Neighborhood-Scale Floodplain Analysis and Flood Mitigation Study for Greens Bayou Watershed

October 2019

GREATER HOUSTON

FLOOD MITIGATION CONSORTIUM

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Executive Summary

The SSPEED Center at Rice University, in cooperation with the Community Design Resource Center (CDRC) at the University of Houston, was retained by the Greater Houston Flood Mitigation Consortium (GHFMC) to conduct this study of four neighborhoods within the Greens Bayou Watershed in order to better understand the flooding issues facing these neighborhoods and how one might address them. A two-dimensional hydraulic model (HEC-RAS 2D) was primarily used to conduct both the flood hazard and flood mitigation analyses. Once the model was developed and validated using the Harvey storm of 2017, the 2D model was run for the new (NOAA Atlas 14) 100- and 500-year storms. The resulting inundation was shown throughout these neighborhoods, indicating that there was both riverine (fluvial) overbank flooding and local drainage (pluvial) flooding impacting these neighborhoods. To improve the delineation of the fluvial as well as the pluvial flood hazard areas, future studies should consider using both 1D and 2D hydraulic models, or a hybrid 1D/2D approach.

There are different types of solutions to the flooding problems in these neighborhoods, and are dependent upon the type of flooding to be addressed. For example, riverine flooding issues are typically addressed either by channel widening or regional detention; whereas local flooding issues are typically addressed by local drainage improvements (e.g. enlarging storm sewers or installing local detention ponds). For this study, only the riverine flooding issues were being addressed, and only regional detention basins were investigated and analyzed. This decision was based primarily on limitations of the hydraulic model used, which are described in this report.

The results of the flood mitigation analyses showed that regional detention basins provided a significant reduction in the extent and depth of the 100- and 500-year floodplains along Greens Bayou and Halls Bayou within these four neighborhoods. Selected watch points located within the existing riverine floodplains benefitted the most from the additional proposed detention, while watch points outside the floodplains (or are located relatively far away from the channel) saw no / negligible changes in flood depth. Additional work is needed to optimize the size and number of detention basins that would be appropriate for providing significant flood reduction/mitigation in each of these neighborhoods, as well as to address their local drainage flooding issues.

Acknowledgements

The SSPEED Center would like to thank the Greater Houston Flood Mitigation Consortium (GHFMC) for funding this study. We would also like to thank our collaborators, the Community Design Resource Center (CDRC) at the University of Houston and the Kinder Institute for Urban Research at Rice University. Finally, we would like to express our gratitude to the communities of Greater Greenspoint, East Aldine, Eastex-Jensen, and East Houston for their valuable input and feedback in this study.

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Introduction and Objectives

The flood impacts of Hurricane Harvey (2017) to the Greater Houston Region had been both severe and widespread. Several neighborhoods within the Greens Bayou watershed (including Halls Bayou), having experienced repetitive flood losses from major floods in the last two decades, were unsurprisingly hit hard during Harvey. As these neighborhoods, and the watershed as a whole, strive to recover from the devastating flood losses, and also plan to mitigate against future losses from storms similar to Harvey, questions arise regarding what additional flood reduction options could be implemented to complement existing strategies within the watershed. To answer these questions, the Severe Storm Prediction, Education, and Evacuation from Disasters (SSPEED) Center at Rice University, in partnership with the Community Design Resources Center (CDRC) at the University of Houston, conducted this floodplain analysis and mitigation study, focusing on the following four neighborhoods within the Greens Bayou watershed: Greater Greenspoint, East Aldine, Eastex-Jensen, and East Houston (see **Figure 1**).

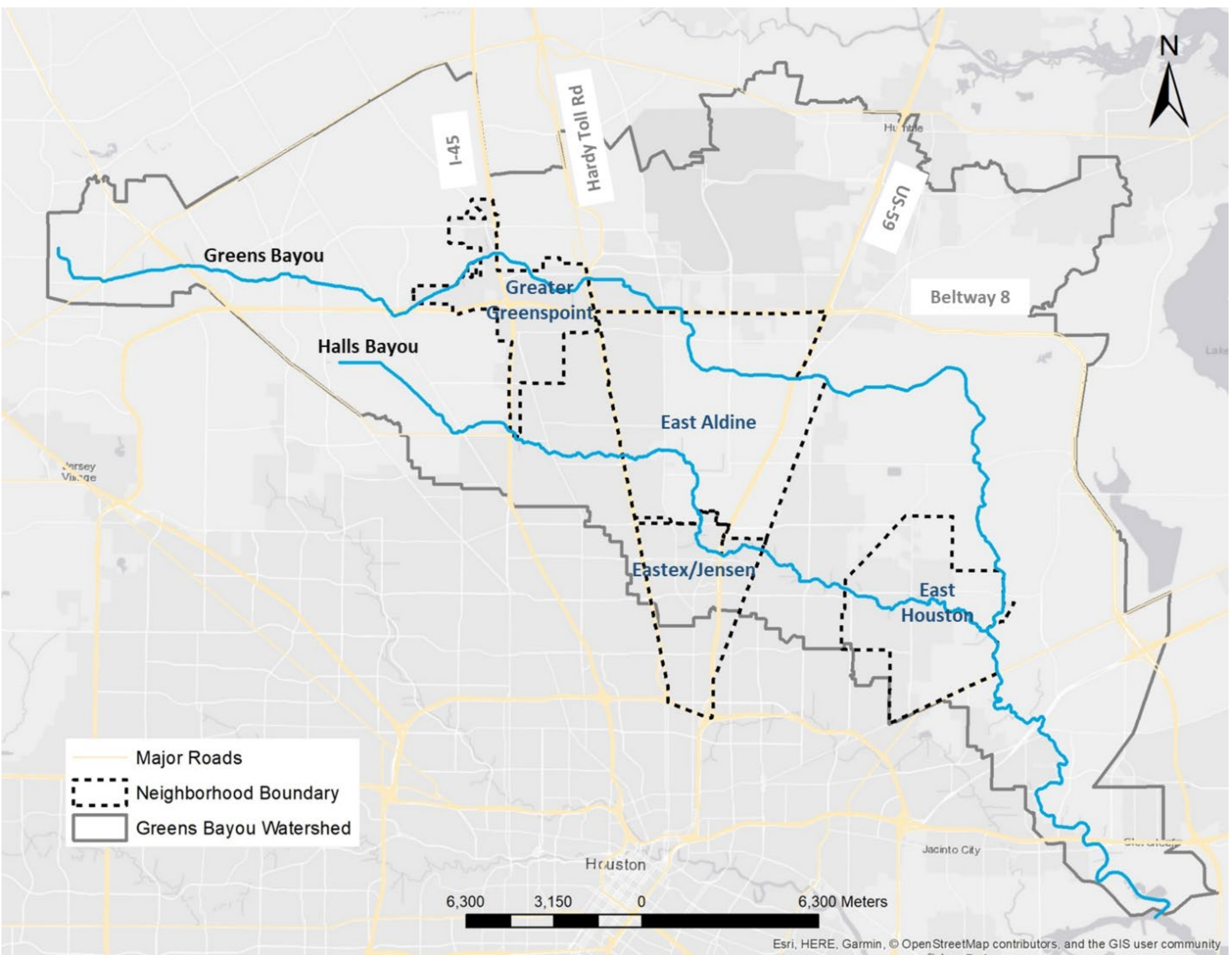

Figure 1: Four focus neighborhoods in the Greens Bayou watershed

The Greens Bayou Watershed is one of 22 major watersheds in Harris County, covering about 212 square miles of area north and northeast of downtown Houston, and includes portions of the cities of Houston and Humble. According to the 2010 Census, this watershed has a population of over 500,000. Greens Bayou, and its major tributary, Halls Bayou, both flow from west to east, with Greens Bayou then flowing south where it meets Halls Bayou and together empty into the Houston Ship channel, east of downtown Houston. These two bayous have had a long history of flooding issues, particularly in these four specific neighborhoods, and thus there was a desire to investigate and better understand these flooding problems and possible ways to address them. This study is intended to accomplish this.

Specifically, the objectives of this study are as follows:

1. Perform a flood hazard analysis of the new (Atlas 14) 100-year and 500-year storms over the Greens Bayou watershed, while focusing on four specific neighborhoods to better understand flood drivers and identify inundation hotspots within those neighborhoods;
2. Consider potential flood mitigation options for reducing bayou overbank flooding to complement existing strategies with input from the communities of the studied neighborhoods; and
3. Evaluate the impacts / benefits of selected flood mitigation options for each neighborhood under the new 100-year and 500-year storm events.

Subsequent sections describe the methodology used in this study, the flood hazard analysis conducted for the new 100-year and 500-year storms, and the flood mitigation assessment results which are presented and discussed for each neighborhood.

Methodology

Hydrologic & Hydraulic Modeling

In the U.S., the two most widely-used computer modeling software for conducting hydrologic and hydraulic analyses were developed by the U.S. Army Corps of Engineers (USACE): Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS[1]) and Hydrologic Engineering Center – River Analysis System (HEC-RAS[2]). HEC-HMS simulates the hydrologic processes that occur within a watershed given a certain rainfall amount and pattern, such as computing rainfall losses due to infiltration, and the accumulation and movement of the resulting runoff into and along the stream system. Meanwhile, HEC-RAS simulates the hydraulic responses to a given flow regime (e.g., water surface elevations and velocities) within streams and channels. Typically, these two models are used conjunctively in performing flood risk and/or damage analyses, such as in the generation of official floodplain maps published by FEMA. The official FEMA floodplains for the Greens Bayou watershed are shown in **Figure 2**.

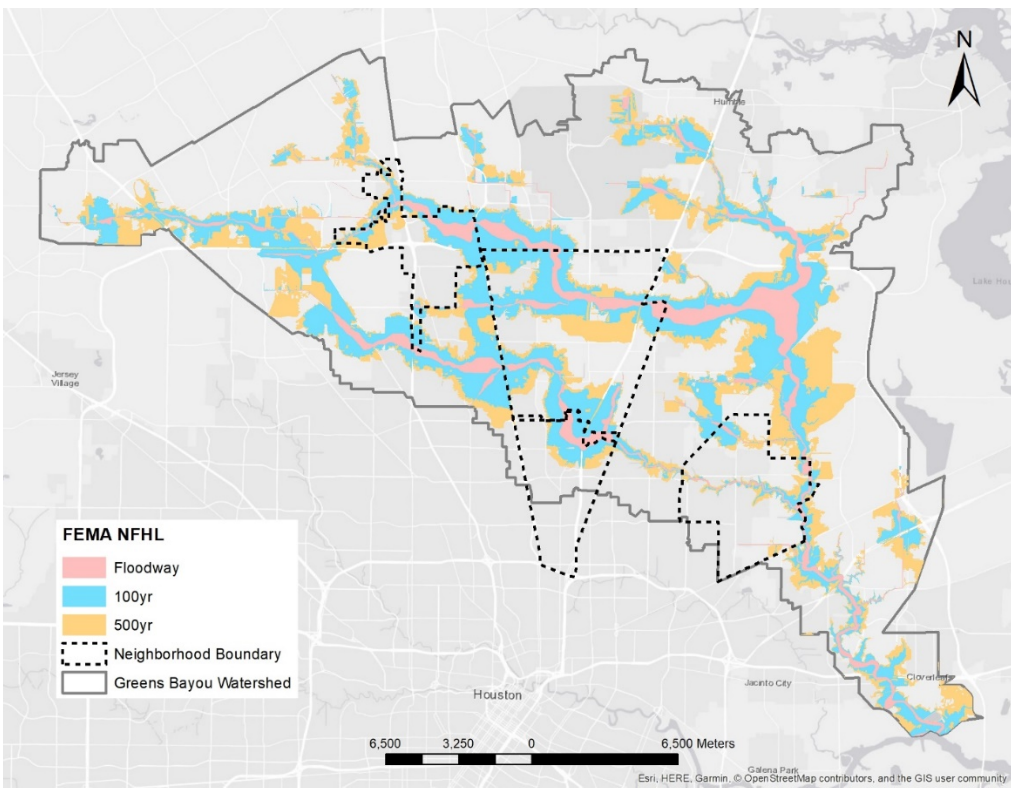

Figure 2: FEMA floodplains (based on old rainfall statistics) for Greens Bayou watershed

[1] https://www.hec.usace.army.mil/software/hec-hms/
[2] https://www.hec.usace.army.mil/software/hec-ras/

While the official FEMA floodplain maps (which depict the 100-year and 500-year floodplains, as well as the floodway, along major streams and channels) provide useful information to help identify flood-vulnerable areas, they are known to often underestimate the actual flood hazard for watersheds in Houston. In fact, a recent study[3] showed that approximately 47% of flood claims from 1978 to 2008 in Harris County originated outside of the official FEMA mapped 100-year floodplains. This is not entirely surprising, since these official floodplain maps generally only consider riverine flooding, which is flooding resulting from streams and channels overtopping their banks, from primary watercourses. In actuality, in addition to riverine (fluvial) flooding, there are other flood drivers in Houston, such as flooding due to intense rainfall over a local neighborhood impacting its drainage system (i.e., pluvial flooding). Such a local flood driver warrants consideration to better represent actual flood hazards within this watershed; however, past modeling efforts by FEMA could not adequately address this local overland flow issue.

Recent updates to HEC-RAS (i.e., version 5.0 and later) have now allowed one to begin addressing the pluvial flooding/overland flow issue. With the introduction of two-dimensional (2D) modeling in HEC-RAS, it is now possible to simulate both fluvial and pluvial flooding within the intended study area. HEC-RAS 2D allows one to represent an entire study area using a mesh of inter-connected grid cells, with properties derived from various spatial datasets, such as terrain and land use / land cover (LULC) data (rather than simply representing the stream or channel with representative cross-sections required when using HEC-RAS 1D). Storm water is introduced into the study area mesh either through inflow hydrographs inputted at specific locations (as boundary conditions), or by inputting rain over the entire grid, or a combination of the two. In turn, HEC-RAS 2D calculates the hydrodynamic response (e.g., flood depth, water surface elevation, velocity) for every storm-impacted cell as storm water is conveyed overland and downstream throughout the study area. Because of these new capabilities, this study primarily used HEC-RAS 2D to perform both the hydrologic and hydraulic modeling of the study area within the focus neighborhoods. HEC-HMS was used as reference to provide some necessary inputs (e.g., inflow hydrographs as boundary conditions) into the developed HEC-RAS 2D models.

[3] Highfield, Wesley E., Sarah A. Norman, and Samuel D. Brody. "Examining the 100-year floodplain as a metric of risk, loss, and household adjustment." Risk Analysis: An International Journal 33, no. 2 (2013): 186-191.

Model Setup and Validation

To simulate the hydrodynamic responses of the four selected neighborhoods, two HEC-RAS 2D model domains were developed in order to better address the 2D model limitation that inputted rainfall is uniformly distributed across the model domain. The "upstream" model domain covers the Greater Greenspoint, East Aldine, and Eastex-Jensen neighborhoods (see **Figure 3**), while the "downstream" model domain covers East Houston (see **Figure 4**). Both model domains have average cell resolution of 150 feet on each side of the cell. The 2018 terrain (LIDAR)[4] and the 2018 land use / land cover (LULC)[5] datasets from HGAC (Houston-Galveston Area Council) were used to represent the physical characteristics of the study areas. Each LULC class is assigned a surface roughness value (Manning's n) adapted from Kalyanapu et al. 2010.[6] Both models were validated based on Harvey rainfall, and the resulting computed flood inundation areas were presented to and reviewed by the four neighborhood communities in the *Greens Bayou Watershed Analysis and Resiliency Planning Workshop* (January 26, 2019) hosted by the University of Houston .

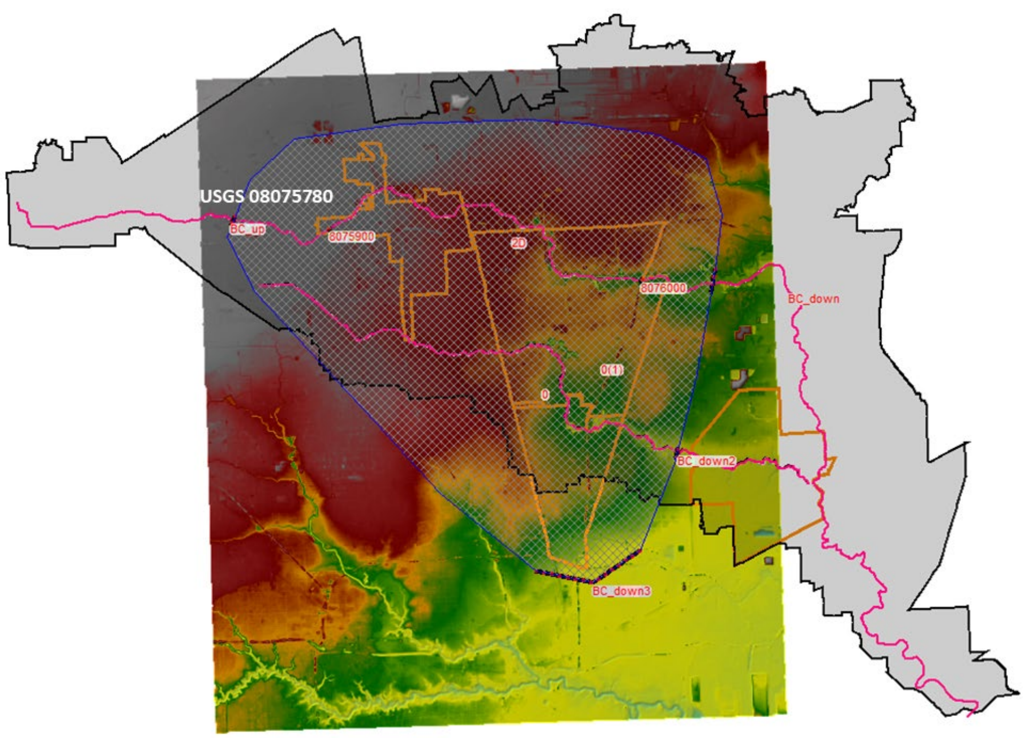

Figure 3: HEC-RAS 2D model domain covering Greater Greenspoint, East Aldine, and Eastex-Jensen neighborhoods

[4] http://www.h-gac.com/imagery/lidar/default.aspx

[5] http://www.h-gac.com/land-use-and-land-cover-data/default.aspx

[6] Kalyanapu, A.J., Burian, S.J., McPherson, T.N., 2010. Effect of land use-based surface roughness on hydrologic model output. Journal of Spatial Hydrology 9.

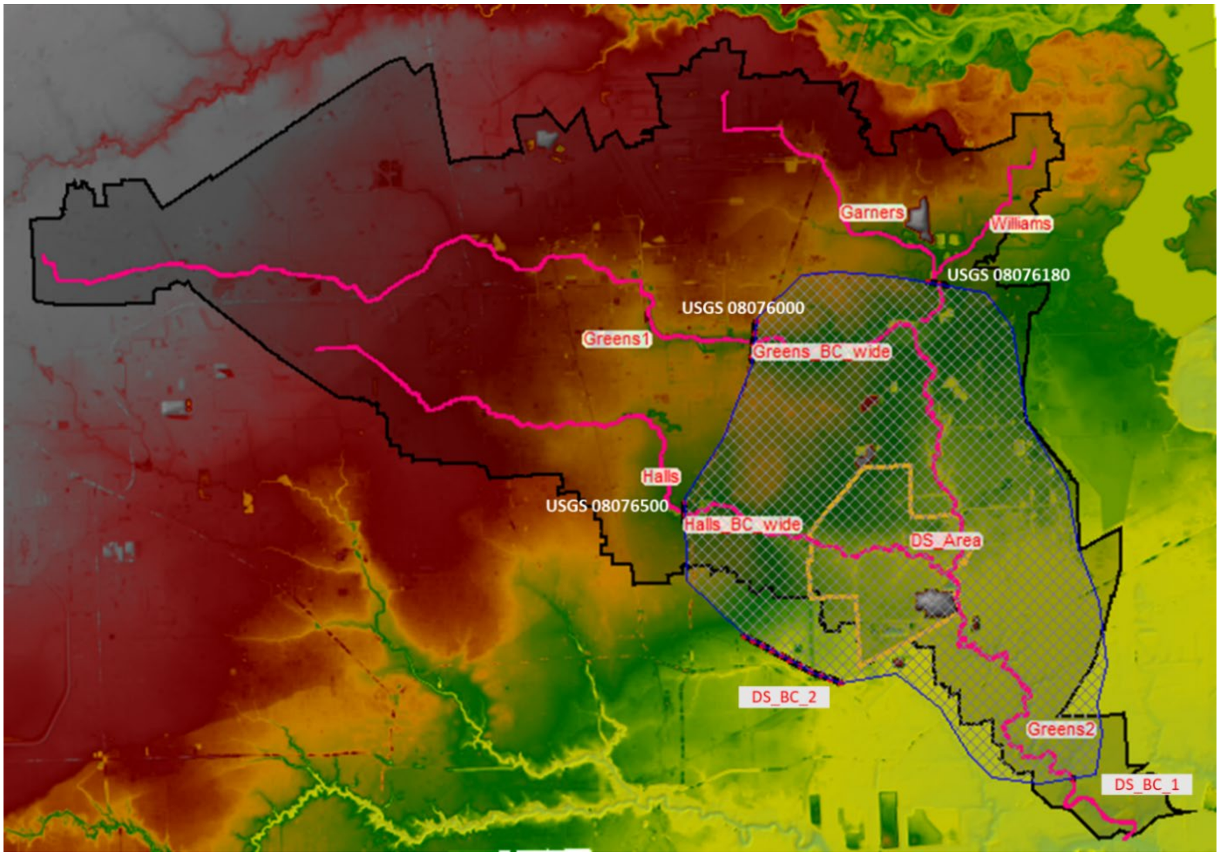

Figure 4: HEC-RAS 2D model domain covering East Houston neighborhood

For the “upstream” model, precipitation is applied uniformly throughout the model domain. Additionally, an inflow hydrograph from an external boundary condition (BC) accounts for upstream basin inflows that are outside of the model domain. The source of the inflow hydrograph differs depending on the modeled scenario. Hurricane Harvey was simulated for model validation (see **Appendix A**), while the new 100-year and 500-year storms were simulated for the specific flood hazard analysis for the four neighborhoods. For Harvey, the upstream boundary condition was an inflow hydrograph based on the USGS gage-recorded flows at Cutten Road[7] (USGS 08075780). For the design storm scenarios, the upstream inflow hydrographs were based on an adapted HEC-HMS model of Greens Bayou watershed obtained from the Harris County Flood Control District (HCFCD) Model and Map Management (M3) system[8]. Finally, to ensure that flood water is able to exit the system instead of accumulating along the edges of the model domain, three external downstream boundary conditions based on normal depth were designated (“BC_Down” in Figure 3).

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[7] https://waterdata.usgs.gov/tx/nwis/uv/?site_no=08075780&PARAmeter_cd=00065,00060

[8] https://www.hcfcd.org/interactive-mapping-tools/model-and-map-management-m3-system/

Similarly, for the “downstream” model, net precipitation is applied over the model domain uniformly. Apart from rainfall, this model also accounts for the flow coming from upstream by assigning three external boundary conditions – one each at Greens Bayou, Halls Bayou and Garners Bayou (which comes into the model domain from the north). Figure 4 shows the locations of these boundary conditions. Also, the inflow hydrographs used as the external boundary condition (BC) were obtained from the USGS gages shown in Figure 4 for the historic storm event (i.e. Harvey), whereas for the 100-year and 500-year events, the outflows computed from the “upstream” model were used as the external BC. Finally, to ensure that flood water is able to exit the system instead of accumulating along the edges of the model domain, two external downstream boundary conditions based on normal depth were designated.

For model validation using Harvey, two different approaches were taken (see **Appendix B**). In the first, all of the three upstream boundary conditions were acquired from USGS gages, both at Greens and Halls bayous near I-59 (USGS 08076000[9] and USGS 08076500[10] respectively) and at Garners Bayou (USGS 08076180[11]). For the second validation approach, computed flow hydrographs were extracted from the “upstream” model output for use as inputted boundary conditions at Halls and Greens bayous, while still using the flow hydrograph from the USGS gage for the inflow from Garners. Once validated, the model is then used for simulating the 100-year and 500-year storms, for which computed flow hydrographs were obtained from the “upstream” model for Greens and Halls Bayous, and from HEC-HMS for the flow coming from Garners Bayou, for the upstream boundary conditions. As mentioned earlier, this HMS model is obtained from HCFCD’s M3 system. While sources and values for the upstream boundary conditions change with different scenarios, the two downstream boundary conditions are defined as the fixed normal depth for all scenarios.

[9] https://waterdata.usgs.gov/nwis/uv?site_no=08076000
[10] https://waterdata.usgs.gov/nwis/uv?site_no=08076500
[11] https://waterdata.usgs.gov/nwis/uv?site_no=08076180

Flood Hazard Analysis

Once the two models were set up and validated, the next phase of the study was to perform a flood hazard analysis for the four neighborhoods in order to identify the location and type (i.e., riverine or fluvial flooding versus local drainage or pluvial flooding) of flooding. While both drivers could be identified in this flood hazard analysis, the mitigation assessment presented in this study primarily focused on addressing the riverine (fluvial) flooding issue, for reasons that would be discussed in later sections of this report.

Aside from focusing only on riverine flooding as mentioned earlier, another major issue with the existing 100-year and 500-year floodplain maps in Harris County is the use of outdated rainfall statistics for creating the rainfall patterns used in the computer modeling for creating these floodplain maps. The existing 100-year and 500-year rainfall amounts published by the Harris County Flood Control District (HCFCD[12]) for Greens Bayou watershed are 13.2 inches and 18.9 inches in 24 hours, respectively. In late 2018, NOAA (National Oceanic and Atmospheric Administration) has published updated rainfall statistics for the State of Texas through the NOAA Atlas 14 program[13]. In Harris County, due to recent storms from 2015 to 2017, rainfall frequency totals have increased significantly, especially for the more infrequent events, as both the 100-year and 500-year rainfall magnitude and intensity have increased by approximately 30%. For Greens Bayou, the 100-year and 500-year rainfall totals are now 17.0 inches and 25.4 inches in 24 hours, respectively. These updated rainfall amounts have been used in the model simulations for this study. The following discussion presents the results of the modeling of these two design storms, along with specific flood depths at selected "watchpoints" in or next to each neighborhood. The flooding at these watchpoints may be associated with riverine and/or local drainage sources.

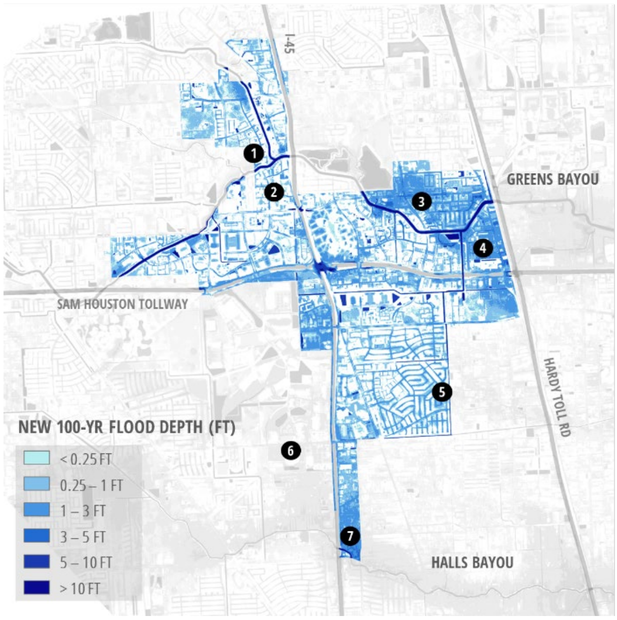
Greater Greenspoint

Below in **Figure 5** are the RAS 2D modeled 100-year and 500-year flood inundation areas that reflect the new rainfall published by NOAA (Atlas 14) focusing on Greater Greenspoint. The maps show the extent of the modeled flood inundation areas as well as flood depths (in feet). The shallow flood depths of less than 1 foot (shown in brown coloring) generally reflect overland flooding resulting from localized drainage topography (pluvial flooding); whereas the flood depths greater than 1 foot generally are adjacent to the bayous and reflect flooding from overflowing the banks of the bayou (fluvial flooding). **Table 1** lists the modeled 100-year and

[12] HCFCD Hydrology & Hydraulics Guidance Manual, December 2009

[13] https://hdsc.nws.noaa.gov/hdsc/pfds/

500-year flood depths at several watchpoints within the neighborhood vicinity. The areas shown in dark blue coloring reflect the existence of detention ponds.



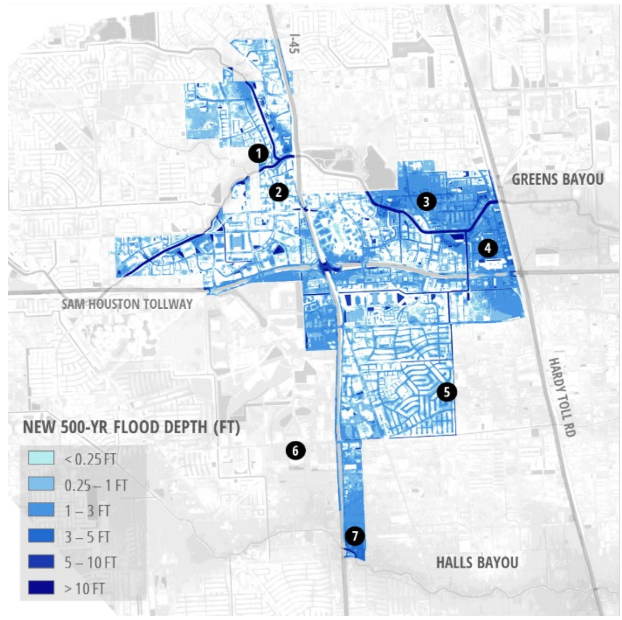


Figure 5: Modeled HEC-RAS 2D 100-yr and 500-yr flood inundation areas for Greater Greenspoint

Table 1: Simulated flood depths (ft) at selected watchpoints for Greater Greenspoint

Watchpoints	100-Yr Flood depth (ft)	500-Yr Flood depth (ft)
1	1.01	1.94
2	0.97	1.03
3	2.15	2.80
4	1.08	1.91
5	0.69	0.86
6	2.61	2.95
7	2.77	3.44

The flood hazard analysis showed that flood depths for the 100-year storm event ranged between 0.7 and 2.8 feet across the selected watchpoints, and 0.9 – 3.4 feet for the 500-year. The analysis also indicated that the Greater Greenspoint neighborhood is subject to fluvial flooding both from Greens Bayou at the northeastern edge of the neighborhood boundary between I-45 and the Hardy Toll Road, as well as from Halls Bayou at the southern tip along I-45. Meanwhile, the central portion of the neighborhood (i.e., south of the Sam Houston Tollway and west of I-45) is vulnerable from pluvial flooding. Moreover, it is likely that the flooding in these areas is exacerbated by backwater effects due to the presence of major highway or railroad bridges/embankments as floodwaters in both Greens and Halls Bayou are partially blocked as they flow eastward.

East Aldine

Below in **Figure 6** are the modeled 100-year and 500-year flood inundation areas that reflect the new rainfall published by NOAA (Atlas 14) focusing on East Aldine. The maps show the extent of the flood inundation areas as well as flood depths (in feet). **Table 2** lists the modeled 100-year and 500-year flood depths at several watchpoints within the neighborhood vicinity.

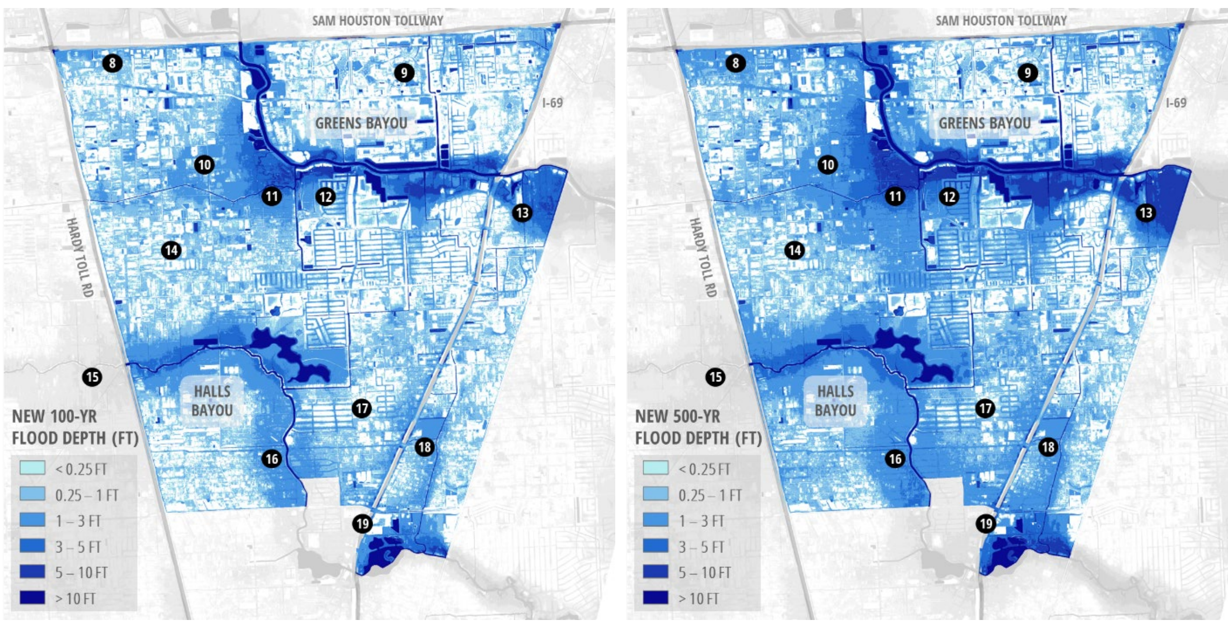


Figure 6: Modeled HEC-RAS 2D 100-yr and 500-yr flood inundation areas for East Aldine

Table 2: Simulated flood depths (ft) at selected watchpoints for East Aldine

Watchpoints	100-Yr Flood depth (ft)	500-Yr Flood depth (ft)
8	0.77	1.44
9	0.27	0.35
10	1.19	2.36
11	2.75	3.99
12	0.99	2.40
13	4.50	6.56
14	0.37	0.48
15	3.06	3.73
16	1.44	2.20
17	0.38	0.66
18	1.40	1.81
19	1.91	3.29

The flood hazard analysis indicated that, besides widespread shallow flooding (i.e., less than 1 ft), the East Aldine neighborhood is subject to overbank flooding from both Greens Bayou and Halls Bayou, with certain areas seeing flood depths by as much as 4.5 feet for the 100-year and 6.5 ft for the 500-year. The flood hazard analysis also identified a potential overflow region from Greens Bayou into Halls Bayou in the central portion of the neighborhood, east of Aldine Westfield Road. Additionally, it is likely that the flooding in these areas is exacerbated by backwater effects due to the presence of major highway bridges/embankments as floodwaters in both Greens and Halls Bayou flow eastward. The areas shown in dark blue coloring in Figure 6 reflect inundation of existing detention ponds along or adjacent to the bayous.

Eastex-Jensen

Below in **Figure 7** are the modeled 100-year and 500-year flood inundation areas that reflect the new rainfall published by NOAA (Atlas 14) focusing on Eastex Jensen. The maps show the extent of the flooded area as well as flood depths (in feet). **Table 3** lists the modeled 100-year and 500-year flood depths at several watchpoints within the neighborhood vicinity.

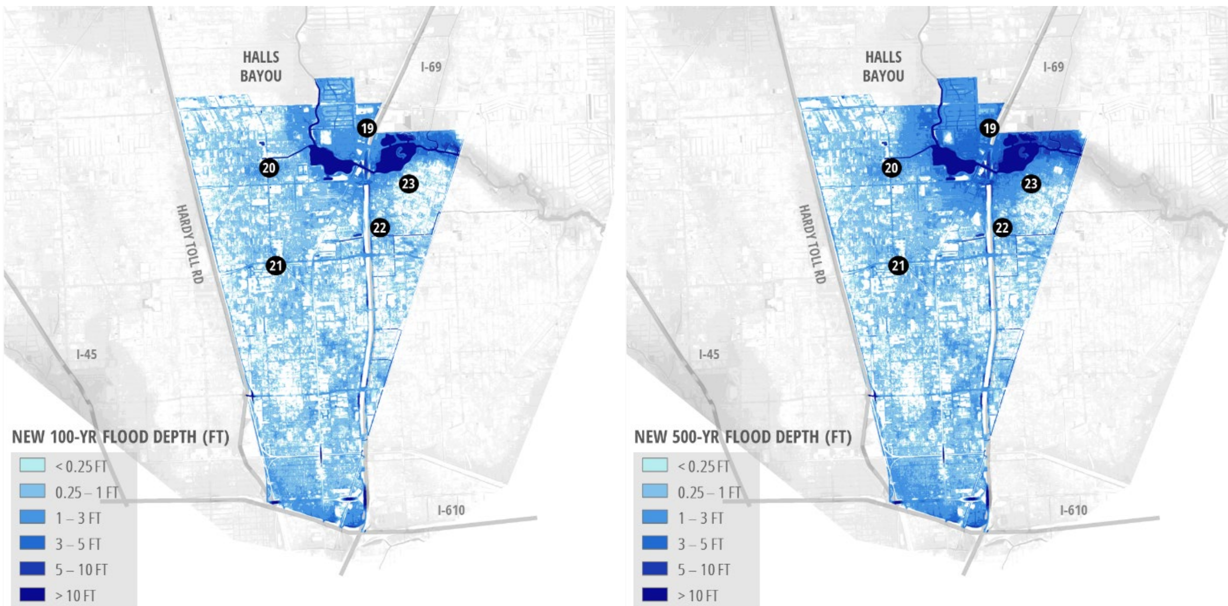


Figure 7: Modeled HEC-RAS 2D 100-yr and 500-yr flood inundation areas for Eastex Jensen

Table 3: Simulated flood depths (ft) at selected watchpoints for Eastex Jensen

Watchpoints	100-Yr Flood depth (ft)	500-Yr Flood depth (ft)
19	1.91	3.29
20	1.43	1.56
21	2.68	2.83
22	1.61	1.79
23	0.80	1.87

The flood hazard analysis showed that flood depths for the 100-year storm event ranged between 0.8 and 2.7 feet across the selected watchpoints, and 1.8 – 3.3 feet for the 500-year. Results showed that the majority of the neighborhood would experience shallow localized (pluvial) flooding, but also indicated that the Eastex Jensen neighborhood is susceptible to overbank flooding from Halls Bayou at the northern edge of the neighborhood. Additionally, it is likely that the flooding in these areas is exacerbated by backwater effects due to the presence of the I-69 bridge/embankment as floodwater attempts to flow southeastward.

East Houston

Below in **Figure 8** are the modeled 100-year and 500-year flood inundation areas that reflect the new rainfall published by NOAA (Atlas 14) focusing on East Houston. The maps show the extent of the flooded areas as well as flood depths (in feet). **Table 4** lists the modeled 100-year and 500-year flood depths at several watchpoints within the neighborhood vicinity.

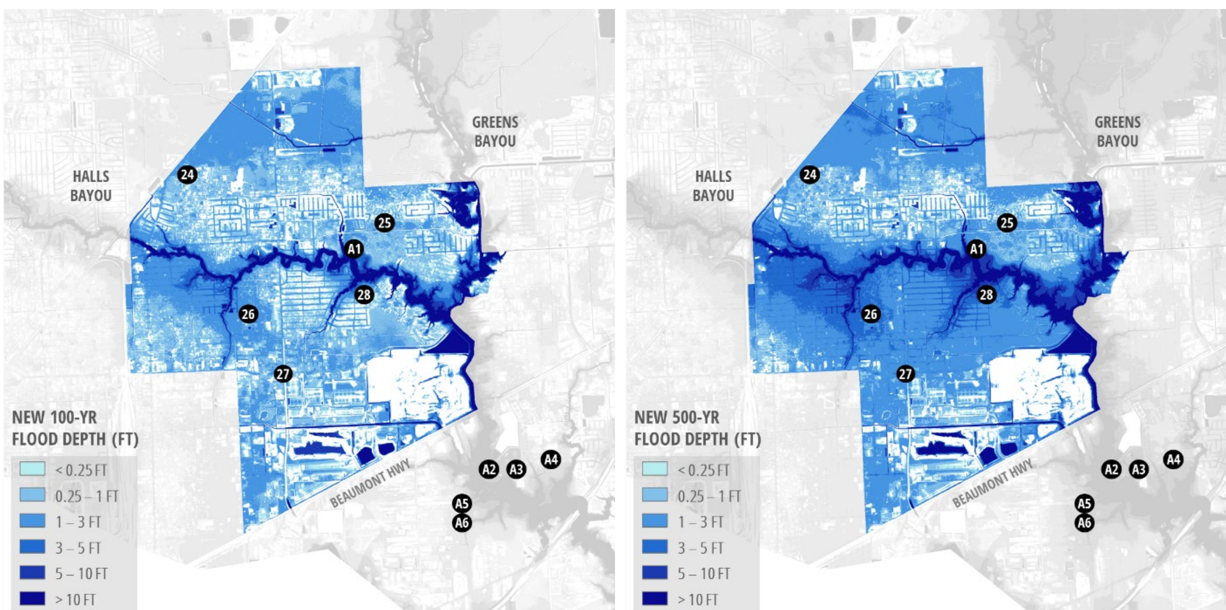


Figure 8: Modeled HEC-RAS 2D 100-yr and 500-yr flood inundation areas for East Houston

Table 4: Simulated flood depths (ft) at selected watchpoints for East Houston

Watchpoints	100-Yr Flood depth (ft)	500-Yr Flood depth (ft)
24	1.07	1.51
25	1.23	1.44
26	1.63	3.46
27	0.70	1.83
28	0.77	3.73
A1	3.76	6.74
A2	6.53	8.66
A3	3.69	5.84
A4	3.13	5.49
A5	3.29	5.45
A6	2.61	4.78

The flood hazard analysis showed that flood depths for the 100-year storm event ranged between 0.7 and 6.5 feet across the selected watchpoints in the vicinity of the neighborhood, and 1.4 – 8.7 feet for the 500-year. Results indicated that the East Houston neighborhood is subject to some overbank flooding from Halls Bayou that flows eastward through the middle of the neighborhood. Likewise, the eastern edge of East Houston is also slightly affected by overbank flooding from Greens Bayou and its confluence with Halls Bayou. Furthermore, East Houston is also plagued by pluvial flooding, as evidenced by inundation outside the riverine floodplain of Halls Bayou within the neighborhood boundary. This condition could be attributed to most of the neighborhood having lower ground surface elevations compared to upstream and/or surrounding drainage areas.

Evaluation of Flood Mitigation Options

The flood hazard analysis discussed above in this study shows that both Greens Bayou and Halls Bayou overtop their channel banks, indicating that these channels do not have sufficient capacity to contain the 100-year (and the 500-year) storm. Increasing capacity of these two bayous by channel widening is likely not economically feasible due to the presence of numerous bridges associated with major highways and a railroad, as well as existing developments along the bayou. Instead, these four neighborhoods should consider buyouts of frequently flooded properties and/or regional detention to increase flood storage, thereby reducing flood hazard within the neighborhood from overbank riverine (fluvial) flooding. Following is a more specific discussion of the results of various regional detention ponds that were investigated for their effectiveness in reducing the overbank flooding in these four neighborhoods, as shown in **Figure 9**.

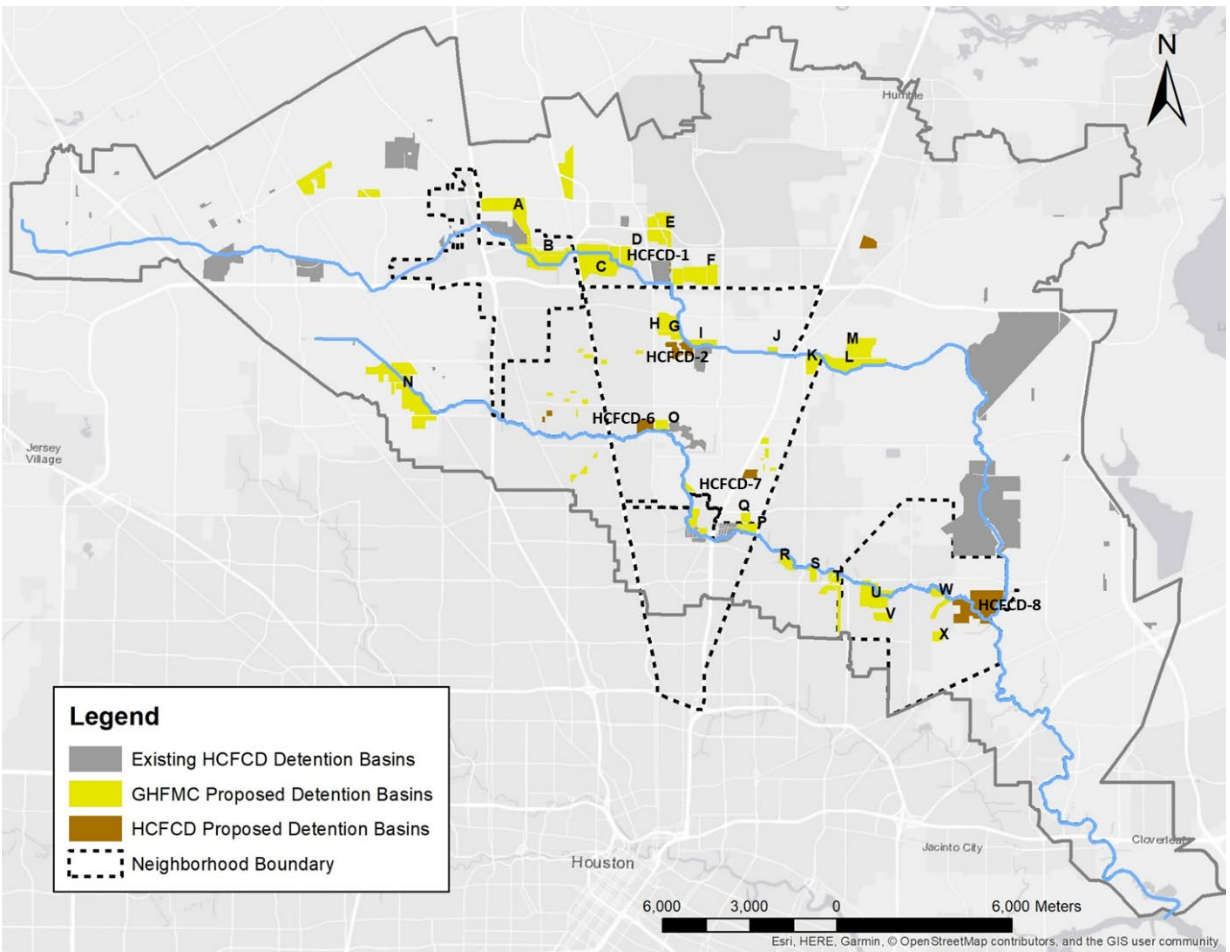


Figure 9. Existing and Proposed Detention Basins in the Greens Bayou Watershed

Greater Greenspoint

The lack of adequate flood storage currently existing along Greens Bayou to contain the flood flows in the Greater Greenspoint neighborhood led to investigating possible new sites for regional detention. Various locations upstream of the neighborhood were investigated for possible regional detention basins, but no sites were found to be suitable. However, some locations were identified as possible detention sites within the neighborhood, in particular at the northeastern edge of the neighborhood along Greens Bayou, which were analyzed in this study (see **Figure 10**). Figure 10 shows several GHFMC-proposed buyout/detention along with any existing and/or proposed HCFCD detention basins within the neighborhood vicinity. The GHFMC-proposed ponds range between 200 and 430 acres, and are assumed to have an average depth of 15 feet, with gravity outfall.

One option is to expand the recently completed Glen Forest detention basin[14] to augment current flood storage capacity in the upstream reaches of Greater Greenspoint. This would require buyouts in areas east and north of the current basin and converting them to new detention basins (Basins A and B in Figure 10). Also, Basin C could be constructed just downstream of this neighborhood, but would still provide some flood reduction benefits for areas within the neighborhood, such as at watchpoint 4. Finally, Basin N could be located upstream of this neighborhood along Halls Bayou, and would provide flood reduction at watchpoint 7 in this neighborhood. Besides at these individual watchpoints, these regional detention basins/ponds provide flood reductions along much of the bayou, thereby reducing the extent and depths of its floodplain. This is best illustrated by plotting the flood profile along the bayou for the 100-year and 500-year events, for both the existing condition as well as the proposed conditions.

[14] https://www.hcfcd.org/projects-studies/greens-bayou/glen-forest-stormwater-detention-basin/

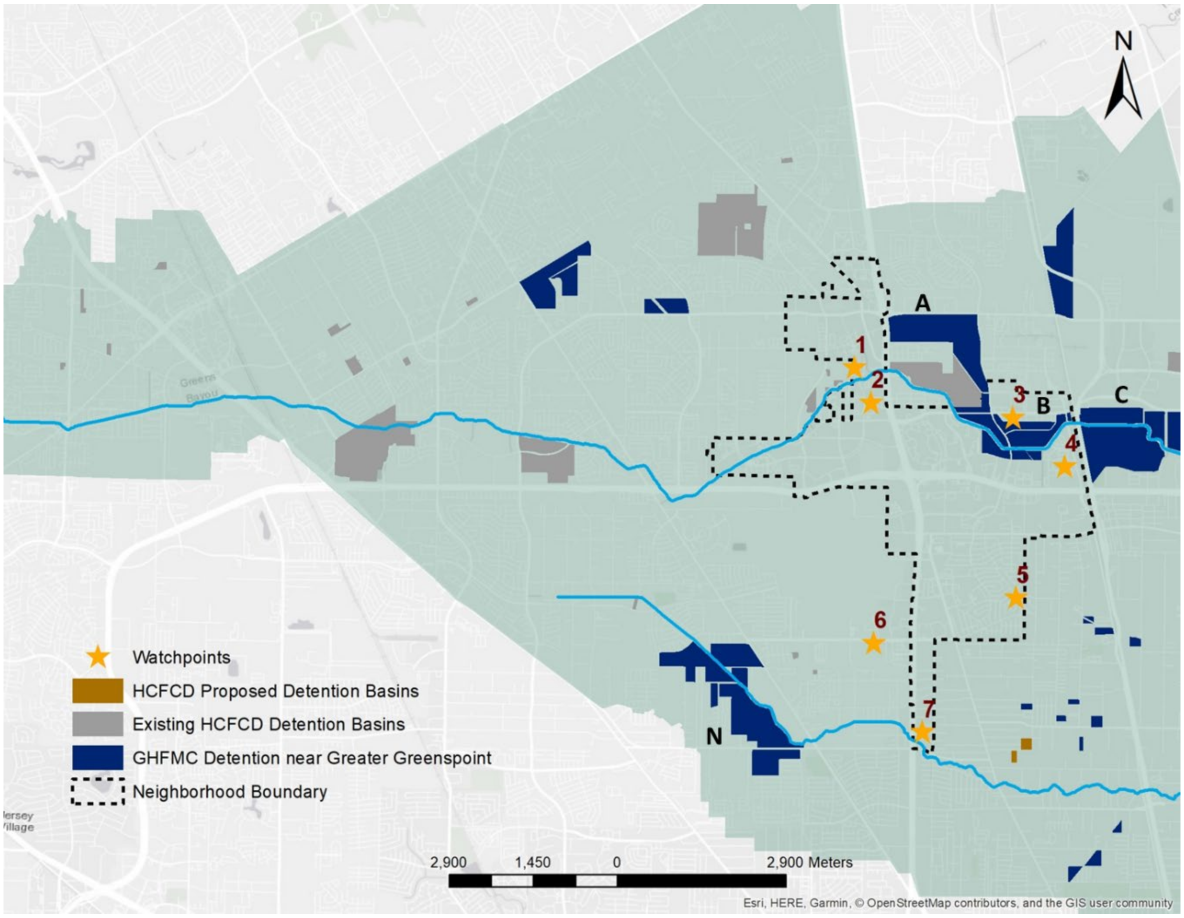


Figure 10: Existing and proposed detention basins with selected watchpoints in Greenspoint

Tables 5 and 6 summarize the 100-year and 500-year flood depth reduction (in feet) at the selected watchpoints for the various possible detention ponds (these tables only show detention ponds that reduce flooding by 0.1 feet or more from existing conditions). The results show that only watchpoints located downstream of the proposed basins and within the riverine floodplain would benefit from additional detention (e.g., 3, 4, and 7). Watchpoints far removed from the riverine floodplain would most likely see no benefit from the additional detention, as evidenced by watchpoints 5 and 6, as well as those watchpoints farther upstream from the detention being proposed, such as at watchpoints 1 and 2.

Watch Point Number	Change in Flood Depth (ft)						
	A (245 Acre)	B (202 Acre)	C (334 Acre)	N (429 Acre)	All HCFCD Detention	All GHFMC Detention	All Detention
1	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-
3	0.58	-	-	-	-	1.29	1.29
4	0.75	0.57	0.76	-	-	1.08	1.08
5	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-
7	-	-	-	0.54	-	0.54	0.54

Table 5: Modeled 100-yr flood depth reduction (more than or equal to 0.1 ft) at selected watchpoints

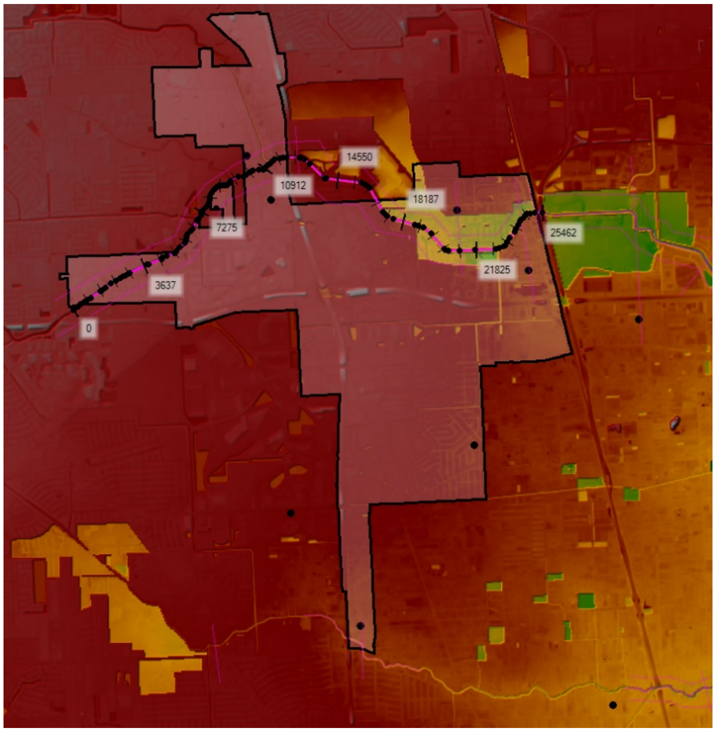
Watch Point Number	Change in Flood Depth (ft)						
	A (245 Acre)	B (202 Acre)	C (334 Acre)	N (429 Acre)	All HCFCD Detention	All GHFMC Detention	All Detention
1	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-
3	0.27	1.22	-	-	-	1.55	1.55
4	0.33	0.29	0.34	-	-	1.91	1.91
5	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-
7	-	-	-	0.54	-	0.54	0.54

Table 6: Modeled 500-yr flood depth reduction (more than or equal to 0.1 ft) at selected watchpoints

Appendix C contains flow hydrograph plots and channel cross-section plots comparing the 100- and 500-year events for Existing Conditions and with all of the proposed detention ponds at selected watchpoints, showing the reduction in peak flood flows and computed flood levels as a result of the proposed detention ponds.

Apart from watchpoints, flood profiles (water surface elevations) along the channel also show evidence of significant reductions from detention ponds. Flood profiles – one set each for Greens and Halls bayous - are presented in **Figures 11 and 12,** respectively. Profile lines follow the centerline of the bayou. As shown in Figure 11, the flood profiles for "Baseline" scenario (100-yr and 500-yr flood levels with only existing ponds and without any proposed detention ponds and the "All detention" scenario are the same in the upstream portion of the bayou where there is no detention pond located nearby (station – 0 to 12,000 feet). Farther downstream, the profiles start to show lower flood levels as they near detention ponds. While the watchpoints show a flood level reduction in the range of 0.25 feet – 1.91 feet, the water elevation in Greens Bayou actually drops by up to 7 feet. Flood profiles in Halls Bayou (Figure 12) show a uniform drop of about 0.5 feet in the profile of the "All detention" scenario compared to "Baseline". This reduction in water depth is the result of detention pond N on Halls Bayou, upstream of the neighborhoods. This effect of detention pond N on the downstream flood profile shows that detention ponds are very effective in reducing flooding throughout a region. While evaluating mitigation strategies for other neighborhoods we will see that detention pond N affects the flooding far downstream of the pond. Apart from flood profile lines, flow hydrographs downstream of the detention ponds also show a reduction in flow (Appendix C), representing a positive effect of the pond in reducing peak flood flows.

It is important to note that the detention ponds presented in this study are designed for controlling fluvial (riverine) and not pluvial (street) flooding. Locations for bigger ponds were found in northeast Greater Greenspoint near Greens Bayou; hence that portion of the neighborhood sees significant reduction in riverine flooding. Local flooding issues, however, still remain. Cross-section plots in Appendix C show any remaining flooding issues even with the detention basins in place.



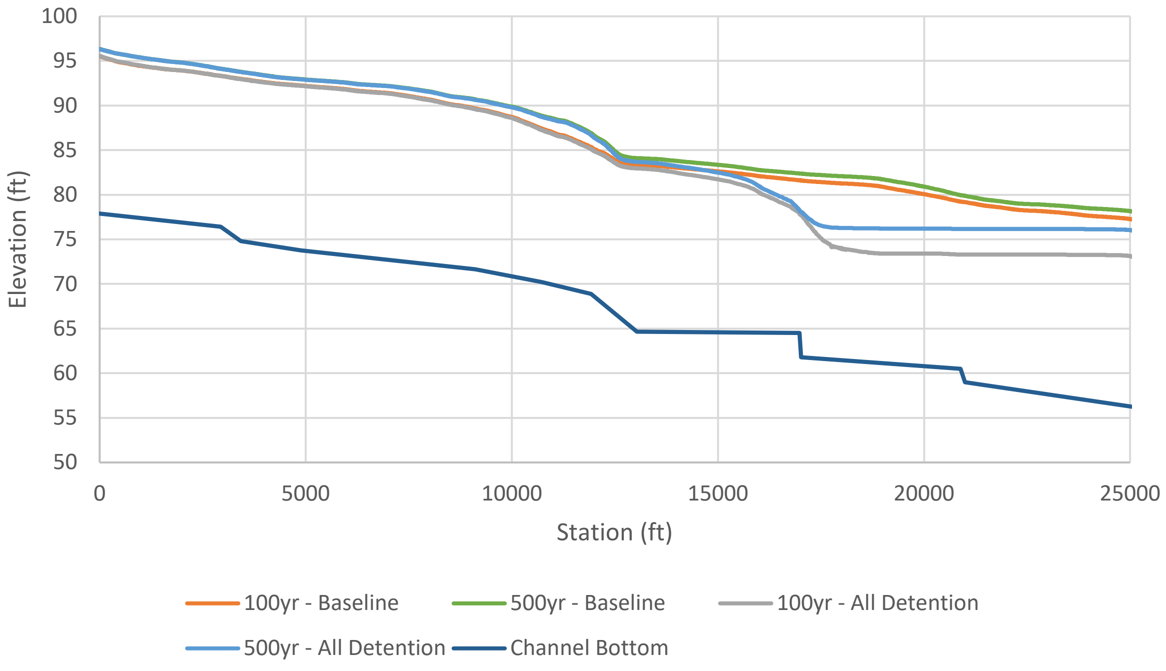
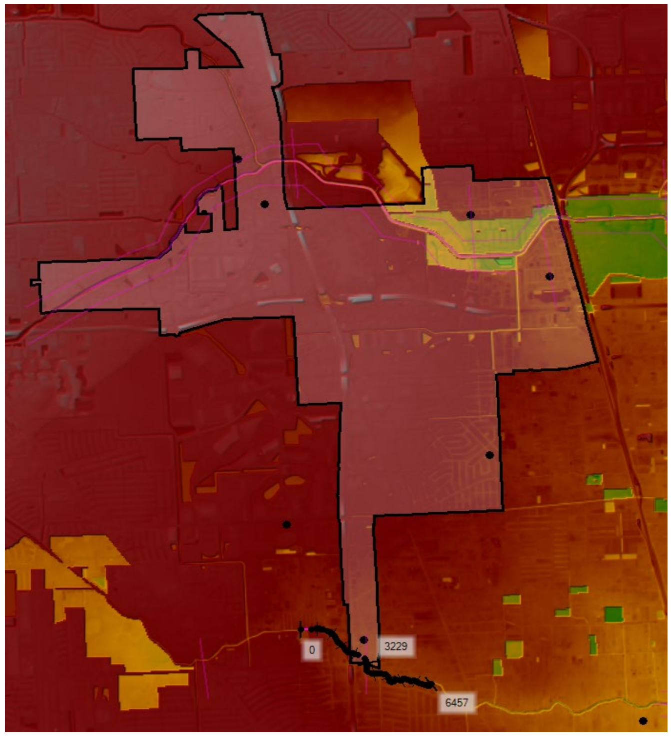


Figure 11: Flood Profiles for 100- and 500-year storm events along Greens Bayou for Existing Conditions (Baseline) and Proposed Conditions (All Detention) basins



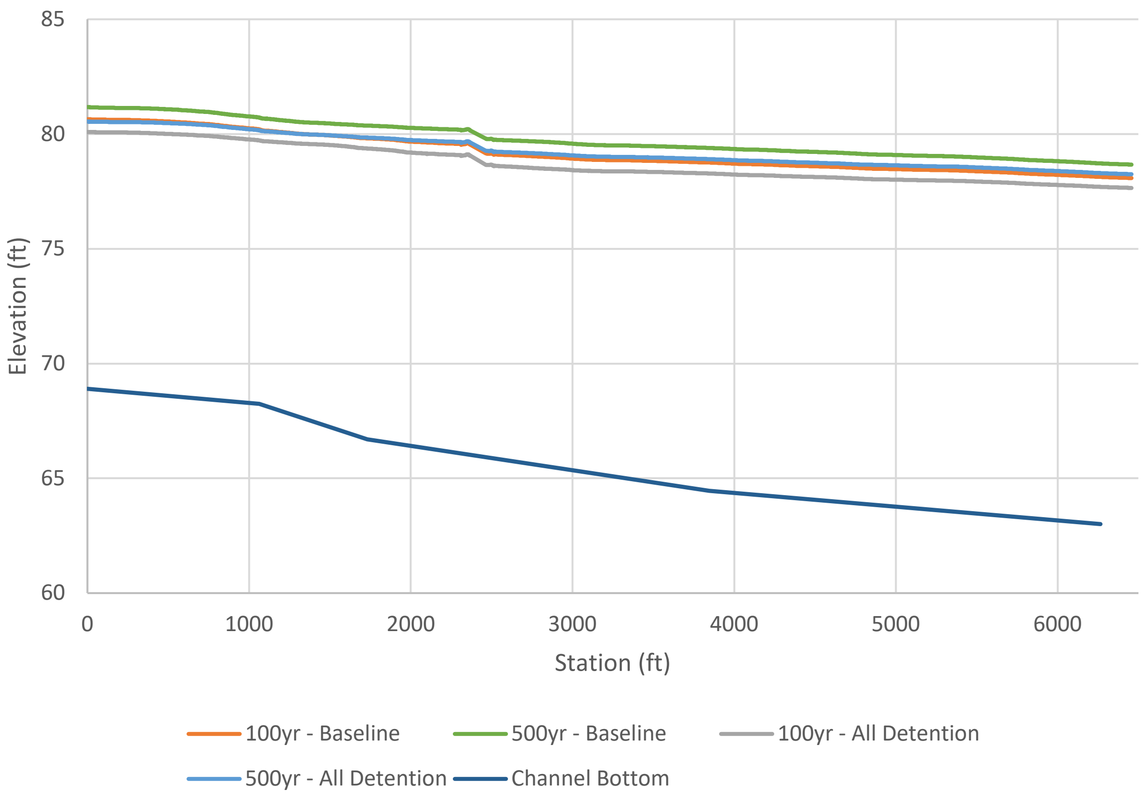


Figure 12: Flood Profiles for 100- and 500-year storm events along Halls Bayou for Existing Conditions and Proposed detention basins

East Aldine

The flood hazard analysis highlighted the shortage of existing flood storage within the neighborhood. Both Greens Bayou and Halls Bayou are shown to overtop their channel banks, indicating that these channels do not have sufficient capacity to contain the 100-year (and the 500-year) storm, despite the presence of detention ponds along both channels. To further increase flood storage capacity, additional buyouts and/or regional detention should be considered for the East Aldine neighborhood.

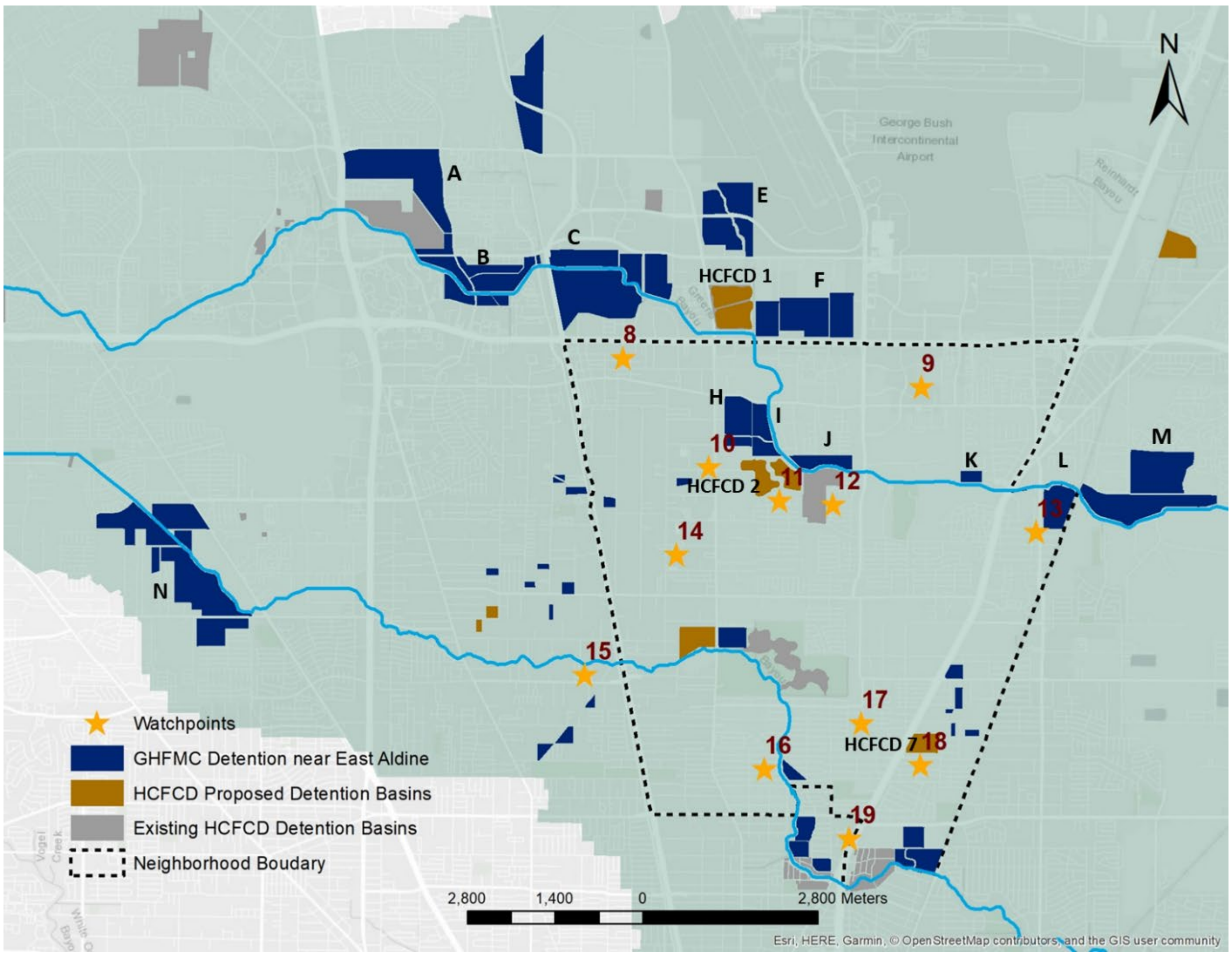


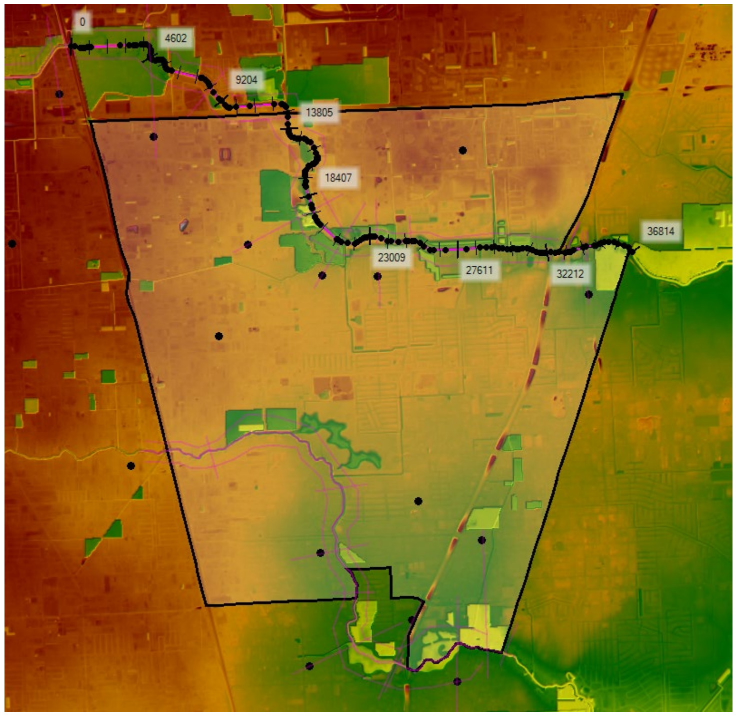
Figure 13: Existing and proposed detention basins with selected watchpoints in East Aldine

Figure 13 shows several GHFMC-proposed buyout/detention areas, along with any existing and/or proposed HCFCD detention basins, within the neighborhood vicinity. The GHFMC-proposed ponds range between 15 and 429 acres, and are assumed to have an average depth of

15 feet with gravity outfall. **Tables 7 and 8** summarize the 100-year and 500-year flood depth reduction (in feet) at the selected watchpoints based on the proposed detention basins. Based on the results, most of the flood depth reduction at the northern portion of East Aldine is produced by the larger ponds along Greens Bayou (e.g., A, B, C, E, and F). Pond N on Halls Bayou only benefits watchpoints 15 and 16 due to their proximity to the bayou. Other watchpoints that are relatively far from either Greens or Halls Bayou (e.g., watchpoints 9, 14, and 17) do not see any flood depth reduction, which indicates that the flooding at these locations are likely to be pluvial (local) rather than fluvial (riverine). To address the flooding issue at these locations, East Aldine should perhaps consider local storm drainage system improvements. Unfortunately, the potential benefit of this option is difficult to quantify, since the current modeling methodology in this study does not allow for the incorporation of underground storm sewer networks. Nevertheless, areas within the floodplains of both Greens and Halls Bayou would benefit from the additional detention basins being proposed.

Apart from watchpoints, flood profiles (water surface elevations) along the channel also show significant reduction caused by detention ponds along Greens Bayou. Flood profile lines – one each on Greens and Halls - are presented in **Figures 14 and 15**, respectively. The flood profiles on Greens reflect the reductions due to the GHFMC detention ponds A, B, C, E, F, H, I, J, K, L, as well as HCFCD proposed detention ponds HCFCD 1 and HCFCD 2. As shown in Figure 14, flood profiles for “All detention” scenarios are lower than “Baseline” scenarios (100-year and 500-year flood levels without any proposed detention ponds) throughout the neighborhood. “All detention” scenarios show more reduction for the stretch adjacent to the larger detention ponds (greater than 150 Acres). Moreover, these scenarios show flood reduction in the range of 0.26 feet - 4.44 feet at the watchpoints, but the water surface elevations in Greens Bayou actually drop by 6 – 14 feet. Flood profiles in Halls Bayou (Figure 15) show reductions up to 1 foot from “Baseline” for the “All detention” scenario. This reduction in water depth is the effect of detention ponds N and P on Halls Bayou. Detention pond N is not located within East Aldine, but it benefits the region because of its size and upstream location. Lower reductions in water levels are observed in Halls Bayou compared to Greens Bayou because detention ponds proposed near Halls are smaller in size: 14 – 51 acres. Apart from flood profiles, flow hydrographs downstream of detention ponds also show a reduction in peak flow (Appendix C), representing positive effects of the ponds.

It is important to note here that the detention ponds suggested by this study are designed for controlling the fluvial (riverine) and not pluvial (street) flooding. Good locations for bigger ponds were found for East Aldine near Greens Bayou and hence that portion of the neighborhood sees significant reduction in riverine flooding. But local flooding issues still remain. Cross-section profiles through watchpoints 8, 10 and 12 reflect this, as shown in Appendix C.



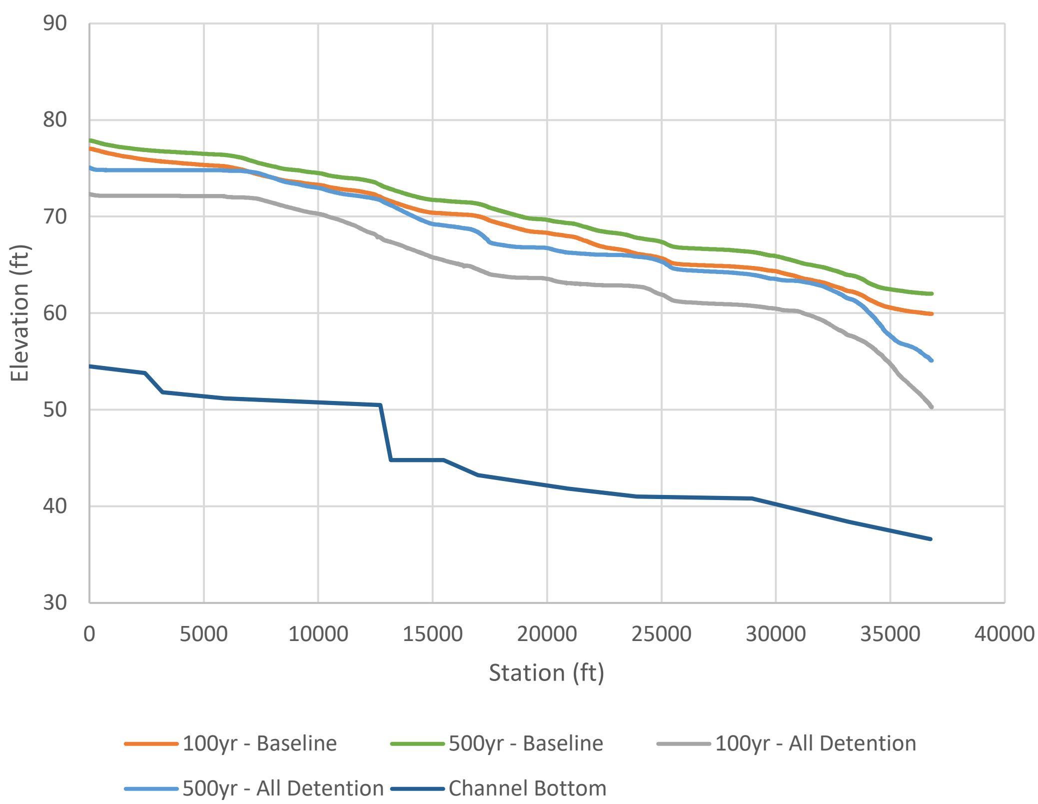


Figure 14: Flood Profiles for 100- and 500-year storm events along Greens Bayou for Existing Conditions and Proposed detention basins in East Aldine

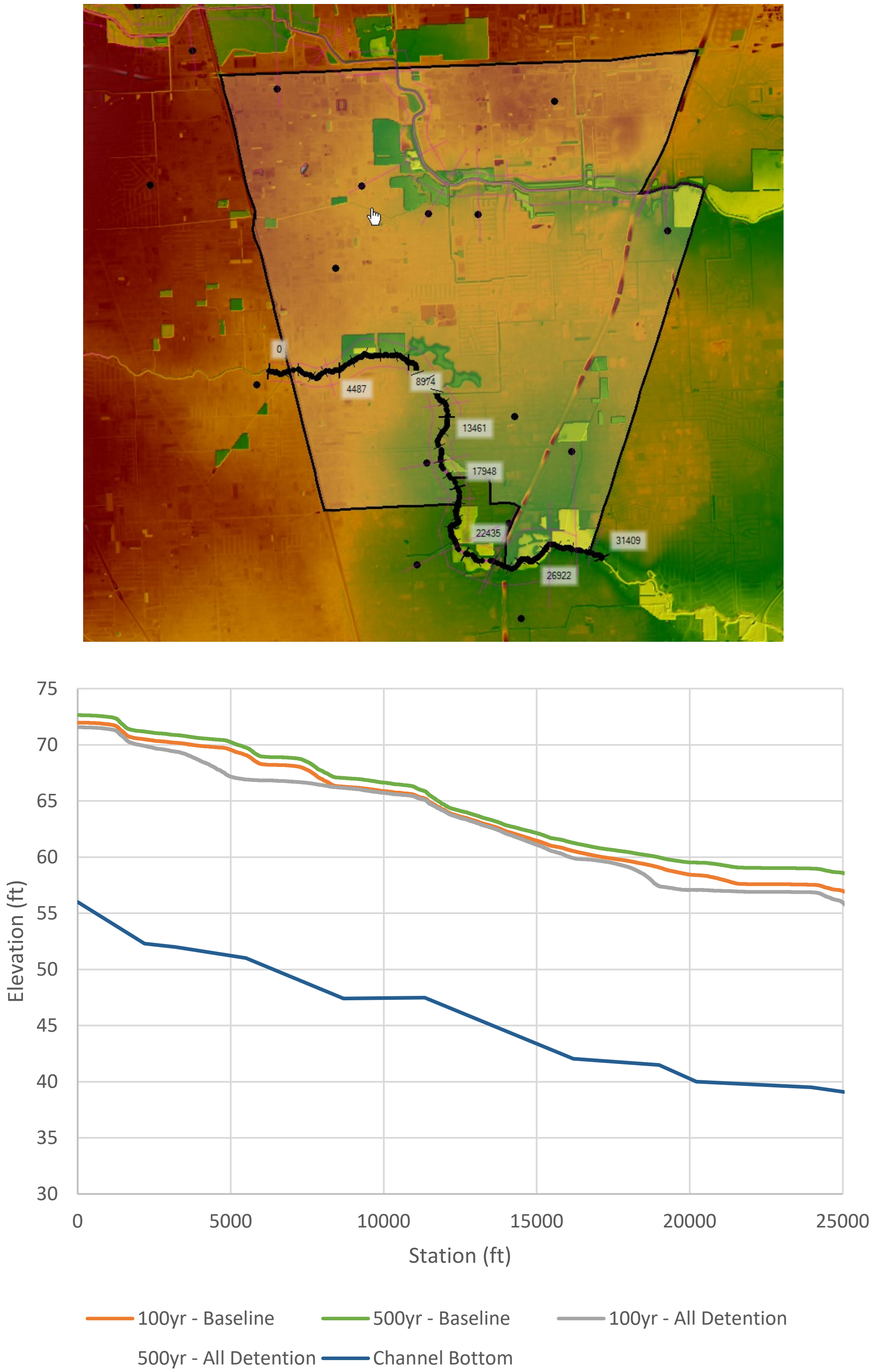


Figure 15: Flood Profiles for 100- and 500-year storm events along Halls Bayou for Existing Conditions and Proposed detention basins in East Aldine

Table 7: Modeled 100-yr flood depth reduction (more than or equal to 0.1 ft) at selected watchpoints in East Aldine

Watch Point Number	Change in Flood Depth (ft)																	
	A (245 Acre)	B (202 Acre)	C (334 Acre)	E (180 Acre)	F (226 Acre)	H (58 Acre)	I (41 Acre)	J (15 Acre)	K (67 Acre)	L (157 Acre)	M (149 Acre)	N (429 Acre)	P (51 Acre)	HCFCD 1 (93 Acre)	HCFCD 7 (35 Acre)	All HCFCD Detention	All GHFMC	All Detention
8	0.23	0.26	0.26	-	-	-	-	-	-	-	-	-	-	-	-	-	0.26	0.26
9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
11	0.22	0.23	0.78	0.35	0.28	0.11	0.11	-	-	-	-	-	-	0.11	-	0.21	1.83	2.16
12	0.26	0.29	0.94	0.44	0.39	0.12	0.12	0.10	-	-	-	-	-	0.14	-	0.12	0.99	0.99
13	0.24	0.29	0.85	0.36	0.43	0.11	0.11	-	0.21	1.70	0.20	-	-	0.19	-	0.27	2.72	2.73
14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-	-	0.30	-	-	-	-	0.37	0.41
16	-	-	-	-	-	-	-	-	-	-	-	0.22	-	-	-	-	0.44	0.49
17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.20	0.22	0.37	0.65
19	-	-	-	-	-	-	-	-	-	-	-	0.31	0.19	-	-	0.10	0.62	0.65

Table 8: Modeled 500-yr flood depth reduction (more than or equal to 0.1 ft) at selected watchpoints in East Aldine

Watch Point Number	Change in Flood Depth (ft)															
	A (245 Acre)	B (202 Acre)	C (334 Acre)	E (180 Acre)	F (226 Acre)	H (58 Acre)	I (41 Acre)	K (67 Acre)	L (157 Acre)	M (149 Acre)	N (429 Acre)	P (51 Acre)	HCFCD 2 (76 Acre)	All HCFCD Detention	All GHFMC	All Detention
8	0.24	0.10	0.44	-	-	-	-	-	-	-	-	-	-	-	0.77	0.77
9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	0.29	-	0.30	0.21	0.10	0.17	0.43	-	-	-	-	-	0.24	0.27	0.61	0.44
11	0.24	-	0.25	0.19	-	0.14	0.60	-	-	-	-	-	-	-	2.29	2.64
12	0.25	-	0.27	0.20	0.10	0.15	0.18	-	-	-	-	-	-	-	2.08	2.24
13	0.24	0.12	0.40	0.26	0.20	0.17	-	0.18	2.00	0.26	-	-	-	0.11	4.43	4.44
14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-	0.27	-		-	0.31	0.36
16	-	-	-	-	-	-	-	-	-	-	0.26	-	-	-	0.51	0.61
17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.12	-
18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.20	0.34
19	-	-	-	-	-	-	-	-	-	-	0.39	0.29	-	-	0.93	1.00

Eastex-Jensen

Based on the flood hazard analysis, Halls Bayou is shown to overtop its banks, indicating that the channel does not have sufficient capacity to contain the 100-year (and the 500-year) storm, despite the presence of existing HCFCD detention ponds along the channel. To further increase flood storage capacity, selective buyouts and/or regional detention basins should be considered for the Eastex Jensen neighborhood.

Figure 16 shows several GHFMC-proposed buyout/detention sites along with any existing and/or proposed HCFCD detention basins within the neighborhood vicinity. Since the neighborhood is mostly developed, there is a lack of land availability for large detention basins. As such, within the neighborhood, only a relatively small-sized pond (i.e., pond P) was modeled. All modeled GHFMC-proposed ponds assume an average depth of 15 feet with gravity outfall. **Tables 9 and 10** summarize the 100-year and 500-year flood depth reduction (in feet) at the selected watchpoints. As expected, pond P has a relatively minor effect in reducing 100-year and 500-year flood depths for the nearest watchpoints (i.e., 19 and 23). Interestingly, pond N, which is located in the far western upstream portion of Halls Bayou outside of the neighborhood, is able to more substantially reduce the flood depth at the same watchpoint due to its much larger storage capacity. Apart from watchpoint 19, the other selected watchpoints throughout Eastex Jensen show no flood depth reduction across all modeled detention scenarios. These results are further evidence that much of the flooding in Eastex Jensen is likely pluvial (local) rather than fluvial (riverine). To address this issue, Eastex Jensen should perhaps consider local storm drainage system improvements. Unfortunately, the potential benefit of this option is difficult to quantify, since the current modeling methodology employed in this study does not allow for the incorporation of underground drainage networks.

Apart from watchpoints, flood profiles (water surface elevations) along Halls Bayou also provide evidence of the impact of detention basins on fluvial flooding. Profiles along Halls (**Figure 17**) show the results of the GHFMC detention ponds O, P and Q as well as HCFCD proposed detention pond HCFCD 6. As per Figure 17, the profiles of “All detention” scenarios show up to a 1 foot drop compared to the “Baseline” (100-yr and 500-yr flood level without any proposed detention ponds) throughout the neighborhood. “All detention” scenarios show more drop along the stretches where detention ponds are located. As mentioned earlier, detention ponds N and P on Halls Bayou are the only ponds in the area affecting flooding in Eastex/Jensen.

Again, it must be noted that the suggested detention ponds are designed to control the fluvial (riverine) and not pluvial (street) flooding. Cross-section plot through watchpoint 23 sees significant reduction in riverine flooding, but local flooding is still present (notice water stored in small pockets). At other watchpoints, riverine flooding is not completely removed, and water level is observed further above the small pockets.

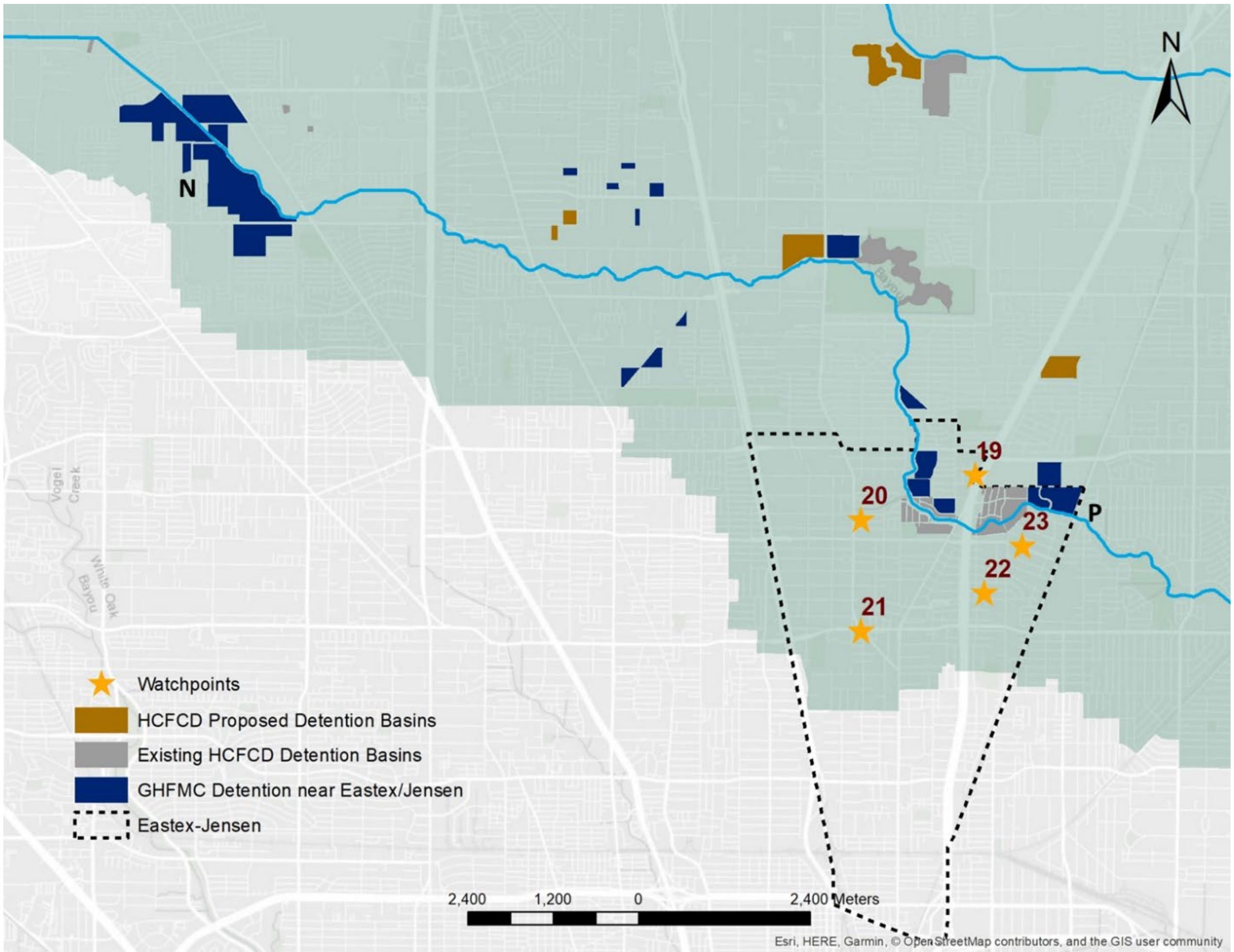


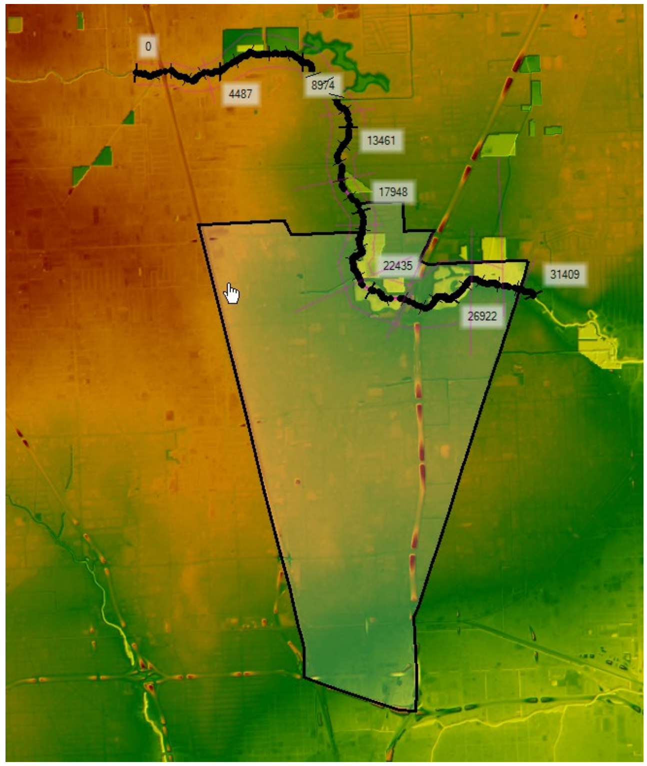
Figure 16: Existing and proposed detention basins with selected watchpoints in Eastex Jensen

Table 9: Modeled 100-yr flood depth reduction at selected watchpoints in Eastex Jensen

Watch Point Number	Change in Flood Depth (ft)				
	N (429 Acre)	P (51 Acre)	All HCFCD Detention	All GHFMC Detention	All Detention
19	0.31	0.19	0.10	0.62	0.65
20	-	-	-	-	-
21	-	-	-	-	-
22	-	-	-	-	-
23	-	-	-	-	-

Table 10: Modeled 500-yr flood depth reduction at selected watchpoints in Eastex Jensen

Watch Point Number	Change in Flood Depth (ft)				
	N (429 Acre)	P (51 Acre)	All HCFCD Detention	All GHFMC Detention	All Detention
19	0.39	0.29	-	0.93	1.00
20	-	-	-	-	-
21	-	-	-	-	-
22	-	-	-	-	-
23	0.35	0.55	-	0.99	0.99



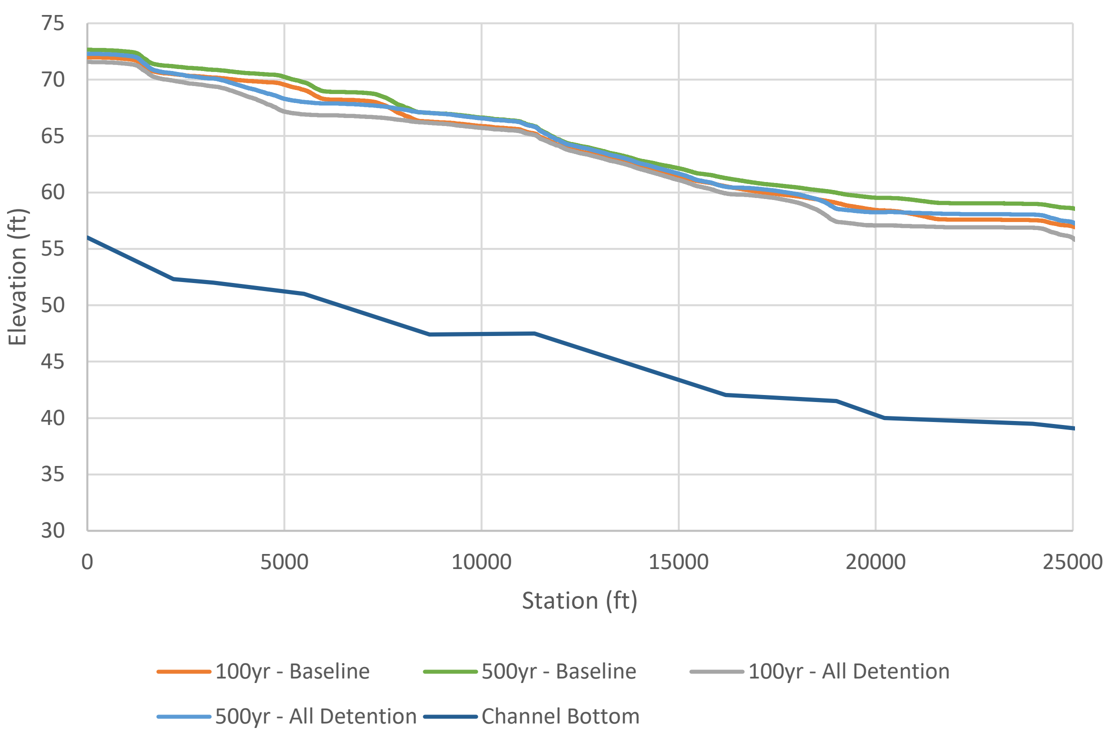


Figure 17: Flood Profiles for 100- and 500-year storm events along Halls Bayou for Existing Conditions and Proposed detention basins in Eastex Jensen

East Houston

The flood hazard analysis showed that Halls Bayou overtops the channel bank, indicating that this channel has insufficient capacity to contain the 100-year (and the 500-year) storm. To further increase flood storage capacity, additional selected buyouts and/or regional detention should be considered for the East Houston neighborhood.

Figure 18 shows GHFMC-proposed buyout/detention along with any existing and/or proposed HCFCD detention basins within the neighborhood vicinity. The GHFMC-proposed ponds range between 72 and 334 acres, and are assumed to have an average depth of 15 feet with gravity outfall. **Tables 12 and 13** summarize the 100-year and 500-year flood depth reduction (in feet) at the selected watchpoints. Based on the results, most of the flood depth reduction in East Houston is produced by the larger ponds proposed for the neighborhood along Halls Bayou (e.g., T, U and W). Ponds T, U, and W on Halls Bayou only benefit watchpoints 26, 28 and A1 due to their proximity to the channel. Other watchpoints that are relatively far from either Greens or Halls Bayou (e.g., watchpoints 24, 25 and 27) do not see any flood depth reduction, which indicates that the flooding at these locations are likely to be pluvial (local) rather than fluvial (riverine). In addition, as one moves downstream beyond the confluence of Greens and Halls Bayou, several watchpoints outside of the neighborhood boundary (watchpoints A2 – A6) saw moderate reduction in flood depths. These watchpoints are located within the wider existing riverine floodplain, and thus benefit from the reduction in floodplain and flood depths due to the proposed detention scenarios. To address the pluvial flooding issue within East Houston, the neighborhood should perhaps consider local storm drainage system improvements. Unfortunately, the potential benefit of this option is difficult to quantify, since the current modeling methodology utilized in this study does not allow for the incorporation of underground drainage networks.

Additionally, flood profiles (water surface elevations) along Halls Bayou provide more insight regarding the impact of detention basins on fluvial flooding. Profiles along Halls (**Figure 19**) show the impacts of the GHFMC detention ponds R, S, T, U, and W and HCFCD proposed detention pond HCFCD 8. Detention pond V is not located right adjacent to the bayou but it is an inline detention on the tributary flowing to Halls Bayou. Pond X is located further away from the bayou and it mainly intercepts overland flow before it reaches the bayou. The profile of “All detention” scenarios show 1 foot to 6 feet drop compared to the “Baseline” (100-year and 500-year flood level without any proposed detention ponds). Moreover, “All detention” scenarios show a sudden drop near station 14,000 feet because of the large detention pond U (194 Acres in area). Here it should be noted that detention ponds U and W are inline detention basins. In addition to the profiles, flow hydrographs downstream of the detention ponds also reflect the effects of detention on flooding (Appendix C).

Importantly, suggested detention ponds are designed to control the fluvial (riverine) and not pluvial (street) flooding. Cross-section plots through watchpoints 27 and 28 show significant reduction in riverine flooding, but local flooding is still present (notice water stored in small pockets which represent streets or other depressions). At watchpoint 26, riverine flooding is not completely removed, and water is observed further above the small pockets.

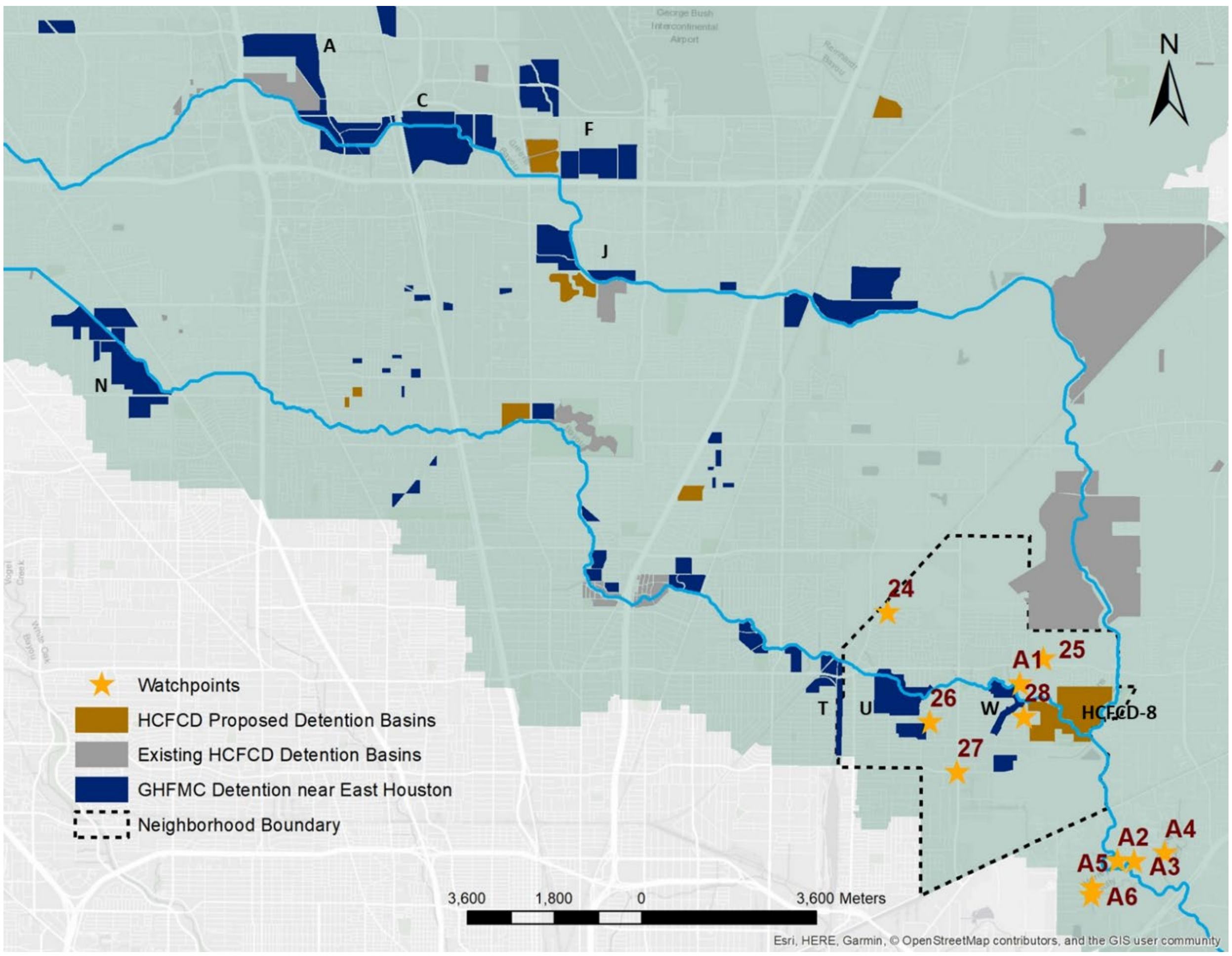


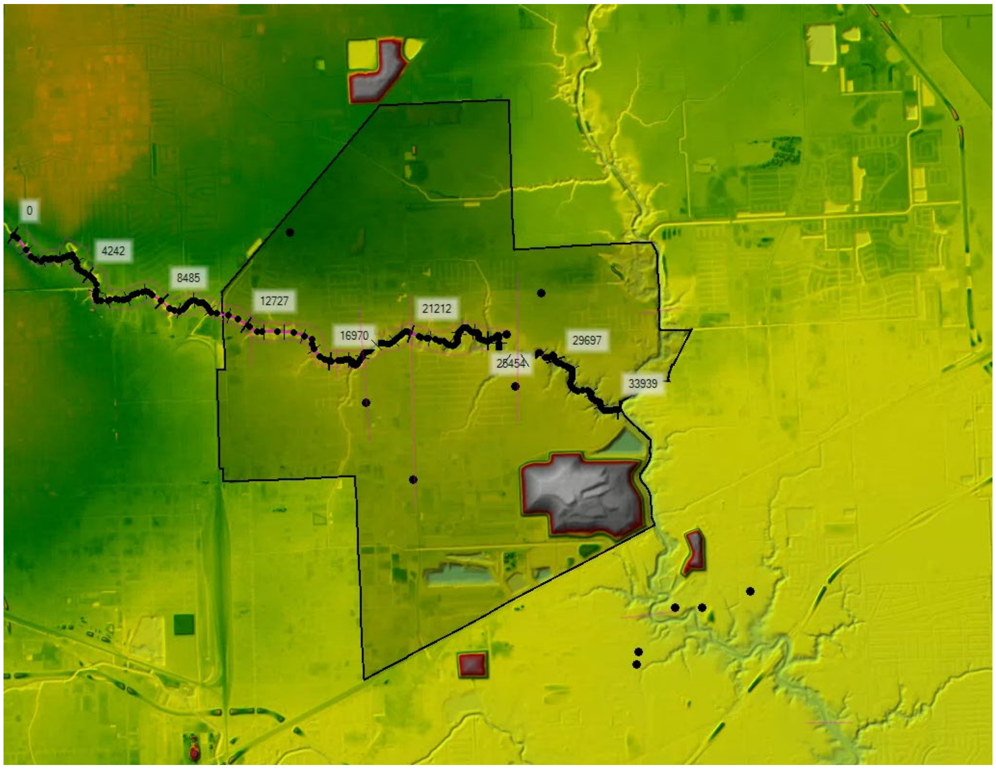
Figure 18: Existing and proposed detention basins with selected watchpoints in East Houston

Table 12: Modeled 100-yr flood depth reduction at selected watchpoints in East Houston

Watch Point Number	Change in Flood Depth (ft)								
	C (334 Acre)	F (226 Acre)	T (106 Acre)	U (194 Acre)	W (72 Acre)	HCFCD_8 (316 Acre)	All HCFCD Detention	All GHFMC Detention	All Detention
24	-	-	-	-	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-
26	-	-	0.20	0.52	0.28	0.31	0.67	1.28	1.28
27	-	-	-	-	-	-	-	-	-
28	-	-	0.13	0.10	-	0.17	0.18	0.18	0.16
A1	0.14	0.11	0.22	0.15	0.16	0.90	1.19	2.29	2.42
A2	0.17	0.12	0.11	0.13	-	0.19	0.43	1.73	2.39
A3	0.17	0.12	0.11	0.13	-	0.20	0.44	1.72	2.37
A4	0.20	0.13	0.13	0.15	-	0.23	0.50	1.91	2.29
A5	0.18	0.12	0.11	0.14	-	0.20	0.44	1.75	2.27
A6	0.18	0.12	0.12	0.14	-	0.21	0.46	1.91	1.94

Table 13: Modeled 500-yr flood depth reduction at selected watchpoints in East Houston

Watch Point Number	Change in Flood Depth (ft)								
	A (245 Acre)	C (334 Acre)	N (429 Acre)	U (194 Acre)	W (72 Acre)	HCFCD_8 (316 Acre)	All HCFCD Detention	All GHFMC Detention	All Detention
24	-	-	-	-	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-
26	-	-	0.24	0.17	0.11	0.18	0.33	1.09	1.66
27	-	-	0.19	0.18	0.11	0.18	0.29	0.67	0.87
28	0.10	0.10	0.33	-	-	1.11	1.27	1.19	2.48
A1	0.10	0.10	0.32	-	-	1.03	1.21	1.21	2.51
A2	0.11	0.11	0.15	-	-	-	0.13	0.78	1.04
A3	0.10	0.10	0.14	-	-	-	0.13	0.78	1.03
A4	0.11	0.11	0.15	-	-	-	0.13	0.82	1.09
A5	0.10	0.10	0.14	-	-	-	0.13	0.78	1.03
A6	0.10	0.10	0.14	-	-	-	0.13	0.76	1.01



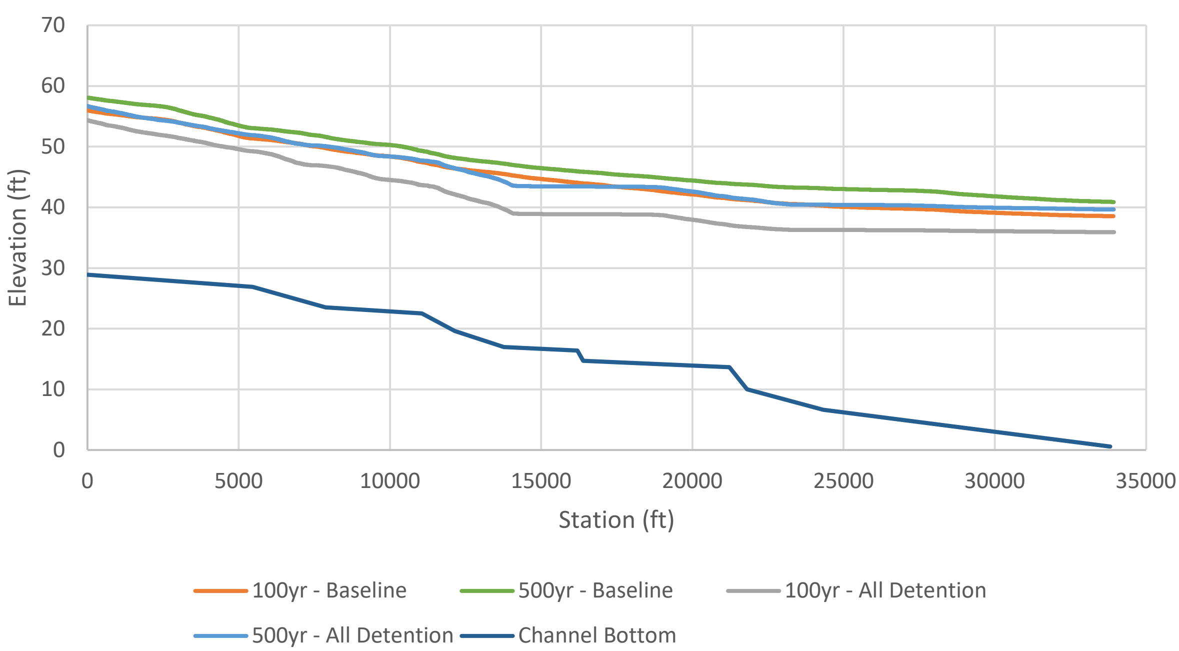


Figure 19: Flood Profiles for 100- and 500-year storm events along Halls Bayou for Existing Conditions and Proposed detention basins in East Houston

Study Model Limitations and Recommendations

This study primarily uses HEC-RAS 2D for all flood hazard and flood mitigation modeling analyses. Despite its capabilities, the current version of HEC-RAS 2D has a few limitations that should be noted. First of all, the model does not allow for rainfall losses to be computed, such as infiltration loss. This means that the rainfall inputted onto the entire model domain is assumed to become runoff, with no loss. A possible solution is to apply estimated infiltration as an abstraction to the inputted precipitation (i.e., using net rainfall as the input) for the entire model domain. This method is not ideal however, due to a different constraint within HEC-RAS 2D, which is its inability to apply spatially-distributed rainfall within a single model domain mesh. This limitation would not necessarily pose a problem if the study area (model domain) were relatively small, or if the study objective were to only examine the effects of hypothetical design storm scenarios. Otherwise, several options to account for this limitation could be considered, including using multiple meshes with each having its own hyetograph, area-weighting or averaging available rain gauges surrounding the model domain (but problems exist at the mesh boundaries), or simply choosing a single rain gauge that best represents the rainfall condition for the model domain, which is what was done for this study for model validation using Harvey rainfall.

Furthermore, while the flood hazard analysis performed in this study identified both fluvial (riverine) and pluvial (local) flooding as flood drivers throughout the Greens Bayou watershed, the flood mitigation assessment in this study was only focused on addressing riverine flooding. This decision was primarily influenced by another shortcoming of HEC-RAS 2D, which only allows for a select few options to represent flood control structures within the model domain, such as weirs/embankments, gates, and culverts. Evaluating mitigation options to alleviate pluvial flooding requires accurate representation of the local storm sewer/drainage network, a feat that is currently impossible in HEC-RAS 2D. The results presented in this report, however, could serve as valuable inputs in current and future studies conducted by multiple stakeholders. Governmental agencies such as the City of Houston and the Texas Department of Transportation (TX-DOT) could use the identified local flooding hotspots to help prioritize storm sewer repair, street/roadway retrofit, and other drainage improvement projects. The same information could also aid private stakeholders (e.g., residents and developers) to consider implementing their own mitigation strategy, such as raising property/building elevations, flood-proofing, and adding flood storage features (e.g., rain garden, green roof, rainwater-harvesting system).

Lastly, HEC-RAS 2D's inability to model complex structures (e.g. bridges with piers) also limits the number of options that could be modeled to mitigate riverine flooding. Modeling the impacts of common strategies such as bridge modifications and channelization (channel widening and/or deepening) would be extremely difficult if not impossible unless certain concessions were made. For this reason, these mitigation strategies are usually modeled in HEC-RAS 1D, which has specific tools to allow its user to more accurately represent these type of structures. Future work should consider using both 1D and 2D approaches, or a hybrid 1D/2D modeling framework to evaluate a more comprehensive set of strategies to mitigate riverine flooding.

Conclusions

This study was intended to help identify flooding issues throughout the Greens Bayou watershed, and in particular, at four specific neighborhoods: Greater Greenspoint, East Aldine, Eastex Jensen, and East Houston, as well as possible solutions. A two-dimensional hydraulic model (HEC-RAS 2D) was primarily used to conduct the flood hazard analyses to assist in this effort. Once the model was set up and validated using the Harvey storm of 2017, the 2D model was run for the new (Atlas 14) 100- and 500-year storm events. The resulting inundation was shown throughout these neighborhoods, indicating that there was both riverine/bayou (fluvial) overbank flooding and local drainage (pluvial) flooding impacting these neighborhoods.

There are different types of solutions to the flooding problems in these neighborhoods, and are dependent upon the type of flooding to be addressed. For example, riverine (fluvial) flooding issues are typically addressed either by channel widening or regional detention; whereas local (pluvial) flooding issues are typically addressed by local drainage improvements (e.g. enlarging storm sewers or installing local detention ponds). For this study, only the riverine flooding issues were being addressed, and only regional detention basins were investigated and analyzed.

The results of the flood mitigation analyses showed that regional detention basins provided a significant reduction in the extent and depth of the 100- and 500-year floodplains along Greens Bayou and Halls Bayou within these four neighborhoods. Additional work is needed to optimize the size and number of detention basins that would be appropriate for providing significant flood reduction/mitigation in each of these neighborhoods, as well as to address their local drainage flooding issues.