Barker Reservoir Feasibility Study

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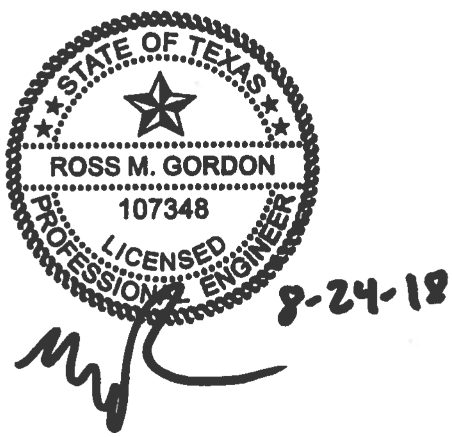

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Executive Summary

In August 2017, Hurricane Harvey caused widespread flooding of homes and streets within the Fort Bend and Harris County communities immediately upstream of Barker Reservoir. This historic multi-day tropical rain event dropped approximately 31.7 inches of rainfall across the reservoir's contributing watershed and resulted in record reservoir water levels which inundated large swaths of privately owned land on the upstream side of the reservoir.

In response to Hurricane Harvey, Fort Bend County has initiated efforts to evaluate potential solutions which could be implemented in partnership with the U.S. Army Corps of Engineers (USACE) to reduce the flood risk for, and increase the resilience of, the communities upstream of the reservoir. Barker Dam and Reservoir is a Federal Flood Control Project constructed in 1945 and maintained and operated by the USACE.

This report evaluates the feasibility and potential cost of enclosing the back-side of Barker Reservoir with a new levee / embankment, and pumping extreme event inflows into the reservoir in order to increase the accessible storage volume within government owned land and to prevent inundation of upstream private property.

Concept Overview

The proposed improvements generally consist of the following components:

- Back-side levee / embankment to enclose the reservoir
- Large pump stations at each of the four tributary channels to the reservoir
- Large gate structures integrated into the new back-side levee to allow gravity flow into the reservoir during lower flows

The general operating concept calls for channels upstream of the new back-side levee to drain into the reservoir during typical flows through gate structures integrated into the new back-side levee. Once water levels in the reservoir reach approximately 95 feet, which is the approximate extent of the government owned land, the gates would close and pump stations located at each of the channels would be activated, pumping channel flows into the reservoir while maintaining water surface elevations upstream of the levee at acceptable levels between 95-98 feet. In this configuration, the reservoir could potentially store water up to the original USACE design elevation of 108 feet, increasing the accessible storage within the government owned land while maintaining acceptable water surface elevations on the upstream side of the reservoir.

Summary of Findings

Volumetric analysis and hydrologic and hydraulic modeling were performed to assess the performance of the existing system and to design and optimize conceptual improvements.

Should the proposed improvements be constructed, there would be sufficient storage volume within the improved reservoir to safely contain, within the footprint of the existing government owned land, the runoff from approximately 36 inches of rainfall across the Barker Reservoir watershed. This encompasses Hurricane Harvey which produced approximately 31.7 inches of rainfall. In order to prevent structural flooding upstream of the reservoir for events up to and including Hurricane Harvey, estimated total pump station capacity (split across four stations) is approximately 40,500 cubic feet per second (cfs). Performance during different storm events, assuming the recommended pump station capacity, is summarized in **Table ES-1**:

Table ES-1: System Performance Summary

Storm Event	Pump Station Activates	Peak Reservoir WSE (ft)	Upstream Structural Flooding
Harvey	YES	105	NO
Harvey Shifted	YES	111	YES
Tax Day	NO	95.9	NO
Tax Day Shifted	YES	98.5	NO
500-Year* Design	YES	98.7	NO
100-Year* Design	NO	95.2	NO
Back-to-Back 100-Year*	YES	101.5	NO

* 500-year = 0.2% Annual Exceedance Probability (AEP). 100-year = 1% AEP

As shown in **Table ES-1**, the recommended pump stations would only activate for large storm events, typically in excess of a 100-year rainfall event (estimated probability: once every hundred years). Based on modeling performed, it is anticipated that protection could be provided for upstream neighborhoods for rain events up to 36 inches, which is more rain than fell across the Barker watershed during Hurricane Harvey. By contrast, under current conditions, it is estimated that structural flooding would occur after approximately 18 inches of rain, or approximately a 500-year event (estimated probability: once every 500 years).

An alternative pump station capacity was also optimized to protect from back-to-back 100-year storms totaling 24.8 inches of rainfall, instead of Hurricane Harvey which totaled 31.7 inches. Under this scenario, approximately 27,750 cfs is estimated to be required (split across four stations) to maintain water elevations below 98 feet upstream of the new back-side levee.

Under either scenario, due to the limitations in storage and pumping capacity, there will be residual risk associated with a storm event greater than the assumed design event. In general, for rain events above 36 inches, flooding is assumed to occur within the communities upstream of the reservoir. This is reflected in the Hurricane Harvey Shifted scenario (51.9 inches of rainfall), which would overwhelm the proposed system and lead to extensive upstream structural flooding.

Estimated Costs

High level order of magnitude cost estimates were developed for the recommended and alternative projects. Due to the uncertainties associated with a project at the feasibility stage, an expected cost range is presented rather than a definitive single estimate (see **Table ES-2**).

Table ES-2: Preliminary Cost Estimates

Item	Cost
Recommended Improvements – Levee & 40,500 cfs capacity	Low: $667M High: $1,020M
Alternative Improvements – Levee & 27,750 cfs capacity	Low: $448M High: $746M

The recommended improvements scenario reflects the estimated cost to maximize the utilization of storage within government owned land and to provide the greatest level of flood protection possible. Should a lower level of service be determined to be sufficient, the estimated cost of the alternative pumping scenario is also provided. This scenario reflects the smaller pump stations sized to protect upstream neighborhoods from back-to-back 100-year floods, compared to Hurricane Harvey.

Next Steps

It is anticipated that modifications or improvements to Barker Dam and Reservoir would be studied/implemented by the USACE through various study efforts anticipated to be initiated in the near future. As a Federal project, modifications cannot be made to the dam and reservoir without approval by the USACE.

The USACE typically follows a formulaic process to identify improvements which maximize benefits while minimizing cost and environmental impact. This process relies heavily on a benefit-cost ratio, based on estimated probabilistic flood damages avoided by the proposed improvements over a defined planning horizon. Different alternatives are typically analyzed, and benefit cost-ratios compared to identify a preferred alternative. Projects with a strong benefit-cost ratio are more likely to be funded by the USACE and Congress.

It is anticipated that the USACE will evaluate a wide range of improvement alternatives, including this back-side levee concept. Assuming the USACE study identifies a preferred alternative with a strong benefit-cost ratio, the project would have to be funded by Congress to advance into design and construction. Such a project would also require support from local and state non-federal sponsors.

Conclusion

The proposed Barker Reservoir improvement project, which includes construction of a back-side levee in addition to four large storm water pump stations, represents a feasible option for increasing flood protection for the communities upstream of Barker Reservoir. As proposed, if the recommended project had been constructed prior to Hurricane Harvey, no structures upstream of the reservoir would have been inundated by the reservoir pool. However, due to the limited storage volume available within the government owned land, even with the back-side levee, the proposed project would only be able to protect upstream neighborhoods from multi-day flood events totaling approximately 36 inches of rainfall. For rain events above 36 inches, residual risk remains and flooding would be anticipated to occur within the communities upstream of the reservoir.

1. Introduction

In August 2017, Hurricane Harvey caused widespread flooding of homes and streets within the Fort Bend and Harris County communities immediately upstream of Barker Reservoir. This historic multi-day tropical rain event dropped approximately 31.7 inches of rain across the reservoir's contributing watershed and resulted in record reservoir water levels which inundated large swaths of privately owned land on the upstream side of the reservoir. Hurricane Harvey followed shortly after the April 2016 "Tax Day" flood event, which represented the previous flood of record for the reservoir. The approximate extents of flooding upstream of the reservoir which occurred during Hurricane Harvey is shown in **Exhibit 1**.

These recent flood events have highlighted the deficiencies of the current reservoir system, including its inability to maintain reservoir pool levels within government owned land during extreme events such as Hurricane Harvey. In response to these floods, Fort Bend County has initiated efforts to evaluate potential solutions which could be implemented in partnership with the U.S. Army Corps of Engineers (USACE) to reduce the flood risk for, and increase the resilience of, the communities upstream of the reservoir.

In line with these efforts, AECOM was contracted by Fort Bend County in April 2018 to conduct a high level feasibility study of potential improvements to Barker Reservoir aimed at improving the level of flood protection for communities upstream of the reservoir. Specifically, the study would evaluate the feasibility and potential cost of enclosing the back-side of Barker Reservoir with a new levee / embankment, and pumping extreme event inflows into the reservoir in order to increase the accessible storage volume within government owned land and to prevent the inundation of private property upstream of the limits of the government owned land.

This Feasibility Study presents the findings of this effort. The following sections summarize the analysis performed and the conclusions generated. Due to the complexity of and magnitude of the proposed improvements, many assumptions were made based on engineering judgment and the best information readily available to AECOM at the time of the study. These assumptions are detailed throughout the report. Any potential improvements recommended in this study are preliminary assessments which will require further detailed evaluation.

2. Barker Reservoir Overview

Barker Dam and Reservoir is a Federal Flood Control Project constructed in 1945 by the USACE as a result of the major flood events in December of 1935. Barker Reservoir is one component of a partially completed comprehensive plan developed by the USACE known as "Buffalo Bayou and Tributaries, TX", which was authorized by Congress in 1938 and modified by the 1954 Flood Control Act. The dam and reservoir is maintained and operated by the USACE.

The facility consists of a "U" shaped earthen embankment designed to impound flood waters within the reservoir pool. Releases from the reservoir, which outfall into Buffalo Bayou, are regulated by a control structure on the east side of the dam. These components are highlighted in **Exhibit 1**. By temporarily retaining flood waters within the reservoir pool, discharges to Buffalo Bayou are reduced and flood protection is provided to the downstream neighborhoods, including downtown core of the City of Houston.

The reservoir is filled from four major channels on the back-side of the earthen embankment as seen on **Exhibit 1**. From north to south; Mason Creek, T103-00-00, Willow Fork Buffalo Bayou and the Willow Fork Diversion Channel drain approximately 133.5 square miles of upstream watershed. During extreme storm events, inter-basin transfers of floodwaters from the Cypress/Addicks watershed into the Barker watershed are possible, however were not considered in the scope of this study.

Table 1 summarizes key information regarding the reservoir, including critical elevations and available storage volume in the reservoir pool.

It should be noted that the Federal government does not own all land within the potential reservoir pool. The Federal government owns all land up to approximately elevation 95 feet, as shown in **Exhibit 2**, which also corresponds closely to the currently defined 100-year, or 1% Annual Exceedance Probability (AEP), floodplain. Structures upstream of the reservoir are generally elevated above elevation 98 feet. When flood waters within the reservoir pool exceed 98 feet, it is anticipated that structural flooding will begin. Water levels in the reservoir reached approximately 101.6 feet during Hurricane Harvey.

Table 1: Reservoir Facts

Description		Source/Detail
Top of Dam Elev.	~113 ft	USACE
Design Max Water Elev.	~108 ft	USACE
Emergency Spillway Elev.	~104 ft	USACE
Approximate Elev. Of Structural Flooding	~98.0 ft	LiDAR + 1.5 ft
Approximate Extents of Government Land	~95.5 ft	USACE
Historic Storm Events		
Harvey Flood Elev.	101.6 ft	Gates Open
April 2016 Flood Elev.	95.2 ft	Gates Closed
Previous Record Flood Elev.	93.6 ft	March 1992

Barker Reservoir is operated by the USACE in accordance with their Interim Operations Manual, dated July 16th, 2010. In general, the operating guidance calls for the gates at the control structure to be closed when heavy rain is anticipated / begins. The gates are to remain closed until after the rain event has passed and no additional rain is anticipated. After the storm event, combined release rates from the reservoirs are controlled to a maximum of 4,000 cfs, split as determined appropriate between Addicks and Barker Reservoir. Releases continue until the reservoir is emptied of flood waters or a potential future major rain event is forecasted in the area.

It should be noted that during Hurricane Harvey, due to multiple concerns, releases from the reservoirs were initiated during the flood event and were increased to a maximum rate of approximately 16,000 cfs split between the two reservoirs. AECOM estimates that these modifications to the standard operating procedure reduced the maximum pool elevation from a potential 103.5 feet to an approximate 101.6 feet, based on a simplistic analysis of total estimated runoff volume and available storage volume. Although these releases helped to limit the extent of flooding which occurred upstream of the reservoir, the releases resulted in flooding downstream of the reservoir along Buffalo Bayou.

For the purpose of this study, it was assumed that no changes to the standard operating procedures would be made, and that discharges from the reservoirs during a flood event would not be allowed. Should discharges be allowed during a storm event, based on approved changes by the USACE to the standard operating guidance, the performance of the proposed solution would be enhanced, potentially reducing project complexity and cost. However, detailed evaluation of this possibility was not part of the scope of this report.

3. Concept Overview

The proposed Barker Reservoir improvement concept places an earthen embankment (levee) along the western boundary of the government owned property that would tie into the existing “U” shaped earthen dam as seen on **Exhibit 3**. Areas and channels upstream of the new back-side levee would drain into the reservoir during typical flows, generally less than or up to a 100-year event, through large gate structures integrated as part of the new levee. Once water levels in the reservoir reach approximately 95 feet, which is the approximate extent of the government owned land, the gates would close and large pump stations located at each of the inflow channels, as shown in **Exhibit 3**, would be activated, pumping channel flows into the reservoir while maintaining water surface elevations upstream of the levee to acceptable levels between 95 and 98 feet. In this proposed configuration, the reservoir could potentially safely store water up to the original USACE design elevation of 108 feet, increasing the accessible storage within the government owned land. It is assumed that any deficiencies in the existing dam embankment which might prevent water from safely reaching and staying at elevation 108 feet would be addressed by the USACE as part of their dam safety program or other means.

Given that flooding upstream of the reservoir generally does not occur until storms greater than 100-year in size, and to minimize operating costs and complexities, runoff would gravity flow into the reservoir through the large gate structures whenever possible. As stated above, when the reservoir pool rises to an elevation of approximately 95 feet, which equates approximately to a 100-year rainfall event, the gates would then shut and the pumps would turn on. The gate structures would need to be designed to convey extreme event flows, such that they are not a restriction to water entering the reservoir during extreme events for storms up to or even greater than the 100-year storm.

The pump stations would continue to pump until the flood event concludes or the elevation of the reservoir pool hits 108 feet. Since the dam was originally designed for a maximum water level of 108 feet, it is assumed that it would not be feasible to maintain water levels in the reservoir higher than 108 feet without risking dam overtopping and/or potential failure. Thus, if water levels within the reservoir were to reach elevation 108 feet, the pumps would need to shut off. Were this to occur, remaining runoff from the watershed would be blocked from entering the reservoir and would pond on the upstream side of the new levee, potentially inundating private property. Therefore, there is still residual risk of flooding upstream of the reservoir during very extreme events. This residual risk is discussed in more detail in subsequent sections.

Should it be possible or feasible to raise the elevation of both the existing dam embankment and the proposed back-side levee, additional storage volume could be obtained within the government owned land which could enhance the performance of the proposed project. However, detailed evaluation of this possibility was not part of the scope of this report.

4. Reservoir Storage Analysis

The Barker Reservoir storage analysis was broken into two phases: estimating the current volume of the reservoir and estimating the proposed volume within the reservoir assuming the levee is in place. For this study, the volume of Barker Reservoir was estimated using the most current LiDAR data (flown in 2008, 2001 adjustment) and Arc Hydro Tools in ArcGIS. From this calculation, a stage-storage relationship was developed from the reservoir's invert elevation at approximately 70 feet to the reservoirs maximum design elevation of 108 feet. An abbreviated version of the developed stage storage relationship is shown in **Table 2**. It's important to note that the volume calculations presented in this report may vary slightly from other published sources based on the elevation source used and how the calculations are performed.

Table 2: Existing Stage-Storage

Elevation (ft)	Area (ac)	Volume (ac-ft)	Percent of Total Volume
85	2,300	5,500	2.0%
90	7,800	27,400	9.9%
95	11,900	79,700	28.9%
98	13,000	117,000	42.4%
100	14,200	144,100	52.2%
104	16,400	205,100	74.4%
108	19,000	275,800	100.0%

As shown in **Table 2**, the lowest 20 feet of the reservoir (under elevation 90 feet) contains only approximately 10% of the maximum available volume. At elevations above 95 feet, the reservoir's pool footprint exceeds the government owned land and spills out into upstream properties. Based on limited field survey and LiDAR, structural flooding upstream of the reservoir begins at approximately 98 feet when the reservoir is providing approximately 117,000 acre-feet of storage.

Table 3 illustrates the estimated distribution of volume stored on government owned land versus on privately owned property. It is important to note the private land volume listed in **Table 3** is not equal to the additional excavation within the reservoir that would be necessary to keep the flood pool within government owned land. That excavation volume would also need to include all volume which is stored on government owned land above elevation 95 feet, and would total upwards of 200,000 acre-feet.

Table 3: Storage Volume: Gov. vs Private

Elevation (ft)	Total Volume (ac-ft)	Gov. Land Volume (ac-ft)	Private Land Volume (ac-ft)
95	79,700	77,800	1,900
98	117,000	112,900	4,100
100	144,100	136,600	7,500
104	205,100	184,100	21,000
108	275,800	231,800	44,000

The estimated stage-storage relationship for the reservoir after the proposed back-side levee is constructed is shown in **Table 4**. As is shown in the table, the footprint (area) of the reservoir stops expanding after approximately elevation 95 feet, as the pool is constrained by the proposed back-side levee. The total estimated storage volume within the government owned land (area enclosed by the proposed levee and existing dam), at elevation 108, is approximately 228,500 acre-feet. This is approximately 50,000 acre-feet less than the total storage available at elevation 108 feet under existing conditions, which includes the storage volume outside the government owned land. In extreme situations where runoff volume exceeds 228,500 acre-feet, the additional runoff would pool behind the proposed levee and inundate private property as would occur during existing conditions.

Table 4: Proposed Stage-Storage

Elevation	Area (ac)	Volume (acre-feet)	Percent of Total Volume
85	2,300	5,400	2.4%
90	7,600	26,900	11.8%
95	11,400	78,000	34.1%
98	11,500	112,500	49.2%
100	11,600	135,600	59.4%
104	11,600	181,900	79.6%
108	11,600	228,500	100.0%

5. Rainfall Volume Analysis

This study focuses on the runoff volume related to the following seven storm events listed below. Runoff volume, compared to peak flow, is most critical as releases from the reservoir are not typically allowed during storm events and the reservoir must store all incoming runoff. Although seven storm events were run, the primary focus was on Hurricane Harvey. During lesser storm events, such as the 100-year event, no structural flooding is anticipated due to the Barker reservoir pool elevation.

For reference, the 100-year storm event is statistically defined as a rainfall event which has an occurrence probability of once over 100 years, or as having a 1% chance of occurrence in any given year. This is also referred to as having a 1% Annual Exceedance Probability (AEP). The 500-year storm is referred to as having a 0.2% AEP.

- Hurricane Harvey (based on gage calibrated radar average ~31.7 inches across Barker Watershed)
- Hurricane Harvey Shifted (the worst rainfall information in Harris County Based on FWS gage 1730, Cedar Bayou – ~51.9 inches)
- Tax Day (based on gage calibrated radar across Barker Watershed ~13.3 inches)
- Tax Day Worst Case (based on gage calibrated radar across Barker Watershed ~17.0 inches)
- The 500-Year Design Storm (17.7 Inches)
- The 100-Year Design Storm (12.4 Inches)
- Back-to-Back 100-Year Design Storms (24.8 Inches)

At the time of writing this report, NOAA Atlas 14 updated design rainfall information is still in draft form. When Atlas 14 is finalized later this year, and assuming no significant changes from the draft information previously released, extreme event rainfall depths are anticipated to increase by approximately 20 percent. This would shift the future definition of a 100-year storm event to more closely match the current definition of a 250-year storm event. Due to this study's reliance on historic rainfall, instead of design rainfall, the current definition of design rainfall events was utilized instead of the draft NOAA Atlas 14 information.

For Hurricane Harvey, Tax Day, and Tax Day shifted storm events, AECOM utilized gridded radar estimates in addition to gauge measurements to construct high-resolution rain fields covering the Barker Reservoir watershed and other adjacent watersheds. Radar estimates preserve the spatial characteristics of rainfall in a gridded format, while gauge measurements are commonly considered as ground truth. By combing both types of data, also known as radar rainfall calibration, the most accurate possible rainfall products (e.g., storm frequency maps, hourly rain depth maps, hourly cumulative rain depth maps, time series of area-averaged rain depths) were derived for various kinds of analyses.

Based on calibration efforts performed for a previous 2016 AECOM study of Barker Reservoir completed for the Willow Fork Drainage District (WFDD), all modeled storm events utilize the more conservative 2005 WFDD HEC-HMS infiltration parameters. The previous study showed that when calibrating the HEC-RAS model, the runoff volumes within the reservoir more closely matched the observed performance compared to the Tropical Storm Allison Recovery Project (TSARP) infiltration parameters. The runoff results computed in HEC-HMS for each of these storm events is provided in **Table 5**.

Table 5: Proposed Runoff Volume

Storm Event	Rainfall Depth (in)	Runoff Volume (ac-ft)
Hurricane Harvey	31.7	198,600
Hurricane Harvey Shifted	51.9	335,900
Tax Day	13.3	83,000
Tax Day Shifted	17.0	114,800
500-Year Design	17.7	116,000
100-Year Design	12.4	76,800
Back-to-Back 100-Year Storms	24.8	155,400

It should be noted that during very large multi-day storm events, total infiltration is limited due to prolonged saturation of soils. Infiltration losses modeled total approximately 10-15% of rainfall depth. For reference, should no infiltration occur (which would be a worst case scenario), the total runoff volume during Hurricane Harvey would increase from 198,600 acre-feet to approximately 225,500 acre-feet.

Based on comparison of anticipated runoff volume to available storage volume within the proposed reservoir system, it is possible to assess level of service which could be provided by the improved reservoir system. Based on the proposed operating scheme of the pump stations, and assuming sufficient sized pump stations are provided, neighborhoods upstream of the reservoir could be protected from inundation by the reservoir pool as long as total storm runoff volume does not exceed the storage capacity available within the proposed reservoir at 108 feet, or 228,500 acre-feet.

As shown in **Table 5**, the runoff from six of the seven storm events analyzed, including Hurricane Harvey, could have been contained within the proposed reservoir storage volume / footprint as the runoff volumes from each of those storm events are less than the available 228,500 acre-feet of storage at elevation 108 feet. However, during the Hurricane Harvey Shifted event (51.9 inches), the runoff volume generated (335,900 acre-feet) would greatly exceed the available storage volume within the proposed reservoir (228,500 acre-feet), resulting in extensive flooding behind the proposed back-side levee.

From a volume standpoint alone, the storage volume available inside the proposed reservoir below elevation 108 feet is equivalent to the resultant runoff volume from a ~36 inch rainfall (subtracting estimated infiltration). For rain events over 36 inches, where the water level inside the proposed reservoir would rise to 108 feet, it is anticipated that the pump stations would have to turn off, and water would rise on the upstream side of the proposed back-side levee, potentially inundating private property. By contrast, under current conditions, it is estimated that structural flooding would occur after approximately 18 inches of rain, or approximately a 500-year event.

In summary, assuming properly sized pump stations, it is determined that structural flooding associated with the reservoir pool could be prevented upstream of the reservoir for events less than or equal to approximately 36 inches of rain, including Hurricane Harvey.

6. H&H Modeling

In addition to analyzing runoff volumes, AECOM also conducted comprehensive hydrologic and hydraulic modeling to determine necessary approximate size of proposed pump stations and to better understand the performance of the proposed drainage system under different circumstances. For this study, hydrologic and hydraulic models utilized were based on models previously developed for WFDD by AECOM for Barker Reservoir following the 2016 Tax Day storm event. These models were calibrated to match observed water surface elevations within the reservoir during the Tax Day storm event.

6.1 Existing Conditions

As previously stated, the basis of the hydraulic modeling was a 1D / 2D HEC-RAS model that was created after the Tax Day storm event for WFDD. This model consists of three 1-D components (Buffalo Bayou, T103-00-00 and Mason Creek). Buffalo Bayou as it approaches the government owned land is partially diverted, splitting the flow into a northern and southern inflow into the reservoir as seen in **Exhibit 4**. The model is setup as an unsteady flow model with lateral and uniform inflows into the 1-D portion of the model that represent sub-watershed drainage.

The 1D portions of the model are connected to large 2D areas that encompass most of the downstream watershed, including the reservoir.

This model simulates the performance of the channel systems, as well as the reservoir. It should be noted that although the existing drainage channels generally provide a 100-year level of service, local rainfall events in excess of the 100-year event are anticipated to result in out of bank flooding which may lead to structural flooding. This flooding would occur independently of the reservoir, and generally relates to the conveyance capacity of the existing channel systems upstream of the reservoir. The improvements proposed, including the back-side levee and pump stations, do not address the capacity of the existing channels, and instead focus on controlling the influence of the reservoir pool on flooding upstream of the reservoir.

6.2 Proposed Conditions

In the proposed condition model, the reservoir basin was simplified as a large storage area given the stage storage relationship determined in the previous section. Subsequently the area was removed from the 2D mesh as to not double count the storage volume. All major 1D inflows into the reservoir are truncated at their entrance into the reservoir. A 10-acre storage area was added to each of the entrances into the reservoir to represent a conceptual pump station forebay. A series of gates was then added to each of the inflow points and set to close when the reservoir elevations exceed 95 feet. Gates were preliminarily sized to cause minimal hydraulic losses through the levee/gates for extreme events. Pumps were then connected from each of the forebays to the reservoir storage area.

6.3 Pump Sizing

Simplified routines were employed to model the performance of different size pump stations on water surface elevations upstream of the back-side levee. The capacity of each of the four proposed pump stations was optimized to maintain water surface elevations during Hurricane Harvey at elevations below 98 feet.

The resulting preliminary pump station sizes anticipated to be necessary are provided in **Table 6**. The sizes shown represent firm pumping capacity. It is expected that a redundant pump or pumps would be provided to ensure the design capacity could be achieved with at least one pump out of service. With these proposed pump sizes, which are close to the 100-year FEMA inflows, during Hurricane Harvey the elevation upstream of the back-side levee would be maintained at approximately 97 feet while the elevation within the reservoir is pumped to ~105 feet as shown on **Exhibit 5**.

Table 6: Recommended Pump Capacities

Pump Station Location	Preliminary Capacity (cfs)
Mason Creek (T101-00-00)	12,000
T103-00-00	4,000
Buffalo Bayou – Main Stem	11,500
Buffalo Bayou – Diversion	13,000
Total Capacity:	**40,500**

Determining a necessary pump station capacity is not straightforward, with pump station needs varying greatly depending on assumed storm intensity, duration, and total depth in addition to desired level of service. Determining a feasible maximum required capacity starts with an understanding of the anticipated operating range of the pump stations. As discussed previously, it takes approximately 12.5 inches of rainfall across the entire watershed to hit the critical elevation within the reservoir of 95 feet which would trigger activation of the pump station. Given that the maximum rainfall depth which could be stored below elevation 108 feet is approximately 36 inches, the maximum depth of rainfall which could theoretically be required to be pumped is 23.5 inches. If assumed to occur over a 24-hour period, this would equate to a rain event well in excess of a 500-year event. However, it would be more likely for this depth of rainfall to occur over a multi-day period, as occurred during Hurricane Harvey. As such, depending on the assumptions made, the required pump station size could increase or decrease.

Results from the hydraulic modeling illustrate how the proposed system may work. For smaller events, such as Tax Day and the 100-year design events, the pump stations do not need to turn on as the water surface elevation generally does not exceed 95 feet. During Hurricane Harvey, the 500-year event, Back-to-Back 100-year events, and the Tax Day Shifted event, the pump station does activate and is adequately sized to maintain upstream water surface elevations between 95 and 98 feet. This is illustrated in the stage hydrograph shown in **Exhibit 5**, which also includes the proposed estimated inundation extents of the reservoir pool. **Table 7** also summarizes the performance of the proposed system under different storm events.

Table 7: System Performance Summary

Storm Event	Pump Station Activates	Peak Reservoir WSE (ft)	Upstream Structural Flooding
Harvey	YES	105	NO
Harvey Shifted	YES	111	YES
Tax Day	NO	95.9	NO
Tax Day Shifted	YES	98.5	NO
500-Year Design	YES	98.7	NO
100-Year Design	NO	95.2	NO
Back-to-Back 100-Year	YES	101.5	NO

As shown in the table, in the Hurricane Harvey Shifted event, the proposed improvements do not meet desired performance in two regards. First, the proposed pump system is not large enough maintain upstream water elevations below elevation 98 feet. This is illustrated in the stage hydrograph shown in **Exhibit 6**. Second, the total storm volume exceeds the available storage volume and the pump stations would have to turn off when the reservoir pool elevation reaches 108 feet. For the remainder of the storm, water would pool behind the back-side levee. This is also illustrated in the stage hydrograph shown in **Exhibit 6**. In summary, if a Hurricane Harvey Shifted event were to happen, the resultant maximum inundation would mirror that if the improvement project were not constructed. The approximate inundation boundaries during a Hurricane Harvey Shifted storm event are illustrated in **Exhibit 6**.

An alternative pump sizing scenario was also analyzed to assess the potential performance of smaller pump stations, designed to protect against back-to-back 100-year storms instead of Hurricane Harvey. This scenario is optimized to protect upstream neighborhoods from flooding during an event totaling approximately 25 inches, compared to the approximately 32 inches which fell during Hurricane Harvey. The estimated pump station capacities necessary to maintain water surface elevations during back-to-back 100-year storms at elevations below 98 feet are shown in **Table 8**. The expected inundation extents and reservoir level is shown in **Exhibit 7**.

Table 8: Alternative Pump Capacities

Pump Station Location	Preliminary Capacity (cfs)
Mason Creek (T101-00-00)	6,750
T103-00-00	1,600
Buffalo Bayou – Main Stem	9,700
Buffalo Bayou – Diversion	9,700
Total Capacity:	**27,750**

As is shown in **Table 8**, if the desired level of service is reduced, the corresponding required pumping capacity is also reduced. Under this scenario, water surface elevation in the reservoir reaches approximately 101.5 feet, with water surface elevations upstream of the reservoir remaining below 97 feet.

7. Levee Overview

As part of this feasibility study, AECOM prepared a preliminary schematic for the back-side levee to support high level cost estimating. The proposed outside toe of the levee was offset from the USACE property boundary by approximately 100-feet to provide room for ditches/channels to capture sheet flow that naturally drains overland into the reservoir and to convey that flow to the new gated structures / pump stations. These ditches/channels are critical to preventing the backup of water against the levee.

Highlighted in **Exhibit 3** is a preliminary levee cross section. The cross section mirrors the existing embankment, with a top elevation of 113.1 feet and 4 (H):1 (V) side slopes. Based on typical practices, a stability berm and slurry cutoff wall are also assumed. Furthermore, it is assumed that the levee would be constructed using suitable material excavated from the existing reservoir footprint.

8. Pump Station Overview

There are several types of pumps typically used for this type of low-head, high-capacity, storm water application. These include, but are not limited to horizontal screw pumps, vertical lineshaft pumps, and concrete volute pumps. These types of pumps are commonly available in sizes below 750 cfs per unit, but in select circumstances can be larger. Each type of pump has varying cost, efficiency, and durability. Due to the complexity involved in pump selection, this feasibility study does not attempt to determine the recommended pump type. Instead it is assumed that any station would likely include anywhere from 5 to 25 pump units in order to meet capacity requirements, including provision of redundant units to allow for repair/servicing of the facility without impacting capacity. Due to the number of pumps, and expected operation, variable frequency drives are not anticipated to be necessary.

It is assumed that primary electrical power would be provided from on-site substations connected to nearby transmission lines. The power demand of each station will be very large. Due to the risk of power interruptions during extreme weather events, backup or standby power would likely have to be provided. Given typical durations of major flood events, multiple days of standby power would need to be provided.

Standby power can be provided to the pump station facilities during times of primary power loss by utilizing either diesel or natural gas generators. Due to size limitations of both fuel sources, it is probable that each pump station will require multiple standby generators. The exact size and number will depend on the electrical requirements of the pump stations. Diesel generators are typically smaller and have a lower capital cost than natural gas generators of equal capacity. However, diesel generators will also require on-site storage of diesel fuel. Therefore, the footprint required for diesel generators will be greater than that of natural gas generators. Assuming natural gas is available at the site locations, natural gas is the more reliable fuel source. Instead of generators, standby power could also be provided by diesel or natural gas driven right hand drive engines.

In addition to the pump selection and design, the intake structure, including screens, and separate gate structure must also be considered. There are many types of gates that may be utilized for this situation including sector gates, tainter gates, sluice gates, and miter gates to name a few. The proposed gate structures would need to be large enough to pass large flood events such as the 100-yr or 500-yr flood with limited head loss through the structure.

Screens are likely required upstream of the pump station to collect large debris in the water and prevent it from entering the pump station. All of the pumps discussed above are capable of handling some debris, but large debris must be removed to prevent damage to the pumps.

Due to the large capacity of the proposed pump systems, a forebay will likely needed to be constructed on the upstream side of the levee at each pump station. The forebay serves to prevent the rapid drawdown of water when large pump stations are turned on.

9. Cost Estimate

To support this feasibility study, AECOM has prepared an order of magnitude cost estimate for the proposed improvements. At this phase, there are still many uncertainties associated with the project and its design. As such, the cost estimates prepared are based on past projects containing similar components. This cost estimate is intended to provide an order of magnitude estimate of potential cost to inform assessment of general feasibility.

9.1 Proposed Levee Cost

The approximately 8 miles of back-side levee embankment costs are comprised of site preparation, excavation, embankment placement, slurry wall, and turf establishment. In addition, the costs for the forebay and drainage swale are included in this total cost. Unit prices for these items were derived from recent AECOM projects and published prices used by local agencies for feasibility study cost estimating.

9.2 Pump Station/Structure Cost

The pump station costs in this section are based on over twenty AECOM designed large storm water pump stations constructed within the Gulf southwest region over the past 20 years. These costs were adjusted for inflation, graphed, and a polynomial trend line generated in order to estimate the cost associated with each pump station based on capacity (e.g. per 1,000 cfs). These costs generally include screens and backup power. Therefore, specific line items were not included for those items. Of the pump stations analyzed, not all included closure structures. Therefore a multiplier was added to the historic estimates to reflect the additional cost of closure structures. Unique differences between these projects and the proposed project would be captured in the estimate of contingency.

9.3 Other Costs

Soft costs, including but not limited to planning, engineering, construction management, legal and real estate is estimated at 25% of construction cost.

Contingency is estimated at 35% of overall costs, and is anticipated to include components which are not explicitly included in the construction cost estimate in addition to project-specific variability compared to example projects referenced.

9.4 Cost Summary

A breakdown of the major costs is provided in **Table 9**. Due to the uncertainties associated with a project at the feasibility stage, it is preferred to present an expected cost range rather than a definitive single estimate. For the recommended scenario, the estimated cost of this project is between $667M and $1.02B. This reflects the estimated cost to maximize the utilization of storage within government owned land and to provide the greatest level of flood protection possible. Should a lower level of service be determined to be sufficient, the estimated cost of the alternative pumping scenario is shown in **Table 10**. This reflects the smaller pump stations sized to protect upstream neighborhoods from back-to-back 100-year floods, compared to Hurricane Harvey. The estimated range for this alternative system is $488M to $746M.

9.5 Operations/Maintenance

In addition to upfront capital costs, a project such as this incurs significant regular operations and maintenance costs. This includes regular day-to-day operating expenses, regular maintenance, periodic testing of gates and pumping facilities, and the replacement of equipment, as necessary, over the extended life-cycle of the project. Operation and maintenance would need to be considered when assessing the overall benefit-cost ratio for this project, but have not been estimated as part of this initial Feasibility Study.

Table 9: Order of Magnitude Cost Estimate – Recommended System (40,500 cfs)

Item	Cost
Backside Levee Embankment	$55M
Mason Creek - Pump Station (12,000 cfs)	$120M
T103-00-00 - Pump Station (4,000 cfs)	$55M
Buffalo Bayou Main Stem – Pump station (11,500 cfs)	$110M
Buffalo Bayou Diversion – Pump Station (13,000 cfs)	$125M
Contingency at 35% of Overall Costs	$163M
Soft Costs at 25% of Construction Cost	$157M
Total Estimate	**$785M**
Estimated Lower Range	**$667M**
Estimated Upper Range	**$1,020M**

Table 10: Order of Magnitude Cost Estimate – Alternative System (27,750 cfs)

Item	Cost
Backside Levee Embankment	$55M
Mason Creek - Pump Station (6,750 cfs)	$70M
T103-00-00 - Pump Station (1,600 cfs)	$25M
Buffalo Bayou Main Stem – Pump station (9,700 cfs)	$95M
Buffalo Bayou Diversion – Pump Station (9,700 cfs)	$95M
Contingency at 35% of Overall Costs	$119M
Soft Costs at 20% of Construction Cost	$115M
Total Estimate	**$574M**
Estimated Lower Range	**$488M**
Estimated Upper Range	**$746M**

10. Comparable Project

The USACE New Orleans District recently (2018) completed a coastal flood risk management project with many similar components to the improvements proposed for Barker Reservoir. This project, titled the Permanent Canal Closures and Pumps Project, involved the construction of three large pump stations and gate structures located at the outfall of three large drainage canals into Lake Pontchartrain. The gate structures tie into existing levees and floodwalls which prevent coastal tides and surge from inundating the low lying neighborhoods adjacent to the lake. The pump stations pump water, collected from the contributing watersheds, over the levee and into Lake Pontchartrain, maintaining acceptable water levels on the upstream canal systems during high tailwater conditions which prohibit gravity flow through the canals.

The core components of this project include:

- Large gate structures at the terminus of each canal
- Large pump stations at the terminus of each canal
  - London Ave: 9,000 cfs
  - Orleans Ave: 2,700 cfs
  - 17^{th} Street: 12,600 cfs
- Redundant power (on-site generation) to power each facility for up to five days

This project, including all three facilities, was procured through a design-build delivery method. The initial design-build cost was $615M. Upon completion in early 2018, the cost had increased to over $700M.

These pump stations include some of the largest low-head storm water pumps available, with the largest pumps employed rated for up to 1,600 cfs each. Additional information on this project can be found at this link:

http://www.mvn.usace.army.mil/Missions/HSDRRS/PCCP/

Similarities to the proposed Barker Project include:

- Similar sized, low-head high capacity storm water pump stations located at the terminus of a drainage canal / channel
- Similar style of gate structure, tied into a levee / flood wall
- Similar requirement for redundant power
- Similar USACE design requirements

Differences with the proposed Barker Project include:

- Likely more complex gate structures, due to geotechnical and outfall conditions
- Likely more complex operating requirements, due to the expected operating conditions (frequency of operation, operating scheme)
- Likely more complex construction phasing and conditions, due to location adjacent to interim pump stations and proximity to existing development

While every project is unique, a comparable project such as this provides the ability to understand potential costs of a complex project, such as the proposed Barker Reservoir project, which is only in the early feasibility stage. The cost per 1,000 cfs of pumping capacity, on average, for the Permanent Canal Closures projects is approximately $25M / 1,000 cfs. Due to known differences between the two projects, it is reasonable to assume that $25M / 1,000 cfs is on the high end of a reasonable cost range for the Barker Reservoir project. Assuming a range of $15M to $25M / 1,000 cfs, the total estimate cost of providing up to approximately 40,000 cfs of total pumping capacity would be between $600M to $1B. This does not include levee construction costs, which would be additional. This estimate follows closely with the above estimate presented in **Section 9**.

11. Current Federal Efforts

Over the past 70 years, the USACE has completed numerous studies and multiple improvements projects for Barker Dam and Reservoir. Most recently, the USACE is nearing completion of their Dam Safety Program (Phase 1) at Barker Reservoir. This work included repairs to the embankment and replacement of the reservoir's control structure to address seepage and piping beneath, around, and near the outlet works structure conduits. This work is currently under construction.

As part of the Bipartisan Budget Act of 2018, a $6M study titled "Buffalo Bayou and Tributaries

Resiliency Study" was funded for initiation in the 2018/2019 timeframe. This multi-year effort is anticipated to merge the following two separate planning efforts related to Barker Reservoir into single integrated planning process.

Dam Safety Program (Phase 2) at Barker Reservoir. This study would assess incremental risk, overtopping with breach, and residual risk in the pool area and downstream, including life safety. This process would identify and develop recommended improvements and carry the improvements through design and construction.

Buffalo Bayou Section 216 Study. This study would assess residual risks associated with flood risk impacts to structures in the pool area upstream of the reservoir and downstream along Buffalo Bayou. This study would evaluate a wide variety of flood risk management measures, such as an additional upstream reservoir/dam, increased reservoir storage capacity, reservoir water level equalization, improved outlet discharge capacity, improved inflow and outlet discharge channels, acquisition of flowage easements and buyouts, and changes in dam operation plan.

The execution and completion of the "Buffalo Bayou and Tributaries Resiliency Study" is considered the first step in a multi-step process to authorize, fund, design, and construct USACE led Federal Civil Works projects. Studies such as this typically take three years or longer to complete.

12. Next Steps

It is anticipated that modifications or improvements to Barker Dam and Reservoir would be studied and implemented by the USACE through the study efforts identified in **Section 11** of this report. As a Federal project, modifications cannot be made to the dam and reservoir without approval by the USACE.

The USACE typically follows a formulaic process to identify improvements which maximize benefits while minimizing cost and environmental impact. This process relies heavily on a benefit-cost ratio, based on estimated probabilistic flood damages avoided by the proposed improvements over a defined planning horizon. Different alternatives are typically analyzed, and benefit cost-ratios compared to identify a preferred improvement alternative. Projects with a strong benefit-cost ratio are more likely to be funded by the USACE and Congress. Benefit-cost analyses were not conducted as part of this feasibility study, but will be performed by the USACE as part of their studies. Challenges to obtaining a high benefit-cost ratio are anticipated to include the relative infrequency of flooding upstream of the reservoir, as a 500-year event or greater is typically necessary to generate flood damages.

As discussed in **Section 11** of this report, it is anticipated that the USACE will evaluate a wide range of potential improvement alternatives, including this back-side levee proposal. Assuming the USACE study identifies a preferred alternative with a strong benefit-cost ratio, the project would have to be funded by Congress to advance into design and construction. Such a project would also require support from local and state non-federal sponsors.

13. Conclusion

The proposed Barker Reservoir improvement project, which includes construction of a back-side levee in addition to four large storm water pump stations, represents a feasible option for increasing flood protection for the communities upstream of Barker Reservoir. As proposed, if the recommended project had been constructed prior to Hurricane Harvey, no structures upstream of the reservoir would have been inundated by the reservoir pool. However, due to the limited storage volume available within the government owned land, even with the back-side levee, the proposed project would only be able to protect upstream neighborhoods from multi-day flood events totaling approximately 36 inches of rainfall. For rain events above 36 inches, residual risk remains and flooding would be anticipated to occur within the communities upstream of the reservoir.

Due to the large contributing drainage area to the reservoir, large pump stations are required to maintain acceptable water levels on the upstream side of the back-side levee during extreme events. Due primarily to the size of the required pump stations, and depending on desired level of service, it is anticipated that this project could cost between approximately $500M and $1B to construct.

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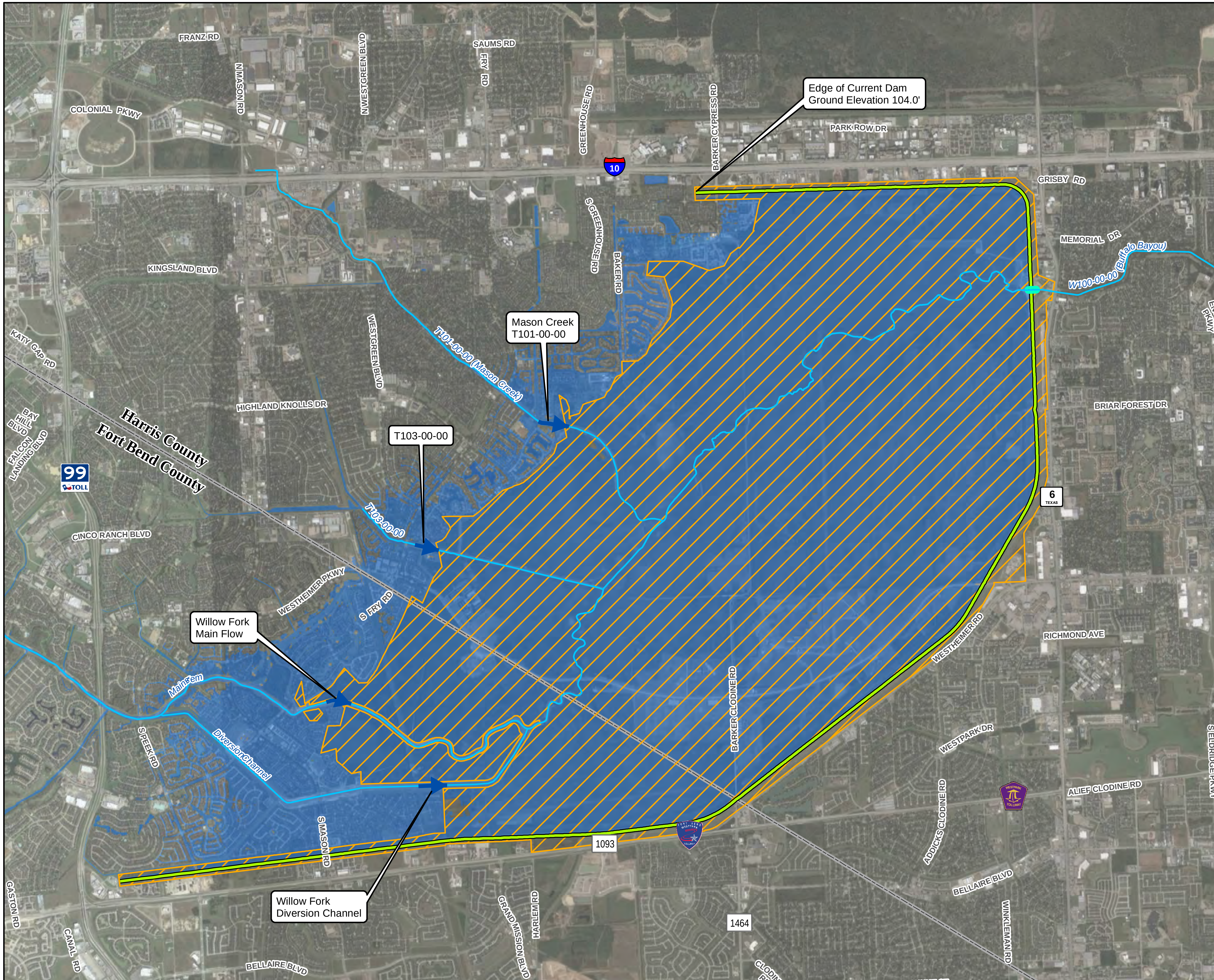

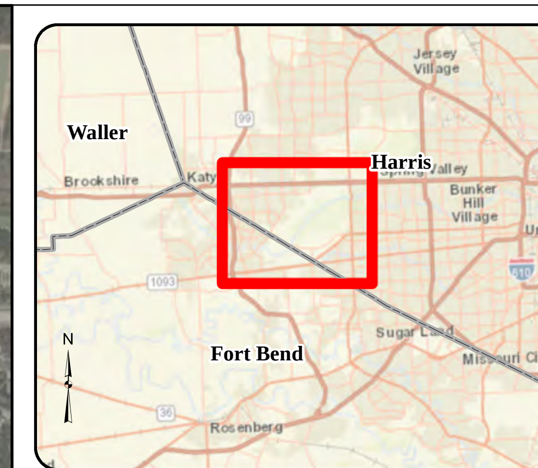

Vicinity Map

Legend

- Major Inflows
- Stream
- OutfallStructure
- Existing Top of Dam (Elevation 113.1')
- USACE Property
- County Boundaries
- Harvey Pool Inundation

0 2,000 4,000 8,000

Feet

N

Imagery: 2017;
Vertical datum: NAVD 1988

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Barker Reservoir Feasibility Study Report

Barker Reservoir Overview

DATE	STATE	COUNTY	PROJECT NO.	EXHIBIT NO.
AUG 2018	TEXAS	FORT BEND\ HARRIS	60571807	01

User: scott.hughes1 Printed on: 7/9/2018
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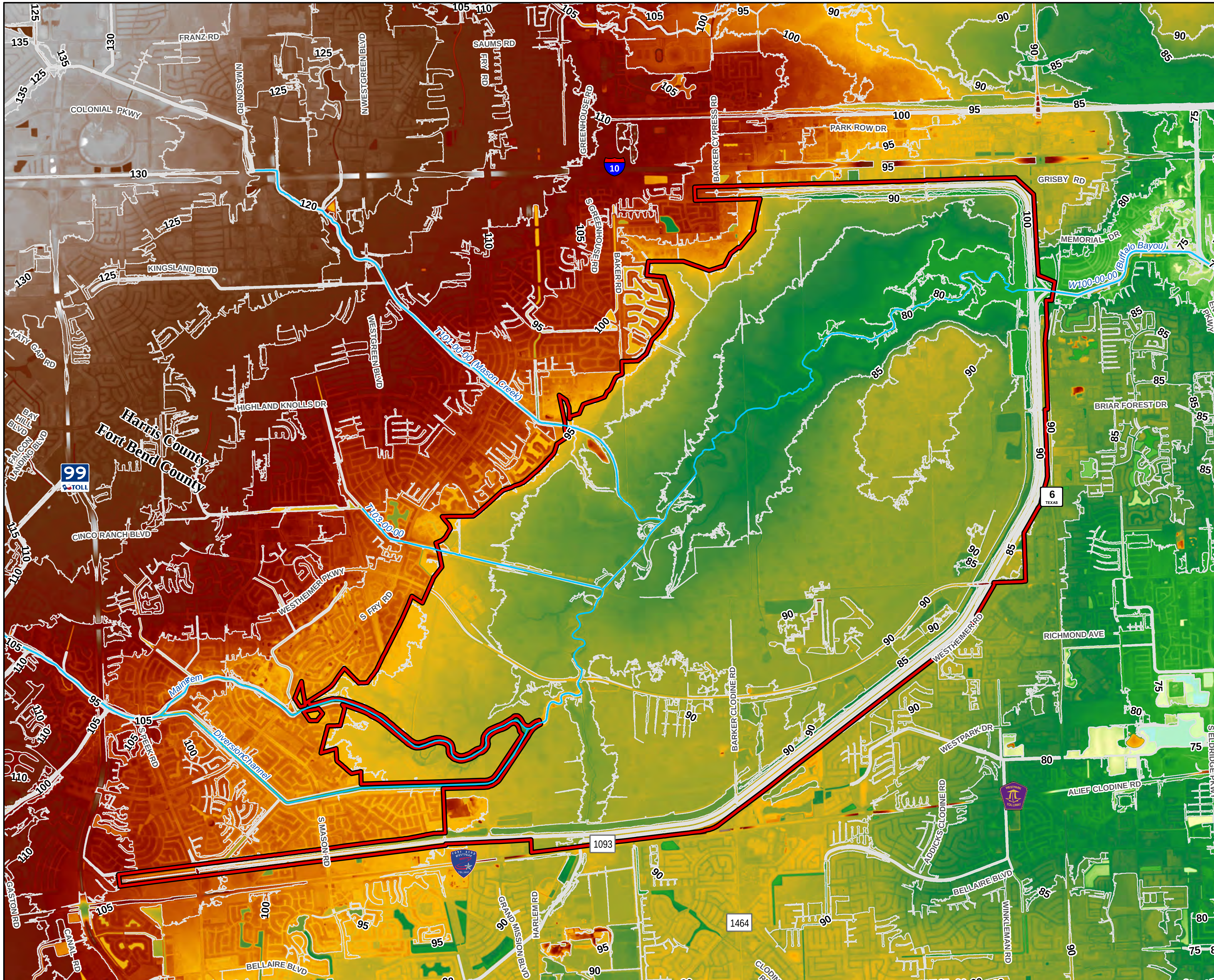

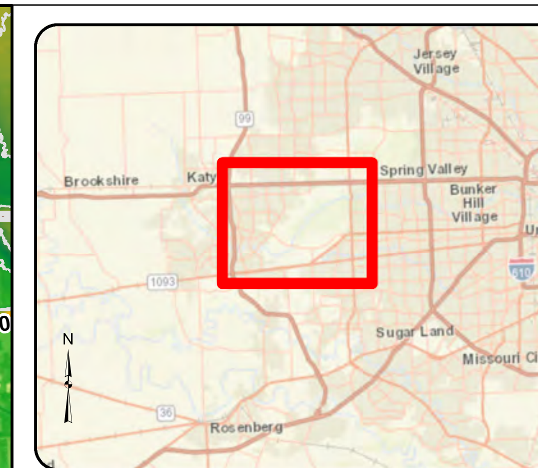

Vicinity Map

Legend

- Stream
- 5ft - Contour
- USACE Property
- County Boundaries

2008 LiDAR Elevation
High : 140
Low : 50

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Feet

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Imagery: 2017;
Vertical datum: NAVD 1988

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Barker Reservoir Feasibility Study Report

Barker Reservoir Topography

DATE	STATE	COUNTY	PROJECT NO.	EXHIBIT NO.
AUG 2018	TEXAS	FORT BEND\ HARRIS	60571807	02

User: scott.hughes1 Printed on: 7/9/2018
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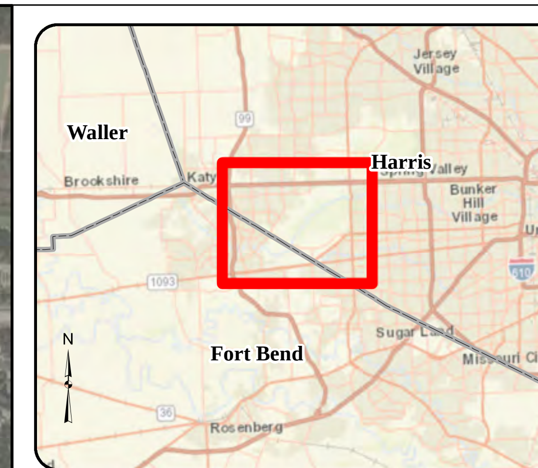

Vicinity Map

Legend

- Major Inflows
- Stream
- OutfallStructure
- Proposed Pump Station
- Proposed Levee
- Existing Top of Dam (Elevation 113.1')
- USACE Property
- County Boundaries

0 2,000 4,000 8,000
Feet

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Imagery: 2017;
Vertical datum: NAVD 1988

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Barker Reservoir Feasibility Study Report

Proposed Improvement Concept

DATE	STATE	COUNTY	PROJECT NO.	EXHIBIT NO.
AUG 2018	TEXAS	FORT BEND\ HARRIS	60571807	03

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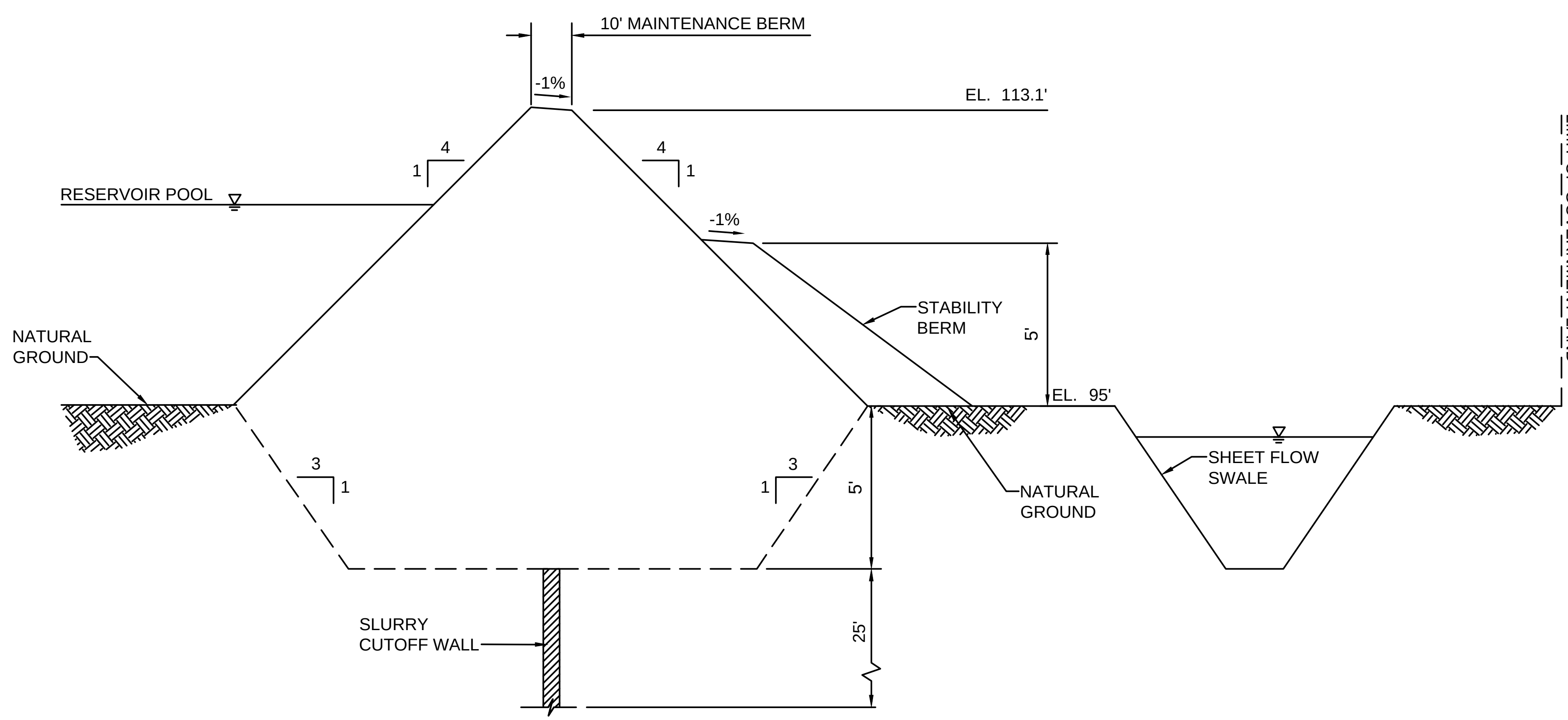

X
-
VIEW LOOKING DOWN STATION
N.T.S.

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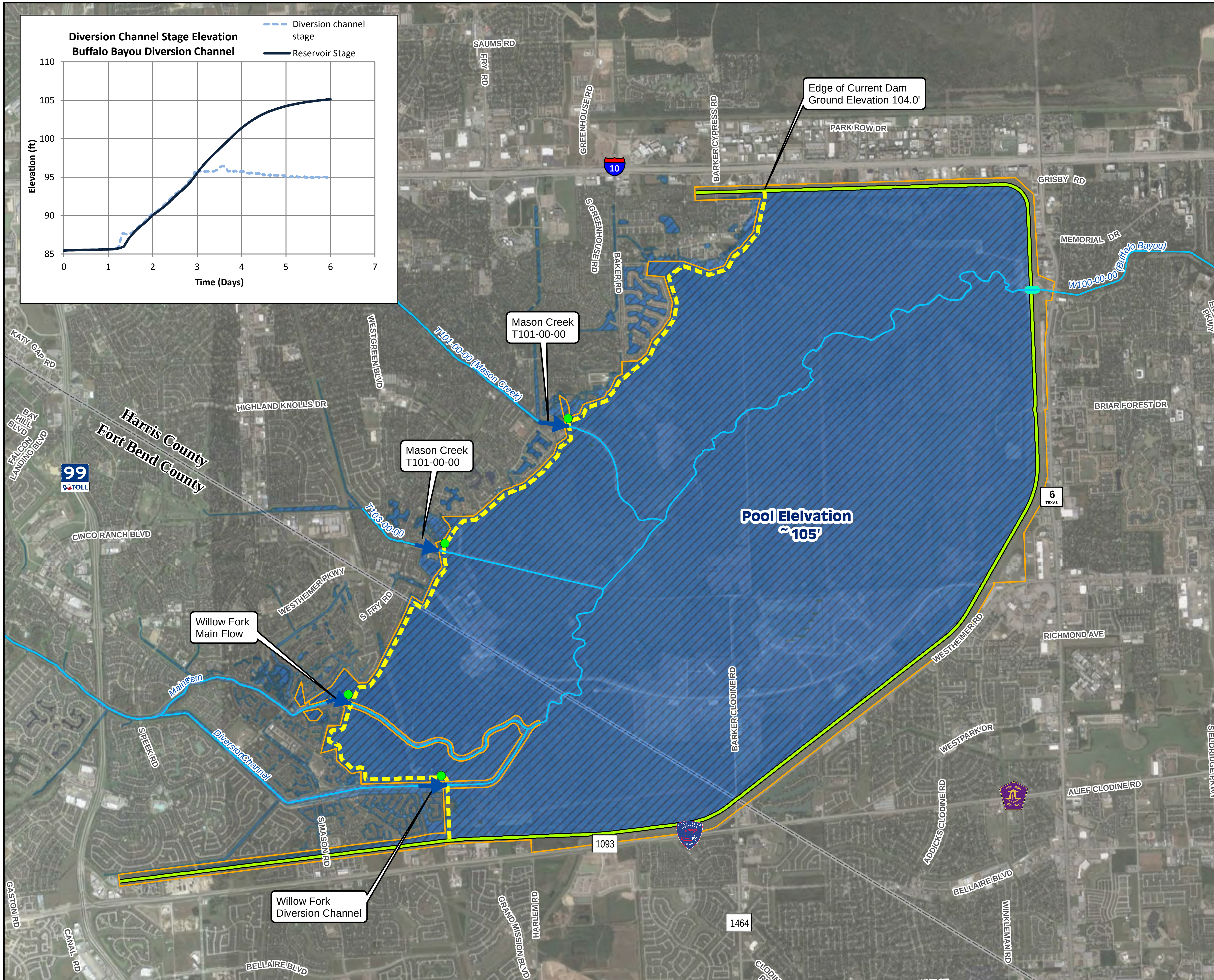
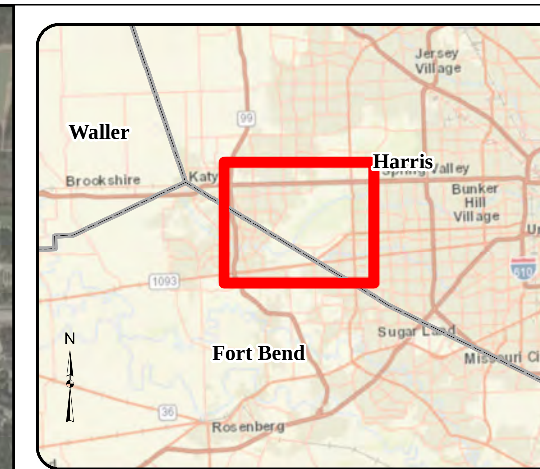
Barker Reservoir Feasibility Study Report

CONCEPTUAL LEVEE CROSS SECTION

DATE	STATE	COUNTY	PROJECT NO.	EXHIBIT NO.
JULY 2018	TEXAS	FORT BEND\ HARRIS	60571807	04





Vicinity Map

Legend

- Major Inflows
- Stream
- OutfallStructure
- Proposed Pump Station
- Proposed Levee
- Existing Top of Dam (Elevation 113.1')
- USACE Property
- Proposed Pool Inundation Extents
- County Boundaries

0 2,000 4,000 8,000
Feet

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Imagery: 2017;
Vertical datum: NAVD 1988

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Barker Reservoir Feasibility Study Report

Recommended System Performance - Hurricane Harvey (31.7")

DATE	STATE	COUNTY	PROJECT NO.	EXHIBIT NO.
AUG 2018	TEXAS	FORT BEND\ HARRIS	60571807	05

User: scott.hughes1 Printed on: 8/10/2018
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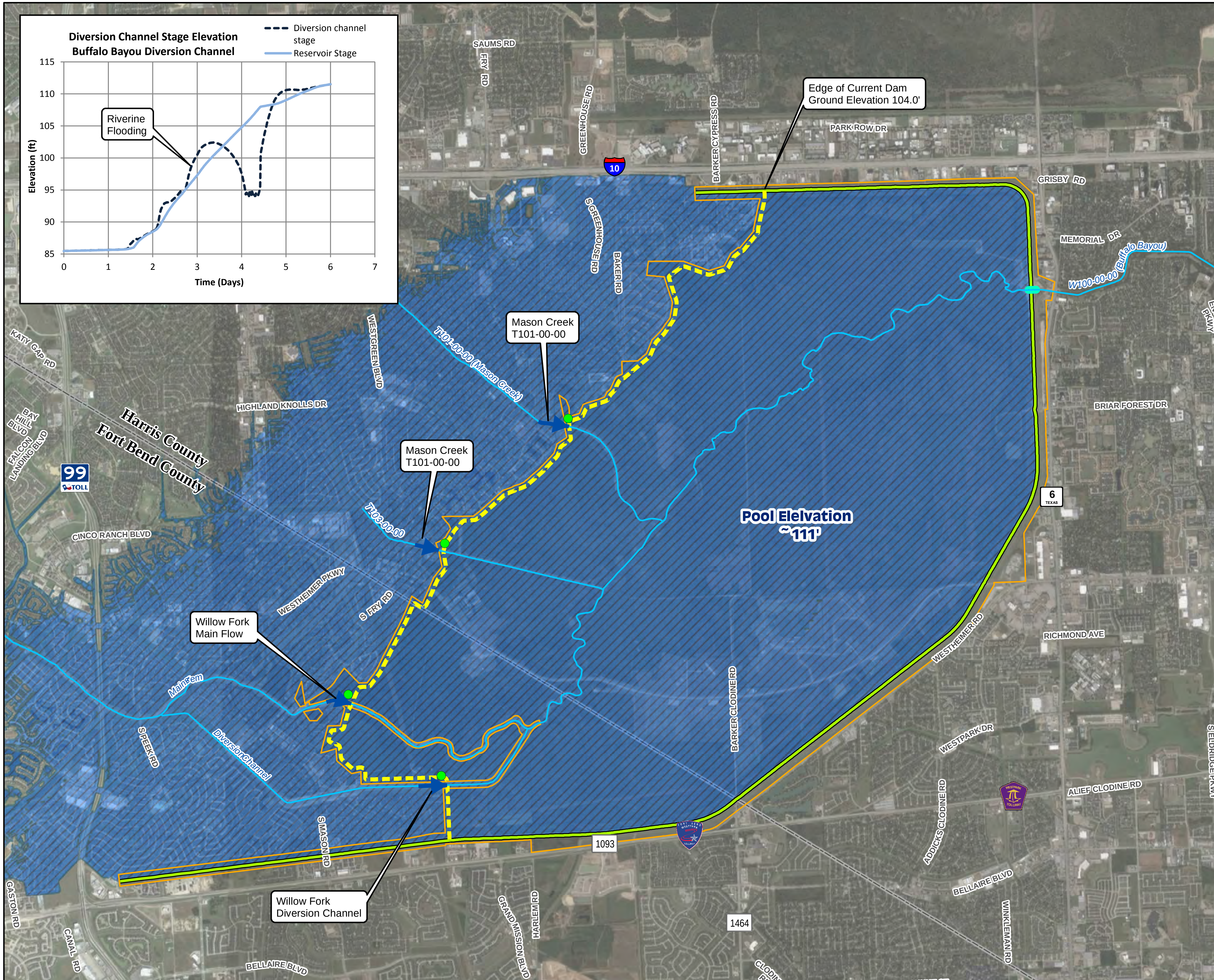
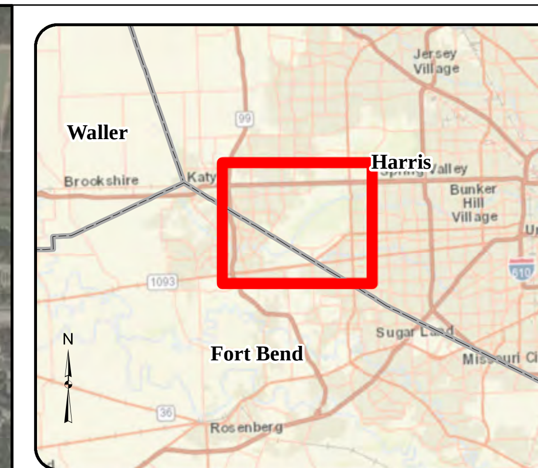


Vicinity Map



Legend

- Major Inflows
- Stream
- OutfallStructure
- Proposed Pump Station
- Proposed Levee
- Existing Top of Dam (Elevation 113.1')
- USACE Property
- Proposed Pool Inundation Extents
- County Boundaries

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Feet

Imagery: 2017;
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Barker Reservoir Feasibility Study Report

Recommended System Performance - Hurricane Harvey Shifted (51.9")

DATE	STATE	COUNTY	PROJECT NO.	EXHIBIT NO.
AUG 2018	TEXAS	FORT BEND\ HARRIS	60571807	06

User: scott.hughes1 Printed on: 8/10/2018
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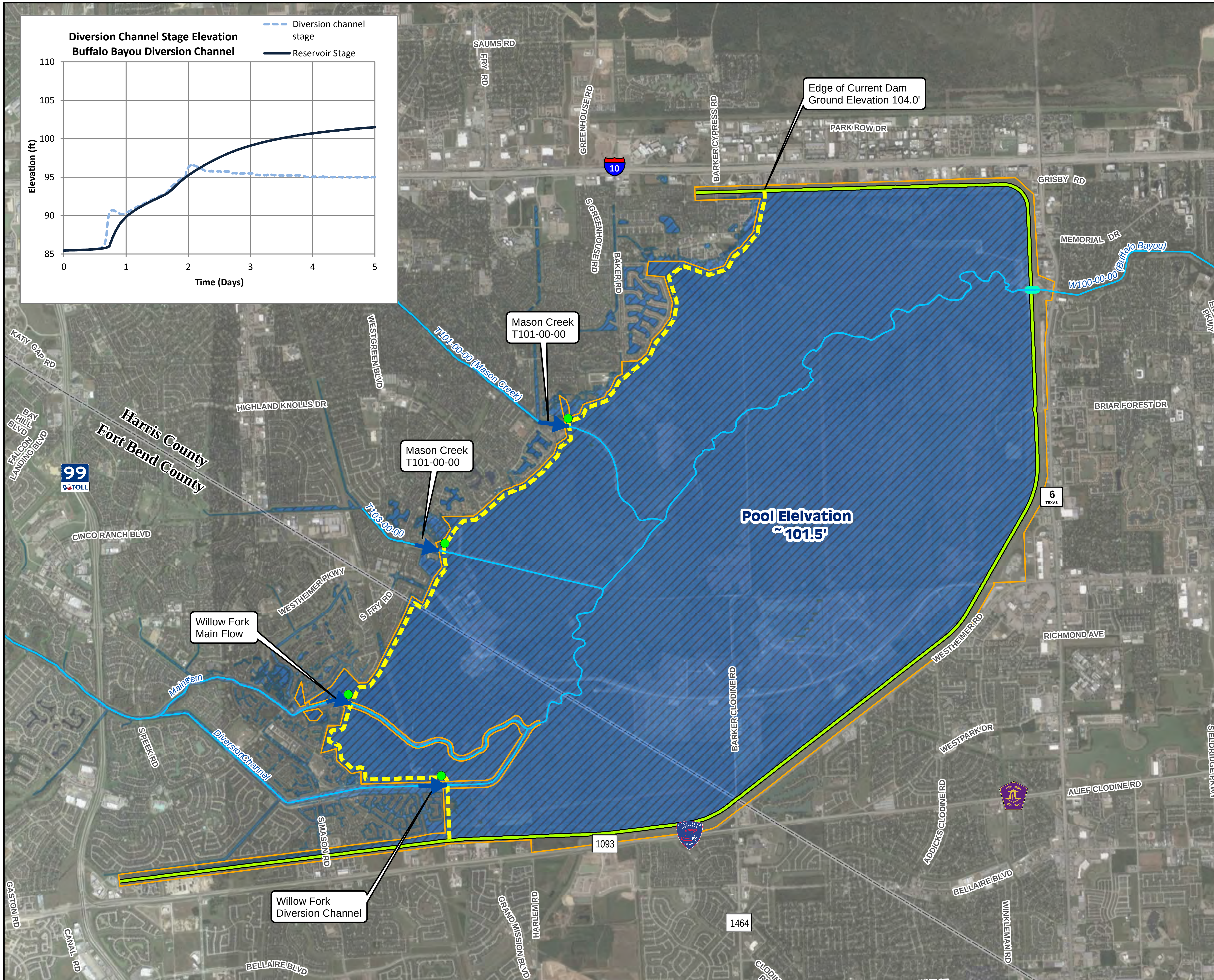

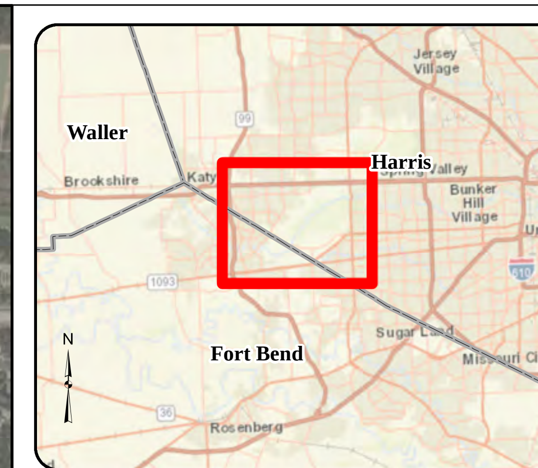

Vicinity Map

Legend

- Major Inflows
- Stream
- OutfallStructure
- Proposed Pump Station
- Proposed Levee
- Existing Top of Dam (Elevation 113.1')
- USACE Property
- Proposed Pool Inundation Extents
- County Boundaries

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Feet

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Imagery: 2017;
Vertical datum: NAVD 1988

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Barker Reservoir Feasibility Study Report

Alternative System Performance - Back-to-Back 100-Year Events (24.8")

DATE	STATE	COUNTY	PROJECT NO.	EXHIBIT NO.
AUG 2018	TEXAS	FORT BEND\ HARRIS	60571807	07

User: scott.hughes1 Printed on: 8/10/2018
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