

Figure 60. Barker 500-Year Stages for FWOP and Structural Alternatives

The graph above displays the stages at Barker for the FWOP and the FWP for the Cypress reservoir, the channel improvement along Buffalo Bayou, and the combination alternatives. As these graphs show, the FWOP 500-year stage can exceed the elevation of government owned land (95 feet NAVD 88) by seven feet. The three full structural alternatives exceed government owned land at the 500-year event by 4.1 to 5.0 feet. At the 100-year event, the FWOP stage exceeds GOL by 2.5 feet while two the three alternatives exceed GOL by 0.6 feet. The reservoir alternative stays within GOL.

Table 46. FWOP and FWP 100- and 500-year Max Stages at Addicks and Barker

Alternative Plans	Addicks		Barker	
	100-Year	500-Year	100-Year	500-Year
Alt 1: No Action	103.4	108.1	97.5	102.0
Alt 2: Cypress Creek Dam	101.1	105.8	95.0	99.5
Alt 6: Buffalo Bayou Channel Improvements	101.6	107.1	95.6	100.0
Alt 8: Alts 2 & 6	99.8	104.7	95.6	100.0

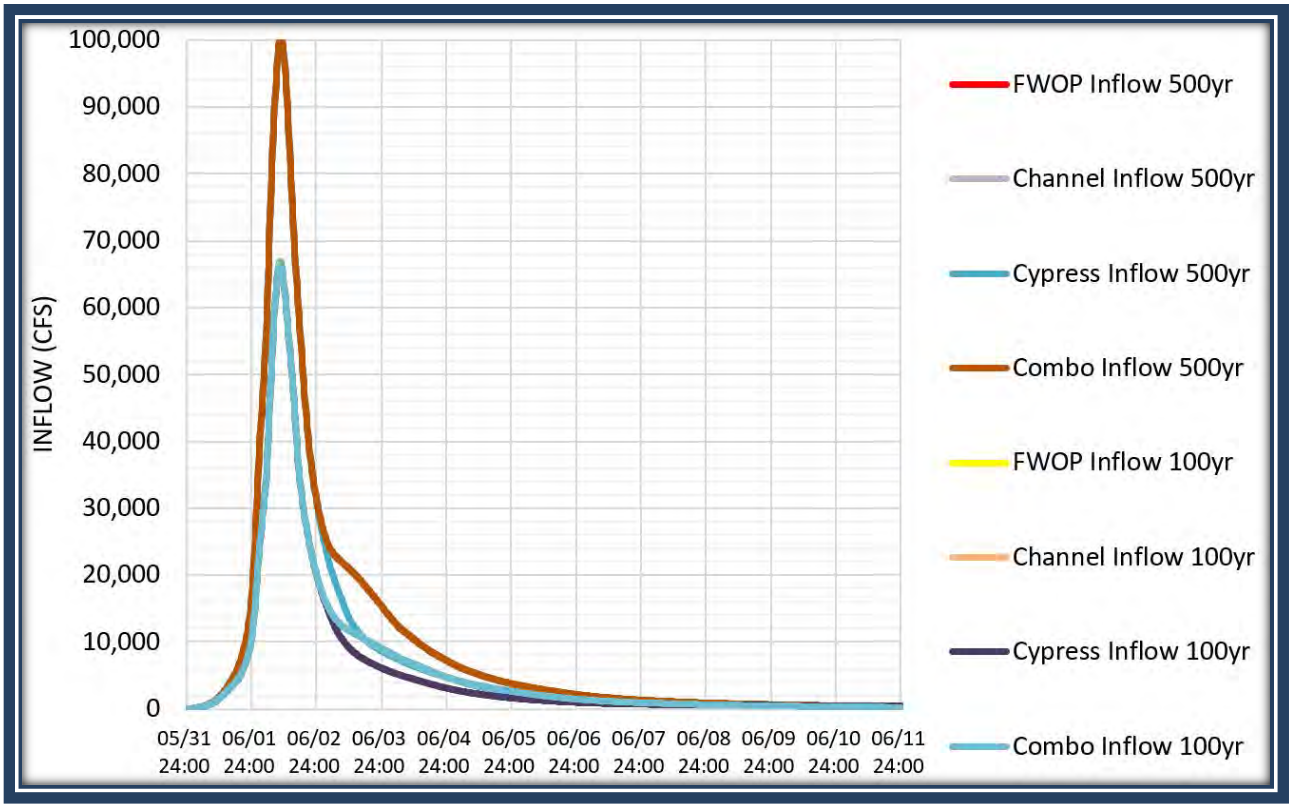

Figure 61. FWOP and Future Under Alternative Scenarios Inflows at Addicks

The graph above displays the inflows into Addicks for the FWOP and the three remaining structural alternatives for the 100- and 500-year events. At the 100-year event, peak inflows into Addicks for the FWOP and future under alternative scenarios are relatively identical at approximately 66.8K cfs. At the 500-year event, peak inflows are also relatively identical at approximately 100.2K cfs among the FWOP and the alternatives. Later in the 500-year event, the inflows of the combination event are relatively the same as the FWOP. The takeaway from this graph is that the alternatives under evaluation do not have an appreciable impact on the inflows at Addicks.

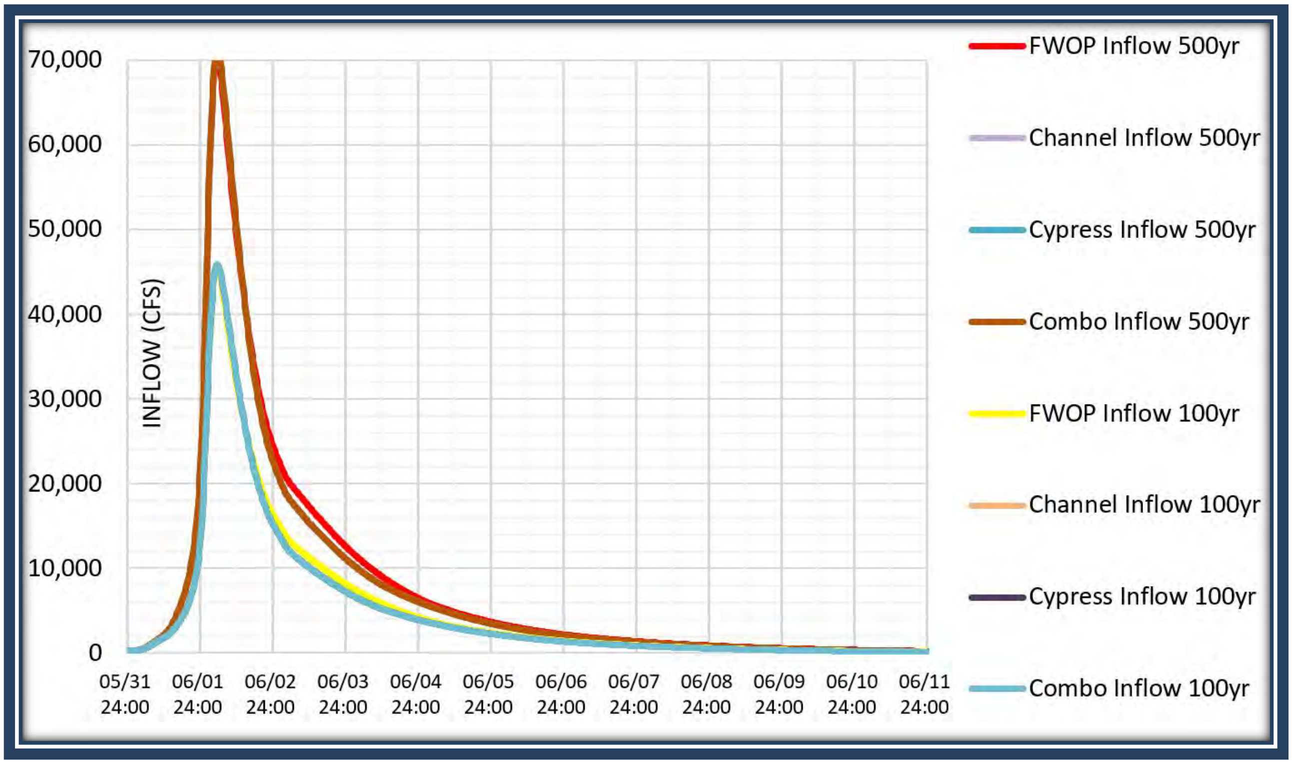

Figure 62. FWOP and Future Under Alternative Scenarios Inflows at Barker

The graph above displays the inflows into Addicks for the FWOP and the three remaining structural alternatives for the 100- and 500-year events. At the 100-year event (approximately 66.8K cfs), peak inflows into Addicks for the FWOP and the alternatives are identical. At the 500-year event, peak inflows are also relatively identical at approximately 100.2K cfs among the FWOP and the alternatives. The takeaway from this graph is that the alternatives under evaluation have a comparable impact on the inflows with the exception of the combination alternative at Barker.

Table 47. FWOP and Alternative Peak Inflows at Addicks and Barker

Alternative Plans	Addicks		Barker	
	100-Year	500-Year	100-Year	500-Year
Alt 1: No Action	66,834	100,212	45,351	69,988
Alt 2: Cypress Creek Dam	66,793	100,148	45,836	70,927
Alt 6: Buffalo Bayou Channel Improvements	66,834	100,214	45,836	70,927
Alt 8: Alts 2 & 6	66,834	100,214	45,836	70,927

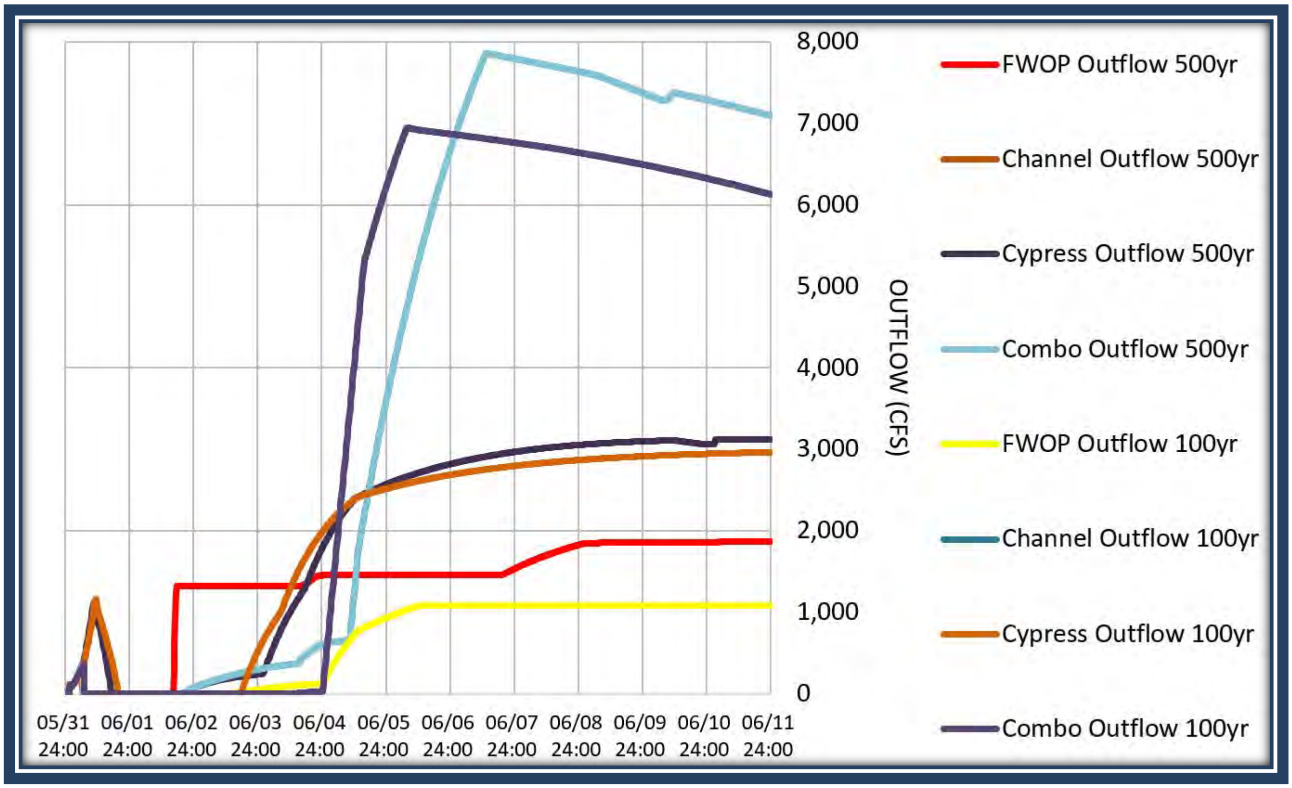

Figure 63. FWOP and Alternatives Outflows at Addicks

The graph above displays the outflows into Addicks for the FWOP and the three remaining structural alternatives for the 100- and 500-year events. At the 100-year event both the channel improvement alternative and the combination lie on top of each other with peak outflows of 6,944 cfs and 6,778 cfs respectively. At the 500-year event, both the channel and combination alternatives also lie on top of each other with peak outflows for those alternatives being 7,857 and 7,562 cfs. As this graph shows, improvements to Buffalo Bayou greatly enhance the ability to evacuate water from Addicks as opposed to just retaining water with an additional reservoir upstream.

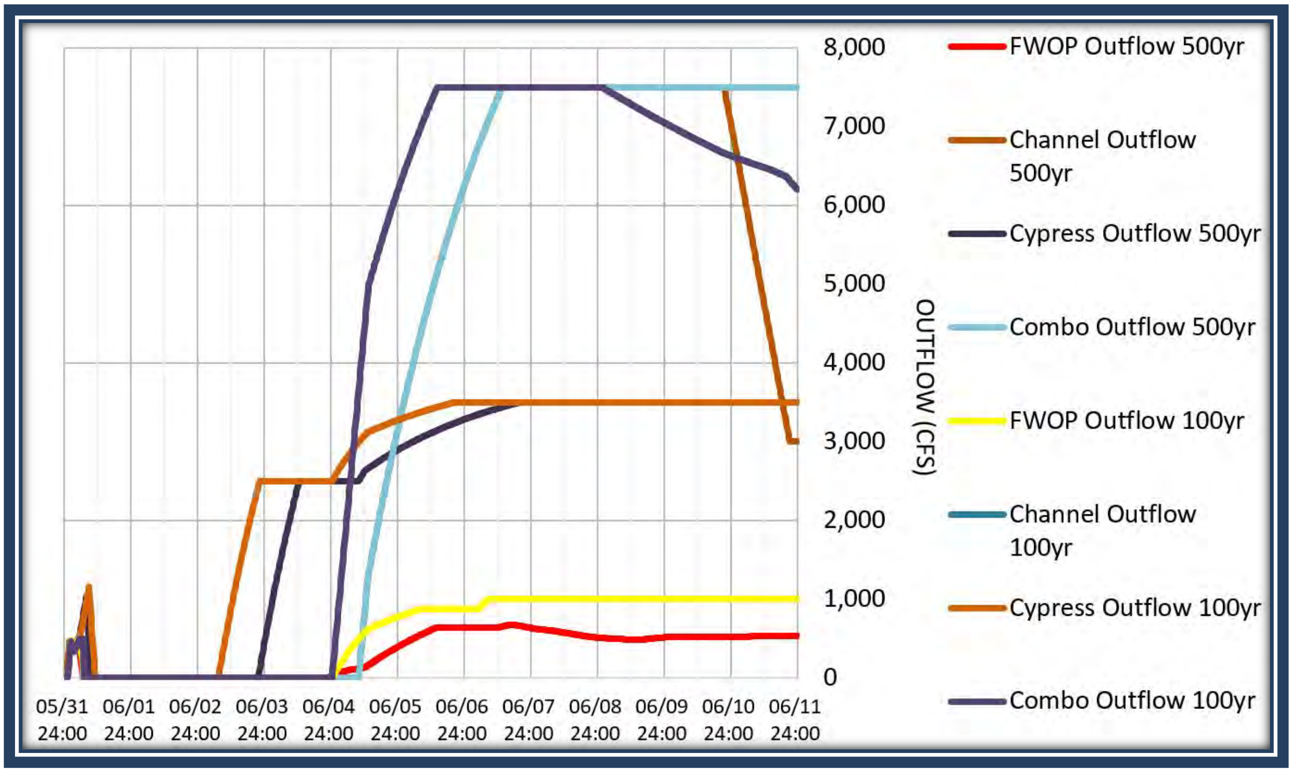

Figure 64. FWOP and Alternatives Outflows at Barker

The graph above displays the outflows into Barker for the FWOP and the three remaining structural alternatives for the 100- and 500-year events. At the 100-year event both the channel improvement alternative and the combination lie on top of each other with peak outflows of 7,500 cfs. At the 500-year event, both the channel and combination alternatives also have peak outflows of 7,500 cfs. As this graph shows, improvements to Buffalo Bayou greatly enhance the ability to evacuate water from Barker as opposed to just retaining water with an additional reservoir upstream.

Table 48. FWOP and Alternatives Peak Outflows at Addicks and Barker

Alternative Plans	Addicks		Barker	
	100-Year	500-Year	100-Year	500-Year
Alt 1: No Action	1,088	1,865	1,000	671
Alt 2: Cypress Creek Dam	2,965	3,119	5,464	5,394
6: Buffalo Bayou Channel Improvements	6,944	7,857	7,500	7,500
Alt 8: Alts 2 & 6	6,944	7,857	7,500	7,500

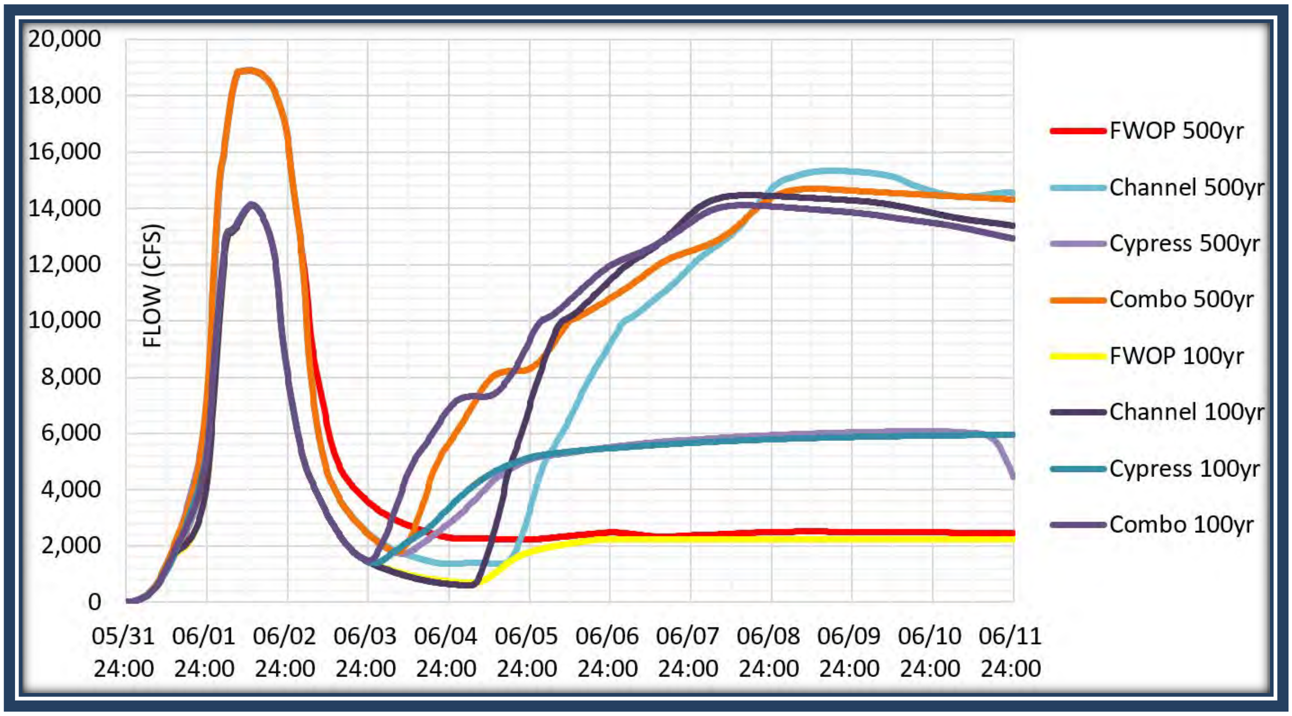

Figure 65. FWOP and Alternatives Flow at Barker at Piney Point

The graph above displays flows along Buffalo Bayou at the Piney Point stream gauge for the FWOP and the three remaining structural alternatives for the 100- and 500-year events. Peak flows early in an event corresponding to direct surface runoff making the FWOP and the FWP essentially the same. As the event progresses and the initial peak recesses and as water is released from the dams, the additional capacity of the channel improvement provide as much as 12,000 cfs in additional conveyance for the 500-year event and almost as much at the 100-year event.

Table 49. FWOP and FWP Peak Flows at Piney Point

Alternative Plans	Piney Point	
	100-Year	500-Year
Alt 1: No Action	14,106	18,896
Alt 2: Cypress Creek Dam	14,107	18,897
Alt 6: Buffalo Bayou Channel Improvements	14,467	18,897
Alt 8: Alts 2 & 6	14,122	18,906

4.8.6 Further Evaluation of Focused Array of Alternatives

Additional evaluation of the focused array of structural alternatives considered the performance contribution of the added (ancillary) measures for Alternative Plans 2 - Cypress Creek Dam, Alternative 6 - Buffalo Bayou Channel Improvements, and 8 - Combination (Table 39 Column 4) relative to their costs and performance.

In all cases, the price increase was substantial. At a minimum, the added measures double the cost of Alternative Plan 8 (Alt Plan 2: Cypress Creek Dam + Alt Plan 6: Buffalo Bayou Channel Improvements).

For Alternative 2 - Cypress Creek Dam, the added measures doubled the cost from $4,496 million to $6,069 million. The relative performance between the "reservoir only" variation and the "full" alternative can be witnessed by observing the hydrographs at both Addicks and Barker to assess their impacts. At Addicks (Figure 66), inflow performance is identical with increases in outflow for the full variation. Outflows at Addicks show to be higher early in an event for the anchor only relative to the full alternative but both converge later in the event. At Barker (Figure 67), virtually identical performance for inflows between the two variations with outflows being substantially higher for the full alternative suggesting that the full alternative may have some benefits to loading at both Addicks and Barker and may reduce flooding upstream of both reservoirs.

For Alternative 6 - Buffalo Bayou Channel Improvements, the added measures doubled the cost from $3,061 million to $4,133 million. Again, the relative performance between the "channel improvements only" variation and the "full" alternative can be witnessed by observing the hydrographs at both Addicks and Barker to assess their impacts.

At Addicks (Figure 68), inflow performance is identical with very similar outflows. At Barker (Figure 69), inflow performance is also identical with very similar outflow performance between the full and the anchor only alternatives.

For Alternative 8 – Combination (Alt Plan 2: Cypress Creek Dam + Alt Plan 6: Buffalo Bayou Channel Improvements), the added measures doubled the cost from $5,197 to $7,015 million. Once again, the relative performance between the "combo only" variation and the "full" alternative can be witnessed by observing the hydrographs at both Addicks and Barker to assess their impacts. At Addicks (Figure 70), inflows are again identical between the two variations and outflows follow similar patterns with the full alternative evacuating water from the reservoir a bit earlier in the event. At Barker (Figure 71), inflows are virtually identical between the anchor and the full alternative as are outflows.

Overall, the main difference in performance appears to be in the releases from Barker for the Alternative 2 – Cypress Creek Dam. Based on these observations, the additional cost of the ancillary measures do appear to justify the any small differences in performance.

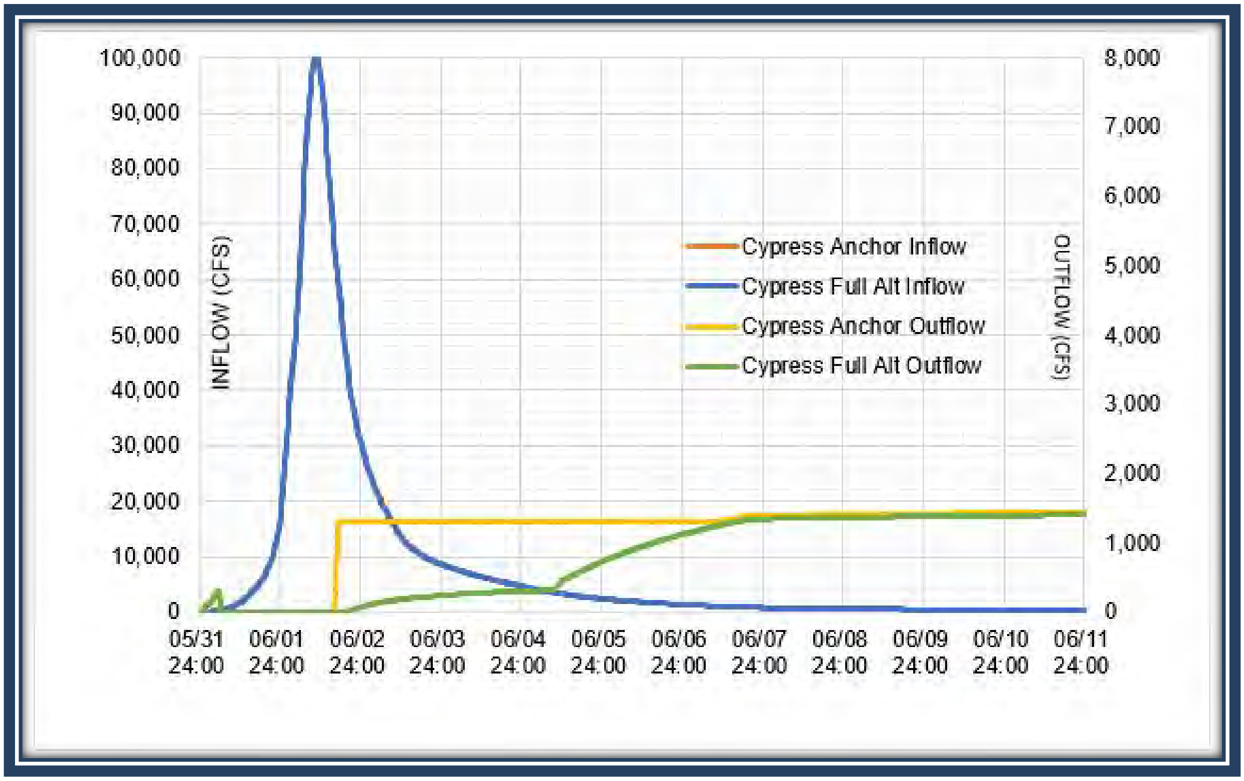

Figure 66. Hydrograph Showing Effect of Alt Plan 2 on Addicks Reservoir Inflows and Outflows

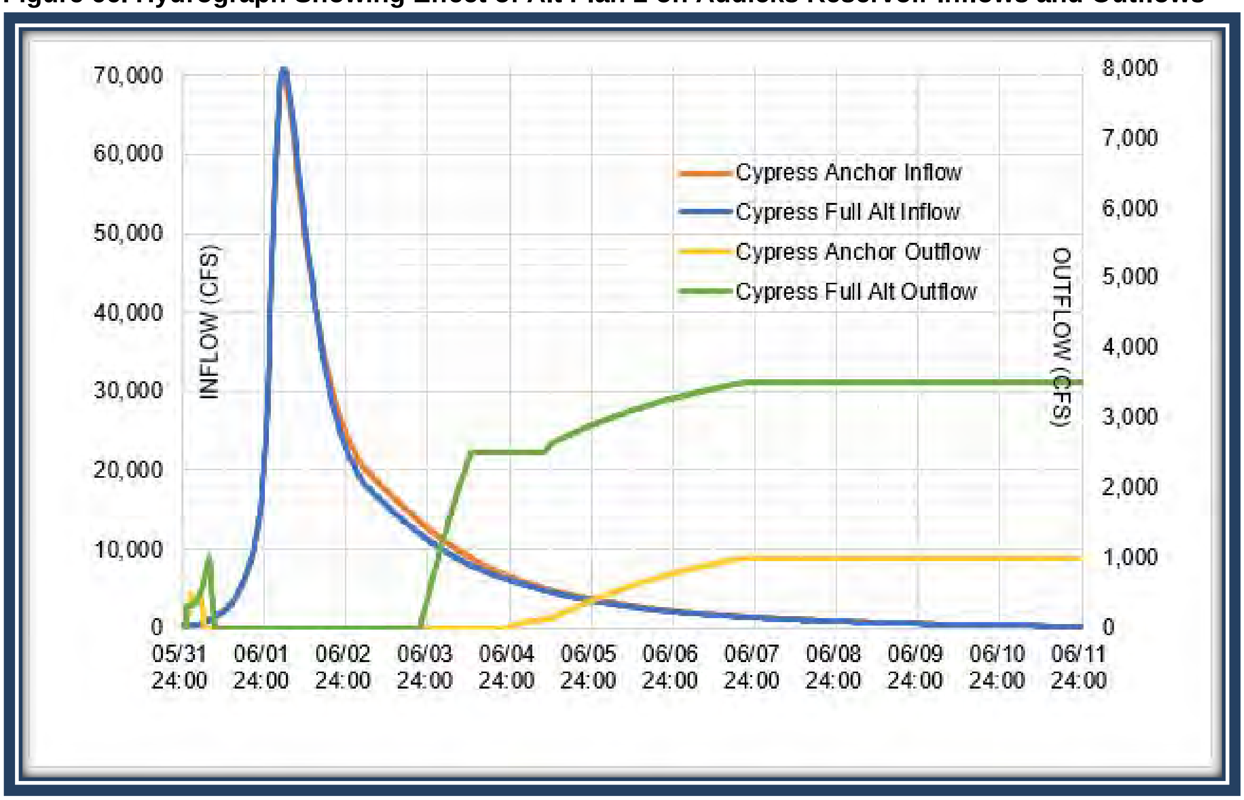

Figure 67. Hydrograph Showing Effect of Alt Plan 2 on Barker Reservoir Inflows and Outflows

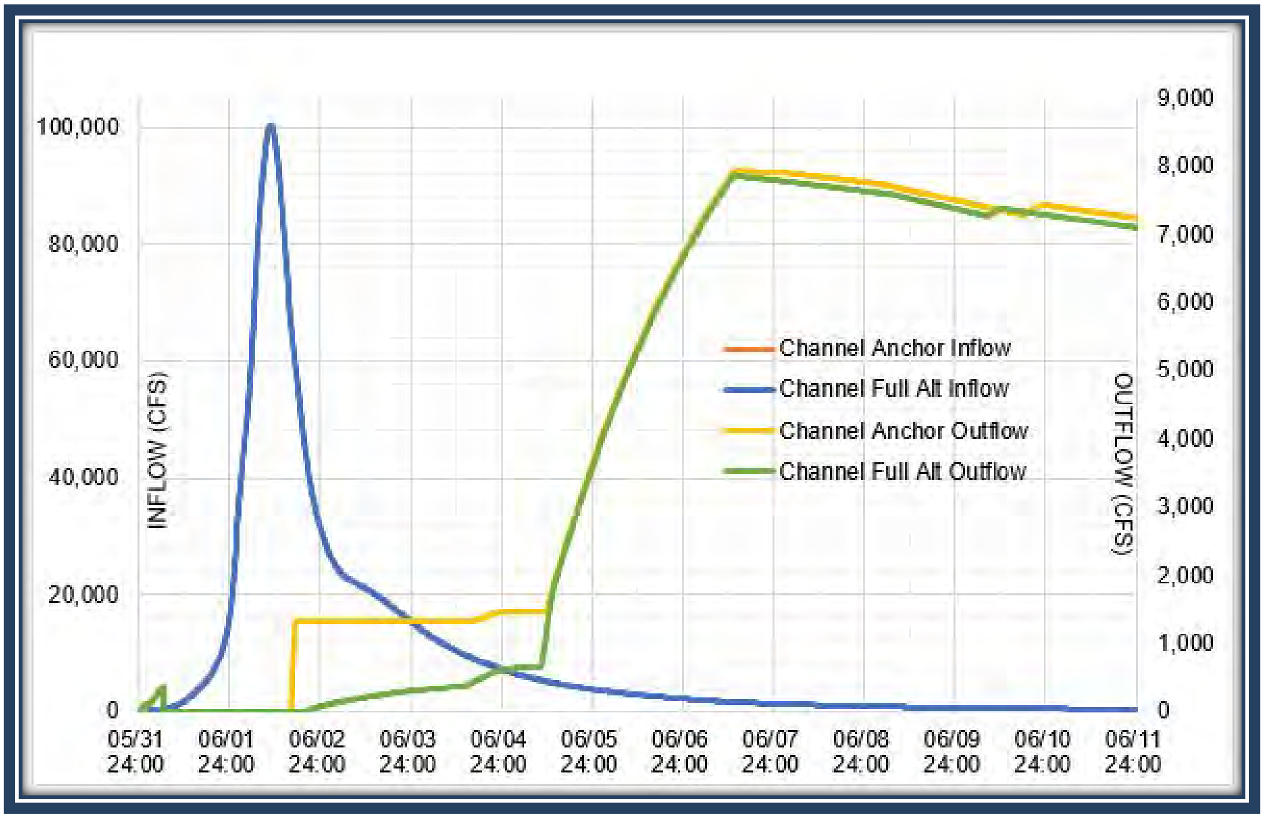

Figure 68. Hydrograph Showing Effect of Alt Plan 6 on Addicks Reservoir Inflows and Outflows

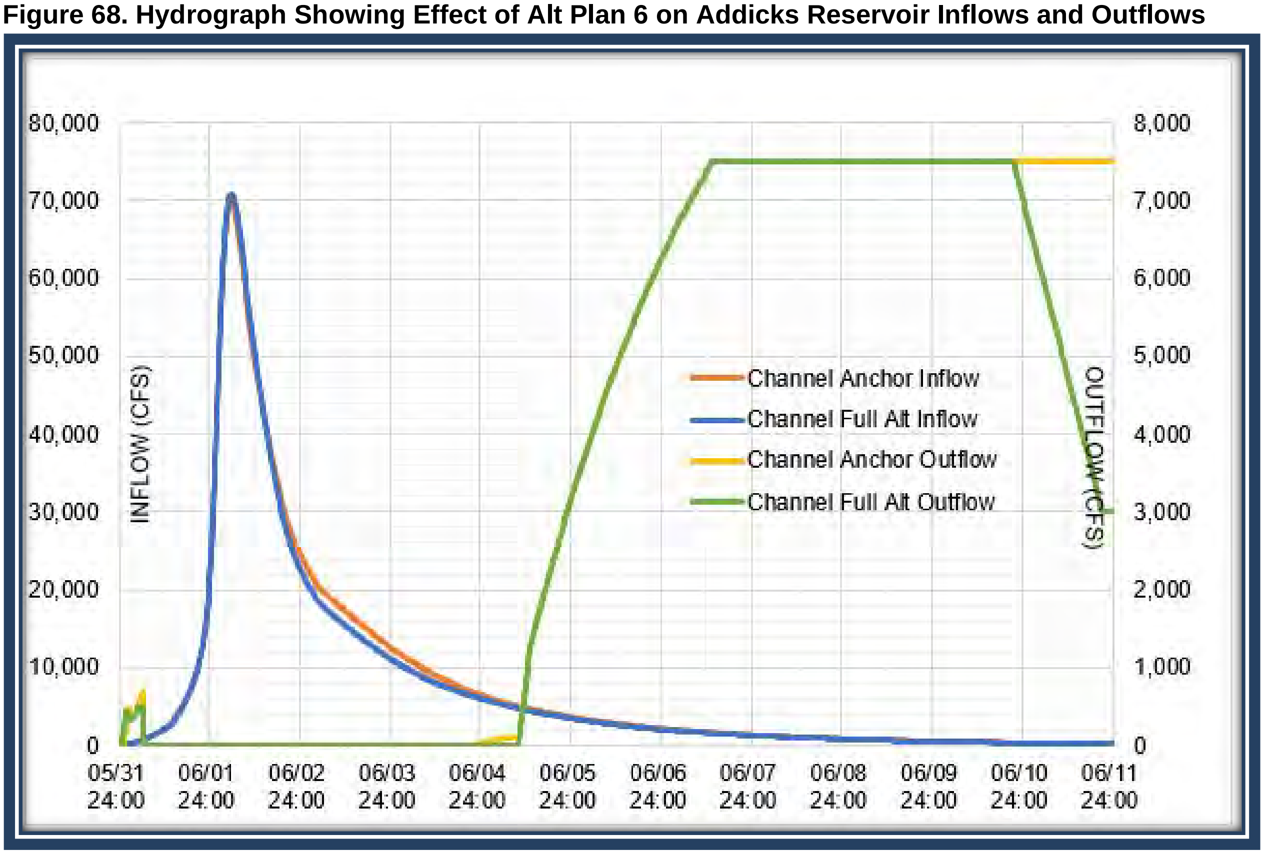

Figure 69. Hydrograph Showing Effect of Alt Plan 6 on Barker Reservoir Inflows and Outflows

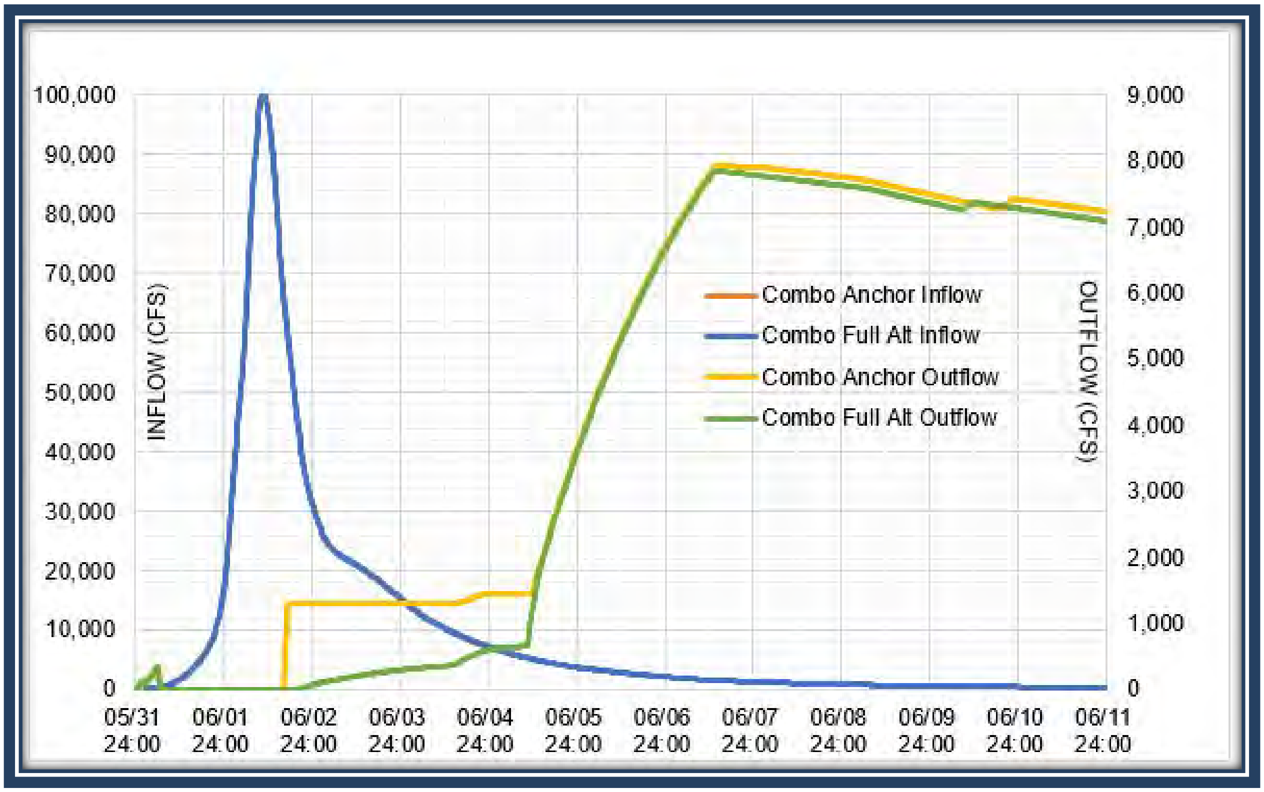

Figure 70. Hydrograph Showing Effect of Alt Plan 8 on Addicks Reservoir Inflows and Outflows

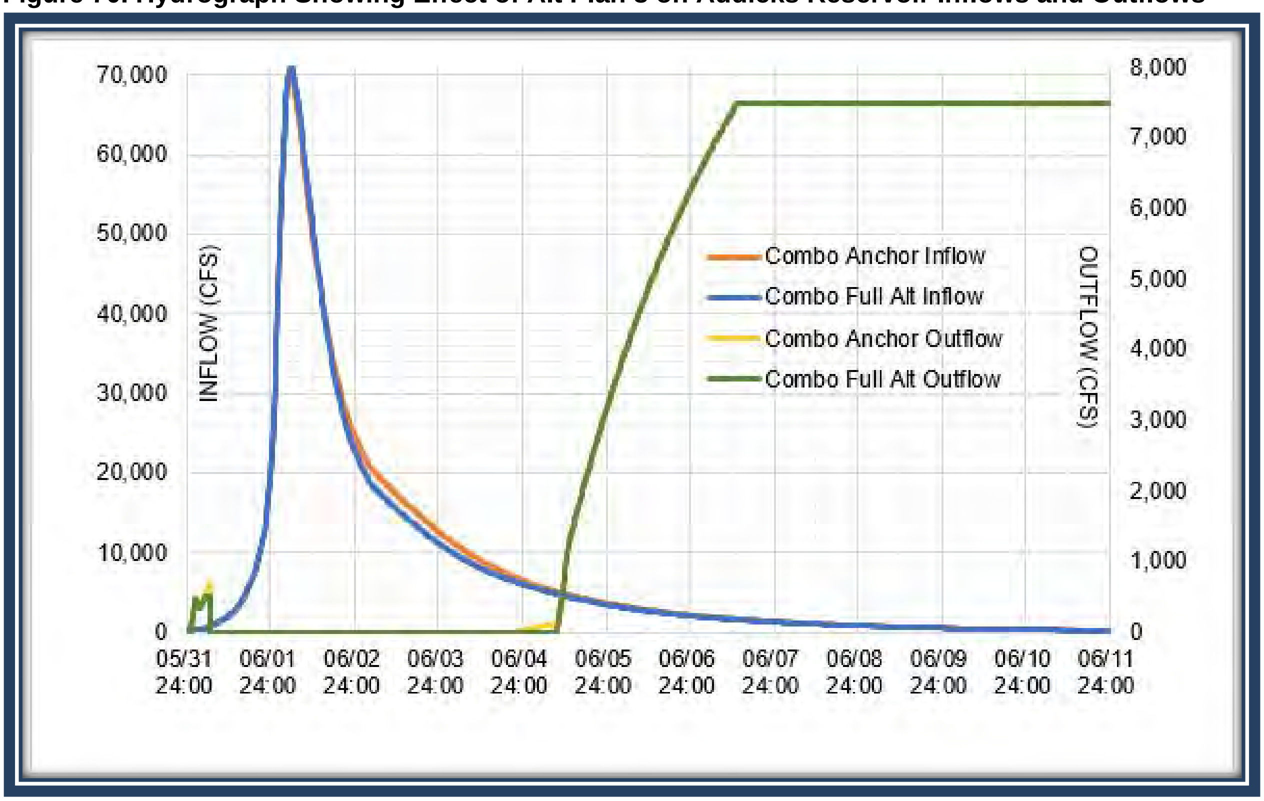

Figure 71. Hydrograph Showing Effect of Alt Plan 8 on Barker Reservoir Inflows and Outflows

4.9 Dam Safety Formulation

Addicks and Barker Dams were constructed in the 1940s 17 miles west of Houston. The main project features are an unzoned earthen dam, concrete outlet works, and uncontrolled auxiliary spillways. Several repairs have been made to the outlet works at both dams since their completion due primarily to the silty and sandy erodible foundation soils underlying the conduits. Repairs include foundation erosion repairs during construction, parabolic chute cavity repair (1968), cantilever wall at Addicks Dam (1973), outlet work repairs at Addicks (1979), and outlet work repairs at Barker (1982).

In 1977, seepage control measures were incorporated at both projects due to seepage and piping is associated with erodible foundation soils and increased storage durations caused by gated operation. Measures included construction of a soil bentonite slurry trench through the embankment and pervious foundation, placement of a downstream berm to enhance slope stability, and placement of clay blankets to thicken the impervious cover over pervious foundation materials. The soil bentonite slurry trench was not constructed beneath the outlet conduits until 1977 and completed in 1982.

As part of the Dam Safety Assurance Program, Addicks and Barker Dams were modified to conform to updated design criteria between 1986 and 1989. First, the main dam was raised to achieve needed freeboard requirements. Second, erosion protection utilizing roller compacted concrete was added to the lower ends of the dams so they could serve as overflow spillways during storms greater than the Standard Project Flood, up to and including the Probable Maximum Flood.

In 2005, the Corps started the Screening for Portfolio Risks Analysis of all 694 Corps' dams. Each was identified and classed based upon level of risk regarding how likely they are to fail and what the consequences of dam failure would have on economics and human life.

The Addicks and Barker Dams were originally classified as Dam Safety Action Classification (DSAC) 2 (highly urgent) after the Screening Portfolio Risk Assessment (SPRA) was performed. Addicks and Barker are currently categorized as DSAC 1 (urgent and compelling: unsafe). The current DSAC was determined from the following events:

- May 2007 – Screening for Portfolio Risk Analysis (SPRA) Team classified Dam as DSAC 2.
- September 2009 – IES Team recommended the classification be changed to DSAC 1.
- October 2009 – Senior Oversight Group (SOG) changed classification to DSAC 1.
- March 2011 – SOG retained classification as DSAC 1.

In 2009, and 2010, 22 and 23 potential failure modes (PFMs) were identified for Addicks and Barker Dams, respectively. Six of the PFMs at each dam were determined to be significant, four of which were identical. Alternative plans for the four PFMs are under construction which including replacement of the outlet works.

The two remaining PFMs are addressed as part of this Review of Completed Projects study are:

- Addicks Dam alone: PFM 4a stated that “Erosion of embankment toe due to flow around the north end of the dam and over the roller-compacted concrete auxiliary spillway results in scour of the ditch at the embankment toe leading to slope failure of the embankment.”
- Addicks and Barker Dams: PFM 5 stated that “Loss of auxiliary spillway roller-compacted concrete slabs and breach of auxiliary spillway at high pools. Spillway embankments for both dams were covered with roller-compacted concrete slabs. When flows over the spillway embankments occur as pool rises to above the spillway levels, the roller-compacted concrete slabs can be displaced because of high uplift pressures developed beneath the roller-compacted concrete slabs. The spillway embankment can then be eroded until breach occurs.”

A thorough review of all technical and historical data was conducted to evaluate the potential risk of the Addicks and Barker Dams in the event of typical to extreme flooding conditions. These evaluations were conducted to establish the baseline risk conditions at Addicks and Barker dams. The evaluations determined that an actionable failure mode exists at the uncontrolled spillways located at the ends of both Addicks and Barker Dams (Figure 72).

The annualized probability of failure was estimated to be unacceptably high for a potential spillway breach. Recently developed hydraulic information known as the hydraulic loading curve (generally the time and duration of estimated flood events) and the draft Probable Maximum Flood (PMF) elevation (the highest reservoir elevation based upon largest anticipated rainfall event for the region) were developed. This information, as well as the existing spillway materials and configuration, were used to determine potential failure probability.

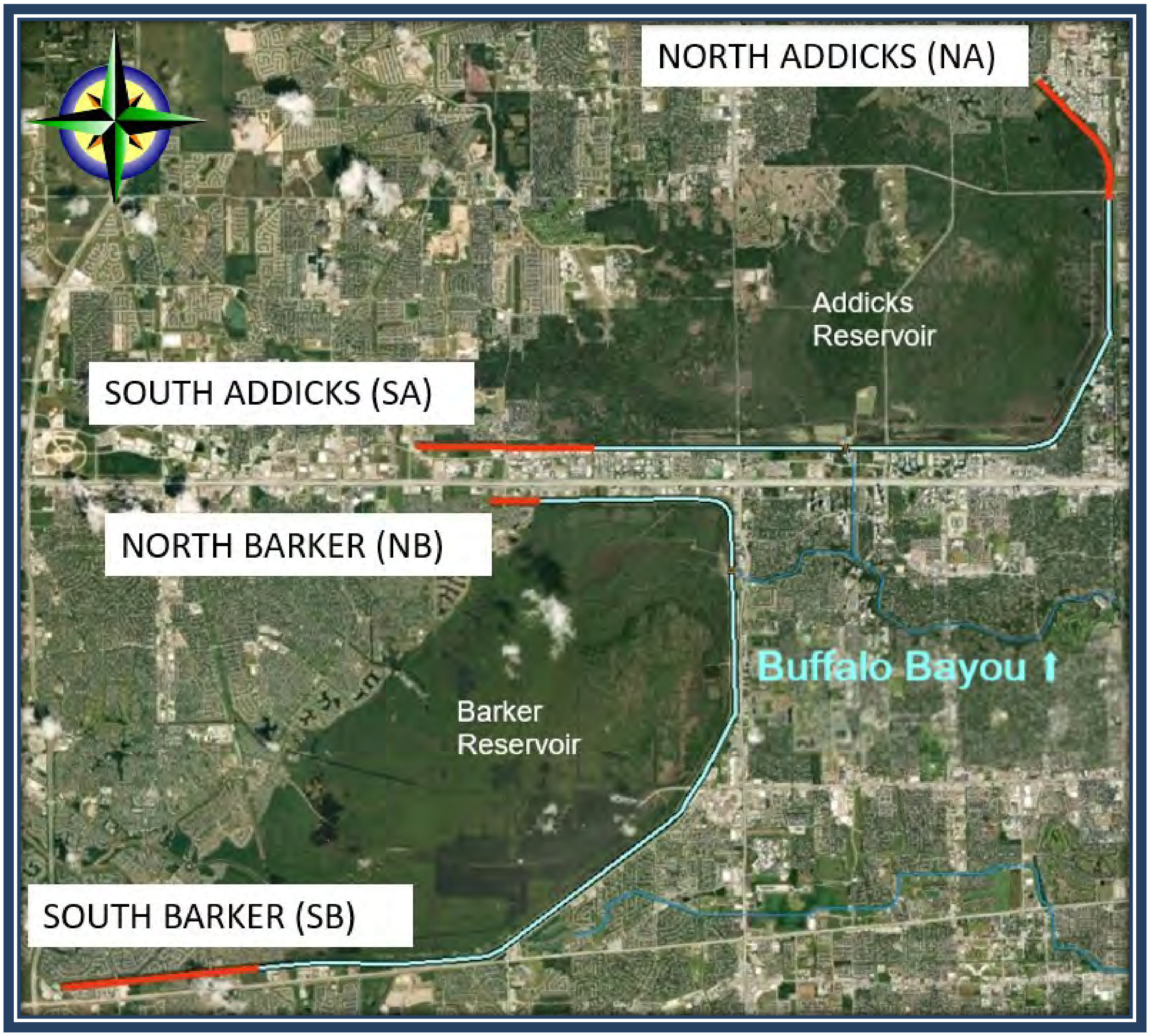

Figure 72. Map Showing Addicks and Barker Spillways (Red)

4.9.1 Dam Safety Problems, Opportunity, Objective and Constraint

Specific Dam Safety Problems, Opportunity, Objective and Constraint

Dam Safety Problem Statement:

In 2009 and 2010, Potential Failure Modes were identified at both Addicks and Barker dams. Regional subsidence is occurring in along coastal Texas and particularly in the greater Houston area. The northeast spillway at Addicks Dam is three feet lower than the southwest RCC auxiliary spillway.

Addicks Dam alone: PFM 4a is “Erosion of embankment toe due to flow around the north end of the dam and over the roller-compacted concrete (RCC) auxiliary spillway results in scour of the ditch at the embankment toe leading to slope failure of the embankment.”

Addicks and Barker Dams: PFM 5 is “Loss of auxiliary spillway RCC slabs and breach of auxiliary spillway at high pools. Spillway embankments for both dams were covered with RCC slabs. When flows over the spillway embankments occur as pool rises to above the spillway levels, the RCC slabs can be displaced because of high uplift pressures developed beneath the RCC slabs. The spillway embankment can then be eroded until breach occurs.”

Specific Dam Safety Problems, Objectives and Constraints

Specific Dam Safety Problems

Probable maximum flood water elevations for both Addicks and Barker dams have increased as well as the frequencies leading to increased loading on spillways.

- Spillway protective concrete layers are 25+ years old and have cracks, separations, and erosion.
- Land subsidence has lowered the spillway elevations.

Specific Dam Safety Opportunity Statement

An opportunity exists to ensure the safety and operability of the Addicks and Barker spillways.

Specific Dam Safety Objective

- Reduce life-safety risks consistent with Corps tolerable risk guidelines

Specific Dam Safety Constraint

- Plans should avoid increasing flood risk or transferring flood risk to other areas

Consideration and development of dam safety risk-management measures and alternatives to address the potential for spillway failure have been performed. These alternative plans will focus on protecting and armoring the existing spillways from erosion and possible breach in the event PMF level loading occurs.

The selected dam safety management alternatives will then be incorporated into the Tentatively Selected Plan as a part of the overall study. It is understood that flood risk-management (FRM) alternative combinations could have potential impacts on risk and consequence estimates for the spillway failure mode. Increased release capabilities, as a part of the proposed channel improvements, could change the baseline loading conditions. Hydraulic analyses continue to be refined and reviewed. The project delivery team and Southwestern Division Risk Cadre will continue to evaluate reservoir impacts and perform updated risk analyses on all potential changes to the current hydraulic loading conditions and reservoir levels.

4.9.2 Formulation and Screening of Dam Safety Measures

Plan formulation is the process of building alternative plans that meet planning objectives, and avoid planning constraints. Combinations of management measures make up alternative plans, and are defined is sufficient detail, that realistic evaluation and comparison of each plan's contributions to the objectives, and other effects, can be identified, measured, and considered.

After the problems, opportunities, objectives, and constraints were agreed upon by the PDT, the next part of the plan formulation process is to brainstorm both structural and nonstructural management measures.

A measure is defined as a means to an end; an act, step, or procedure designed for the accomplishment of an objective. In other words, a measure is a feature (structure), or an activity, that can be implemented at a specific geographic site to address one or more planning objectives. Measures are the building blocks of Plans and are categorized as structural and nonstructural. Equal consideration was given to these two categories of measures during the Planning process.

Structural Measures that Stop Erosion

Build Seepage Barrier (Cutoff Wall) Inside Existing Spillways With Concrete Cap – The centerline of each spillway would be dug out and replaced with a waterproof wall made of concrete or bentonite.

Build Sheet-Pile Barrier Inside Existing Spillway With Concrete Cap – A line of sheet-pile would be pounded down into the middle of each spillway and then capped with concrete.

Structural Measures that are LARGE and Expensive

Relocating Spillways Closer To Outlet Channel – This measure would require the removal of the existing spillways, and the design and construction of new spillways that would be built to the full embankment height closer to each dam's gates.

Raise And Extend Spillways – This measure involves the removal of each spillway's existing concrete caps, removal of dam sections closer to the dam's center, and then reconstructing the spillways to make them higher.

Build Concrete Floodwall Along Top Of Existing Spillways With Concrete Cap – This measure requires the building and setting of concrete vertical walls into the centerline of each spillway.

Replace Existing Spillways With Bell Shaped Weir And A Flip Bucket –


Bell Weir From the Side


Bell Weir From Above

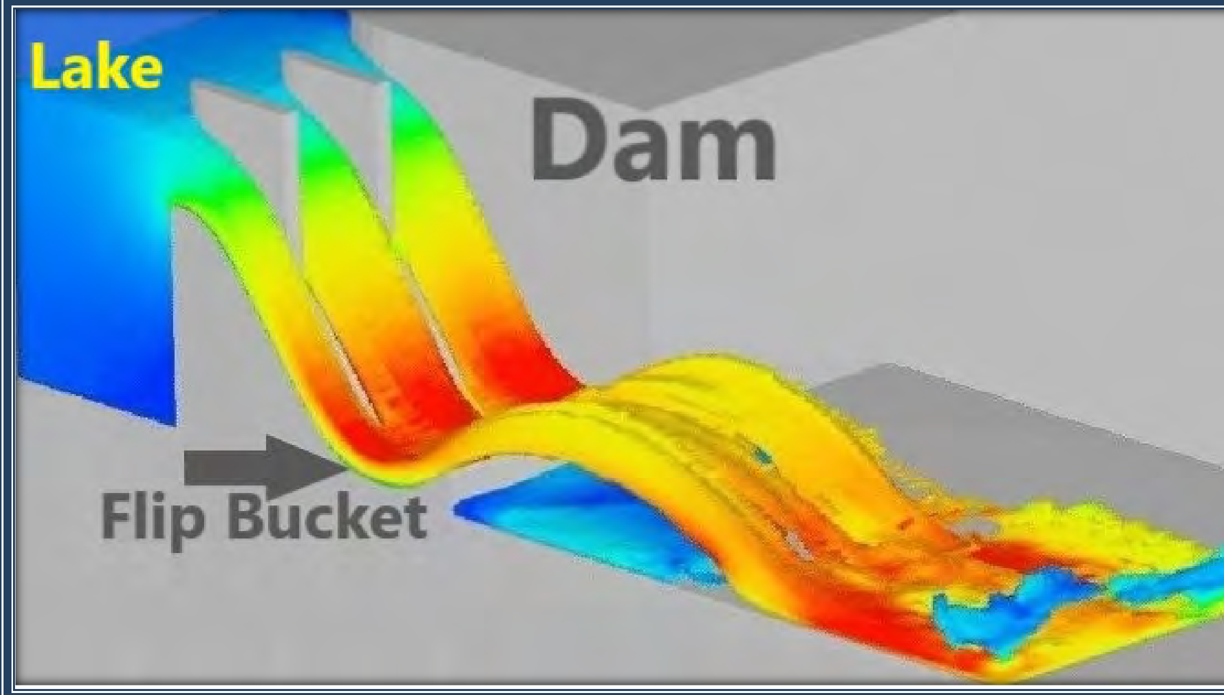

Figure 73. Typical Flip Bucket Configuration Showing Water Energy (Red = High Energy, Blue = Low Energy)

<u>Lowering Spillways</u> – The measure requires the removal of the existing concrete caps and then the removal of spillway fill material to a determined elevation. Concrete caps would then be replaced.

<u>Shorten Spillway Length</u> – This measure is the opposite of a spillway extension. The dams would be lengthened to the existing dam crest at each spillway.

Channel Between Spillway & Buffalo Bayou – At the downstream bottom of each dam's spillway, a channel would be excavated to direct water to Buffalo Bayou.

Dam Removal – Both Addicks and Barker Dams would be removed allowing upstream waters to travel directly into Buffalo Bayou without obstruction.

Dam Replacement – Both Addicks and Barker Dams would be removed and replaced.

Structural Measures that Armor the Spillways

Flattening Downstream Slope Of Existing Spillways – This measure involves adding fill to the downstream side of each spillway lengthen the distance from the top of the spillway to its bottom.

Replace Existing Poured-In-Place Concrete Surface With New Poured-In-Place Concrete – This measure is self-explanatory.

Vegetate Both Sides Of Dam – This measure involves covering both the upstream and downstream side of the dam and spillway with turf grasses.

Replace Existing Poured-In-Place Concrete Surface With Reinforced Concrete Slabs – Reinforced concrete slabs are pieced of prepared concrete reinforced with iron rods and set in place next to each other. These would be set in place after the existing concrete caps are removed (Figure 74).

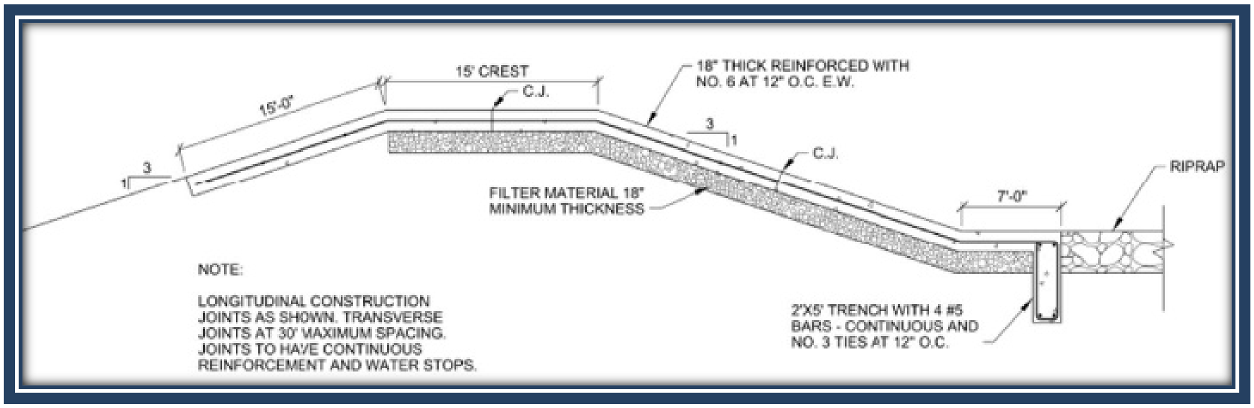

Figure 74. Example of Reinforced Concrete Slabs

Replace Existing Spillway With Roller Compacted Concrete (RCC) – After the existing concrete caps are removed, a concrete pavement is placed and then compacted with a steel drum or rubber-tired roller. Example: plane runways (Figure 75).

Figure 75. Laying Roller Compacted Concrete (www.theconstruction.org)

Replace Existing Poured-In-Place Concrete Surface With Hydro-Turf (“Astroturf” With Concrete) – Hydro-turf is a specialized concrete and “Astroturf” like material. This would be set in place, and anchored, after the existing concrete caps are removed (Figure 76).

Figure 76. Example of the use of hydro-turf (www.acfenvironmental.com)

Replace Existing Poured-In-Place Concrete Surface With Articulated Concrete Blocks (ACB) – After the existing concrete caps are removed, a matrix of individual concrete block locked together would be placed over the spillways and anchored down (Figure 77).

Figure 77. Articulate Concrete Block Mats (www.environmental-expert.com)

<u>Replace Existing Poured-In-Place Concrete Surface With Stepped Roller-Compacted Concrete (RCC)</u> – This measure is similar to measure 16 except that instead of a smooth slope, the concrete would set in steps to reduce water velocities (Figure 78).

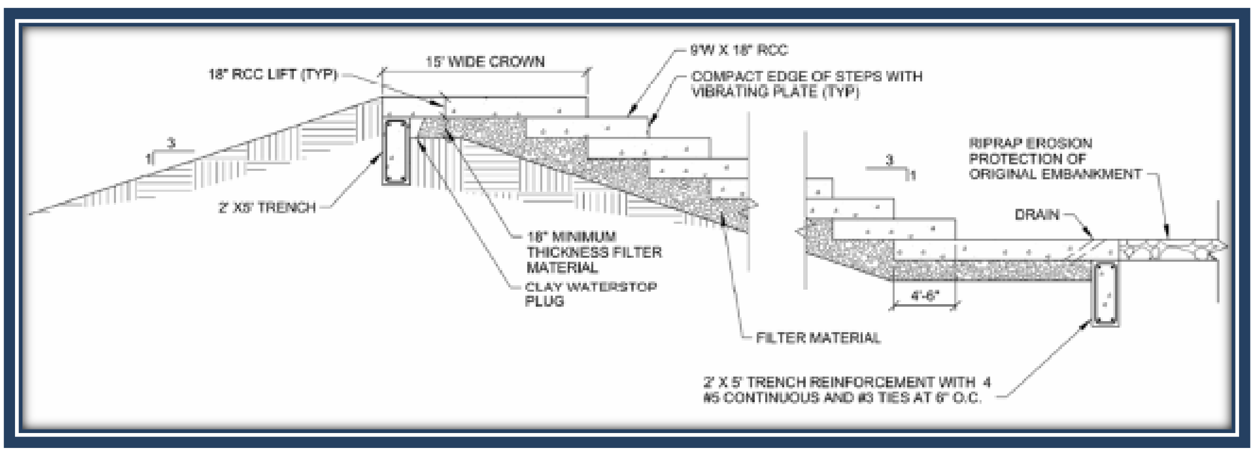

Figure 78. Typical Cross-Section for Stepped Roller Compacted Concrete

Nonstructural Measures

It was agreed that any tentatively selected plan for dam safety concerns and risk mitigation would include a nonstructural measures plan. These measures could include, but not be limited to the four following measures:

Acquisitions Of The Downstream Properties Inundated By Failure Of The Dam

<u>Improvements Of The Early Warning Systems</u> – The current emergency warning system is considered highly effective. However, improvements in the estimated effectiveness of an early warning system and mobilization rates should be considered further.

Improved Communication And Coordination Between the Corps And Local Emergency Management – Improved communication and coordination includes review of downstream inundation maps, breach formation time estimates, flood wave arrival times developed by the Corps. The Corps would participate with the local emergency management to identify evacuation locations and routes not subject to inundation. Evacuation routes from the potentially inundated areas is extremely limited due to flooding of access and feeder roads, traffic congestion, and wide spread area of inundation.

Improve Evacuation Effectiveness through shared knowledge of inundated areas, timing of inundation, assist in evacuation planning, and develop and maintain contacts and relationships with local emergency officials.

4.9.2.1 Dam Safety Measures Screened from Further Evaluation

The PDT conducted a preliminary screening of management measures to evaluate the applicability of each measure, and the potential for each measure to contribute to the study's specific planning objectives consistent with planning constraints.

The following measures required expensive and major structural changes to the existing spillways. They involve time-consuming planning, engineering and design efforts prior to implementation.

3. Relocating Spillways Closer To Outlet Channel – It would change the current consequence center associated with the spillways. This would then require a re-evaluation of the ends of embankment. There would likely be significant real estate issues and conflicts with government owned property. Altogether, these changes would be extremely expensive.

4. Raise And Extend Spillways – This measure would require real estate purchases or easement of private properties along the outside of the reservoir basins and would increase costs. Raising the spillway would change the overtopping frequency and would lead to reevaluation of the hydraulics.

5. Build Concrete Floodwall Along Top Of Existing Spillways – This is an unproven design to protect against overtopping. An expensive cofferdam, built to spillway height would be required before construction could start on the spillway. Water energy dissipaters, such as dragon teeth, would be needed at the downstream toe. Spillover discharge would be faster. There would likely be the need for an aeration structure to dissipate cavitation.

6. Replace Existing Spillways With Bell Shaped Weir And A Flip Bucket – This measure would require removal and replacement of the existing spillway structures. A different shape would require significant design and construction efforts, which would increase costs. Energy dissipation measures would be required at the downstream toe of the embankment.

7. Lowering Spillways – This measure would change the overtopping and storage conditions and greatly affect downstream consequence centers. Increased non-breach risk and

downstream damages would be anticipated. This would essentially involve a transfer of risk from upstream to downstream. It would also require real estate purchases or easement of private properties along downstream channel and Buffalo Bayou.

8. Shorten Spillway Length - This measure would change the overtopping conditions and would increase the peak pool elevations. This would increase consequences. It would also require real estate purchases or easement of private properties along the outside of the reservoir basins.

9. Channel Between Spillway & Buffalo Bayou - This measure would require costly design and construction efforts to transfer all spillway flows to travel safely along the downstream embankment toe. It would also require real estate purchases or easement of private properties along downstream channel and Buffalo Bayou.

The following measures required expensive and major structural changes to the existing spillways. They involve time-consuming planning, engineering and design efforts prior to implementation.

1. Build Seepage Barrier (Cutoff Wall) Inside Existing Spillway – There would be limited stability, if unreinforced once the downstream embankment eroded. Therefore, the cutoff wall would need steel reinforcement, design, and construction. This is very complicated and requires a construction platform for larger excavators and equipment. This measure would need to be combined with concrete overlay, and additional protection of the downstream slope and toe, to prevent erosion. Requires specific skill sets with few experienced contractors available. Depth of wall would be minimal based upon subsurface.

2. Build Sheet-Pile Barrier Inside Existing Spillway – This measure requires additional protection of the downstream slope and toe. Wall depth (and stability) would be minimal based upon subsurface. Downstream erosion would be likely if flow occurs leaving wall exposed and possibly unstable. Construction platform for equipment would be needed. Could be considered viable with a slope protection measure, however, this would greatly increase costs

12. Flattening downstream slope of existing spillways – This may induce a constriction and damages upstream (i.e. releases and flow duration would change). May need to move crest upstream in order to stay within government property; this might decrease reservoir storage capacity. High real estate costs to implement. A large volume of earthwork would be required with high construction costs. It was determined that flattening slopes would not offer sufficient slope protection or erosion resistance against anticipated velocities.

13. Replace Existing Poured-In-Place Concrete Surface With New Poured-In-Place Concrete – This did not provide long-term protection per current conditions; only lasts about 25 years. It has cracked, deteriorated, separated, and moved. This measure does not include internal reinforcement, has no connections between the joints.

14. Vegetate Both Sides of Dam – This is not an improvement to existing conditions. The measure would not provide erosion protection for high water velocities or for long periods.

Vegetation would be easily damaged from people walking on it, and would have high operations and maintenance costs (mowing contracts, inspections).

15. Replace Existing Poured-In-Place Concrete Surface With Reinforced Concrete Slabs – The costs for this measure are much higher than for either the roller compacted concrete or articulate concrete measures with no additional benefits.

16. Replace Existing Spillway With Roller Compacted Concrete (RCC) – This measure has a higher cost than either the articulated concrete blocks.

17. Replace Existing Poured-In-Place Concrete Surface With Hydro-Turf ("Astroturf" With Concrete) - The long-term durability of hydro-turf when exposed to sunlight is questionable. Polyethylene matting, relatively fast installation is very expensive to install. Fast water could rip it off the spillways.

4.9.2.2 Dam Safety Measures Carried Forward for Further Evaluation

The following dam safety measures were carried forward for further consideration and evaluation based on the potential for each measure to contribute to the study's specific planning objectives consistent with planning constraints.

10. Dam Removal

11. Dam Replacement

18. Replace Existing Poured-In-Place Concrete Surface With Articulated Concrete Blocks (ACB)

19. Replace Existing Poured-In-Place Concrete Surface With Stepped Roller-Compacted Concrete (RCC)

4.9.3 Dam Safety Alternative Plans

A risk-management alternative plan consists of a system of structural and/or nonstructural measures, strategies, or programs formulated to meet, fully or partially, the identified DSM study risk-management objectives subject to the constraints.

The team considered the following array of Dam Safety alternatives as viable solutions in evaluating and approaching the residual risk associated with potential floods that overtop the spillways.

Alternative 1: No Action

The Council on Environmental Quality's regulation (40 CFR 1500–1508) for implementing NEPA do not define the "No Action Alternative," stating only that NEPA analyses shall "include the alternative of No Action" (40 CFR 1502.14).

For purposes of this interim report, under the No Action Alternative, the Corps would implement no changes to Addicks and Barker dams. The Future Without-Project conditions are expected.

Alternative 2: Dam Removal

Both Addicks and Barker Dams would be removed allowing upstream waters to travel directly into Buffalo Bayou without obstruction.

Alternative 3: Dam Replacement

Both Addicks and Barker Dams would be removed and replaced.

Alternative 4: Tolerable Risk – Engineering Regulation 1110-2-1156 *Safety of Dam – Policy and Procedures*, defines a tolerable risk as a risk "that society is willing to live with so as to secure certain benefits." Example: People are willing to live downstream of a dam that could possibly fail in order to live in a certain area, possibly near a stream, creek, or river. These are risks that are not considered to be broadly acceptable, but they are risks "that society is confident are being properly managed by the owner." In addition, they are risks "that the owner [Corps] keeps under review and reduces still further if and as practicable." To do this, the Corps uses the Dam Safety Program.

To formulate a Tolerable Risk alternative plan, the Dam Safety team considered all of the reservoir conditions including the probable maximum flood should any of the Flood Risk Management alternative plans be determined to be the tentatively selected plan. Economic and engineering data were also used to inform their decisions (Figure 79).

The team decided that this alternative plan would include:

18. Replace Existing Poured-In-Place Concrete Surface With Articulated Concrete Blocks (ACB) *on the two southern spillways*

19. Replace Existing Poured-In-Place Concrete Surface With Stepped Roller-Compacted Concrete (RCC) *on the two northern spillways*

Alternative 5: Tolerable Risk + As Low As Reasonably Practicable (ALARP) – Per Engineering Regulation 1110-2-1156 risk needs to be below established societal guidelines; acceptable rates balanced again diminishing economic returns (Figure 79).

After a Tolerable Risk alternative is identified, the team then looks at other alternative plans that would provide the same benefits for less costs, whether those costs be monetary or in society's ability to accept risk. This means that additional actions should be taken to reduce risk below the tolerable risk limit until such actions are impractical or no longer cost effective.

To reach the as low as reasonably practicable, the team looked at, and decided upon, replacing existing poured-in-place concrete surface with stepped roller-compacted concrete (RCC) *on all spillways of both Addicks and Barker dams*.

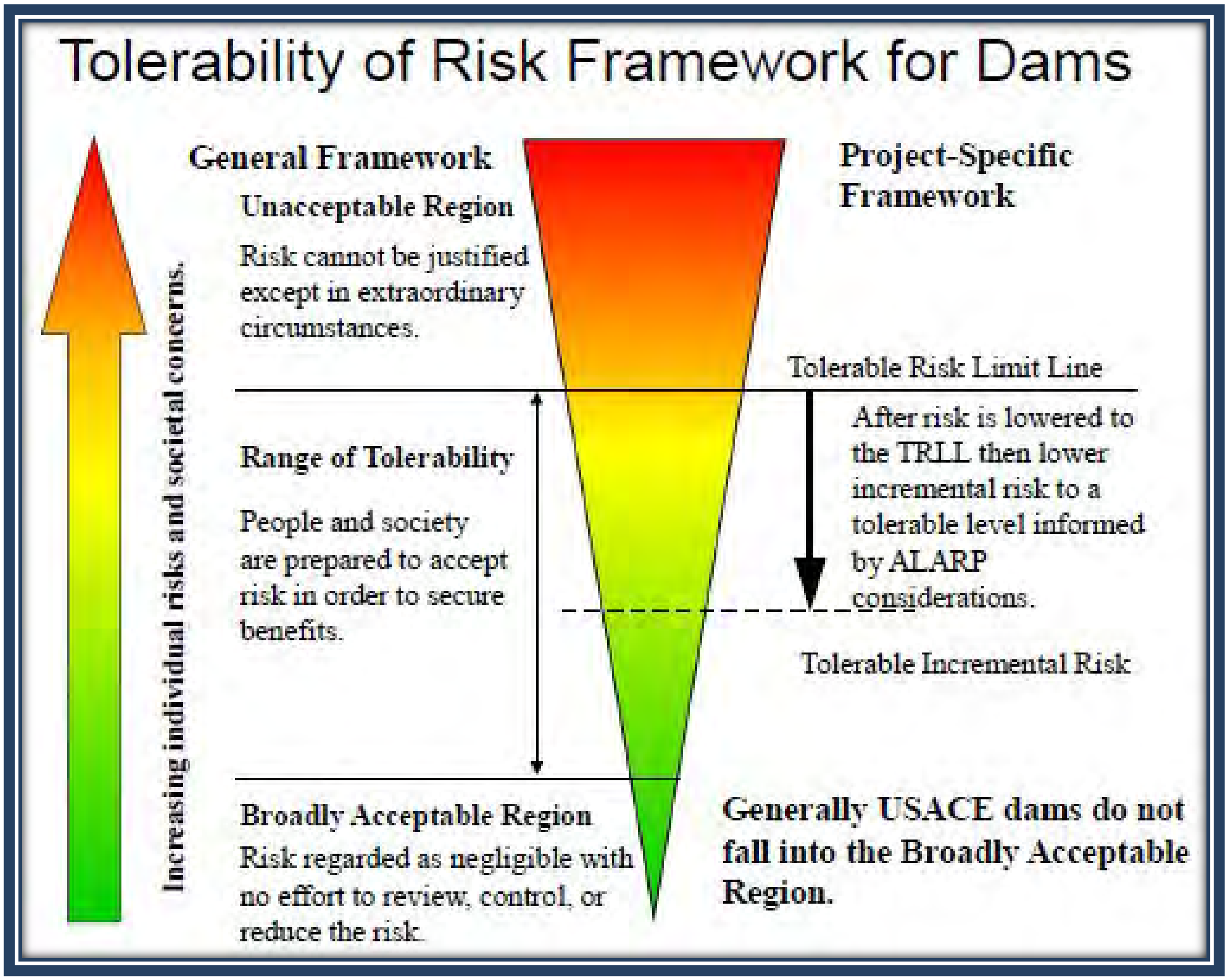

Figure 79. ER 1110-2-1156, Figure 5-1

4.9.4 Screening of Dam Safety Alternative Plans

Alternative Plan 1: No Action

The probability of failure risk and very high consequences would not be addressed or mitigated. The flaws that exist in the existing spillway structures and natural foundation conditions would remain unchanged. Over time and under increased loading conditions, this would lead to spillway overtopping and failure. All other plans were compared to the No Action Plan to determine their effectiveness at reducing risk levels from baseline conditions.

Alternative Plan 2: Dam Removal

This would impose undue downstream flooding and objectionable consequences that are currently mitigated by the projects. Additionally, removing the structure is not considered cost effective. Addicks and Barker Dams sit directly upstream of Houston, Texas, the fourth largest city in the United States, and the largest city in the state of Texas. If the dams were to be removed, the loss of benefits in the form of flood damage reduction in single-event damages is estimated to be $41,600,000. If Addicks or Barker Dams were not in-place, the impact (not included or computed) of flooding in bayous downstream under current study would be much greater.

Alternative Plan 3: Dam Replacement

Portions of the entire dams (outlet structures, cutoff walls) are currently being constructed to mitigate risk associated with foundation seeping and piping issues as part of the Addicks and Barker Dam Safety Modification Project. Earth embankment portions of the dams have predominately functioned well and continue to function very well over all ranges of reservoir loading conditions. The primary dam safety risk that currently remains involves only a potential failure mode associated with spillway overtopping and erosion failure.

4.9.5 Dam Safety Alternative Plans Carried Forward for Evaluation

Alternative Plan 4: Tolerable Risk

The alternative that would address Achieving only Tolerable Risk limit for life-safety would consist of constructing a stepped roller compacted concrete (RCC) structure at both north spillways of Addicks and Barker (2 new RCC armored spillways). Additionally, the south ends of both dams could be armored with a less technically efficient and less expensive structure such as ACB mats (articulated concrete blocks). The final configuration of this type of structural alternative would be dependent upon potential depth and duration of flow determined by hydrologic models.

Alternative Plan 5: Tolerable Risk + ALARP

The ALARP alternative would mitigate current, as well as future, residual risk associated with potential floods that overtop the spillways. The structural measures involved with this alternative would consist of constructing a stepped RCC structure at all four spillways for both Addicks and Barker Dams. This completed structural alternative would mitigate risk of erosion failure at the spillways for all baseline and future loading conditions.

4.10 Environmental Consequences

Alternative 2: Cypress Creek Dam & Reservoir

Beneficial Impacts

All measures in this alternative are designed to reduce the flooding risk in the study area. These actions would modify the base floodplain and, in some areas, narrow the floodplain width, reducing the risk to lives and property in the current floodplain.

Additionally, both Cypress Creek and Upper Buffalo Bayou reservoirs provide benefits through preserving open space, which is expected to be lost to development in the future. Preserving open space ensures continued aquatic and terrestrial habitat in the future for fish and wildlife species, even if it is lower quality than currently exists. As well, the open space is expected to provide recreational opportunities that either currently do not exist or would been reduced in the future because of development.

The historic and current ranching and agricultural activities within the proposed reservoirs have altered the native habitats and impacted the soils. Removal of these land uses will allow some habitats to reestablish or develop in new areas. For example, small levees, generally 1 to 2 feet high, built for rice farming activities would remain on the land which would allow both rain and floodwaters to fill the leveed area providing more surface water and area for establishment of wetlands. Ceasing grazing and agricultural practices along the creeks and within historic wetlands, where not laser leveled, would allow riparian obligate and wetland-dependent species to establish in areas where they would have previously been plowed under or grazed. As well, borrow areas excavated to construct the embankment would create lower areas within the reservoir allowing them to fill up and be another source of wetland and riparian establishments. These habitat changes would create more suitable habitat for wetland-dependent and riparian-obligate species.

Adverse Impacts

The chance for inducing development within the floodplains is likely in undeveloped areas. The complete alternative lowers the frequency of flooding in many areas of the study area, which would lower the cost of potential development and could potentially provide economic incentive for the addition of inventory to the existing floodplain (i.e. lower water elevations means construction of the first floor would not need to be as high and cost less than under the No Action Alternative). It is assumed that any future development within the floodplain would be regulated consistent with applicable state, county, and local regulations for floodplain development, which would lower the overall risk to the development, but would not prevent it. The Cypress Creek Reservoir would be most likely to induce development, particularly in areas where Cypress Creek overflows currently affect lands.

While the Katy Prairie is not formally defined as a park or wildlife refuge, it has been identified by natural resource agencies (US Fish and Wildlife Service and Texas Parks and Wildlife) and conservation groups (Katy Prairie Conservancy, Legacy Land Trust, and Sierra Club) as an area of special cultural and ecological significance. As well, the North American Waterfowl Management Plan identified wetlands within the Katy Prairie as having international significance (Texas Mid-Coast Initiative Team 1990). These agencies and conservation groups have expressed concern over the future of the Katy Prairie, in light of Houston's westward expansion and the increasing urbanization of western Harris County. It is estimated that less than 20,000 acres of Katy Prairie remain in Harris and Waller counties.

Implementation of the Cypress Creek Reservoir would significantly alter and degrade more than 75 percent of the remaining range-wide Katy Prairie habitat and a significant portion of the actively managed and preserved remaining habitat. Approximately 90 percent (about 10,400 acres) of the project area is operating under Habitat Conservation Plans, including mitigation banks, in which funding has been provided to maintain and enhance Katy Prairie, stream, riparian, and wetland habitats in perpetuity. Construction and operation of the reservoir would prevent future development; however, the primary purpose of the project would be for flood risk management and not habitat conservation. Long-term operation of the project would change the hydrology of the area and make it very difficult to manage the land for conservation of the specific habitats and species. While it is not anticipated that the habitats would be completely lost, it is very likely that they would have lower habitat quality than under the existing condition or No Action Alternative. Additionally, construction and operation of the dam would violate a number of the conservation easements. Mitigation for the mitigation banks would be needed to ensure paid for credits are appropriately accounted.

These impacts would also apply to approximately an additional 6,000 acres of Katy Prairie conservation lands that are immediately downstream of the embankment, where the embankment would sever hydrologic connections thereby affecting hydrologic regimes, sediment and nutrient inputs and fragmenting habitats. These indirect impacts would also cause the lands to underperform in expected habitat quality for conservation and could result in conflicts with the conservation easements and mitigation banks.

Implementation of this measure would be expected to significantly impact local and range-wide population levels of Texas prairie-dawn flower (*Hymenoxys texana*), an extremely rare endemic plant listed as Endangered under the Endangered Species Act that is restricted to the Texas Gulf Coastal Plain of Fort Bend, Harris, Waller, Gregg and Trinity counties. The proposed alignment would bisect the highest concentration of all known populations and result in direct and indirect mortality of the species and loss of available habitat. A loss of this magnitude would set back the recovery and conservation efforts that have been made thus far. The 5-year recovery plan changed the Recovery Priority Number from 5c (high degree of threat and recovery potential remains low) to 2c (high species recovery potential) due to increased species presence that significantly contribute to the overall species population. Reducing to potentially eliminating the largest concentration of sites would increase the number of new sites that must be found or established to meet the recovery plan's downlisting criteria.

Implementation of some or all measures of this alternative would result in adverse significant and unavoidable impacts. The following discussion briefly describes the adverse and beneficial impacts of each measure making up this alternative.

The Cane Island Branch Channel Modification would further widen and deepen Cane Island Branch, which was historically modified throughout most of the length. The grass-lined channel currently provides little to no quality fish and wildlife habitat. In general, most adverse impacts would be associated with construction activities and would be considered temporary, ceasing after completion of construction. These include excessive noise disturbances to nearby residences.

This measure would use an ACB system to form an erosion-resistant overlay rated for the anticipated flows under extreme events. The system is static protection and will prevent bank or grade movement, thereby preventing any bank erosion or stream migration once excavated. However, unlike other armoring technologies, ACB allows infiltration and exfiltration and does not convert the soil to a completely impervious surface.

Long-term water quality impacts to this channel would come from the increase in width and depth of the channel and the addition of ACB. The increase in width would spread the surface water out over a wider distance effectively creating a shallower water depth during non-flood event conditions. This, combined with the increase in concrete from placement of ACB, would increase the average water temperatures and lower dissolved oxygen levels. This system is currently marginally suitable at best for aquatic species who are tolerant of poorer quality water, so an increase in temperature would further degrade the system and potentially lead to a complete loss of aquatic life, especially when combined with the decrease in depths.

Barker-to-Brays Bayou Diversion measure would involve construction of an inlet and outlet structure and a tunnel approximately 30 feet below the surface. The most significant concern with tunneling is the potential for shallow groundwater aquifers to be encountered while drilling or modification to subsurface geology which would induce subsidence or seismic activity. Additional investigations are required to fully understand the potential impacts of tunneling the study area.

Significant public concern has been raised about diverting water into Brays Bayou from Barker Reservoir. Current modeling shows that Brays Bayou is capable of supporting the increase in flows without inducing flood damages along Brays Bayou. Brays Bayou would see an increase in flood stages but would not be expected to cause more frequent or higher flooding rates than exists under the No Action.

The areas off all potential actions under this alternative have not been subjected to intensive cultural resources investigation. In the footprint of the Cypress Creek Reservoir there is one archeological site. Within the Cane Branch Island project area, there is one National Register property, the B. Ray and Charlotte Woods House within 75 meters of the centerline. Further intensive cultural resource investigations within the footprints of some of the impacted areas is recommended.

Alternative 6: Channel Improvements to Buffalo Bayou

Beneficial Impacts

Under this alternative, more water could be released down Buffalo Bayou without causing damage to properties downstream. It would allow more pass through of flows requiring less storage time in Addicks and Barker under extreme events. This alternative would reduce the risk to properties downstream and some of the properties upstream immediately adjacent to the government owned land.

Because the design would incorporate a low flow channel and terracing type features, implementation of the measure is not expected to modify the heterogeneity in channel morphology and low flow characteristics. The terracing would not constrain channel morphology, shorten the stream length, or increase the speed of drainage. Conversely, future flood flows are spread over the widened floodplain reducing the erosive forces from high-velocity flows in the channel. Reduced erosion would allow stream banks and the stream bottom to be more stable for a longer period of time, which should limit the amount of deposition into the navigation channel and need for future stream bank stabilization efforts.

Incorporation of native riparian species would also help to limit erosion. Healthy deep-rooted vegetation on the terraces would be expected to dampen energy in the water, slow velocities and promote infiltration. The roots of trees and other woody vegetation promote stable soil and bank structure. Better structure gives the stream bank more cohesiveness, protecting it from erosive forces of water, resulting in smaller amounts of erosion and deposition.

Long-term benefits to fish and wildlife communities compared to the No Action are anticipated with the increase in the riparian corridor widths and lengths, which would increase the amount of available terrestrial habitat. It is anticipated that the riparian area would become higher quality than currently exists once the vegetation matures. Aquatic habitats are also anticipated to be higher quality with the increase in cover (lower water temperatures), organic material (increase in nutrients), and in-stream structure (more cover and habitat).

Terracing and incorporation of riparian vegetation may result in minor long-term beneficial impacts to water quality. Increasing the width and decreasing the slope of the bayou floodplain will allow water to flow over more surface area. Increasing the amount of surface area provides for an increase in physical removal of pollutants through adsorption, absorption, and filtration during high flow events than would occur under the No Action.

Adverse Impacts

Short-term adverse impacts would include the loss of the existing mature vegetation along the bayou resulting in reduced habitat diversity and the potential for increased erosion and sedimentation. Quality of the riparian habitat would be poorest immediately after construction and improve as planted vegetation matures (approximately 20 years for high quality). A reduction in aquatic species diversity from the current community structure would be expected, particularly for species that are less tolerant of environmental stresses.

For the first 10 years, water temperature along the bayou would be expected to rise due to the loss of riparian canopy cover. The temperature change would be greatest through Terry Hershey Park where currently overhanging canopies shade and cool the water. The increase in temperatures here would contribute to higher water temperatures downstream. Removing vegetation along the remaining 17+ miles of the bayou is not expected to incrementally increase water temperatures, as these areas are currently relatively unshaded, with minimal to no overhanging canopy cover. Once riparian vegetation establishes, water temperatures would be expected to at a minimum return to pre-project temperatures; however, it is possible that water temperatures could be lower throughout the bayou because of the increase in vegetation shading the bayou as compared to the No Action. Temperature change will impact dissolved oxygen levels in the bayou.

Construction activities are likely to at a minimum impact Alligator Snapping Turtle (state-listed). Modifications to Buffalo Bayou, which supports the largest breeding population in all of Texas and possibly the US, would remove breeding, nesting, and foraging habitat in the short- to long-term. Significant concerns have been raised about their ability to survive in the bayou until conditions stabilize. Trap and relocation has been considered but this also poses a significant risk to individuals as the species is highly territorial. It is fully anticipated that the existing population of Alligator Snapping Turtles would decline in the years during and following construction. It is possible that population numbers could rebound but this would not likely occur for 15-20 years or more and once the bayou has fully established the riparian environment.

A well-known roosting and maternity bat colony exists under Waugh Bridge and may be the largest year-round roosting site in Texas. Modification or replacement of this bridge or any other bridges in the area hosting bat species would be subjected to injury and mortality and loss of suitable habitat. Bats are extremely sensitive to textures, temperatures, air flow, and a host of other habitat parameters that any changes very well could cause bats to abandon the site, which would result in displacement of hundreds of thousands of bats.

Roadways would be temporarily impacted by construction activities. A number of bridges would need to be modified and would require temporary closures and detours. A number of these roadways are considered major thoroughfares to accessing I-10 and are along public transit routes. Travelers along these roadways would be temporarily disrupted. Detours would result in travelers having to use another route which would result in traveling approximately 1-2 miles east or west to access the nearest roadway crossing the bayou or accessing I-10. All of the roadways are heavily traveled and closing one would cause a significant increase on nearby roadways potentially increasing traffic delays by several minutes during normal hours and even longer delays during rush hour.

There are 34 identified archeological sites along the bayou as well as 3 NRHP properties and 3 cemeteries. However approximately on 30 percent of the project area has been investigated for cultural resources. There is a high probability to encounter both historic and prehistoric age resources in the project area and a cultural resource investigation is recommended.

Alternative 7: Nonstructural Measures Only

Beneficial Impacts

Under this alternative, no physical changes to the channel would occur, but properties that are currently at risk from releases greater than 2,000 cfs in Buffalo Bayou would be purchased and the risk would be eliminated or significantly reduced under all frequency events. This would allow larger releases from Addicks and Barker which would function similarly to FRM Alternative 6, where there would be less storage time of floodwaters and a decrease in floodplains in a number of areas throughout the study area.

Adverse Impacts

The nature of the acquisition would limit the extent of natural resource impacts particularly, since all work would be completed in currently developed areas. However, with that patchwork approach, there is a greater chance for the acquired areas to become vacant lots that become extremely expensive to maintain and provide low quality habitat sites with minimal to no productive use.

Impacts to property owners would be considered significant as a number of families would have to relocate outside of their community. It is not anticipated that this level of acquisition would induce additional development; however, finding comparable housing would be difficult given the uniqueness of the communities (views of Buffalo Bayou) and structures (custom homes of all ages and styles including some from the Frank Lloyd Wright era) that would be acquired.

It is unlikely that this alternative would have a significant impact on community services since the acquisition would not involve acquiring entire neighborhoods and businesses. All of the communities would continue to function in the absence of the properties, although there may be some reconsiderations in how some of the communities share operating costs (e.g. homeowners associations).

There is a potential for architectural resources to be identified in the Addicks acquisition project area that are older than 50 years in age, or will be at the time of project construction. Deed research and an architectural survey are recommended to determine the age and significance of existing buildings within the proposed project area.

Alternative 8: Combo Plan

The impacts of this alternative would identical to FRM Alternative 2, except for construction of the Barker-to-Brays Diversion, and FRM Alternative 6. The aggregate impacts of implementing the complete alternative are considered Adverse and Significant with unavoidable long-term impacts.

Alternative 4: Tolerable Risk

Implementation of this alternative would have minor temporary adverse environmental and social impacts associated with construction activities. Impacts would include: increases in air emissions and noise; soil movement and disturbance; and avoidance of the area by wildlife. All adverse impacts would be expected to cease upon completion of construction activities and return to baseline conditions. None of the anticipated adverse impacts are expected to rise to the level of significant or cause long-term unavoidable losses. Both the Addicks and Barker reservoir dams are historic in age. However, as part of a previous dam safety project, the USACE determined that neither dam was eligible for inclusion in the NRHP.

Long-term beneficial impacts of implementing this alternative include mitigating the risk of erosion failure at the spillways for all loading conditions to acceptable levels. This would reduce the risk of a breach in the dam and subsequent damages potentially caused by an uncontrolled release of water downstream.

Alternative 5: Tolerable Risk + As Low As Reasonably Practicable (ALARP)

Implementation of this alternative would be very similar in impacts, except that more heavy equipment on site would be required, which would increase the length of time noise and aesthetic disturbance are realized. However, as with DS Alternative 5, the impacts would be temporary and cease upon completion of construction activities and not rise to the level of significant or result in unavoidable long-term losses.

This alternative would also mitigate risk of erosion failure at the spillway for all conditions, but uses methods and materials that make this alternative more sustainable under future conditions and would reduce the risk to as low as reasonably possible.

Real Estate Required for Systems Operations

Beneficial Impacts

Long-term beneficial impacts would be realized through removal of 9,259 – 12,771 acres of impervious surface, which would increase the infiltration potential in these areas. As a result, vegetation would be able to establish increasing suitable habitat and creating a refuge for wildlife in a region where natural environments are scarce. As well, the increase in open space would provide more recreation opportunities. Acquisition would permanently reduce the surrounding communities' vulnerability to flooding.

Adverse Impacts

Addressing systems operations would require acquisition of 14,868 – 24,707 tracts of land, of which 10,606 – 21,302 are residences and 259 – 492 are commercial properties. Acquisition would be mandatory and not voluntary as is typical of many acquisition programs. As a result, entire neighborhoods would be dissolved resulting in a socially dramatic and permanent solution. Social impacts can include disruption of community relationships, crowding in new environments, and psychological anxiety. Economic impacts could include loss of revenue and community services and/or increase in personal and governmental expenses. The adverse impacts potentially realized with implementation of this alternative are considered significant and would result in long-term unavoidable losses to socioeconomics resources in the acquisition and surrounding areas.

There is a potential for architectural resources to be identified in the Addicks acquisition project area that are older than 50 years in age, or will be at the time of project construction. Deed research and an architectural survey are recommended to determine the age and significance of existing buildings within the proposed project area.

Impacts to Individuals

Relocating individuals will be separated from their communities, which may affect their quality of life by increasing the distance from their customary places of work, shopping, worship, and medical care. For some relocation would pose an economic hardship, despite being paid fair market value for their home and relocation costs. Increasing their commute to work would increase the wear and tear on their vehicle requiring more regular maintenance and increased distances would contribute to higher monthly fuel expenses. This may in turn warrant needing to find new employment closer to their new residence, which comes with its own potential benefits and impacts on the social and economic quality of life.

A relocation and increase in the need for housing of this magnitude, coupled with demand from increases in population and first-time homebuyers, would necessitate the construction of replacement housing elsewhere. Additionally, available housing within 5.0 miles of the acquisition area would not meet the demand, which will require a substantial number of occupants to relocate to areas further from the city center than their current residence. Finding comparable housing may be difficult and for many the cost of their new residence will likely be more than their previous, which would add additional financial strain for some.

Acquiring businesses and places of employment would result in job loss or relocation for all employees. Upon initial review, it appears that the closure of public schools in the acquisition area would have the greatest impact on employment. For some, new employment may come with a pay increase, better benefits, support staff and equipment better suited to the employee's unique needs, shorter commutes, or excitement for change. However, for some, the inverse is true. As well, some will feel a sense of loss of friendships, community, and memories or have anxiety about having to start over. Many of the same psychological and economic impacts associated with having to relocate a residence would be applicable to finding and starting new employment.

Impacts to Community Services

Property acquisition is expected to significantly adversely impact local, State and Federal governments. The main fiscal adverse impact of the proposed acquisition is the loss of tax revenues from homes, businesses, and properties that are acquired and demolished. The tax rate of properties provides revenues to a number of taxing jurisdictions including but not limited to: the county, local school districts, incorporated cities, special taxing districts, flood control districts, hospital districts, county department of education, and community college system. Upon initial review, residential and taxable non-residential property tax loss would be between $76 and $159 million annually for Harris County and between $47 and $73 million annually for Fort Bend County, for a total loss of $123 and $232 million annually. The acquisition area would become Federal property and not subject to future taxation.

The acquisition area primarily impacts Katy Independent School District (ISD) and to a lesser degree Cy-Fair ISD. The anticipated loss in revenue would not be expected to significantly impact the overall ability of either school district as a whole to continue operating. It is anticipated that the loss in attendance would be proportional to lower operating costs requiring less tax revenue. In instances where attendance would drop below a threshold where continuing to operate the school would not be cost-effective, it is assumed the school districts would modify attendance boundaries and close schools to avoid significant cost impacts, particularly if more than 50 percent of the attendance boundary is impacted.

A total of seven school properties (1 Katy ISD High School, 2 Katy ISD Junior Highs, 4 Katy ISD Elementary Schools) are within any acquisition boundary, while an additional four schools (1 Katy ISD Junior High, 2 Katy ISD Elementary Schools, 1 Cy-Fair ISD Elementary School) would be acquired under a maximum acquisition option. This would result in a permanent school closure and removal of facilities. A permanent school closure has many adverse impacts on school districts, communities, and individuals. With a closure, each school district would have to modify the attendance boundaries to accommodate displaced students. A boundary modification would result in the receiving schools increasing the number of students which would result in larger class sizes and potentially the need for more space from overcrowding. Schools districts could consider building a new school to accommodate the displaced students, but identifying a feasible and cost-effective location would be challenged by the lack of available development space and the number of remaining properties in the attendance boundary affected. Additionally, a boundary modification could result in increased costs related to transportation, need for more staff, and supplies/equipment.

In addition to impacts to schools, a portion or all of 52 Special Taxing Districts (e.g. Municipal Utility Districts [MUDs], Planned Unit Developments [PUD], or Unit Developments [UD]) would be affected under the minimum acquisition plan and 62 Special Taxing Districts under the maximum acquisition plan. The purpose of these districts is to provide a developer an alternate way to finance infrastructure, such as water, sewer, drainage, and road facilities. Loss of tax revenue from acquired properties in the special tax district could impact their overall ability to meet their debt service and operation liabilities. Districts with higher percentages of the service area removed would be expected to have higher impacts. For districts with significant loss, a reconsideration of how the district operates and will meet its obligations in the future would be required, which could include dissolution or merging with another district or increasing their tax rate and/or user fees of properties not the in the acquisition area to offset the loss of revenue.

Acquisition of 259 – 492 commercial properties would result in a substantial loss of jobs within the localized area and potentially radiating to a regional scale. Business such as restaurants, grocery stores, drug stores, auto repair shops, places of worship, schools, daycares, etc., would be closed down resulting in a loss of revenue for the company and job losses for employees. Nearby residents not within the acquisition area would have to travel further to find comparable businesses, which for some may pose a hardship, particularly if they do not have reliable transportation. As well, business closures would reduce business and sales tax revenue, which would further exacerbate the impacts described above.

4.11 Floodplain Impacts

Executive Order (EO) 11988 directs Federal agencies to evaluate the potential effects of proposed actions on floodplains. Such actions should not be undertaken that directly or indirectly induce growth in the floodplain unless there is no practicable alternative. This requirement applies to the following actions: (1) acquiring, managing, and disposing of Federal lands and facilities; (2) providing Federally-undertaken, financed, or assisted construction and improvements; and (3) conducting Federal activities and programs affecting land use, including but not limited to water and related land resources planning, regulation, and licensing activities.

EO 11998 requires federal agencies to avoid, to the extent possible, the short- and long-term adverse impacts associated with occupancy and modification of floodplains of the base flood plain (1 percent annual event) and the avoidance of direct and indirect support of development in the base flood plain wherever there is a practicable alternative. Federal agencies are to avoid direct and indirect support of floodplain development wherever there is a practicable alternative. In accomplishing this objective, “each agency shall provide leadership and shall take action to reduce the risk of flood loss, to minimize the impact of floods on human safety, health, and welfare, and to restore and preserve the natural and beneficial values served by floodplains in carrying out its responsibilities.”

The alternatives under evaluation would lower the risk of flooding and beneficially impact human safety, health, and welfare of communities along the bayou and upstream of Addicks and Barker reservoirs. Reductions in the base floodplain downstream would occur predominantly in areas that are currently developed but would not be expected to encourage development. Existing local ordinances regulate further development in the base floodplain. Acquisition of upstream areas would be enveloped into the existing reservoirs and would therefore prohibit future development. Therefore, implementation of any of the alternatives being considered would not directly or indirectly support development in the floodplain.

4.12 Impacts to Environmental Resources

This report has previously discussed the potential beneficial and adverse impacts that may result with the implementation of any of the flood risk management and dam safety alternatives as well as acquisition measures that may be put in place to address improvements in the systems operations at both Addicks and Barker. The following table lists the environmental and other resources that could be impacted along with the potential to mitigate any impacts. These potential impacts are categorized as either short- or long-term, significantly beneficial or significantly adverse, and whether potential impacts may need additional investigation to determine their significance.

Table 50. Significance of Impacts from Implementing Each Alternative

Significance Criteria	Mitigation	No Action/ FWOP	FRM Alt 2	FRM Alt 6	FRM Alt 7	FRM Alt 8	DS Alt 4	DS Alt 5	System Ops Acq
LDU-01: Conflict long-term with any applicable land use plan, policy, or regulation of an agency with jurisdiction over the project	No feasible mitigation	--	●	--	--	●	--	--	--
LDU-02: Directly or indirectly support development in the base flood plain, per Executive Order 11988	No feasible mitigation	--	●	--	--	●	--	--	--
LDU-03: Not consistent with the Texas Coastal Management Program	No feasible mitigation	--	N/A	--	--	--	N/A	N/A	N/A
LDU-04: Conflict with any applicable habitat conservation plan or natural community conservation plan	No feasible mitigation	--	●	--	--	●	--	--	--
LDU-05: Substantial change in land use that would affect local economies or cultural activities	No feasible mitigation. Lessen impacts by making payments to local governments to offset property tax losses	●	--	--	--	--	--	--	●
AIR-01: Exceeding the General Conformity Rule *de minimus* thresholds (50 tons per year [tpy]) for the ozone precursors VOCs and NO_x	Phase work to reduce cumulative emissions within the same year	--	●	--	--	●	--	--	--
AIR-02: Increase net mobile source emissions in excess of NAAQS thresholds for SO_x, CO, $PM_{2.5}$, and PM_{10}		--	--	--	--	--	--	--	--
GEO-01: Substantially alter the existing drainage pattern of the site or area that would result in substantial erosion or siltation on- or off- site	Construction of bank and soil stabilization measures	●	P	--	--	P	--	--	--
GEO-02: Increase in channel and/or bank erosion	Construction of bank and soil stabilization measures	●	P	--	--	P	--	--	--
GEO-03: Substantial loss of sediment supply	No feasible mitigation	●	P	--	--	P	--	--	--
GEO-04: Substantially modify the geology which would induce seismic activity	No feasible mitigation	--	--	--	--	--	--	--	--
MIN-01: Surface access to mineral estate would be severely limited violating the mineral estate's right to freely use the surface estate to the extent reasonably necessary for the exploration, development and production of the oil and gas under the property.	Purchase mineral rights	●	--	--	--	--	--	--	--
HYD-01: Substantial increase in the rate or amount of surface runoff in a manner that would result in flooding on or off site	Construct FRM measures to address inducement	●	●	--	--	--	--	--	--
HYD-02: Significantly change flood stage elevations	No feasible mitigation	●	+	+	+	+	--	--	--
HYD-03: Substantially change the frequency and duration of inundation of lands	No feasible mitigation	●	●	+	+	●	--	--	●
HYD-04: Substantial change the expose people or structures to a significant risk of loss, injury, or death involving flooding, including flooding as a result of the failure of a levee or dam	No feasible mitigation	●	+	+	+	+	+	+	+
GRW-01: Reduction in yields of adjacent wells or well fields (public or private).	No feasible mitigation	--	--	--	--	--	--	--	--
GRW-02: Adversely alter the rate or direction of flow of groundwater	No feasible mitigation	--	--	--	--	--	--	--	--
GRW-03: Result in demonstrable and sustained reduction of groundwater recharge capacity	No feasible mitigation	--	--	--	--	--	--	--	--
WQL-01: Violate any water quality standards or otherwise substantially degrade water quality to the detriment of beneficial uses	No feasible mitigation	●	P	P	--	P	--	--	--
WQL-02: Provide substantial additional sources of polluted runoff	No feasible mitigation	●	--	--	--	--	--	--	--

WQL-03: Require or result in construction of new storm water drainage facilities or expansion of existing facilities, the construction of which could cause significant environmental effects	No feasible mitigation	●	--	--	--	--	--	--	--
BIO-01: Result in a substantial change of native vegetation	Compensatory mitigation	●	●	S● L+	--	●	--	--	--
Bio-02: Substantially change the quality of important habitat or access to such habitat for wildlife species	Compensatory mitigation	●	●	S● L+	--	●	--	--	--
BIO-03: Result in substantial change of a resource(s), including fish and wildlife and their associated habitats, that are technically, institutionally, or publicly recognized as having substantial nonmonetary value	Compensatory mitigation	●	●	S● L+	--	●	--	--	--
SS-01: Substantial adverse effects, either directly or through habitat modification, on any species identified as a candidate, sensitive or special status species in local or regional plans, policies, regulations, or by the USFWS, NMFS, or TPWD	Compensatory mitigation	●	●	●	--	●	--	--	--
SS-02: Take of a Federally- or State-listed threatened or endangered species	Reasonable and Prudent Measures as described in a Biological Opinion	●	●	--	--	●	--	--	--
SS-03: Adversely affect designated critical habitat		●	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CUL-01: Substantial alteration of National Register of Historic Places listed or eligible resources	As recommended by the State Historic Preservation Office (SHPO)	--	P	P	P	P	--	--	P
CUL-02: Disturb any human remains, including those interred outside of formal cemeteries	Relocate remains outside the project area	P	P	P	P	P	--	--	--
CUL-3: Cause a substantial adverse change in the significance of a tribal cultural resource (site, feature, place, cultural landscape that is geographically defined in terms of size and scope of the landscape, sacred place, or object with cultural value)	No feasible mitigation	P	--	--	--	--	--	--	--
SOC-01: Induce substantial growth or declines in and around the study area, either directly (e.g. need for more/fewer homes and businesses) or indirectly (e.g. adding/decommissioning roads and infrastructure)	No feasible mitigation	●	P	--	--	P	--	--	●
SOC-02: Displace substantial numbers of existing housing or people, necessitating the construction of replacement housing elsewhere	No feasible mitigation	--	--	--	●	--	--	--	●
SOC-03: Substantial change in tax revenue that would require modification of operations of receiving entities	No feasible mitigation. Lessen impacts by making payments to local governments to offset property tax losses	●	--	--	--	--	--	--	●
SOC-04: Substantially reduce employment opportunities or income levels in an area	No feasible mitigation	--	--	--	--	--	--	--	●
SOC-05: Complete loss of communities or substantial separation of communities from public resources	No feasible mitigation	--	--	--	--	--	--	--	●
AG-01: Convert substantial active farmland of Statewide or local importance to nonagricultural use	No feasible mitigation	●	●	--	--	●	--	--	--
AG-02: Conversion of prime farmland inconsistent with the Farmland Protection Policy Act and NRCS's internal policies	No feasible mitigation	●	●	--	--	●	--	--	--
TRN-01: Change in circulation patterns that would result in substantial delays (more than several minutes) or would require rerouting that would increase travel times by 15 minutes or more	No feasible mitigation. Lessen impacts by coordinating with the public during construction	●	●	●	--	●	--	--	--
TRN-02: Change in bayou flows and stages that could affect timing or use of the navigation channel	No feasible mitigation	N/A	N/A	--	--	--	N/A	N/A	N/A

TRN-03: Increase in sediment flows that would substantially increase the dredging need in order to maintain the authorized depth	Construct sediment traps upstream of the navigation channel.	N/A	N/A	--	--	--	N/A	N/A	N/A
TRN-04: Increase the potential for wildlife hazards to aviation on or within five miles of an airport	No feasible mitigation	--	●	--	--	●	--	--	●
AES-01: Substantial changes to views of any creek, bayou, or open space area from existing viewpoints including trails, over crossings, buildings, and residences	No feasible mitigation. BMPs such as vegetation plantings consistent with surrounding environment; painting structures with colors that would blend with the surrounding	●	●	S● L+	--	●	--	--	--
AES-02: Substantial changes to views of other significant environmental resources such as mid-ground and background views of the overall landscape	No feasible mitigation	●	●	--	--	●	--	--	--
AES-03: Substantial changes to significant landmarks or defining features	No feasible mitigation	●	--	S● L+	--	●	--	--	--
AES-04: Substantial obstruction of significant public views or view corridors	No feasible mitigation	●	●	--	--	●	--	--	--
AES-05: Development that is not harmonious with the surrounding visual setting (i.e. introducing a form, line, color, or texture that contrasts with the visual setting)	Same as AES-01	●	●	--	--	●	--	--	--
REC-01: Substantially disrupt any institutionally recognized recreational facility or activity	Coordinate with the public	--	●	S● L+	--	●	--	--	--
REC-02: Substantially reduce availability of and access to recreational or open space areas	Implement a replacement recreation site	●	●	--	--	●	--	--	--
NOI-1: Exposure of persons to or generation of noise levels in excess of standards established in the local general plan or noise ordinance, or applicable standards of other agencies	Erect sound barriers around worksites	●	●	●	●	●	--	--	●
NOI-2: Substantial temporary or periodic increase in noise levels	Erect sound barriers around worksites	●	●	●	●	●	--	--	●
NOI-3: Substantial permanent increase in ambient noise levels in the project vicinity, above levels existing without the project	Erect sound barriers around sites	●	--	--	--	--	--	--	--
NOI-4: Exposure of persons to or generation of excessive groundborne vibration or groundborne noise levels	No feasible mitigation	●	--	--	--	--	--	--	--
HAZ-01: Be located on a site which is included in a list of hazardous material sites	Clean-up site	P	●	--	--	●	--	--	●

● Significant and Unavoidable Adverse Impacts **+ Significant and Beneficial Impacts** **-- Less than Significant Adverse or Beneficial Impacts**

P Potential Impacts but further investigation needed to determine significance **S Short-term** **L Long-term**

4.13 Alternatives Summary

This section is intended to summarize the alternatives analyzed to this point and put them in the context of their ability to address the area's flood risk. Although life-safety and economic risks are reduced by each of the alternatives in the focused array, risk remains regardless of the alternative that would eventually be put in place. Addicks and Barker Dams have performed well over their years of operation, preventing loss of life and billions of dollars in property damage along Buffalo Bayou despite being constructed in the 1940s. While these two flood risk management projects provide a level of protection from frequently occurring flooding events, recent large-scale events have demonstrated that risks remain both adjacent to the pools and downstream of the reservoirs. Continuing urbanization and increased frequency of large-scale flooding events will exacerbate the flood risk. Hurricane Harvey in 2017 showed that large-scale events have a significant impact on flood structures upstream of both reservoirs, as well as downstream along Buffalo Bayou.

For the FRM alternatives, economic risk is expressed in an annualized dollar amount. This economic risk for the structural alternatives in the focused array is displayed in Table 51. Future without project expected annual damages are estimated at approximately $122 million. Alternative 2 (Cypress Creek reservoir) reduces damages by $37 million but leaves $85 million in damages. Alternative 6 (Buffalo Bayou channel improvement) reduces damages by $56 million but leaves $66 million in damages. Alternative 8 (Combination Cypress Creek reservoir and Buffalo Bayou channel improvement) reduces damages by $58 million and leaves $63 million in expected annual damages (Table 51). Lastly, Alternative 7 Nonstructural could reduce damages by as much as $79 million annually and potentially remove as many as 1,200 people from harm's way.

Each of these alternatives also reduces loss of life but still leaves life loss. These beneficial impacts to life safety and the associated life safety from Table 44 are redisplayed in Table 52. No action life loss night vs. day at Addicks is 123/224 and 70/124 at Barker. Alternative 2 reduces 112/202 (night vs. day) at Addicks while Alternative 6 reduces life loss by 96/167 (night vs. day). Alternative 8 reduces life loss by the same amount as Alternative 2. At Barker, all three alternatives reduce impacts to life safety by the same amount; 52 at night and 99 during the day.

For the dam safety alternatives that remain under consideration, Alternative 4: Tolerable Risk and Alternative Plan 5: Tolerable Risk + ALARP, from a life safety perspective, Alternative 4 would achieve only the Tolerable Risk limit, the range between what is unacceptable and what is negligible, for life-safety. The alternative consists of constructing a stepped roller compacted concrete structure at both north spillways of Addicks and Barker (2 new RCC armored spillways). The south ends of both dams would also be armored with a less technically efficient and less expensive structure such as ACB mats (articulated concrete blocks). The final configuration of this type of structural alternative would be dependent upon potential depth and duration of flow determined by hydrologic models. Costs for this alternative $156 million.

Alternative 5: Tolerable Risk + ALARP would mitigate current and future risk associated with potential floods that overtop the spillways. This alternative would consist of constructing a stepped RCC structure at all four spillways for both Addicks and Barker Dams. Once completed, this alternative would mitigate risk of erosion failure at the spillways for all baseline and future loading conditions. Costs for this alternative are estimated at $162 million.

Finally, potential real estate acquisition for systems operations provides opportunities to address changed conditions within the system that have led to increased runoff and larger storms. While some land may be acquired to expand the current surcharge storage area, the number of parcels varies greatly depending on the elevation even though it may only be a range of 9 to 10 feet. Costs, depending on the acquisition scenario at each dam, could range from $6,827 million to $13,115 million.

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Table 51. Flood Risk Management Focused Array Residual Damages

Alt 1: No Action		Alt 2: Cypress Creek Dam	Alt 6: Buffalo Bayou Channel Improvements	Alt 8: Alts 2 + 6
Damage Reach	**EAD**	**Residual Damages**	**Residual Damages**	**Residual Damages**
Buffalo Bayou 1	$4,666	$4,473	$9,073	$8,886
Buffalo Bayou 2	$19,076	$19,603	$17,644	$17,291
Buffalo Bayou 3	$60,812	$53,051	$30,963	$28,890
Buffalo Bayou 4	$14,510	$203	$127	$1,240
Harris Addicks	$3,522	$3,682	$4,282	$3,202
Harris Barker	$2,207	$406	$291	$290
Ft Bend Barker	$14,000	$2,492	$2,390	$2,391
Waller Barker	$2,818	$1,109	$1,109	$1,109
Total	**$121,611**	**$85,019**	**$65,879**	**$63,299**

October 2019 Price Levels ($1,000s)

Table 52. Summary of Array of Alternatives and Risk Reduction

Alternative	Cost	Damages Reduced	Life Risk Reduced[23]	Residual Damages	Residual Life Risk
Alt 1: No Action		0	0	$191.6M	Addicks Dam: 224 lives at risk - day 123 lives at risk - night
Flood Risk Management Alternatives					
Alt 2: Cypress Creek Reservoir	$2.1B - $2.9B w/Ancillary: $4.5B - $6.1B	$37M	Addicks Dam: 202 lives - day 112 lives - night	$186M risk damages remains	Addicks Dam: 22 lives at risk – day 11 lives at risk - night
Alt 6: Buffalo Bayou Channel Improvements	$946M - $1.2B w/Ancillary: $3.1B to $4.1B	$56M	Addicks Dam: 167 lives - day 96 lives - night	$165M risk damages remains	Addicks Dam: 57 lives at risk – day 27 lives at risk - night
Alt 7: Nonstructural	$2.3B to relocate – 441 structures	$79M	1,200 Addicks Dam: TBD TBD	$112.6M	Addicks Dam: TBD TBD

[23] Barker Dam – Life risk reduction and residual risk is the same for all alternatives and not indicated in the table. Barker Dam Life safety numbers include: life risk reduced at 99 lives/day and 52 lives/night; and residual life risk of 25 lives/day and 18 lives/night.

Alternative	Cost	Damages Reduced	Life Risk Reduced[23]	Residual Damages	Residual Life Risk
Alt 8: Combination of Cypress Creek Reservoir and Buffalo Bayou Channel Improvement	w/Ancillary: $5.2B to $7.0B	$58M	Addicks Dam: 202 lives - day 112 lives - night	$167M risk damages remains	Addicks Dam: 22 lives at risk – day 11 lives at risk - night
Dam Safety Alternatives					
Alt 4: Tolerable Risk	$156M	-			
Alt 5: Tolerable Risk + ALARP	$162M	-			
System Operation Alternative					
System Operations - Government Owned Land Acquisition	$6.8B to $13.1B	9 to 10 feet of flooding	TBD	TBD	TBD

4.14 Next Steps

Following receipt of comments on this interim report, the feedback received will be used to inform additional technical analyses and evaluations to be conducted prior to release of a draft report containing a TSP. Additional public engagement and agency coordination is a critical component of that process and there will be additional opportunities for engagement going forward.

Comments Are Necessary to Refine Analyses

Comments on this interim report received from the public, local sponsor, and Cooperating Agencies will be used to inform additional technical analyses for the focused array of alternatives and address concerns identified.

Future Opportunities for Public Engagement

After the array of alternatives has been further refined, the Buffalo Bayou and Tributaries draft decision document and EIS will be released to the public for comments in accord with the National Environmental Policy Act. The public, non-federal sponsor, governmental and non-governmental agencies, as well as an Independent External Review team of recognized technical specialists, will be provided a minimum of 45 days to review and provide comments. These comments will be used by the PDT, and the Corps' vertical team, to determine whether the TSP should become the government's recommended plan for the final report and EIS.

After a recommended plan has been determined, additional technical analyses will be focused on the recommended plan in order to refine the design and develop a reasonable cost estimate. The final decision document and EIS will go through additional public, sponsor, internal Corps', and State and Agency reviews.

REVIEW SCHEDULE

DRAFT decision document and EIS

Public review and 45-day comment period

Governmental and non-governmental agency review

Non-federal sponsor review

Independent External Peer Review

FINAL decision document and EIS

- Non-federal sponsor review

- Corps' internal reviews

FINAL decision document and EIS

- Record of Decision
- State and Agency Review

In addition to the reviews listed, the Corps anticipates holding meetings to update the public of any significant changes in study strategy or direction. Public input will be requested with responses provided as part of the FINAL decision document and EIS.

Non-Federal Sponsor Responsibilities

After the Buffalo Bayou and Tributaries study completes the final review process, the Corps will seek authorization from Congress to design and construct the recommended plan. It is important to note that a local sponsor is required to share in the cost of pre-construction, engineering, and design, and in the construction of the recommended flood risk management plan.

The Water Resources Development Act of 1996, Section 202(a)(1), established the cost share requirements for flood risk management projects. The section states that the minimum non-Federal cost share for implementation of traditional structural flood control projects will be 35 percent and the maximum non-Federal cost share will be 50 percent. Cost share percentages apply to all flood risk management projects unless the non-Federal sponsor qualifies under the ability to pay provision as stated in WRDA 86 Section 103(m), as amended by WRDA 96 Section 202(b).

After the Buffalo Bayou and Tributaries study is completed, the Chief's Report signed, and Congress has appropriated funds for the project, the Preconstruction, Engineering, and Design (PED) phase begins. This phase is cost shared between the federal government and the local sponsor at 65/35 percent. This is the same cost share allocation for construction of the recommended flood risk management plan.

As part of the sponsor's cost share, they must provide all lands, easements, rights-of-way, relocations and disposal (LERRDs), including those necessary for the borrowing of material and disposal of excavated material. They perform or assure the performance of all relocations, including utility relocations, as determined by the Government to be necessary for the construction or operation and maintenance (O&M) of the recommended plan.

If there is no cost-shared sponsor willing to share in the design and construction, and assume responsibility for O&M of the recommended plan, the project would not be implemented unless an appropriate solution is specifically authorized.

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5 Coordination and Public Review

5.1 Agency Coordination

An introductory resource agency meeting was held on 03 October 2018 with US Fish and Wildlife Service (USFWS), National Marine Fisheries (NFMS), Environmental Protection Agency (EPA), Bureau of Ocean Energy Management (BOEM), Texas Parks and Wildlife Department (TPWD), and Texas Commission on Environmental Quality (TCEQ). Since then, a number of formal and informal discussions have occurred regarding resources present within the study area, anticipated impacts of the focused array of alternatives, methods to model the existing habitat conditions and habitat impacts, and mitigation needs, methods, and opportunities. Discussions have primarily been with USFWS, NMFS, EPA, TPWD, TCEQ, Texas General Land Office (GLO), and the Katy Prairie Conservancy. The formal discussions include:

23 April 2019 – In-Depth Study Kick Off Meeting (webinar)

12 September 2019 – Presentation of Alternatives and Impacts Discussion (webinar)

01 - 02 October 2019 – Conceptual Model Development for Katy Prairie (in-person)

04 October 2019 – Habitat Model Needs for Alligator Snapping Turtle (in-person)

28 January 2020 – Alligator Snapping Turtle Model Development (in-person)

02 - 12 March 2020 – Habitat Surveys Field Data Collection (in-person)

03 April 2020 – Future Habitat Condition Forecasting for Habitat Models (webinar)

Resource agency concerns have predominantly been with implementing any proposed measures within Katy Prairie habitat and along Buffalo Bayou. The Katy Prairie is the last remaining coastal prairie in Harris County and less than 1 percent remains throughout the state. The Cypress Creek Reservoir would have enveloped and impacted nearly all of the known quality Katy Prairie habitat remaining. An environmental team began working on a conceptual ecological model to understand the function and productivity of the Katy Prairie better; however, no models were ever built and no data collected due to the removal of the Cypress Creek Reservoir measure from further consideration.

Modifying the Buffalo Bayou is a significant concern shared by various resource agencies because of the value the bayou provides as the last remaining “naturalized” channel that is capable of supporting aquatic species and other common terrestrial and avian fauna. All other waterways in the Houston Metropolitan Area have been converted to trapezoidal, grass-lined channels with no riparian habitat and provide little to no ability to support aquatic species. The resource agencies are extremely concerned about how the bayou would function after channel improvements are completed and whether or not suitable habitat would exist for the Alligator Snapping Turtle.

The PDT has identified ways to create additional capacity in the channel while “restoring” the channel. Designs would maintain a low flow channel roughly where it exists today. To gain the capacity, widening/deepening would occur and benches would be constructed at various elevations that would be commensurate with various frequency events. These areas would be planted with species suitable for that flood frequency. This would promote a more natural riparian environment than existing conditions or a traditional trapezoidal channel. While resource agencies are supportive of the PDTs efforts to maintain natural environments, they are concerned about the length of time it will take for riparian species to provide quality habitat. They note that most of the existing riparian habitat along the channel took several decades or more to provide the habitat that it does today and that it would take a significant amount of time to regain the structure and quality, predicting that it could not occur within the project life timeframe. Even with the temporal accounting in the impact and mitigation analyses, the loss of mature habitat is significant in this urban environment and may be unavoidable.

The resource agencies also have significant concerns in how Alligator Snapping Turtle losses will be avoided during construction.

5.2 Compliance with Environmental Laws

Federal projects must comply with Federal and State environmental laws, regulations, policies, rules, and guidance. Significant coordination with local, state, and federal resource agencies has already occurred since the beginning of the feasibility study to identify concerns. On December 27, 2019, a Notice of Intent (NOI) to Prepare an Environmental Impact Statement (EIS) was published in the Federal Register formally announcing that an EIS will be prepared using the Council on Environmental Quality’s National Environmental Policy Act regulations (40 CFR Part 1500-1508) and the Corp of Engineer’s Engineering Regulation 200-2-2, Environmental Quality: Policy and Procedures for Implementing NEPA, 33 CFR 230 to satisfy the requirements of all applicable laws and regulations. An EIS is being prepared for this study since a number of significant environmental resources exist within the study area and, as indicated in Table 50 significant impacts are expected from any alternative recommended. Additionally, the level of controversy for this study is high with the level of impact to local communities from proposed actions. At the AMM it was decided that due to the complexity of the planning story and level of controversy expected, the EIS would be a standalone document and not integrated with the Feasibility Report. The interim report aims to collect comments from the impacted public to help guide in the decision making process to ensure decisions can be made with an understanding of the impacts to the local community.

Environmental law compliance will formally commence after receipt of public comments on the interim report, at which time compliance documentation would be prepared and submitted to the agencies with regulatory oversight. Close coordination with each of the regulatory agencies has been ongoing and have included discussions relating to assessment of impacts and mitigation needs. The relevant laws that are likely to require coordination and/or receipt of compliance documentation include:

- Fish and Wildlife Coordination Act: A Final Coordination Act Report will be provided by USFWS
- Endangered Species Act (Section 7): informal or formal consultation with USFWS will be highly dependent on the identified footprints and presence of listed species
- Magnuson-Stevens Fishery Conservation and Management Act (Section 305): Essential Fish Habitat (EFH) consultation only applicable to Alternative 6. EFH Conservation Recommendation provided by NMFS
- Clean Water Act (Section 401): a water quality certification will be requested from the State of Texas
- Clean Water Act (Section 404): a 404(b)(1) analysis will need to be completed as any of the alternatives are likely to require disposing of fill material in jurisdictional waters and wetlands of the US; impacts will drive compensatory mitigation need
- Clean Air Act: A General Conformity Determination may need to be requested from the Texas Department of Environmental Quality; need will be dependent on the level of construction effort required for each plan
- National Historic Preservation Act: a programmatic agreement will be executed and ACHP and tribal nations will be invited to participate as signatories.
- Farmland Protection Policy Act: coordination with Natural Resource Conservation Service to determine the impacts of any alternatives on prime or unique farmlands
    - Coastal Zone Management Act: consistency determination will be requested from the Texas General Land Office

5.3 Public Involvement

Early scoping meetings were held in May 2019. Four hundred and seventy-three people attended the five public meetings held upstream of Addicks and Barker reservoirs and between the dams and downtown Houston. During this period, public comments were accepted during a 30-day period, in which 279 comment letters were submitted and 541 substantive comments were identified. A Notice of Intent (NOI) was published in the Federal Register on 27 December 2019 and was followed by a 30-day formal scoping period.

The main themes identified during scoping include:

General agreement and support for the intent of the study; however, commenters are discouraged by the length of the study and the amount of time that will pass before measures are fully functional and flood risk benefits are realized. Many suggested implementing interim projects that could be completed in the next couple of years to afford some protection during this process.

Strong support for implementing Nature-Based Features (e.g. preserving the Katy Prairie through land acquisition, restoring native habitats and bayous, using green infrastructure, preserving natural features such as oxbows and meanders, etc.) to store water and mitigate flooding risks in lieu of or in concert with traditional engineered solutions. Comments also cite a substantial cost-savings by implementing nature-based features, protection of existing green space from future development, and opportunity to provide additional outdoor recreation.

Lack of support for the Brays Bayou Diversion Channel and the Cypress Creek Levee from residents in the Brays Bayou Watershed and in the Cypress Creek Watershed, respectively, who indicate implementing these measures, would increase the flooding risk within the already overtasked receiving waters.

General concern for environmental and social impacts because of implementing any flood risk reduction measures. Most concerns surround how the measure would impact flooding downstream or in the receiving watershed and the associated cost or loss with a potential increase in flooding; significant resources such as riparian corridors, wetlands, and wildlife; and recreation and open space.

Identification of new measures or alternatives to consider including those from existing independent reports/studies and the commenters own knowledge for where and/or how to conduct storage or conveyance of storm waters. Some of the ideas that were not presented to the public during scoping include: pumping floodwaters out of the watersheds; dredging the bayous, tributaries, canals, and reservoirs to increase capacity; removing trees from the reservoirs; constructing a series of detention ponds throughout the system; and preserving and restoring the Katy Prairie and other important wetland, grassland and forested habitat types.

Identification of measures that regulate commercial and residential development in floodplains, drainage areas, and critical watersheds and changes in policy, regulations, and codes related to development. [Comments are considered non-substantive and out of scope of the study because the Corps cannot impose floodplain zoning, building standards, or regulations as that is within the local government authority.]

In compliance with the National Environmental Policy Act (NEPA) and Engineering Regulation (ER) 1105-2-100, public participation is an integral component of the feasibility study process. All Corps planning studies are required to incorporate public involvement, collaboration, and coordination with the public.

Traditionally, the Corps would have hosted public meetings throughout the study area closely mimicking the scoping meetings that were held in May 2019. The meetings would have informal information sharing sessions (e.g. poster boards with Corps staff available to answer questions), followed by a formal presentation by the Corps and acceptance of oral public comments. In light of recent events surrounding COVID-19, senior leadership determined that public meetings for BBTRS must be held virtually to comply with local and state ordinances regarding large gatherings and social distancing. An engagement plan is being prepared outlining the tasks and tools required to achieve the goals of more traditional public meetings in a virtual environment.

(NOTE: This page intentionally left blank.)

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7 List of Preparers and Quality Control

Project Delivery Team	
Name & Location	**Title**
Andrew Weber, CESWG	Project Manager
Jodie Foster, CESWF (RPEC)	Lead Planner
Kathy Skalbeck, CESWF (RPEC)	Assistant Planner
Kenneth Darko-Kagya, CESWG	Engineering Technical Lead & Dam Safety Program Manager
Melinda Fisher, CESWF (RPEC)	Environmental Technical Lead
Bobby Van Cleave, Dam Safety Production Center	Dam Safety Technical Lead, CESWL-EC-S
Mario Beddingfield, CESWG	Hydraulic Engineer
Michael Esteban, CESWG	Environmental Engineer
Arden Sansom, CESWF (RPEC)	Economist
Robert Needham, CESWF (RPEC)	Economist
Shelby Scego, CESWF (RPEC)	Biologist
John Campbell, CESWF (RPEC)	Archeologist
Kristin Walsh, CESWG	Geospatial Information Systems
David Clark, CESWF (RPEC)	Environmental Engineer
Nichole Schlund, CESWG	Real Estate

District Quality Control (DQC) Team	
Name & Location	**Title**
Natalie Garrett, CESWF (RPEC)	SWD DQC Lead
Tacy Jensen, CESWF (RPEC)	Plan Formulation
Michael Kauffman, CESWG	Hydrology & Hydraulics
Manus Chaiprasert, CESWG	Hydrology & Hydraulics
Stuart Norvell, CESWF (RPEC)	Economics
Kim Rightler, CESWF (RPEC)	Environmental
Gary Chow, CESWG	Geotechnical Engineering
Brian Murphy, CESWG	Real Estate
Jose Castro, CESWG	Civil Engineering

District Quality Control (DQC) Team	
Martin Regner, CESWG	Cost Engineering
George Hall, CESWT	Dam Safety
Paul Hamilton, CESWG	Climate Change

Agency Technical Review (ATR) Team	
Name & Location	**Title**
Scott Shewbridge, IWR	ATR Team Lead
Karen Miller, LRH	Plan Formulation
Brian M. Hall, LRH	Hydrology & Hydraulics (RAS2D)
Derek Kinder, LRH	Hydrology & Hydraulics (HMS, PMF, ResSIM, Loading Curves)
Nicholas Lutz, LRL	Economics
Rebecca Latka, HNC	Environmental Resources and NEPA
Marcos Paiva, NAE	Cultural Resources
Scott Shewbridge, IWR	Geotechnical Engineering
Ronald Jansen, NWK	Civil Engineering
David W. Howell, SWL	Construction Engineering
Jeffrey D. Ross, LRN	Operations
TBD	Cost Engineering
Doris Cope, NWS	Real Estate
Hans Moritz, NWP	Climate Change

Independent External Review (IEPR) Team	
Name	**Title**
	IEPR Team Lead
	Plan Formulation/Economics
	Hydrology, Hydraulics and Sediment
	Environmental Resources and NEPA
	Civil/Tunneling/Structural Engineering

8 Acronyms and Definitions

Acceptable Risk	A risk, for the purposes of life or work, everyone who might be impacted is prepared to accept assuming no changes in risk control mechanisms; insignificant and adequately controlled. No action necessary to reduce risk further.
Acre-foot	A unit of measure equaling one acre with a depth of one foot, 43,560 cubic feet, or ~325,851 gallons.
Agency Technical Review	An independent in-depth review designed to ensure the proper application of clearly established standards, regulations, laws, codes, principles, and professional practices. The ATR team reviews the various work products and assures that all of the parts fit together in a logical whole.
Annual Exceedance Probability	**AEP** – The probability of a flood event occurring in any year. The probability is expressed as a decimal. For example, a large flood that may be calculated to have a 1% chance to occur in any one year may be described as 0.01 AEP.
As Low As Reasonably Practicable	**ALARP** – The concept that risks, below the tolerability limit, are tolerable only if risk reduction is unrealistic, or if the next rise in risk reduction is not cost effective when compared to the improvement added.
Average Annual Life Loss	**AALL** – The expected average of potential life loss from dam failure.
Breach	A controlled breach is a constructed opening that allows draining of a reservoir. An uncontrolled breach is an unintended opening caused by water releases from the reservoir.
Broadly Acceptable Risk	Risks generally regarded as insignificant and adequately controlled. Risks comparable to those that people regard as insignificant or trivial in their daily lives. This does not apply to dams.
Completeness	The extent to which an alternative plan provides and accounts for all necessary investments, or other actions, to assure the realization of the planned effects.
Corps	US Army Corps of Engineers
Cubic Yard	A unit of measure equaling a cube one yard on each side.
Dam	An artificial barrier constructed for the purpose of storage, control, or diversion of water.

Dam Safety	The art and science of ensuring the integrity and viability of dams so that they do not present unacceptable risks to the public, property, and the environment.
Dam Safety Action Classification	**DSAC** - System intended to provide consistent and systematic guidelines for appropriate actions to address the dam safety issues and deficiencies of Corps dams.
DSAC 1	Very High Urgency – Where progression toward failure is confirmed to be taking place under normal operations and 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.
DSAC 2	High Urgency – Where failure could begin during normal operations or be initiated as the consequence of an event. The likelihood of failure from one of these occurrences, prior to remediation, is too high to assure public safety; or, the combination of life or economic consequences with probability of failure is very high.
DSAC 3	Moderate Urgency –Where the dam is significantly inadequate or the combination of life, economic, or environmental consequences with probability of failure is moderate to high.
DSAC 4	Low Urgency – Dams are inadequate with low risk such that the combination of life, economic, or environmental consequences with a probability of failure is low and the dam may not meet all essential Corps engineering guidelines.
DSAC 5	Normal – Dams considered adequately safe, meeting all essential agency guidelines and the residual risk is considered tolerable.
District Quality Control	**DQC** – A team of local experts that reviews proposed Corps studies and construction projects to ensure the proper application of clearly established standards, regulations, laws, codes, principles, and professional practices. The DQC team reviews the various work products and assures that all of the parts fit together in a logical whole.
Dam Safety Modification	Any planning, design, or construction activity whose implementation, or improper implementation, could significantly affect a project's ability to operate as intended.
Dam Safety Modification Study	The study, documentation, and reasoning for modifications for dam safety at completed Corps projects. The report presents the formulation and evaluation for a full range of risk reducing alternatives.
Diversion Channel, Canal, or Tunnel	A constructed means to divert water from one point to another.
Economic Damages	Damages to private and public buildings, building contents, vehicles, public infrastructure such as utility lines and bridges expressed in dollars.

Effectiveness	The amount to which an alternative plan improves the specific problems and accomplishes the specific opportunities.
Efficiency	The amount to which an alternative plan is the most cost-effective way of improving the specific problem and accomplishing the specific opportunities, in harmony with protecting the Nation's environment.
Environmental Impact Statement	A document that must be filed with the Federal government when a Federal agency plans a "major Federal action significantly affecting the quality of the human environment."
ER	Engineering Regulation
Failure Mode	Any way that a dam or levee failure could occur. The means by which a component failure must occur to cause loss of part or all of a system ending in failure.
Flood	A general and temporary condition of partial or complete inundation of two or more acres of normally dry land area or of two or more properties. For this study, it is caused by the unusual and rapid accumulation or runoff of rain.
Flood Risk-Management	There are different levels of risk in flood control structures and in flood damage reduction activities. All flood management structures and elements have a risk of failure, the current practice is to reduce risks to a tolerable level that the public is willing to accept.
Floodplain	An area next to a water body or natural stream that has been, or may be, covered by floodwater.
Independent External Peer Review	**IEPR** – An external independent in-depth review designed to ensure the proper application of clearly established standards, regulations, laws, codes, principles, and professional practices. The team of experts reviews proposed Corps studies and construction projects.
Inundation Map	A map showing the actual or predicted extent of flooding within an area: past flooding, current flooding, or future predicted flooding.
IWR	Institute for Water Resources
Levee	An earthen embankment whose primary purpose is to furnish flood risk-management from seasonal high water.
Mean Higher High Water	**MHHW** – In this study, it is the average height of high tide in the Houston Ship Channel over a 19-year period.
NAVD 88	North American Vertical Datum - In 1993, NAVD 1988 was confirmed as the official vertical datum for the Contiguous United States and Alaska. A vertical datum, or height datum, is a reference surface for vertical positions, such as the elevations of mountains, water levels, and man-made structures.
National Environmental Policy Act	**NEPA** – The law requires federal agencies to integrate environmental values into their decision-making processes by considering the environmental impacts of their proposed actions and reasonable alternatives to those actions. Federal agencies prepare a detailed statement known as an Environmental Impact Statement. The

	Environmental Protection Agency reviews and comments on the statements, maintains a national filing system for all statements, and assures that its own actions comply with the law.
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
Outgrant	A grant of interest, or right to use, government real property through a lease, easement, license, or permit. Ex. Marinas, parks, concession stands.
Population at Risk	The population downstream of a dam that would be subject to risk from flooding if a dam should fail.
Potential Failure Mode	The chain of events leading to dam failure or a portion thereof that could lead to dam failure. The dam does not have to fail completely in the sense of a complete release of the impounded water.
Probable Maximum Flood	The most severe flood that is considered reasonably possible resulting from precipitation and hydrologic conditions.
Risk	A measure of the probability and severity of unwanted consequences or outcomes.
Risk Assessment	A systematic, evidence-based approach for quantifying and describing the nature, likelihood, and scale of risk associated with the current conditions, and then with the same values following a change in conditions due to some action. Risk assessments include recognition of uncertainties.
RPEC	Regional Planning and Environmental Center
Spillway	A structure over or through which water is discharged from a reservoir. If the water is controlled by mechanical means such as gates, it is a controlled spillway. If the size and shape of the spillway is the only water control, it is an uncontrolled spillway.
Stakeholders	Elected, and agency officials, public and private individuals, and groups that have a direct stake in the topic of the study and alternative plans.
SWD	Southwestern Division
SWF	Fort Worth District
SWG	Galveston District
SWL	Little Rock District
SWT	Tulsa District
Tolerable Risk	Risks that society is willing to live with to secure certain benefits; that society is confident are being properly managed by the owner, and that the owner keeps under review and reduces still further if and as practicable.
Unacceptable Risk	Risk that cannot be justified except in exceptional circumstances.

Uncertainty	The result of imperfect knowledge about the present or future condition of a system, event, situation, or population. The level of uncertainty controls the confidence in predictions, assumptions, or conclusions.
USACE	US Army Corps of Engineers
Vertical Land Movement	**VLM** - Vertical Land Movement is a generic term for processes that cause land to move up or down.
Watershed	A drainage area.