

CITY OF FRIENDSWOOD FLOOD VULNERABILITY AND MITIGATION STUDY

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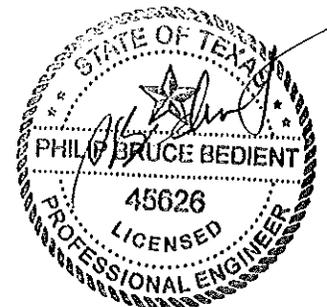


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EXECUTIVE SUMMARY

This study evaluates the existing flood vulnerability of the City of Friendswood, TX in the context of Hurricane Harvey (2017) and the 100-yr storms (HCFCD and NOAA ATLAS 14 - 2018 depths). A distributed hydrologic model (Vflo®) was used to simulate watershed response (i.e., stormwater runoff) for the various storms. Peak discharges were exported into a 1D steady-state hydraulic model, HEC-RAS, to compute water surface elevations throughout the main channel, Clear Creek. These results were then used to generate floodplain maps focusing on the City of Friendswood. The baseline models representing existing conditions of the watershed were validated against available stream gages and high water marks for Harvey.

Next, the study investigates various mitigation options to address the city's flooding problem: bridge removal, de-snagging, grass terracing, diversion and detention. Among the five individual mitigation scenarios, the Terracing II option from Dixie Farm Rd to I45 provides the most flood reduction benefit, with an estimated peak water surface elevation reduction in the range of ~3-6 ft within Friendswood for the new (NOAA ATLAS 14) 100-yr storm. However, it is important to note that there are limitations to the modeling method which make it difficult to capture the altered hydrodynamics and conveyance of mitigation options such as de-snagging and terracing. As a result, there remains uncertainty in the downstream impacts of the mitigation strategies which require physical modifications to large stretches of the main channel. In addition to the standalone mitigation scenarios, the impacts of selected combination scenarios were assessed. The scenario with terracing performed from Dixie Farm Rd to I45 combined with 50% flow diversion at Bay Area Blvd showed the most flood reduction of all the scenarios analyzed. However, the caveats regarding modeling limitations apply in this scenario as well.

I. PROJECT OBJECTIVES

The main objectives of this project are twofold: (1) perform a flood vulnerability analysis at the City of Friendswood in the context of Hurricane Harvey (August 2017), the existing 100-yr (HCFCD), and the new 100-yr (NOAA Atlas 14 – 2018) storms; and (2) evaluate the effectiveness of various flood mitigation options proposed by the City of Friendswood.

1. Flood Vulnerability Analysis

This task is accomplished by developing a distributed hydrologic model (Vflo®) and using a 1D steady-state hydraulic model (HEC-RAS), focusing on the City of Friendswood. Modeled results for Hurricane Harvey are validated against available observed data (i.e., USGS or HCFCD stream gages and official high water marks). In addition, the City's flood vulnerability under the existing and new 100-yr 24-hr storms are also evaluated. The three models serve as baseline for subsequent flood mitigation analysis.

2. Assessment of Flood Mitigation Scenarios

The effectiveness of the following mitigation options are compared against the baseline scenarios:

- Bridge removal
- Bank de-snagging
- Terracing
 - I: Dixie Farm Rd to Bay Area Blvd
 - II: Dixie Farm Rd to I45
- Diversion
 - I: Divert flow at Bay Area Blvd
 - II: Divert Turkey Creek to Bay Area Blvd
- Detention
- Combination scenario
 - I: FM 2351 bridge removal + Terracing
 - II: Terracing I + 50% Diversion at Bay Area Blvd
 - III: Terracing II + 50% Diversion at Bay Area Blvd

II. BACKGROUND AND STUDY AREA

The City of Friendswood, TX (Figure II.1) is located approximately 18 miles southeast of downtown Houston. The city limit covers an area of 21.2 mi², predominantly within the Clear Creek watershed. The city's land use mostly consists of residential and developed open / green spaces. The main drainage channels in Friendswood include Clear Creek and its tributaries (i.e. Mary's Creek, Coward's Creek, Chigger Creek, Mud Gully, and Turkey Creek).



Figure II.1. City of Friendswood, TX

Friendswood is prone to flooding from heavy storms, as evidenced by the extensive flood damage caused by Hurricane Harvey in August 2017 which caused flood impacts to over 2,000 single-family homes. Upper Clear Creek including Mud Gully and Turkey Creek contributed about 55% of the flows into Friendswood while Mary's, Coward's and Chigger

Creek contributed the remaining 45% of flows combined. The heavy rainfall combined with hydraulic properties of the region including low slopes and high imperviousness were likely drivers of the flood event. Additionally, due to its flat topography and its proximity to the coast, the city is also vulnerable to flooding from storm surge. To better understand and address the various flood issues in Friendswood, this study aims to evaluate the existing flood vulnerability of the city in the context of Hurricane Harvey and the 100-yr design storms and also to investigate potential mitigation options for implementation.

III. METHODOLOGY

Hydrologic Model (Vflo®)

In this study, hydrologic analysis is conducted using a physics-based, distributed hydrologic model, Vflo®¹. This model was developed by Dr. Baxter Vieux (Vieux & Associates), and has been used in numerous floodplain and/or watershed studies throughout the Greater Houston Region. The main advantage of using a distributed hydrologic model such as Vflo® over lumped parameter models (e.g., HEC-HMS) is its capability to better represent the topography and land use conditions of a study area. A Vflo® model domain (Figure III.1) consists of a series of inter-connected grid cells, each having its own set of physical (e.g., slope, flow direction) and hydraulic (e.g., roughness, hydraulic conductivity) properties. The model employs the Green and Ampt equation to compute infiltration. Overland runoff and channel flow are routed via the Kinematic Wave and Modified Puls methods. Rainfall input options are uniform precipitation (e.g., design storms), rain gage interpolation, and radar rainfall. For this project, a Vflo® model that covers the entire Clear Creek and Armand Bayou watersheds was developed and calibrated against historic storms.

¹ <https://www.vieuxinc.com/solutions/Vflo@distributed-hydrologic-model/>

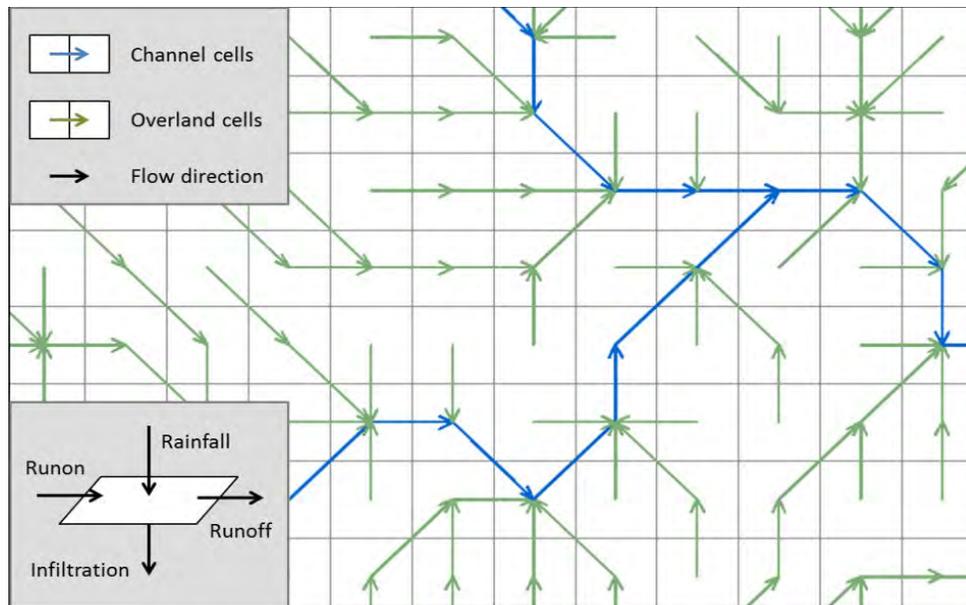


Figure III.1. Vflo® domain overview

Hydraulic Model (HEC-RAS)

The hydraulic model, HEC-RAS², is developed by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers. This model has been widely used in various channel and floodplain studies throughout the U.S., and is also the basis for the generation of the official FEMA floodplain maps. This study uses a 1D steady-state HEC-RAS model of Clear Creek/Armand Bayou watershed developed by the HCFCD, obtained through the Model and Map Management (M3) system³. As shown in Figure III.2, the 1D steady-state model represents the channel by a number of cross-sections (i.e., River Stations), and iteratively computes the water surface elevations within each cross-section based on head difference using the Energy Balance and Manning's equations. Some limitations of the 1D steady-state HEC-RAS model include time independent results, no hydraulic routing, and 1D flow. For this study, the original M3 HEC-RAS model (Version 3.1) was converted to and run in Version 5.0.6. This was done due to the new capabilities of the software, such as the ability to import terrain data and generate floodplain maps within the model.

² <https://www.hec.usace.army.mil/software/hec-ras/>

³ <http://www.m3models.org/>

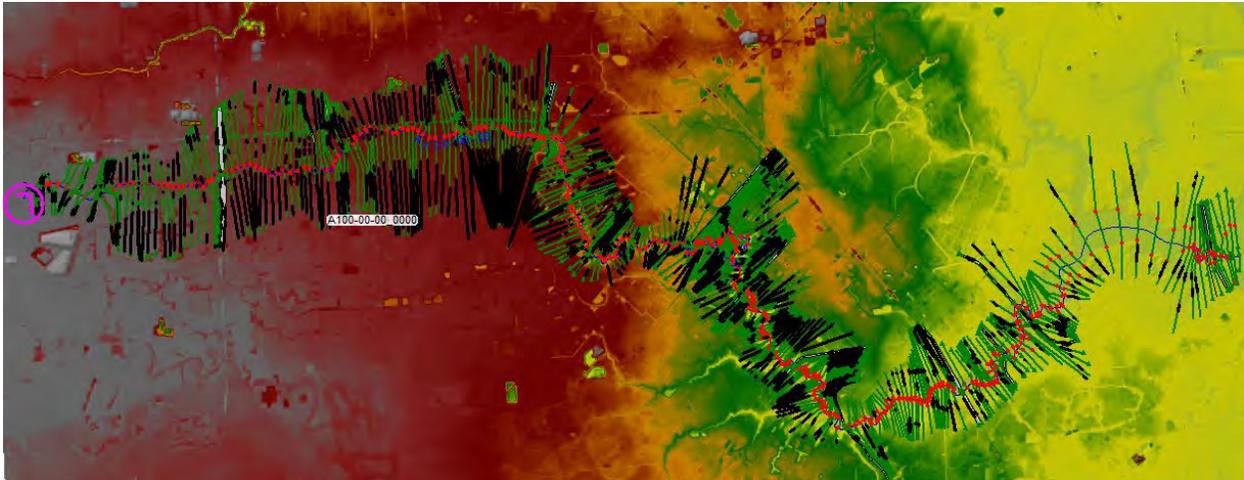


Figure III.2. HEC-RAS domain of Clear Creek with cross-sections with terrain data (2018 LIDAR)

Data Sources

To develop a hydrologic model that best represents the actual conditions of the study area, high-resolution spatial and temporal datasets are required. For topography, 1-meter resolution LIDAR 2008 (HCFCD) was used⁴. Land use and land cover (LULC) and imperviousness (30-meter) were obtained from the National Land Cover Database⁵ (NLCD 2011). Soil data was obtained from the Natural Resources Conservation Service⁶ (NRCS). To simulate Hurricane Harvey (2017), hourly gage-adjusted radar rainfall data was obtained from NOAA's National Severe Storms Laboratory⁷ (NSSL). This equates to approximately 40 inches of rain in 4 days. For the 100-yr storms, published values from HCFCD⁸ (i.e., 13.5 inches in 24 hrs) and NOAA Atlas 14⁹ (i.e., 17.65 inches in 24 hrs) were used. For model validation, stream gages from HCFCD¹⁰ and USGS¹¹, as well as USGS high water marks¹² were used.

⁴ In February 2019, Rice University obtained access to LIDAR 2018 from HGAC (<https://www.hgac.com/lidar-cost-share/default.aspx>). This new dataset was compared to the 2008 LIDAR dataset (see Appendix A), with results showing that the majority of the study area experienced no significant elevation change. As such, LIDAR 2018 was not used to update the previously developed Vflo® model, however for visualization purposes, LIDAR 2018 was used to generate floodplain maps in HEC-RAS

⁵ <https://www.mrlc.gov/data>

⁶ <https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm>

⁷ <https://www.nssl.noaa.gov/projects/mrms/>

⁸ https://www.hcfcd.org/media/1999/hcfcd-hydrology-hydraulics-manual_03-2016.pdf

⁹ https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_gis.html

¹⁰ <https://www.harriscountyfws.org/>

¹¹ <https://waterdata.usgs.gov/tx/nwis/inventory/>

¹² <https://stn.wim.usgs.gov/STNDataPortal/#>

IV. FLOOD VULNERABILITY ANALYSIS

The peak water surface elevation (WSEL) results produced by the HEC-RAS model were compared to Harris County stream gage data for Harvey and the HCFCF 100-yr storm for model validation and to assess Friendswood's existing flood vulnerability. Floodplain maps for the storms were also included in this analysis. For all modeled baseline scenarios, downstream boundary conditions were set to normal depth. The stream gages used for model comparison are shown in Figure IV.1.

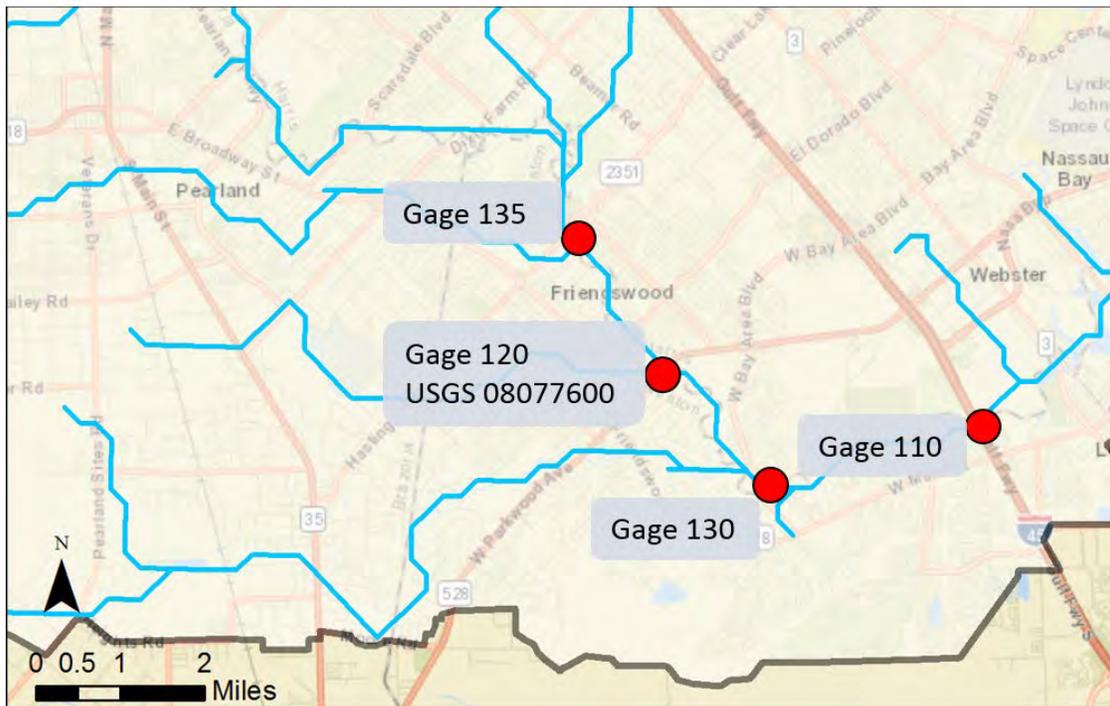


Figure IV.1. HCFCF stream gages for model validation

For Hurricane Harvey, an available USGS highwater mark located at Gage 135 was also used for comparison. The validation results for Harvey are shown in Table IV.1. Overall, the modeled peak WSELs matched well with the reported peak WSELs with less than a foot difference. At Gage 135, the stream gage peak WSEL differed by the USGS highwater mark by about 1.7 ft. Since the modeled peak WSEL at this location lies between the range reported by the stream gage and the highwater mark, the model results here were considered satisfactory.

Table IV.1. Model validation at Friendswood for Harvey; all values are shown in ft

Measurement Location	Observed (HCFC) WSEL	USGS High Water Mark	Modeled Peak WSEL	Difference from Observed
Gage 135	27.70	29.43	28.97	-0.46 (from HWM)
Gage 120	24.20	-	24.50	0.30
Gage 130	21.10	-	21.79	0.69
Gage 110	16.60	-	16.64	0.04

Figure IV.2 shows a floodplain depth map for Harvey created using HEC-RAS. Although the floodplain map does not delineate actual flood impact from Harvey, it highlights Friendswood’s vulnerability for extensive flood impact during large storms.

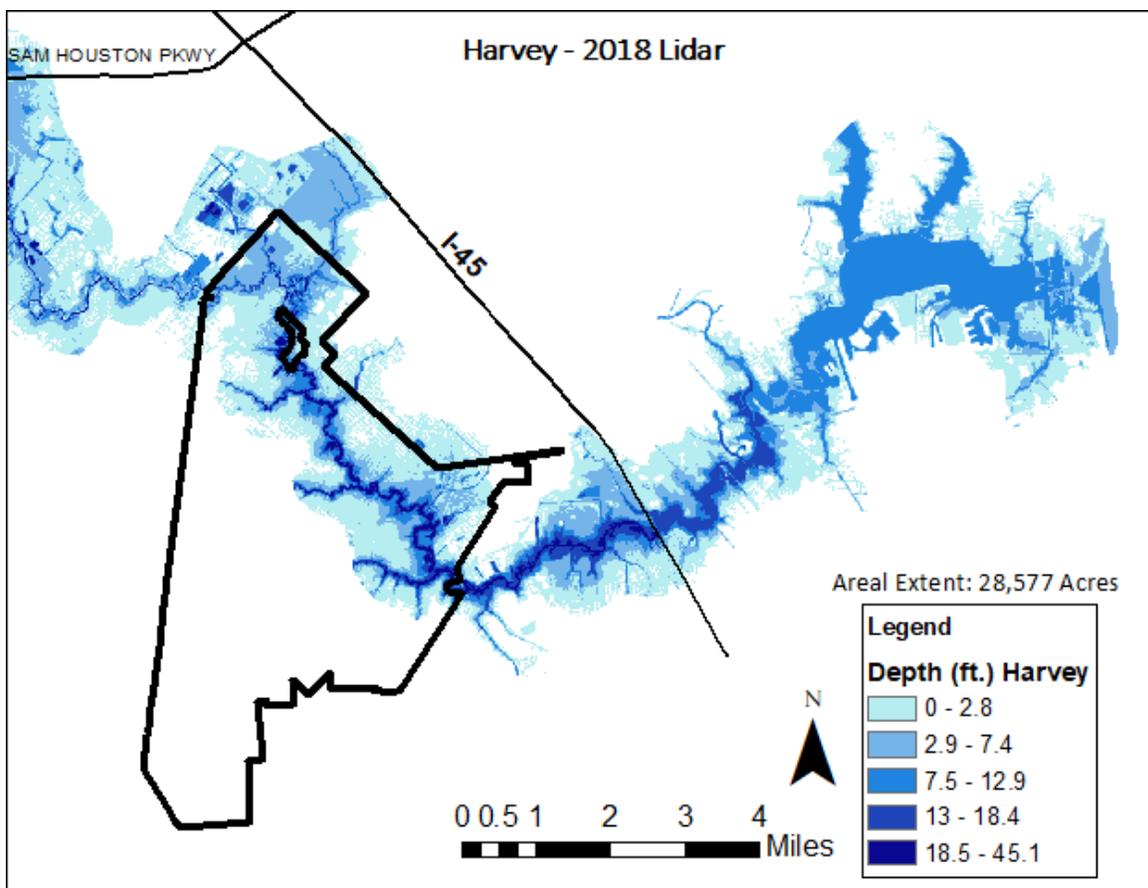


Figure IV.2. Harvey floodplain map with updated 2018 LIDAR

For the HCFCF 100-yr storm, the model comparison results are shown in Table IV.2. Results for the 100-yr storm using the M3 model are also shown. There are a number of discrepancies between the reported peak WSEL from the HCFCF FWS site and the results from the M3 model also developed by HCFCF. At the stream gage locations, although our RAS model showed discrepancies larger than half a foot compared to what HCFCF reported online, our RAS model matched with the M3 model by less than half a foot difference. Since our model better corresponds with the M3 model, which is considered the official model released by HCFCF, the model results obtained for the 100-yr storm are considered satisfactory.

Table IV.2. Model comparison at Friendswood for the HCFCF 100-yr storm; all values are shown in ft

Measurement Location	Reported WSEL (HCFCF)	Modeled Peak WSEL	Modeled - Reported (HCFCF)	M3 Peak WSEL	Modeled - M3
Gage 135	25.90	25.32	-0.58	25.83	-0.51
Gage 120	21.00	20.09	-0.91	20.53	-0.44
Gage 130	17.20	16.74	-0.46	16.68	0.06
Gage 110	12.40	11.30	-1.10	11.15	0.15

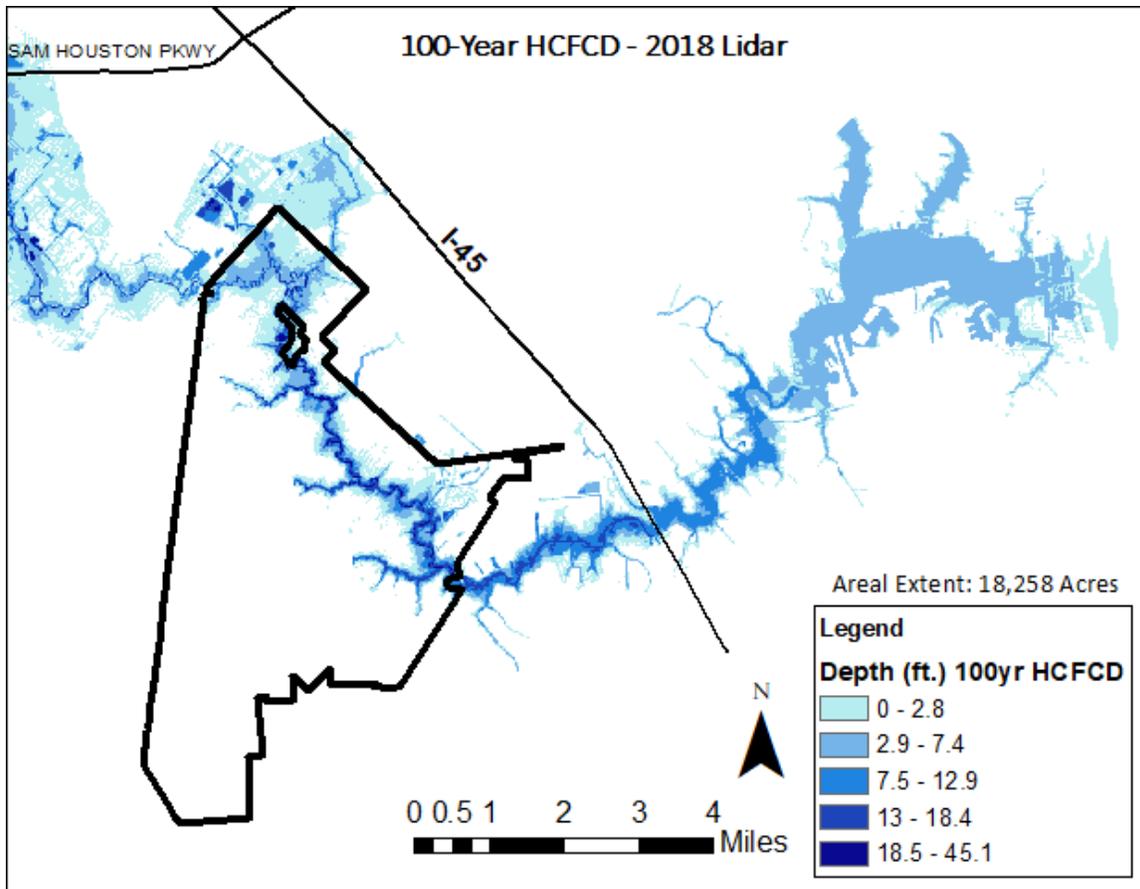


Figure IV.3. City of Friendswood, TX; 100-yr (HCFCFlood) floodplain map with updated 2018 LIDAR

For the NOAA Atlas 14 (2018) 100-yr storm, there are no available stream gage peak comparisons available yet from HCFCFlood. However, the modeled peak WSELs are shown in Table IV.3 for reference.

Table IV.3. Modeled peak WSEL for the NOAA Atlas 14 - 2018 100-yr storm; all values are shown in ft

Measurement Location	Modeled Peak WSEL
Gage 135	28.17
Gage 120	23.14
Gage 130	20.15
Gage 110	13.75

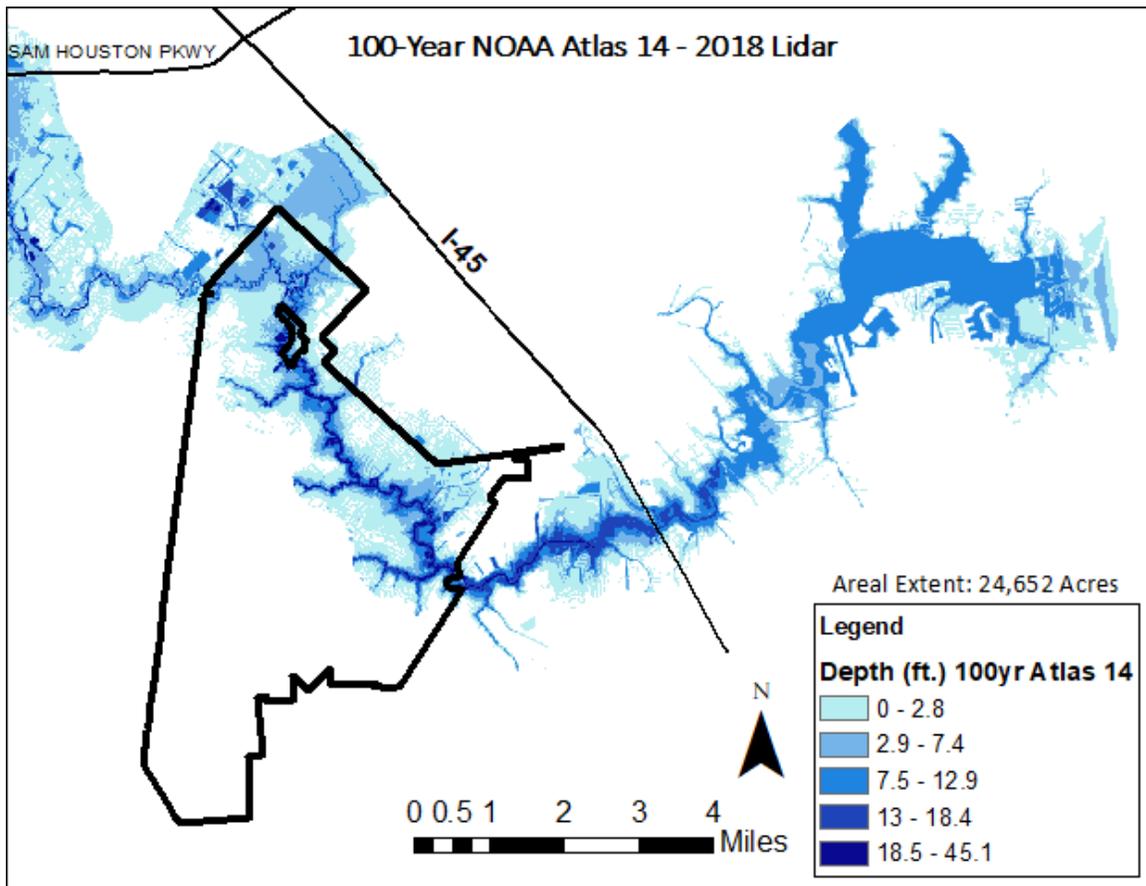


Figure IV.4. City of Friendswood, TX; 100-yr (NOAA Atlas 14 2018) floodplain map with updated 2018 lidar

The results shown for Harvey and the 100-yr storms provide a baseline for the flood vulnerability of Friendswood. In the proceeding sections, the impacts of the various flood mitigation strategies are presented as changes in peak WSEL from the baseline condition to show the flood reduction potential expected with each strategy.

V. ASSESSMENT OF FLOOD MITIGATION SCENARIOS

For the flood mitigation scenarios discussed in the next sections, results from HEC-RAS were obtained for the 9 watchpoints shown in Figure V.1. The supplementary Excel workbook provided with this report contains data tables for all mitigation scenarios at all 9 watchpoints. The pre-mitigation (i.e., existing) peak WSEL at these watchpoints for the three storms analyzed are shown in Table V.1.

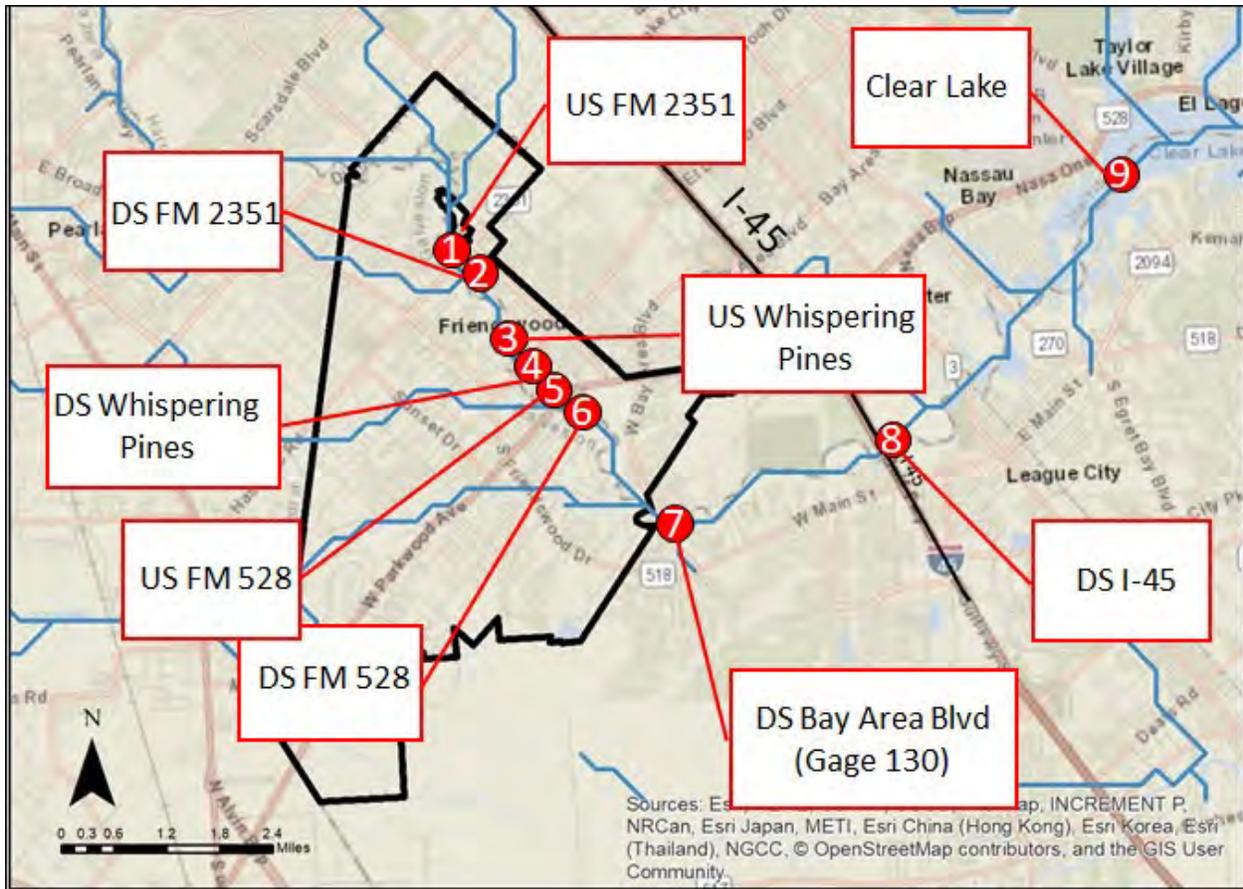


Figure V.1. Location of HEC-RAS watchpoints. US = upstream and DS = downstream

Table V.1. Pre-mitigation Peak WSEL at each watchpoint for all 3 modeled storms

Watchpoint	Location	Storm	Peak WSEL (ft)
1	US FM 2351	100yr (HCFCF)	24.72
		100yr (Atlas 14)	27.72
		Harvey	28.03
2	DS FM 2351	100yr (HCFCF)	23.3

		100yr (Atlas 14)	26.27
		Harvey	27.16
3	US Whispering Pines	100yr (HCFCD)	20.8
		100yr (Atlas 14)	23.78
		Harvey	24.79
4	DS Whispering Pines	100yr (HCFCD)	19.79
		100yr (Atlas 14)	23.05
		Harvey	24.2
5	US FM 528	100yr (HCFCD)	19.18
		100yr (Atlas 14)	22.42
		Harvey	23.64
6	DS FM 528	100yr (HCFCD)	18.51
		100yr (Atlas 14)	21.63
		Harvey	23.12
7	DS Bay Area Blvd.	100yr (HCFCD)	16.68
		100yr (Atlas 14)	20.1
		Harvey	21.79
8	I-45	100yr (HCFCD)	11.13
		100yr (Atlas 14)	13.62
		Harvey	16.49
9	Clear Lake	100yr (HCFCD)	6.18
		100yr (Atlas 14)	8.59
		Harvey	10.38

Methods

The modeling of the mitigation options required separate approaches. Bridge removal, de-snagging, terracing, and bridge removal + terracing were implemented in HEC-RAS. In these scenarios, the same Vflo® peak flows obtained in the pre-mitigation scenario were applied to the modified HEC-RAS geometries; this limitation prevents channel hydrodynamics from being accurately resolved, and the implications are further explained in the Model Limitations section of the report. Diversion and detention scenarios were implemented in Vflo® and supplied to HEC-RAS with no geometry modifications. Terracing + diversion was implemented using Vflo® for the diversion and HEC-RAS for the terracing. The following describes the setup and implementation of each mitigation option in more detail.

Bridge Removal

The bridge removal scenario focused on removing three major bridges within Friendswood: the bridge located at FM 2351, the bridge at Whispering Pines and the bridge at FM 528 (Figure V.2).

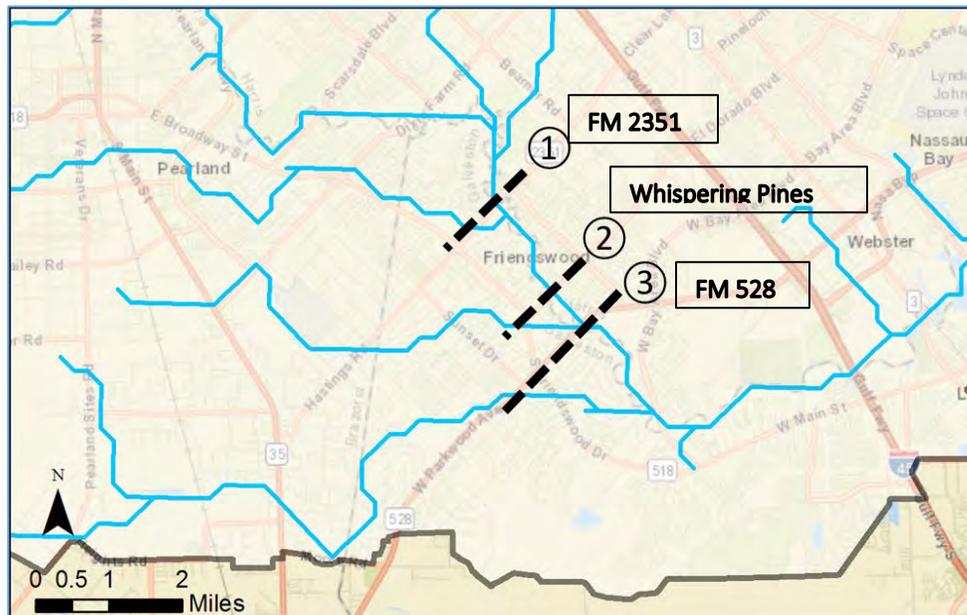


Figure V.2. Bridges removed in bridge removal mitigation scenario; (1) FM 2351, (2) Whispering Pines (3) FM 528.

Four modeling scenarios were analyzed: three individual bridge removals and one combined removal of all three bridges. To simulate the removal of the bridges (see below for example of bridge cross-section), the selected bridge cross-sections and the corresponding upstream

and downstream ineffective flow areas were removed from the HEC-RAS geometry file. For each bridge removal scenario, Harvey and the 100-yr storms were simulated using peak flows obtained from Vflo®.

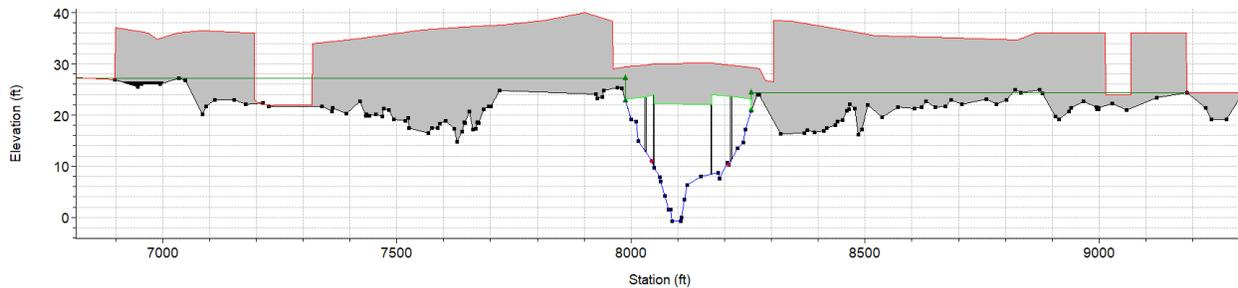


Figure V.3. Cross-section view of bridge at FM 2351

De-snagging

De-snag was modeled by changing the overbank surface roughness coefficient of the cross-sections from Dixie Farm Rd to Bay Area Blvd. in HEC-RAS. The original roughness coefficients in this region range from 0.12 to 0.15, which typify vegetative environments. The de-snagging performed here simulates the clearing of trees and vegetation that contribute to increased friction, and assumes a uniform short grass surface of roughness coefficient 0.04.

This de-snagging (Figure V.4) was performed up to a distance of 200 ft from the left and right banks of the main channel. The meanders of the natural channel were not altered. Harvey and the 100-yr storms were simulated using peak flows from Vflo®.

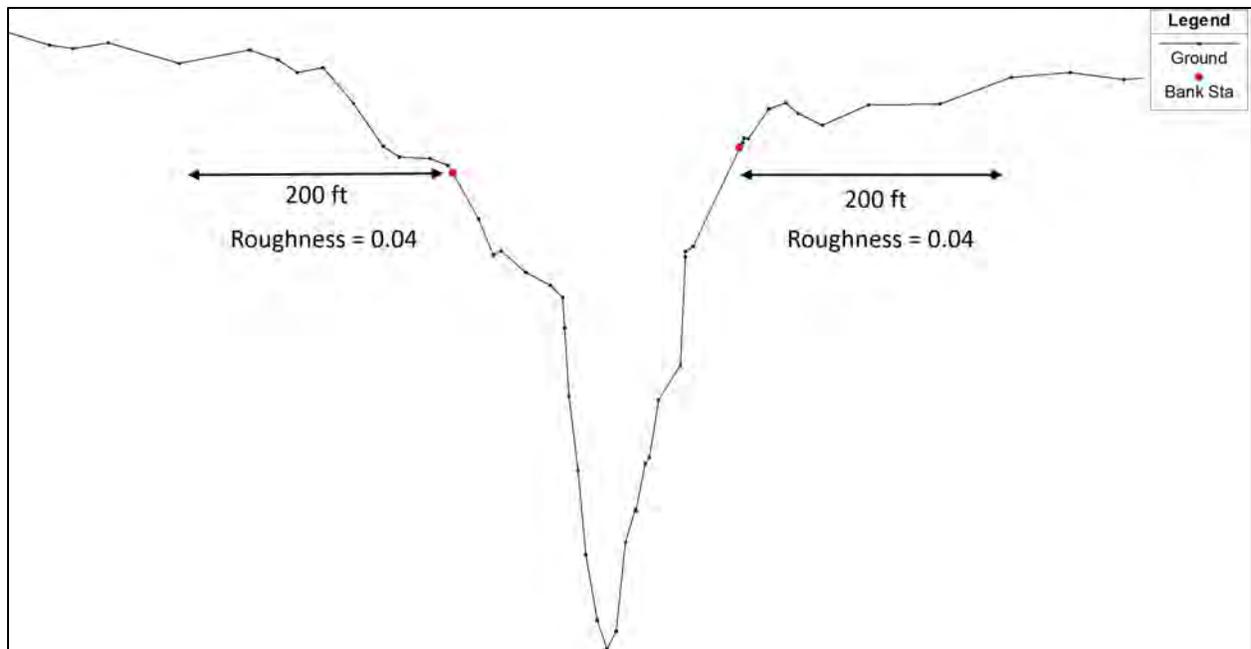


Figure V.4. De-snagging sample configuration

Terracing

The following design for grass terracing was applied to channel cross-sections in HEC-RAS. For Terracing I, the template was applied from Dixie Farm Rd to Bay Area Blvd. For Terracing II, the template was applied from Dixie Farm Rd to I45.

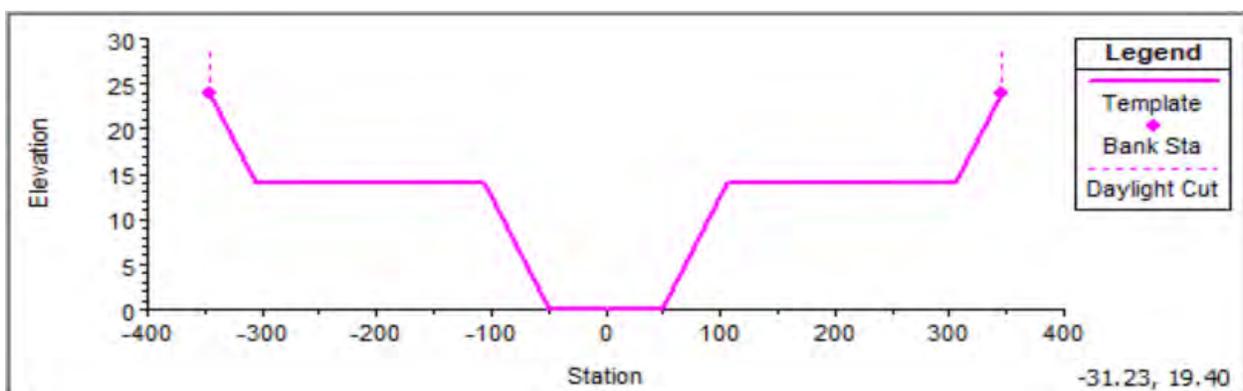


Figure V.5. Terracing channel geometry template

A channel template was generated in HEC-RAS's 'Channel Design / Modification' module. The template (Figure V.5) consists of 200 ft terraces (10 ft deep) on both banks of the main

channel, and a trapezoidal channel with a depth of 14 ft and a bottom width of 60 ft. Side slopes for both the terraces and the channel are 1:4. A uniform roughness coefficient of 0.04 is applied to both the terraced banks and the channel to represent grass lining. The following figure shows an example of how the terracing is implemented at the cross-section representing Watchpoint 1.

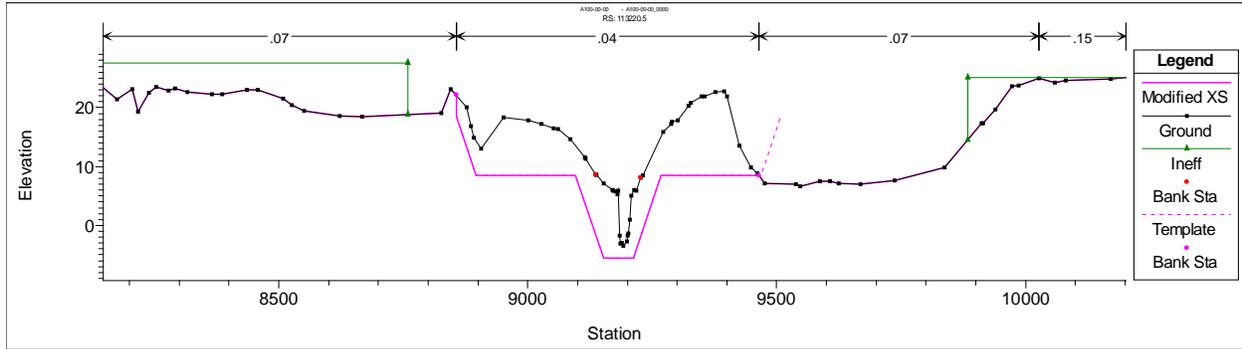


Figure V.6. RAS Cross-section showing terracing implementation at Watchpoint 1

Diversion

Two modeling techniques were used to simulate the diversion scenarios presented in this report.

Diversion I: Divert flow at Bay Area Blvd

Three diversion scenarios were modeled to represent the diversion of flows at Bay Area Blvd. by 10%, 25%, and 50%. The diversions were modeled by reducing the existing volume of flow at Bay Area Blvd., which coincides with the location of Gage 130 (Figure V.7), by 10%, 25% and 50% in Vflo®. These reductions in flow were then propagated downstream of the diversions. Note that no actual diversion structures/channels were modeled using this method. A reduced flow hydrograph was simply supplied at the Gage 130 cell in Vflo® as a forcing parameter. New peak flow values were then obtained from Vflo® for Harvey and the 100-yr storms and exported to HEC-RAS.

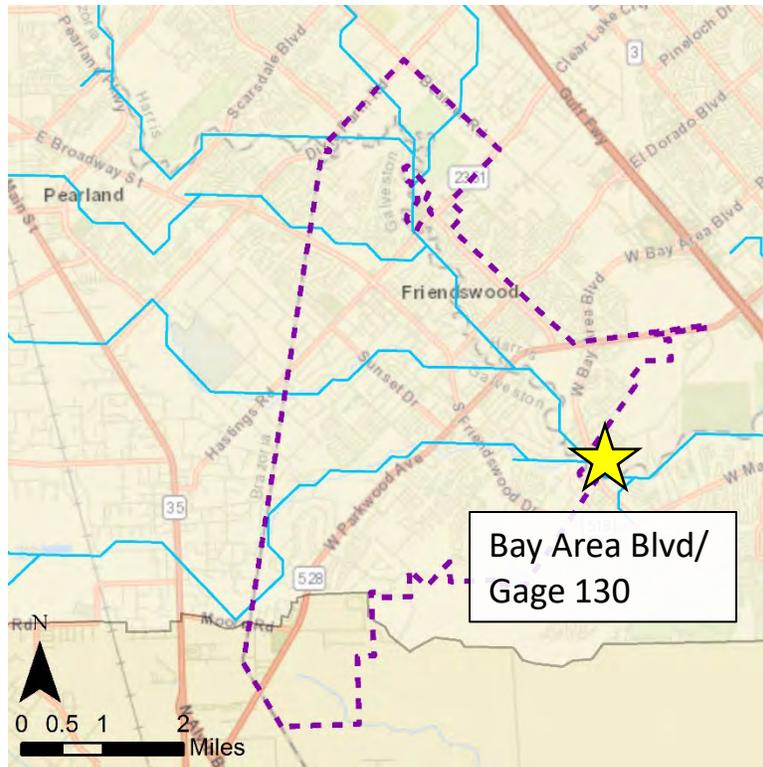


Figure V.7. Location of proposed diversions

Diversion II: Divert Turkey Creek to Bay Area Blvd

A diversion scenario where 50% of the flows introduced by Turkey Creek into the main channel were diverted to Bay Area Blvd. Figure V.8 shows the drainage area of Turkey Creek that was selected for the diversion. Vflo® was used to simulate the diversion, and the corresponding peak flows were provided to HEC-RAS. The HEC-RAS geometry was not modified to represent the implementation of the diversion channel. Thus, results of the diversion are only reported within the main channel in the next section.

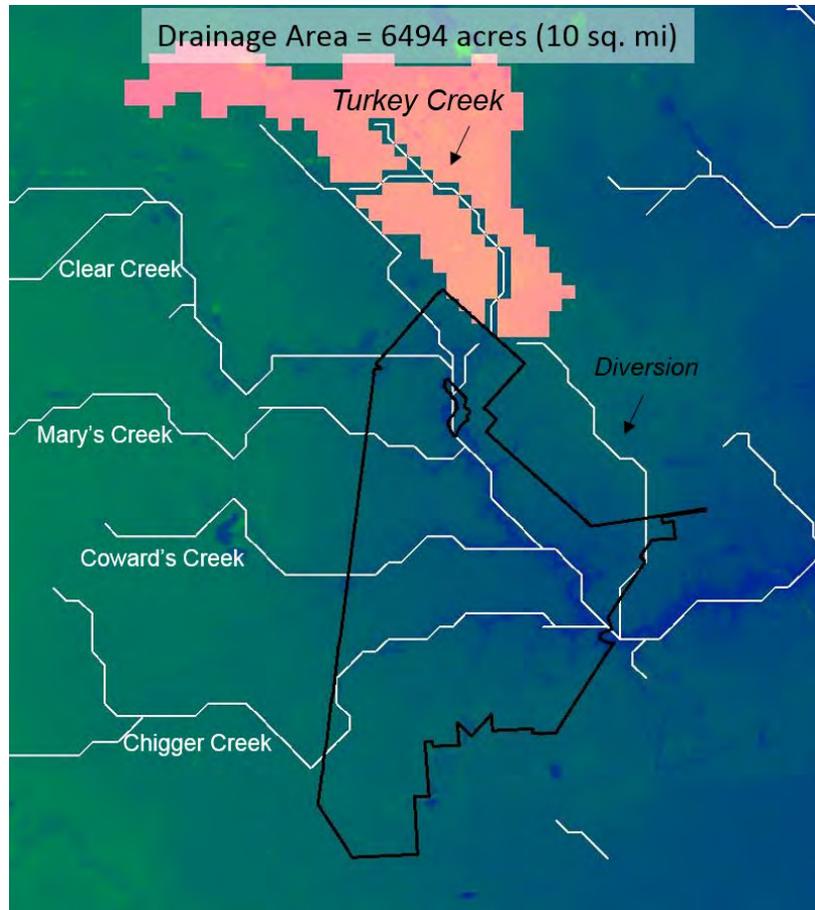


Figure V.8. Drainage area of Turkey Creek for Diversion (shown in orange)

The location and route of the diversion, shown in Figure V.9, was chosen to avoid developed areas and take advantage of available green space. Unlike the Diversion I scenario, the Turkey Creek diversion was simulated by modifying the directions of the Vflo® cells underlying the diversion route toward Bay Area Blvd and re-enter the main channel. The cells along the diversion were modified to trapezoidal cross-sections with a bottom width of 60 ft with a side slope of 1:4. The lining of the diversion channel was modeled as grass (manning's roughness = 0.04). For the 100 yr storms and Harvey, a flow hydrograph at the location of the diversion at Turkey Creek was scaled by 50% and supplied to the two cells immediately downstream (one to feed into the diversion channel and one to feed into the main channel). These reduced hydrographs served to simulate 50% of Turkey Creek's flow being diverted to Bay Area Blvd and 50% still allowed to enter the main channel.

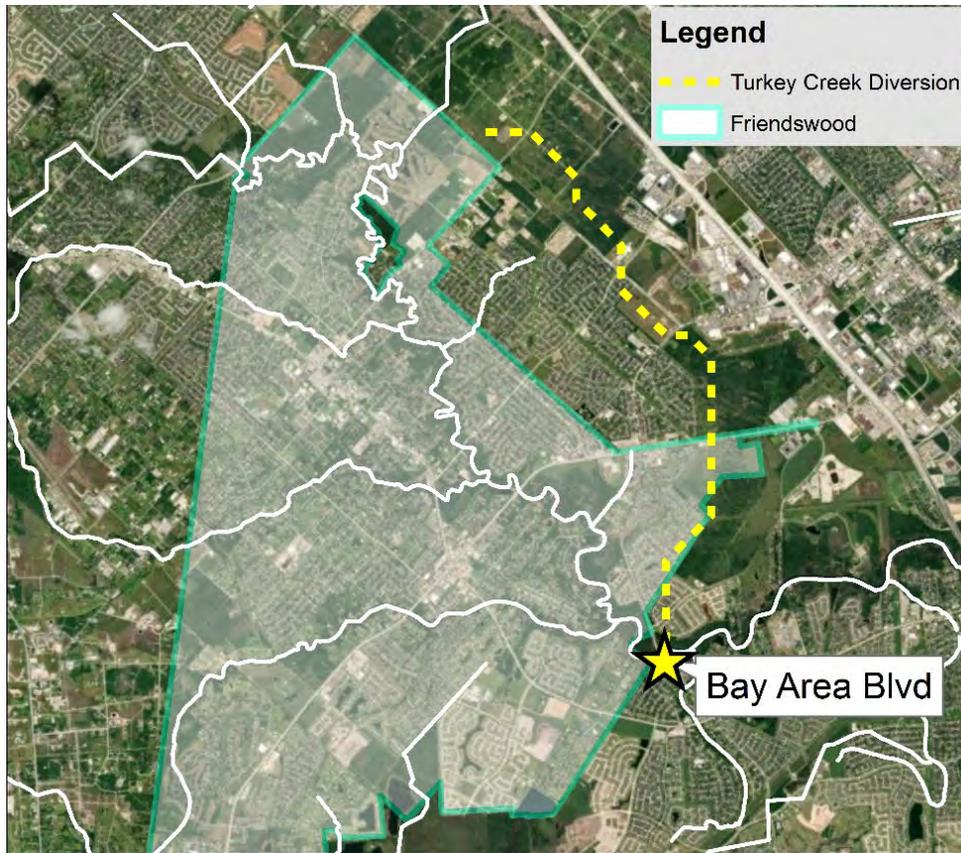


Figure V.9. Location of Turkey Creek Diversion

Detention

Proposed detention ponds (Figure V.10) were incorporated into Vflo® using shapefile provided by the City of Friendswood as reference.

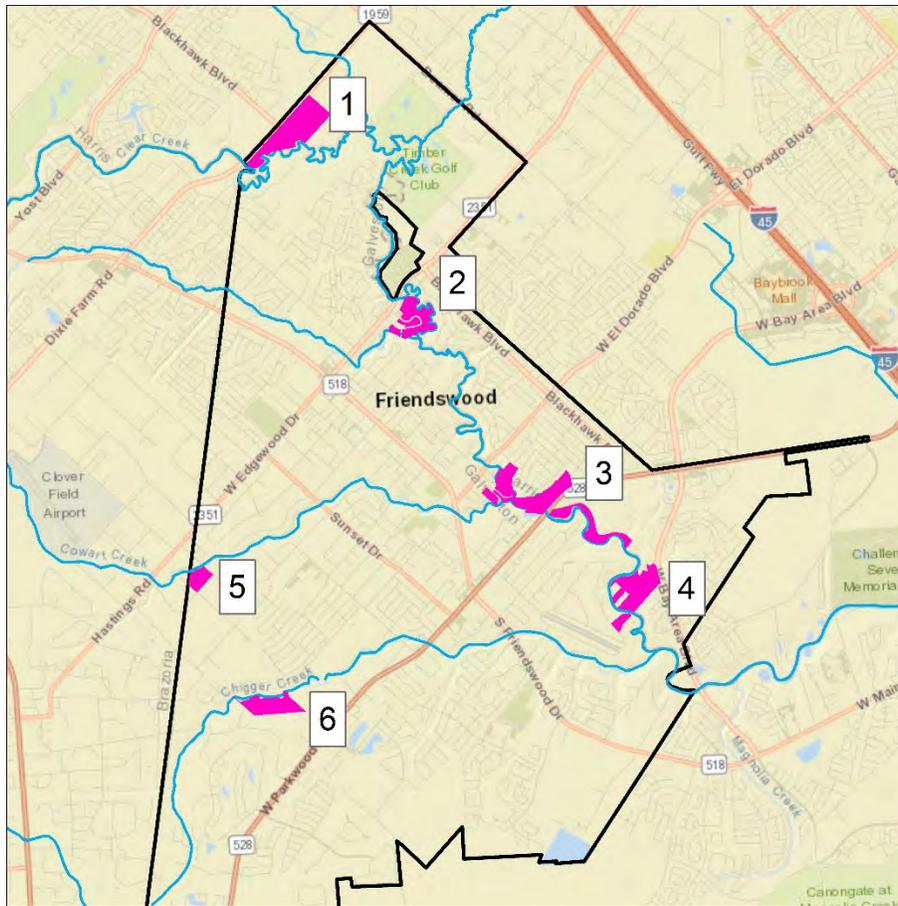


Figure V.10. Location of proposed detention ponds

Design rating curves were not available for the modeling team, and thus the ponds were assumed to have a 10-ft depth and resemble theoretical “box-shaped” detention ponds (see Figure V.11) with acreage equal to the aerial extent of the shapefiles (Table V.2).

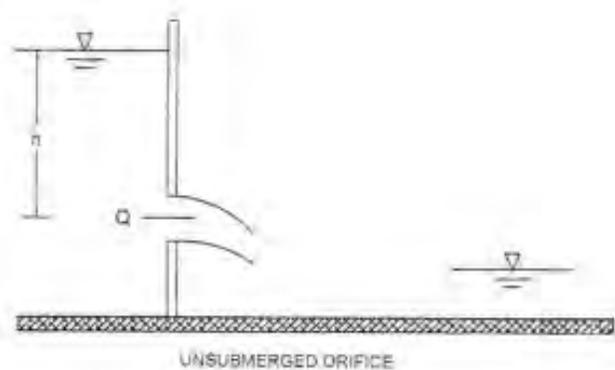
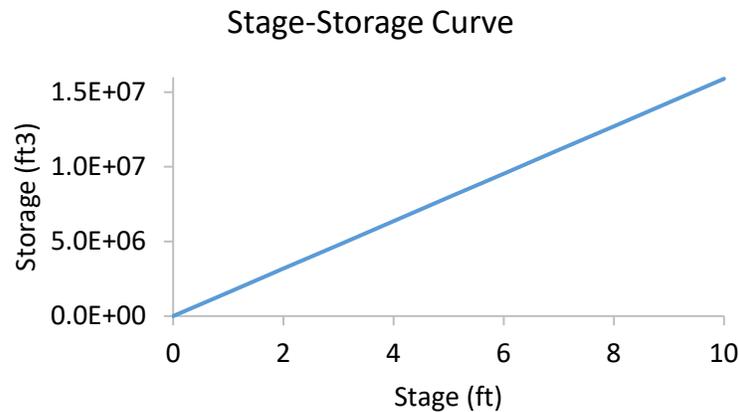


Figure V.11. Detention pond schematic

Table V.2. Acreage of proposed detention ponds calculated using GIS

Pond #	Designed Acreage
1	73.0
2	36.5
3	64.2
4	53.1
5	21.2
6	33.3

The modeling team acknowledges the intended nature of the ponds for capturing riverine overflow, however, due to the limitation of the finite difference implementation of Vflo® and the 1-D steady-state nature of the HEC-RAS model, the modeled detention ponds were modeled to capture drainage areas that are approximately 3 times the size of the pond and release flows directly into the main channel. The stage-discharge relationship assumes a 3 ft diameter orifice located at the 8 ft stage for all ponds and an emergency outflow structure represented by a 50 ft broad-crested weir above the 10 ft stage. The respective rating curves are shown in Figure V.12.



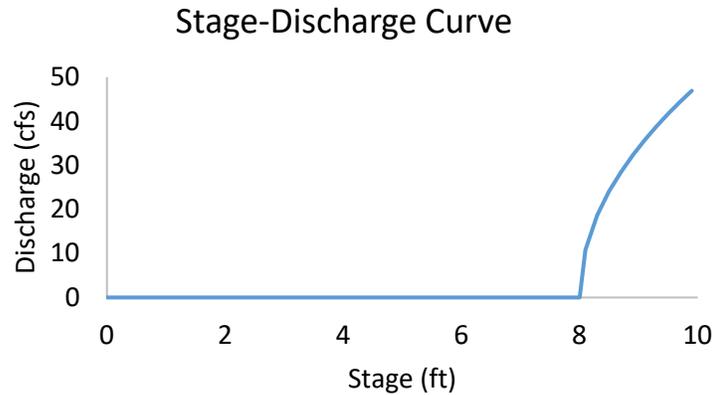


Figure V.12. Rating curves used for detention ponds in Vflo®. (above) stage-storage curve for pond #2; (below) stage-discharge curve for all ponds

Combination Scenarios

Bridge Removal + Terracing to Bay Area Blvd

For this scenario, in addition to the grass terracing being applied from Dixie Farm Rd. to Bay Area Blvd. as discussed in the previous section, the bridge at FM 2351 was also removed to model the combined effects of the scenarios. A RAS geometry file was developed with these combined mitigation options implemented. Harvey and the 100-yr storms were simulated using peak flows from Vflo®.

Terracing + Diversion

To model the combination of terracing and diversion, peak flows computed by Vflo® which reflect Diversion I at Bay Area Blvd are supplied to HEC-RAS where the terraced geometry is used. For the first terracing and diversion scenario, the peak flows from the 50% diversion scenario were used with the terraced geometry to Bay Area Blvd. In the second terracing and diversion scenario, the peaks flows from the 50% diversion scenario were used with the terraced geometry to I45. Harvey and 100-yr storms simulated for both combination scenarios.

Results and Discussion

The effects of each mitigation scenario are summarized in this section for the Atlas 14 100-yr storm. Results at each of the 9 watchpoints for each storm are provided in Appendix B.

Bridge Removal

Table V.3 shows the change in peak WSEL for the Atlas 14 100yr storm.

Table V.3. Changes in peak WSEL under the 100yr (Atlas 14) storm for bridge removal scenarios

Watchpoint	Location	WSEL Change (ft)			
		FM 2351 Removed	Whispering Pines Removed	FM 528 Removed	3 bridges Removed
1	US FM 2351	-1.22	-0.03	-0.03	-1.37
2	DS FM 2351	0.00	-0.08	-0.09	-0.17
3	US Whispering Pines	0.00	-0.16	-0.19	-0.36
4	DS Whispering Pines	0.00	0.00	-0.26	-0.26
5	US FM 528	0.00	0.00	-0.31	-0.31
6	DS FM 528	0.00	0.00	0.01	0.01
7	Bay Area Blvd.	0.00	0.00	0.00	0.00
8	I-45	0.00	0.00	0.00	0.00
9	Clear Lake	0.00	0.00	0.00	0.00

For the individual bridge removal scenarios, the greatest flood reduction impacts occurred immediately upstream of the location of the removed bridge due to the elimination of backwater effects caused by the obstruction. Among individual bridge removal scenarios, removing the bridge at FM 2351 resulted in the largest reduction in WSEL upstream (~1.2 ft). Interestingly, removing all three bridges did not show significant changes from the FM 2351-only removal scenario upstream of FM 2351. This is likely partially attributed to the varying elevations of the bridges which can either interfere with or have minimal impact on water levels. The FM 2351 bridge deck is at an elevation of 22-30 ft whereas the Whispering Pines and the FM 528 bridge decks are at an elevation of 17-22, and 20-27 ft, respectively. For higher peak WSELs especially observed in Harvey and the Atlas 14 100-yr storm, bridges at lower elevations create minimal obstructions as compared to bridges at higher elevations. Generally, the impacts to flood levels are muted the farther one moves away from the bridge

removal location. No noticeable changes in peak water levels were observed downstream of Friendswood toward I-45 and Clear Lake due to the 1D steady-state modeling methodology. In actuality, there might be slight changes in downstream water levels due to improved conveyance upstream.

De-snagging

Table V.4 shows the change in peak WSEL for the Atlas 14 100yr storm.

Table V.4. Changes in peak WSEL under the 100yr (Atlas 14) storm for de-snagging

Watchpoint	Location	WSEL change (ft)
1	US FM 2351	-1.23
2	DS FM 2351	-1.57
3	US Whispering Pines	-0.96
4	DS Whispering Pines	-0.92
5	US FM 528	-0.57
6	DS FM 528	-0.41
7	Bay Area Blvd.	*0.00
8	I-45	*0.00
9	Clear Lake	*0.00

De-snagging reduces peak WSEL throughout Friendswood by approximately 0.4-1.5 ft for the Atlas 14 100yr storm. The clearing of vegetation across a distance of 200 ft from the banks reduces friction in the channel and improves overall channel conveyance. This in turn reduces peak WSELs for the Friendswood area with greater impact upstream and decreasing impact moving downstream.

*We would expect de-snagging to have some impacts past the de-snagged segment, however due to modeling limitations (i.e., 1D steady-state), these impacts are not well-captured.

Terracing

Table V.5 shows the change in peak WSEL for the Atlas 14 100yr storm.

Table V.5. Changes in peak WSEL under the 100yr (Atlas 14) storm for grass terracing

Watchpoint	Location	WSEL change (ft)	
		Terracing to BAB	Terracing to I45
1	US FM 2351	-4.83	-6.23
2	DS FM 2351	-3.96	-5.44
3	US Whispering Pines	-2.37	-4.29

4	DS Whispering Pines	-2.05	-4.13
5	US FM 528	-1.53	-3.65
6	DS FM 528	-1.09	-3.30
7	Bay Area Blvd.	*-0.11	-2.68
8	I-45	*0.00	*0.00
9	Clear Lake	*0.00	*0.00

For the Atlas 14 100-yr storm, grass terracing to Bay Area Blvd decreases flood depth in the range of 0.1 to 4.8 ft within Friendswood and terracing to I45 decreases flood depth from 2.7 to 6.2 ft within Friendswood. The large overbank setbacks provide additional flood storage capacity. The additional channel capacity with terracing extended to I-45 causes water levels to decrease throughout Friendswood as compared to the terracing to Bay Area Blvd.

It is important to note that since the hydraulic analysis was conducted using a 1D steady-state approach, potential detention and/or storage responses (which are time-dependent) of the modified channel and terraces could not be accounted for. In other words, the grass terracing results presented in this study only accounts for the effect of conveyance improvement due to the modification of channel configurations at the applied cross-sections.

*We would expect terracing to have more notable impacts at locations past the terraced segment, however due to modeling limitations (i.e., 1D steady-state), these impacts are not well-captured.

Diversion

Table V.6 shows the change in peak WSEL for the Atlas 14 100-yr storm for Diversion I at Bay Area Blvd.

Table V.6. Changes in peak WSEL under the 100yr (Atlas 14) storm for the proposed diversions.

Watchpoint	Location	WSEL Change (ft)		
		10% Div	25% Div	50% Div
1	US FM 2351	-0.03	-0.05	-0.09
2	DS FM 2351	-0.08	-0.15	-0.24
3	US Whispering Pines	-0.16	-0.33	-0.52
4	DS Whispering Pines	-0.21	-0.48	-0.78
5	US FM 528	-0.26	-0.58	-0.97
6	DS FM 528	-0.37	-0.84	-1.39
7	Bay Area Blvd.	-0.65	-1.54	-2.77
8	I-45	-0.68	-1.63	-3.03
9	Clear Lake	-0.40	-0.65	-0.67

Results from diversion scenarios showed some change in water surface elevation within Friendswood (in the range of ~0.1 to 1 ft for the 50% diversion). Generally, more significant reduction in both water surface elevation and peak flow was observed downstream of the diversion, at I-45 and Clear Lake (in the range of 1 to 3 ft). The impact of the diversions decreases with increasing distance upstream. Recall, that the modeling method used here represents the diversion as a “black hole” and does not re-introduce the diverted water into the main channel/system.

Table V.7 shows the change in peak WSEL for the Atlas 14 100-yr storm for Diversion II from Turkey Creek toward Bay Area Blvd.

Table V.7. Changes in peak WSEL under the 100-yr (Atlas 14) storm for the Turkey Creek Diversion

Watchpoint	Location	WSEL change (ft)
1	US FM 2351	-0.89
2	DS FM 2351	-0.92
3	US Whispering Pines	-0.71
4	DS Whispering Pines	-0.71
5	US FM 528	-0.63
6	DS FM 528	-0.54
7	Bay Area Blvd.	-0.34
8	I-45	0.04
9	Clear Lake	0.08

The Turkey Creek Diversion reduces water levels within Friendswood by about 0.3 - 0.9 ft. There are minor increases in water levels (less than 0.1 ft) downstream of Bay Area Blvd with the flow re-routing. As shown in Table V.8, Turkey Creek’s drainage area accounts for only ~8% of the combined drainage area of the reaches that enter the main channel at Friendswood. Therefore, it is not surprising that diverting 50% of Turkey Creek’s flows does not have a significant impact in reducing water levels throughout Friendswood, especially approaching the location where the diverted water re-enters the main channel. Because the Turkey Creek diversion was not physically implemented in the HEC-RAS geometry, a floodplain map and WSEL data within the diversion channel could not be obtained.

Table V.8. Drainage area comparison of reaches feeding into Friendswood

Reach	Contributing Drainage Area (sq. mi)
Upper Clear Creek + Mud Gully	61
Mary’s Creek	16
Coward’s Creek	12
Chigger Creek	32

Detention

Table V.9 shows the change in peak WSEL for the Atlas 14 100yr storm.

Table V.9. Changes in peak WSEL under the 100yr (Atlas 14) storm for the proposed detention ponds

Watchpoint	Location	WSEL change (ft)
1	US FM 2351	-0.01
2	DS FM 2351	-0.02
3	US Whispering Pines	-0.04
4	DS Whispering Pines	-0.05
5	US FM 528	-0.06
6	DS FM 528	-0.08
7	Bay Area Blvd.	-0.13
8	I-45	-0.19
9	Clear Lake	-0.15

Results of this preliminary modeling effort showed minimal effect in reduction of water surface elevation throughout Friendswood with the additional detention. Peak flows were reduced throughout the channel, on the order of 1-3%, for both Harvey and the 100-yr rainfalls. Within Friendswood, WSEL was reduced on the order of hundredths of a foot for the Atlas 14 100-yr, with elevation falling in greater increments moving downstream. The minimal impact of the ponds is not surprising due to the small, regionally-distributed nature of the ponds. Additionally, as noted in a presentation to the City of Friendswood in Dec 2018, the impacts of hypothetical ponds located at Mary's Creek (Figure V.13) and Coward's Creek were evaluated. These ponds had 3-4 times the capacity of the ponds modeled in this report, and also showed little flood reduction during Harvey and 100-yr storms.

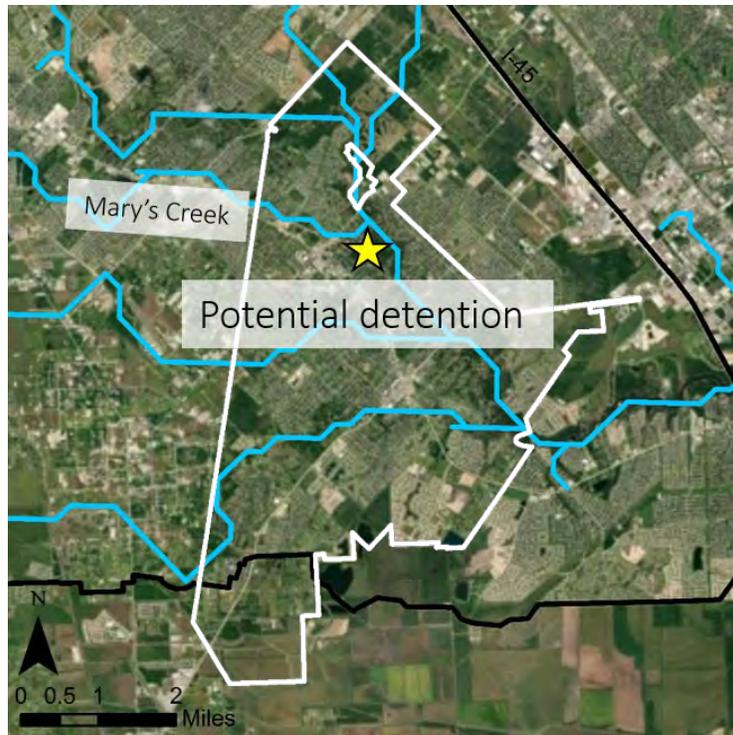


Figure V.13. Location of modeled detention pond designed to capture Mary's Creek drainage area; theoretical box pond capacity was 12,500 acre-ft

Table V.10. Change in peak WSEL at the middle of Friendswood with detention pond at Mary's Creek

Storm	WSEL Change (ft)
100-yr	-0.81
100-yr, Atlas 14	-0.69
Harvey	0.00

Combination Scenarios

Bridge Removal + Terracing to Bay Area Blvd

Table V.11 shows the change in peak WSEL for the Atlas 14 100yr storm.

Table V.11. Changes in peak WSEL under the 100yr (Atlas 14) storm for bridge removal + grass terracing

Watchpoint	Location	WSEL change (ft)
1	US FM 2351	-5.24
2	DS FM 2351	-3.96

3	US Whispering Pines	-2.37
4	DS Whispering Pines	-2.05
5	US FM 528	-1.53
6	DS FM 528	-1.09
7	Bay Area Blvd.	*-0.11
8	I-45	*0.00
9	Clear Lake	*0.00

For the Atlas 14 100-yr storm, the combination of FM2351 bridge removal and grass terracing decreases water surface elevation in Friendswood in the range of 0.1 to 5.2 ft. Other than at the site of the bridge, the differences between the results of the combined scenario versus grass terracing-only are minimal.

*We would expect terracing to have more notable impacts at locations past the terraced segment, however due to modeling limitations (i.e., 1D steady-state), these impacts are not well-captured.

Terracing + Diversion

Table V.12 shows the change in peak WSEL for the Atlas 14 100-yr storm.

Table V.12. Changes in peak WSEL under the 100yr (Atlas 14) storm for the terracing+ 50% diversion scenarios

Watchpoint	Location	WSEL change (ft)	
		Terracing to BAB + 50% Diversion	Terracing to I45 + 50% Diversion
1	US FM 2351	-6.37	-7.74
2	DS FM 2351	-5.60	-7.12
3	US Whispering Pines	-4.51	-6.91
4	DS Whispering Pines	-4.39	-7.02
5	US FM 528	-3.93	-6.68
6	DS FM 528	-3.60	-6.63
7	Bay Area Blvd.	*-3.06	*-7.32
8	I-45	*-3.03	*-3.03
9	Clear Lake	*-0.67	*-0.67

The combination scenario with terracing to Bay Area Blvd is expected to decrease water surface elevation by between 3 and 6.4 ft within Friendswood. The flow diversion in addition to the terracing reduces water levels past Bay Area Blvd and enhances flood reduction within Friendswood. The combination scenario with terracing extended to I45 decreases water

levels in Friendswood by about 6.6-7.7 ft. The extended terracing adds channel capacity and increases flood reduction impacts.

*Due to modeling limitations (i.e., 1D steady-state), the impacts of this mitigation strategy, especially in the area where the terraced channel meets the diversion location, are not well-captured.

Model Limitations

This section serves to summarize and reiterate the limitations and assumptions of the modeling method for each of the mitigation scenarios performed in this study.

Bridge Removal: Because Vflo® does not account for the presence of bridges or channel obstructions, the peak flows throughout the main channel before and after the bridge removals were assumed to remain the same in the HEC-RAS model. Additionally, beyond the deletion of bridges and associated ineffective flow areas from the HEC-RAS geometry, no other channel modifications were performed. These assumptions, although minor, should be noted when reviewing the modeling results.

De-Snagging: The Vflo® peak flows throughout the main channel before and after the de-snagging were assumed to remain the same in the HEC-RAS model. Therefore the hydrodynamics of the de-snagging are not well-captured especially past the location of the de-snagged segment. Therefore there is uncertainty in the modeling results obtained at the watchpoints past Bay Area Blvd.

Terracing: The Vflo® peak flows throughout the main channel before and after the terracing were assumed to remain the same in the HEC-RAS model. In reality, the drastic increase in channel capacity and added storage during a flood event would alter the peak flows observed along and past the terraced segment. Since Vflo® is not currently capable of capturing these impacts, the assumption that the peak flows remain the same is overly simplifying. In other words, the current modeling method could not account for the actual channel hydrodynamics (i.e., hydraulic routing).

Diversion: For Diversion 1 at Bay Area Blvd, the diverted water is assumed to leave the system without any physical re-routing back into the main channel. This assumption introduces some uncertainty in the modeling results if the water were to be routed back into the main channel in reality. For Diversion 2 from Turkey Creek to Bay Area Blvd, it was out of the scope of the project to alter the HEC-RAS geometry to account for the presence of the diversion channel. This does not allow for assessing flood levels around the diversion channel - only in the main channel.

Detention: No design rating curves were available for incorporating into Vflo®. Instead, theoretical rating curves were developed, which might not capture the actual behavior of the

ponds. Additionally, Vflo® is currently not suitable for modeling inline detention and capturing riverine overflow. Similarly, the 1-D nature of the HEC-RAS model does not capture the physics of the inline detention ponds.

Bridge Removal + Terracing: The same limitations and assumptions remain for the bridge removal-only and terracing-only scenarios.

Terracing + Diversion at Bay Area Blvd: The same limitations and assumptions remain for the terracing-only and diversion-only scenarios. Importantly, assuming that the flows in the diversion scenario can then be applied to the HEC-RAS model where the terracing is applied does not capture the interaction between the two mitigation strategies where we expect peak flows would be impacted especially in the downstream areas. The use of a 1-D steady state model in this scenario is not the most suitable approach for representing the highly time-dependent nature of this scenario.

VI. CONCLUSIONS AND RECOMMENDATIONS

A summary of the results for each mitigation scenario for the Atlas 14 100-yr storm is shown in the table below.

Table VI.1. Summary of peak WSEL reduction (in feet) under the 100yr (Atlas 14); values indicate approximate range of changes in peak WSEL within Friendswood

Mitigation Scenarios							
3 Bridge Removal	De-snagging	Terracing to I45	Diversion at BAB (50%)	Turkey Creek Diversion	Detention	FM 5321 + grass terracing	Terracing to I45 + 50% Diversion
-0.3 to 1.4	-0.4 to 1.6	-2.7 to 6.2	-0.1 to 1.0	-0.5 to 0.9	Negligible	-1.1 to 5.2	-6.6 to 7.7

The specific implications of each mitigation scenario are as follows:

Bridge Removal

Removing the bridge at FM 2351 has the greatest effect on lowering water levels at locations that are immediately upstream of the bridge.

De-Snagging

De-snagging has the greatest flood reduction impact at the first few watchpoints and decreases in effectiveness progressively downstream.

Terracing

Terracing reduces flood levels the most at the first watchpoints and decreases in effectiveness progressively downstream, however significant flood reduction is observed throughout Watchpoints 1-7.

Diversion Scenarios at Outlet

Greatest overall impact from the diversion scenarios was seen at I-45 and Clear Lake while imparting minimal change on WSEL (less than 1 ft) within Friendswood. Generally, reduction in WSEL increased with closer proximity to the diversion location.

Detention Ponds

There was minimal change in WSEL throughout the reach due to the small, regionally distributed ponds.

Bridge Removal + Terracing

This combination scenario does not show significant differences in flood reduction impact as compared to the terracing-only scenario. There are slight peak WSEL reductions upstream

of the FM 2351 bridge, but the results are largely controlled by the significantly increased channel capacity due to the terracing.

Terracing + 50% Diversion

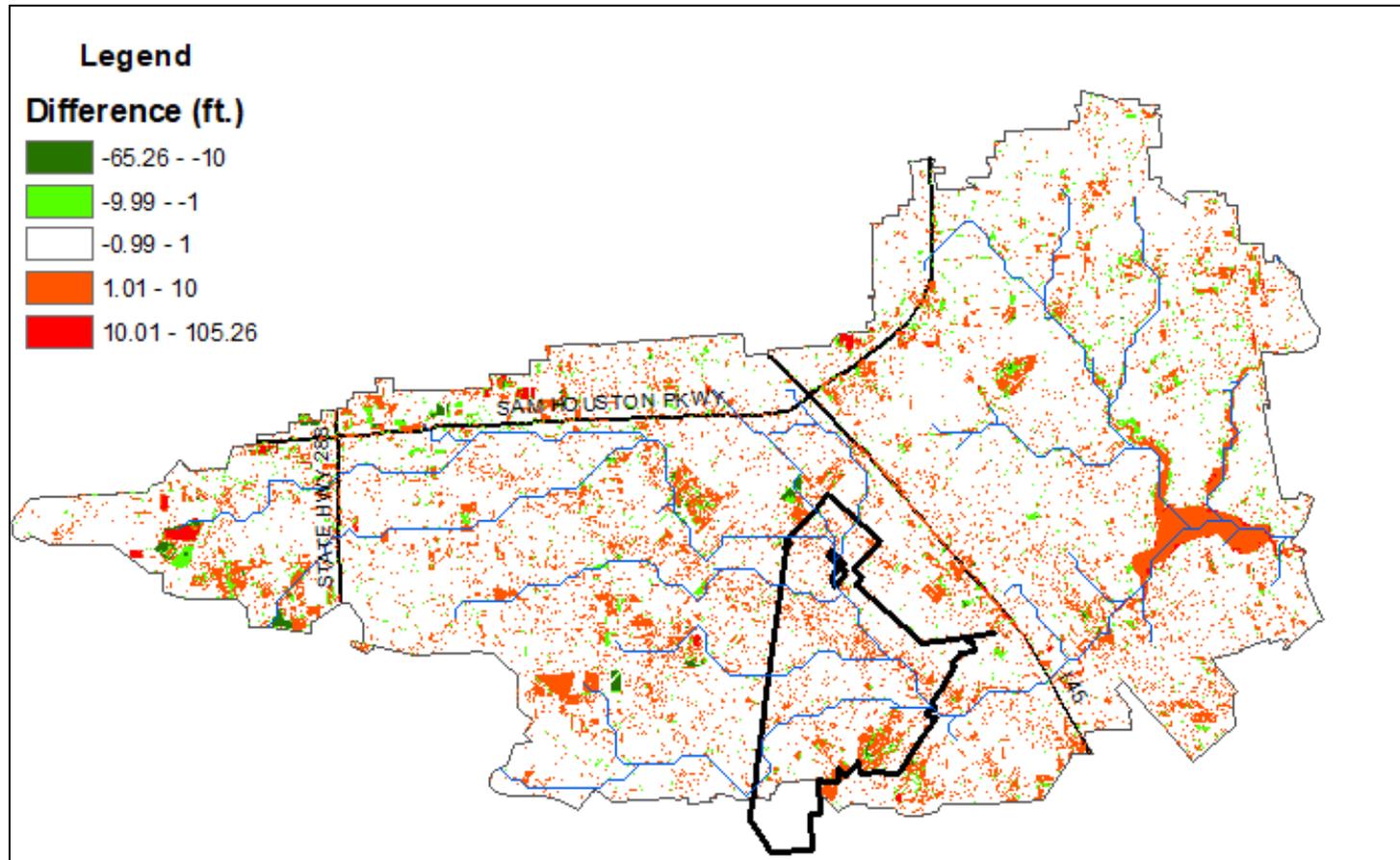
This combination scenario showed large flood reduction impacts at all watchpoints in Friendswood.

Additional Considerations

Although it is not within the current scope of the project, future improvements to the modeling method might require the use of unsteady and/or 2D approaches to better represent the responses and quantify the performances of specific mitigation options. For example, the impacts of diversions could potentially be better quantified by modeling the physical structure in a 2D environment. The evaluation of other mitigation options such as detention and terracing could also benefit from using an unsteady modeling approach. Due to the inherent limitations discussed previously, the results presented in this study are not meant to serve as the basis for the actual engineering design and/or construction of specific mitigation scenarios. Instead, this study's main purpose is to provide a better understanding of the existing flood vulnerability of the City of Friendswood and also to provide valuable insights regarding the potential impacts and benefits of a wide range of mitigation strategies.

VII. APPENDICES

Appendix A: LIDAR Difference Map



Map shows elevation difference in ft between the 2018 and 2008 LIDAR

Appendix B: Summary Tables by Storm

Table VII.1. Summary table for Harvey

Watch Point Location	Change in Peak WSEL (ft)									
	3-Bridge Removal	De-Snag	Terracing to BAB	Terracing to I45	50% Diversion at BAB	Turkey Creek Diversion	Detention	FM 2351 + Terracing	Terracing to BAB + 50% Diversion	Terracing to I45 + 50% Diversion
1: US FM 2351	-0.79	-0.86	-3.78	-4.64	-0.11	-0.35	-0.03	-4.11	-5.24	-6.67
2: DS FM 2351	-0.09	-1.47	-3.38	-4.38	-0.15	-0.40	-0.04	-3.37	-5.00	-6.54
3: US Whispering Pines	-0.20	-0.87	-1.83	-3.07	-0.38	-0.31	-0.04	-1.83	-3.87	-6.11
4: DS Whispering Pines	-0.19	-0.75	-1.56	-3.00	-0.47	-0.29	-0.04	-1.56	-3.93	-6.37
5: US FM 528	-0.19	-0.44	-1.10	-2.57	-0.74	-0.26	-0.05	-1.10	-3.52	-6.07
6: DS FM 528	0.00	-0.37	-0.90	-2.51	-1.03	-0.25	-0.06	-0.90	-3.48	-6.27
7: DS Bay Area Blvd	0.00	0.00	-0.09	-1.94	-2.9	-0.16	-0.09	-0.09	-3.13	-6.88
8: DS I-45	0.00	0.00	0.00	0.00	-3.62	0.01	-0.06	0.00	-3.62	-3.62
9: Clear Lake	0.00	0.00	0.00	0.00	-1.52	0.02	-0.04	0.00	-1.52	-1.52

Table VII.2. Summary table for 100-yr (HCFCF)

Watch Point Location	Change in Peak WSEL (ft)							
	3-Bridge Removal	De-Snag	Terracing to I45	50% Diversion at BAB	Turkey Creek Diversion	Detention	FM 2351 + Terracing	Terracing to I45 + 50% Diversion
Watch Point 1: US FM 2351	-1.25	-1.77	-7.34	-0.07	-1.24	0.03	-6.10	-8.20
Watch Point 2: DS FM 2351	-0.20	-1.50	-6.47	-0.10	-0.74	0.01	-4.86	-7.43
Watch Point 3: US Whispering Pines	-0.55	-1.09	-5.36	-0.25	-0.62	-0.07	-3.22	-6.91
Watch Point 4: DS Whispering Pines	-0.15	-1.08	-4.73	-0.33	-0.47	-0.10	-2.47	-6.42
Watch Point 5: US FM 528	-0.18	-0.73	-4.26	-0.44	-0.37	-0.16	-1.94	-6.03
Watch Point 6: DS FM 528	0.01	-0.55	-3.90	-0.48	-0.25	-0.16	-1.48	-5.82
Watchpoint 7: DS Bay Area Blvd	0.00	0.00	-2.94	-1.93	-0.11	-0.19	-0.14	-5.51
Watch Point 8: DS I-45	0.00	0.00	0.00	-2.54	0.07	-0.19	0.00	-2.54
Watch Point 9: Clear Lake	0.00	0.00	0.00	-0.31	0.13	-0.14	0.00	-0.31

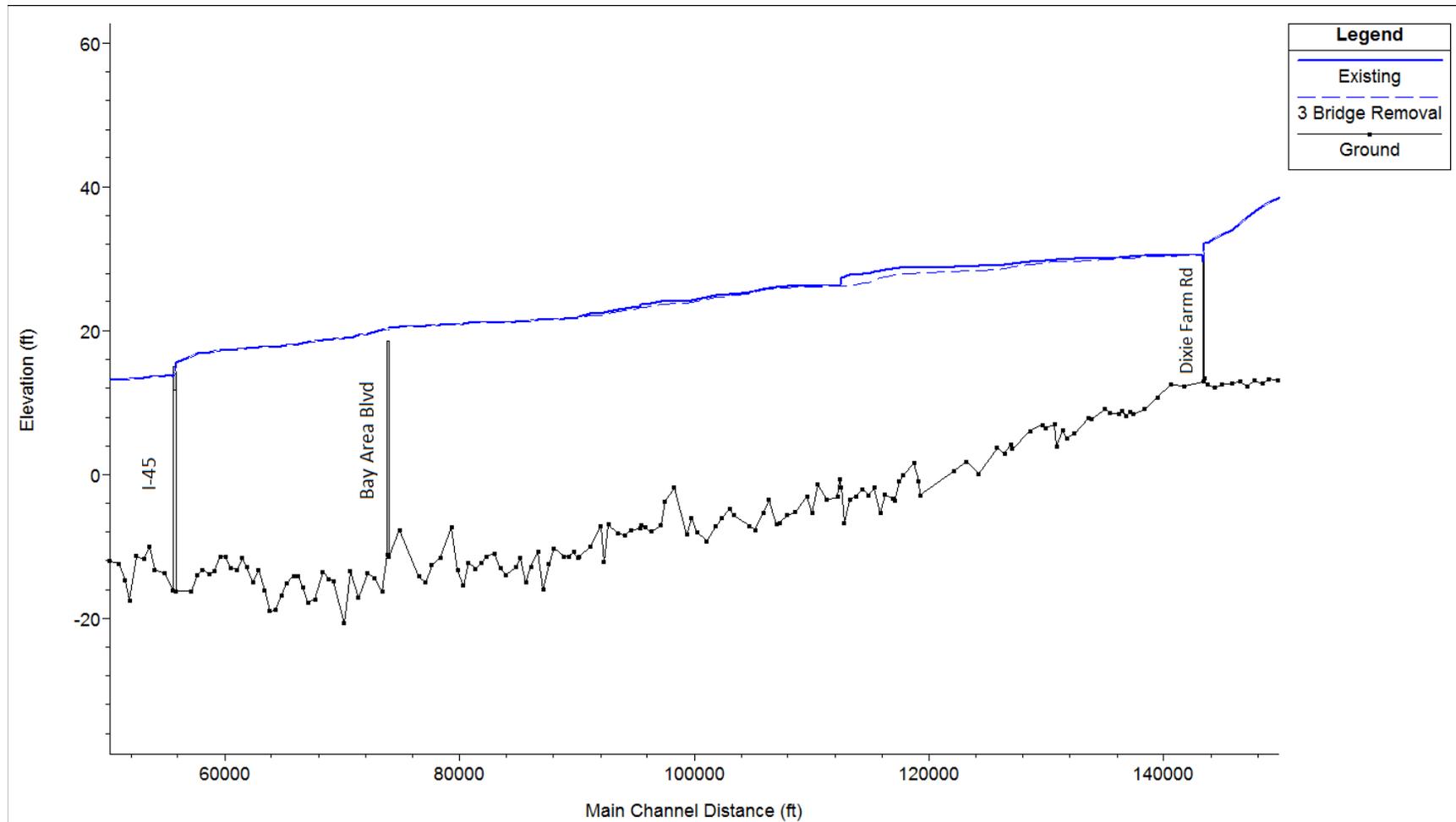
Table VII.3. Summary table for 100-yr Atlas 14

Watch Point Location	Change in Peak WSEL (ft)							
	3-Bridge Removal	De-Snag	Terracing to I45	50% Diversion at BAB	Turkey Creek Diversion	Detention	FM 2351 + Terracing	Terracing to I45 + 50% Diversion
Watch Point 1: US FM 2351	-1.37	-1.23	-6.23	-0.07	-0.89	-0.01	-5.24	-7.74
Watch Point 2: DS FM 2351	-0.17	-1.57	-5.44	-0.10	-0.92	-0.01	-3.96	-7.12
Watch Point 3: US Whispering Pines	-0.36	-0.96	-4.29	-0.31	-0.71	-0.02	-2.37	-6.91
Watch Point 4: DS Whispering Pines	-0.26	-0.92	-4.13	-0.41	-0.71	-0.03	-2.05	-7.02
Watch Point 5: US FM 528	-0.31	-0.57	-3.65	-0.64	-0.63	-0.05	-1.53	-6.68
Watch Point 6: DS FM 528	0.01	-0.41	-3.30	-0.96	-0.54	-0.06	-1.09	-6.63
Watchpoint 7: DS Bay Area Blvd	0.00	0.00	-2.68	-2.77	-0.34	-0.14	-0.11	-7.32
Watch Point 8: DS I-45	0.00	0.00	0.00	-3.03	0.04	-0.20	0.00	-3.03
Watch Point 9: Clear Lake	0.00	0.00	0.00	-0.67	0.08	-0.15	0.00	-0.67

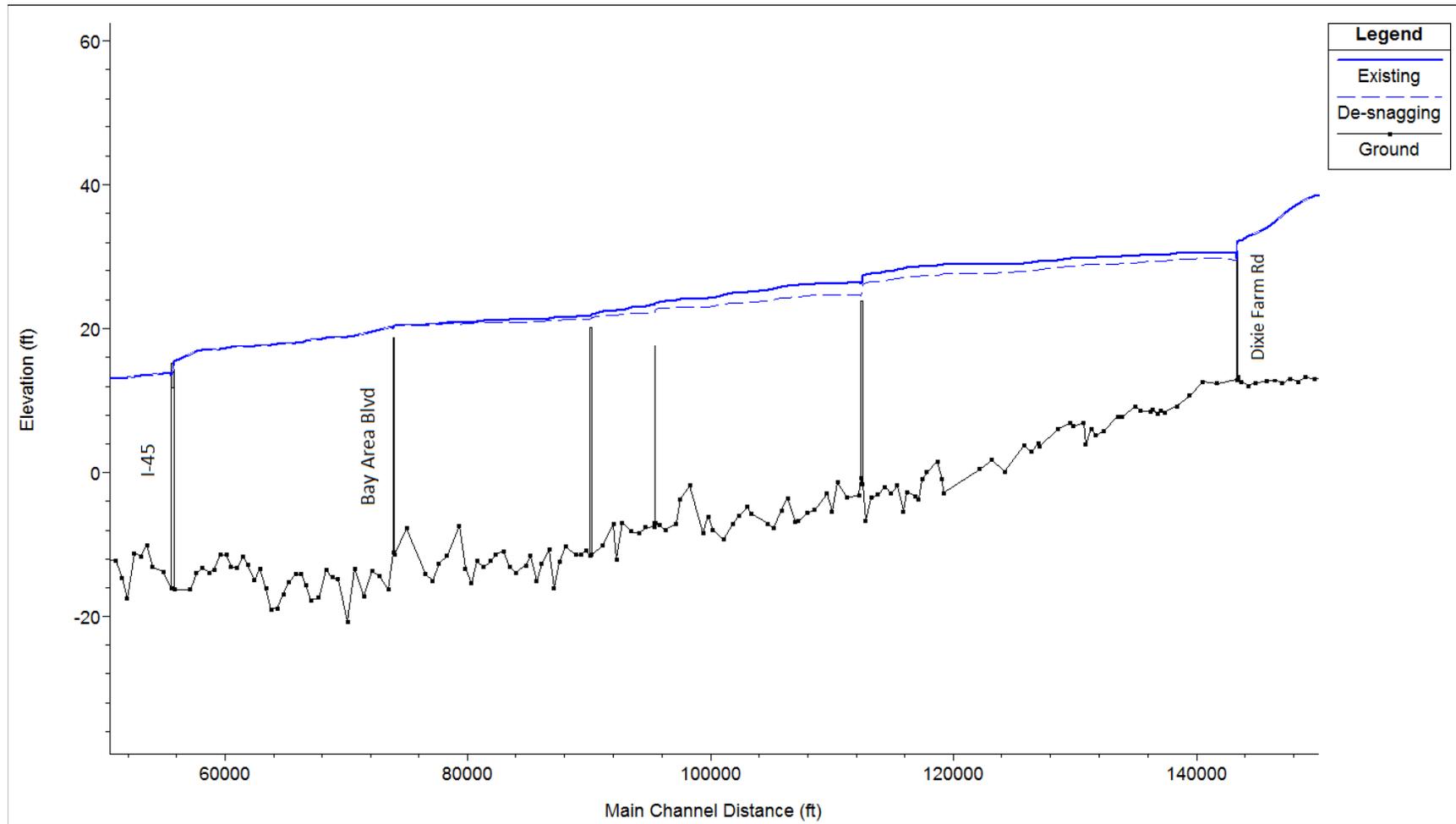
Appendix C: Profiles

The following figures are channel profile plots for each mitigation scenario under the 100-yr Atlas 14 storm.

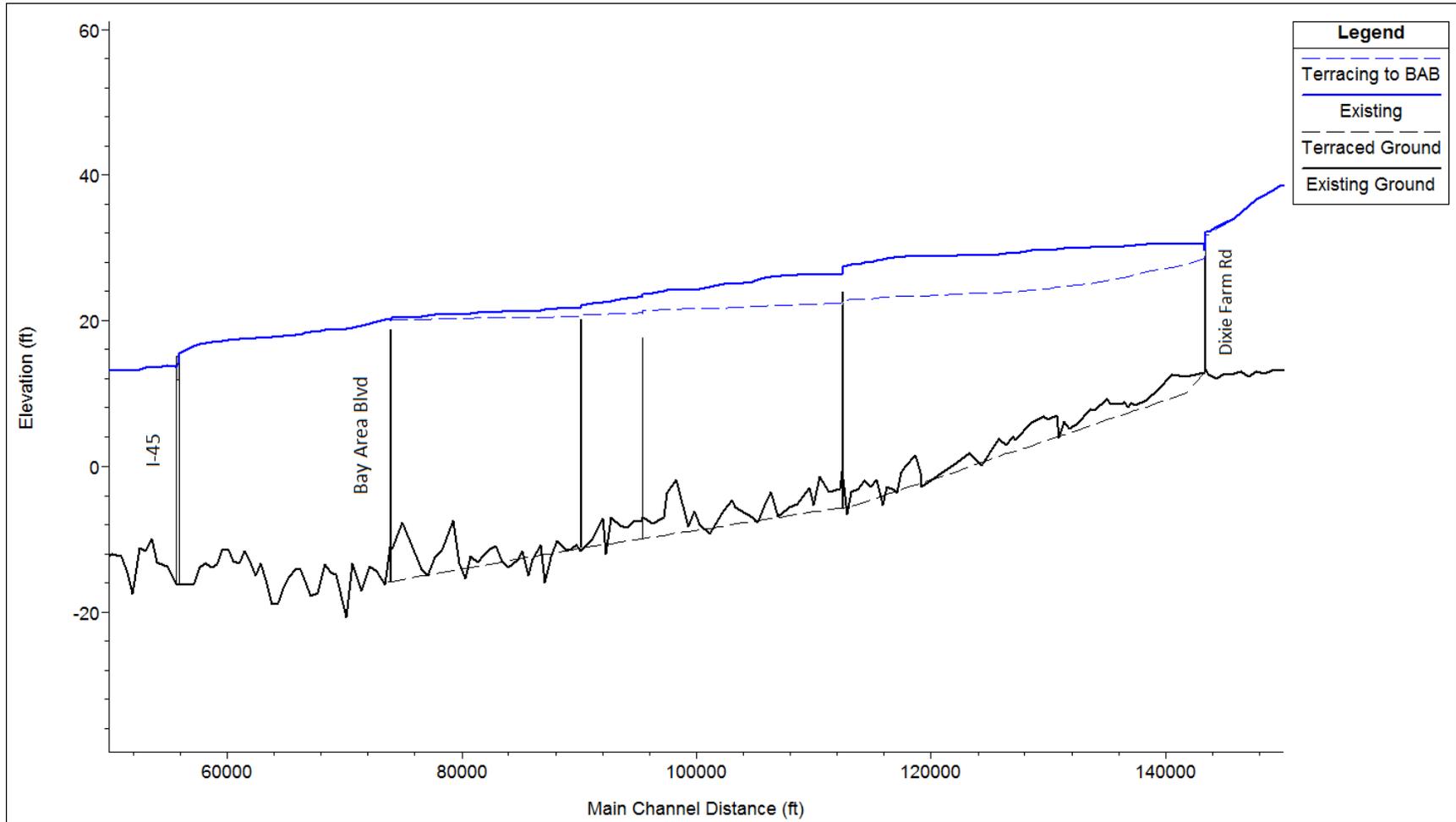
Three Bridge Removal



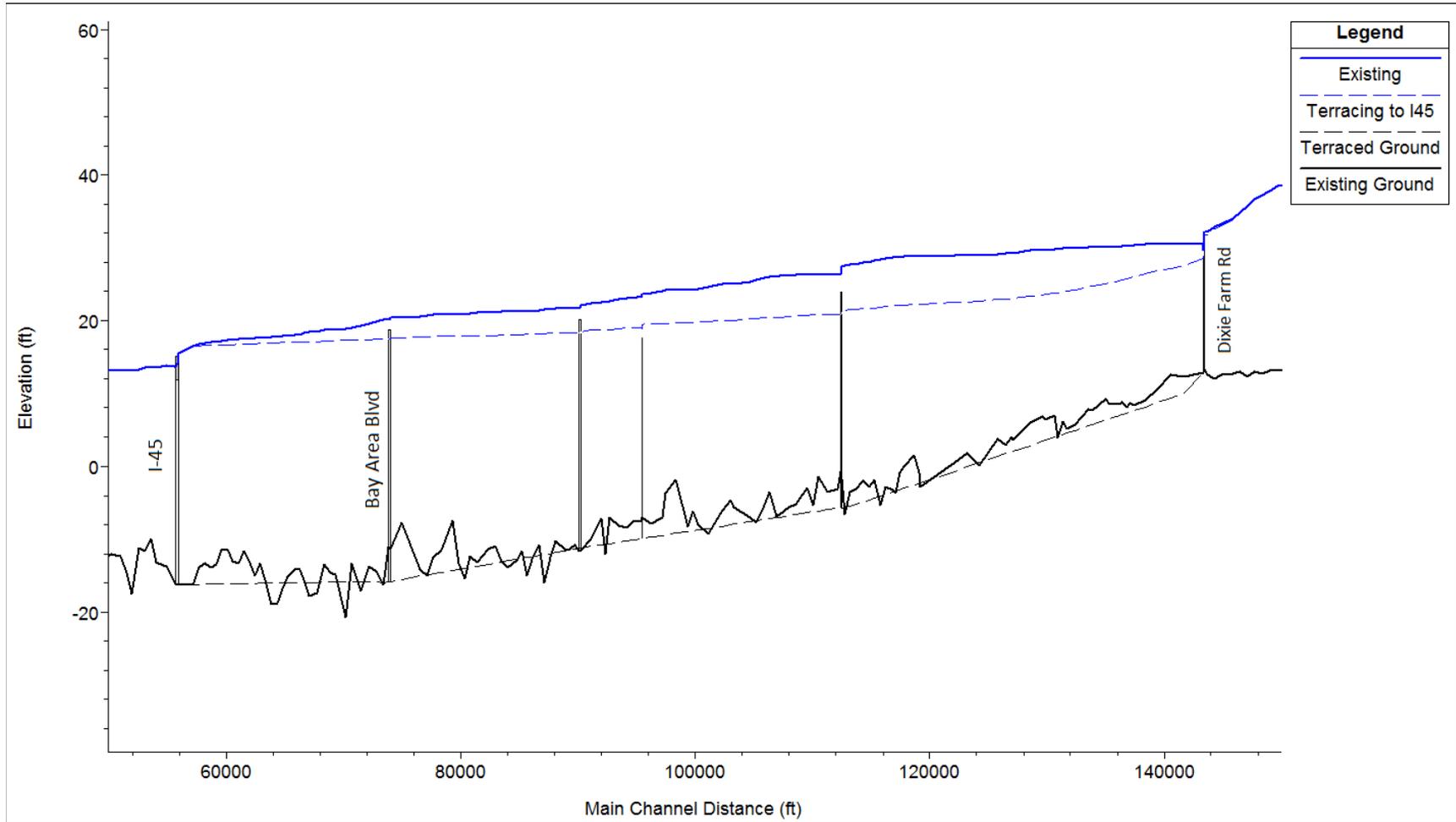
De-Snagging



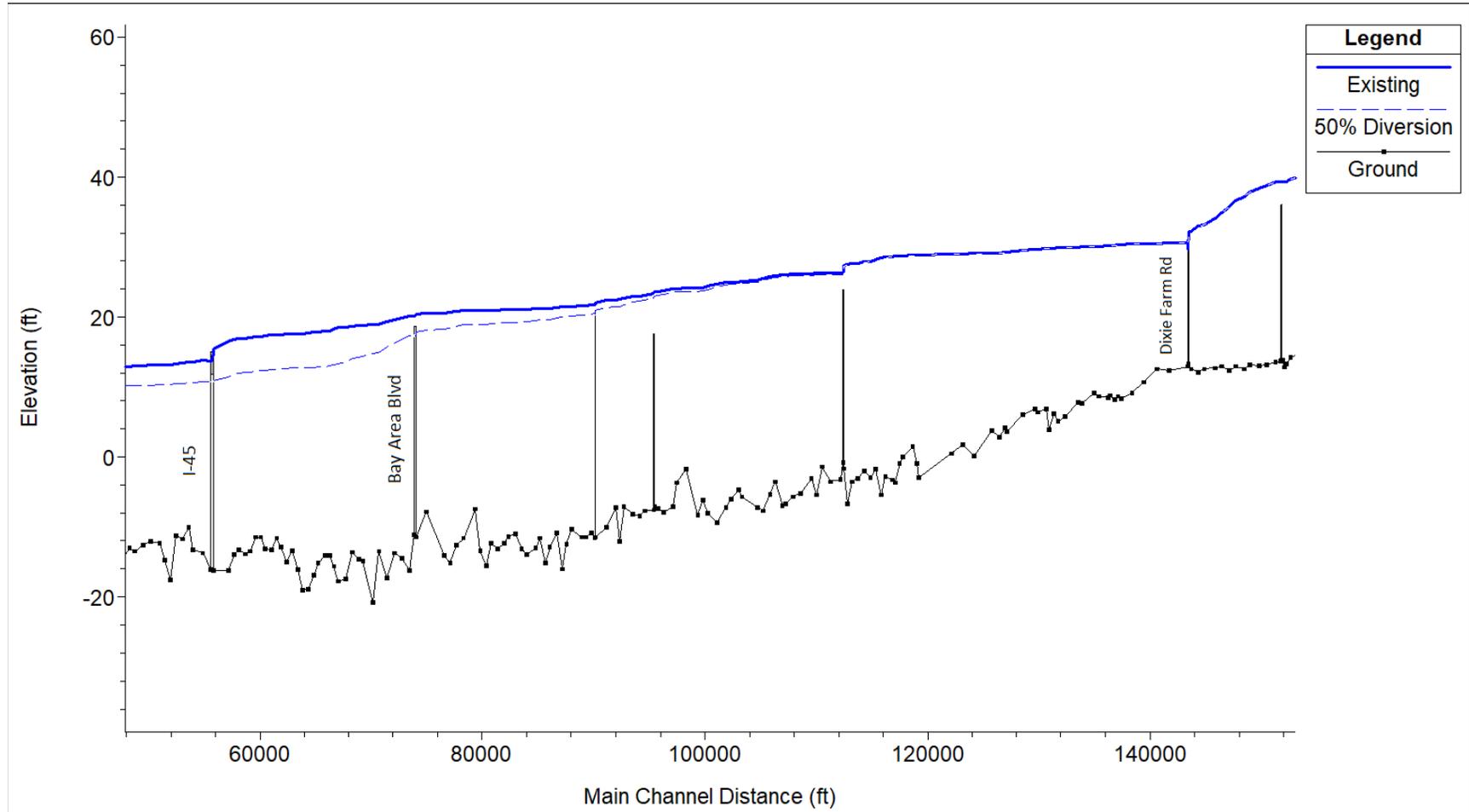
Terracing to Bay Area Blvd



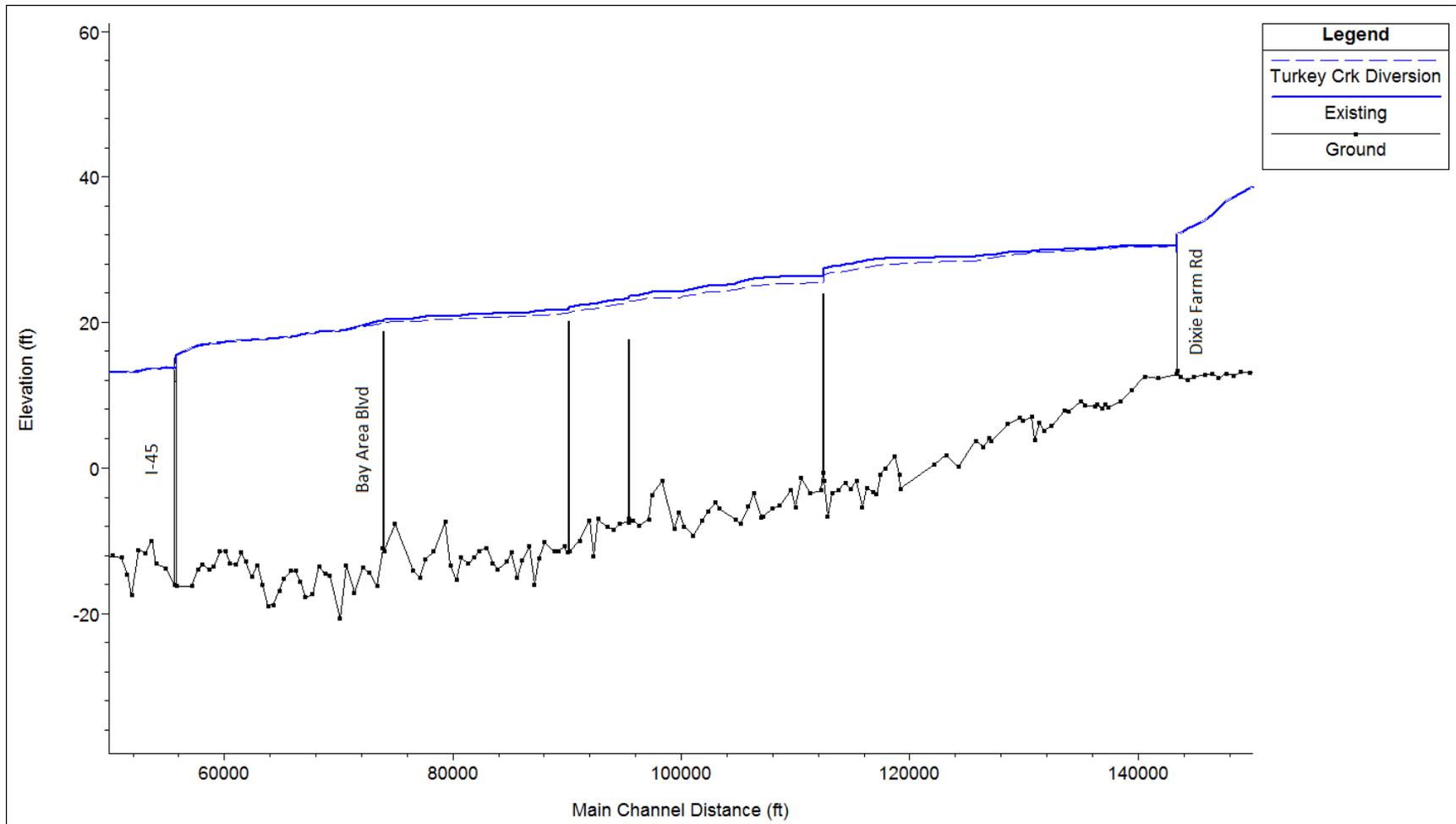
Terracing to I45



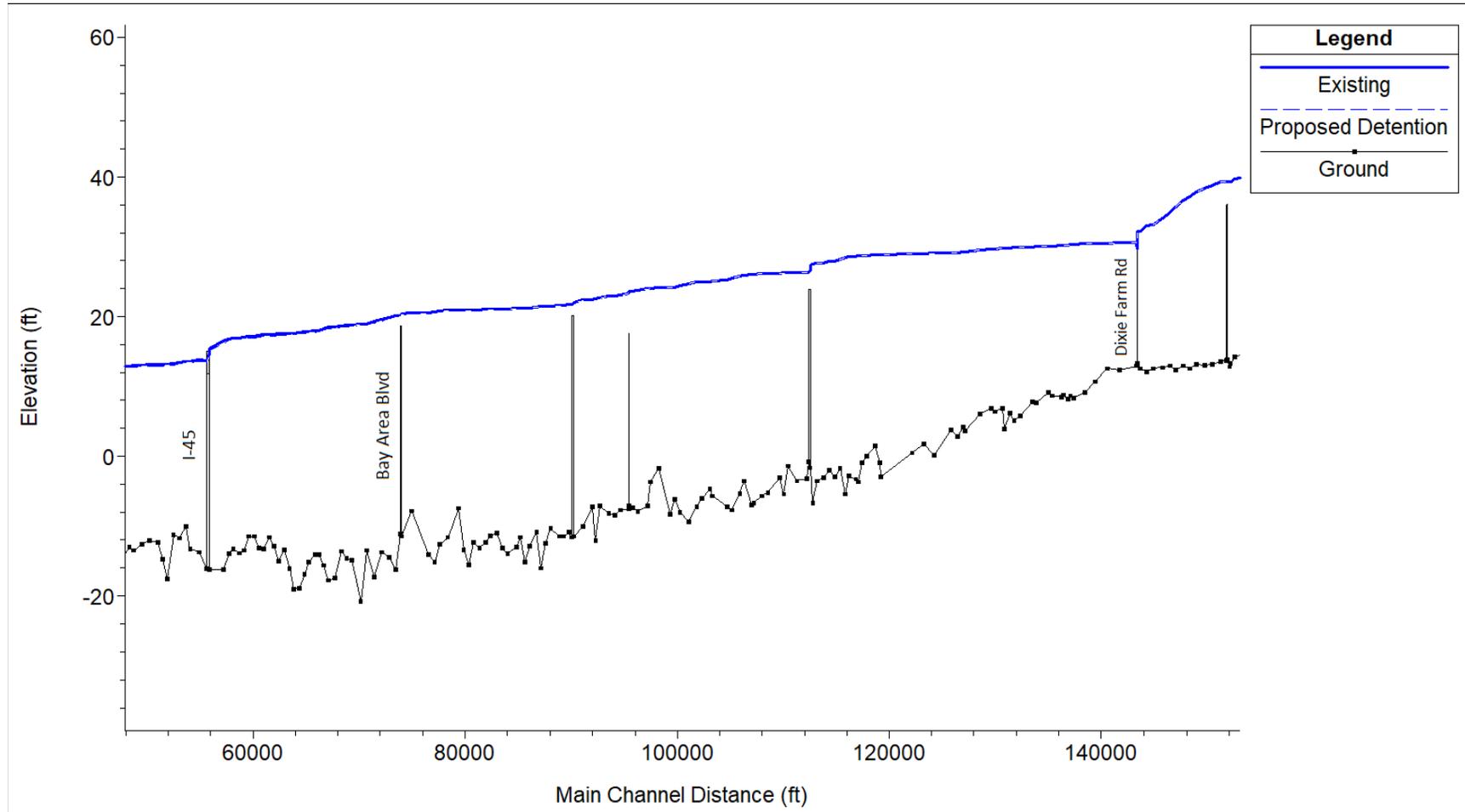
50% Diversion at Bay Area Blvd



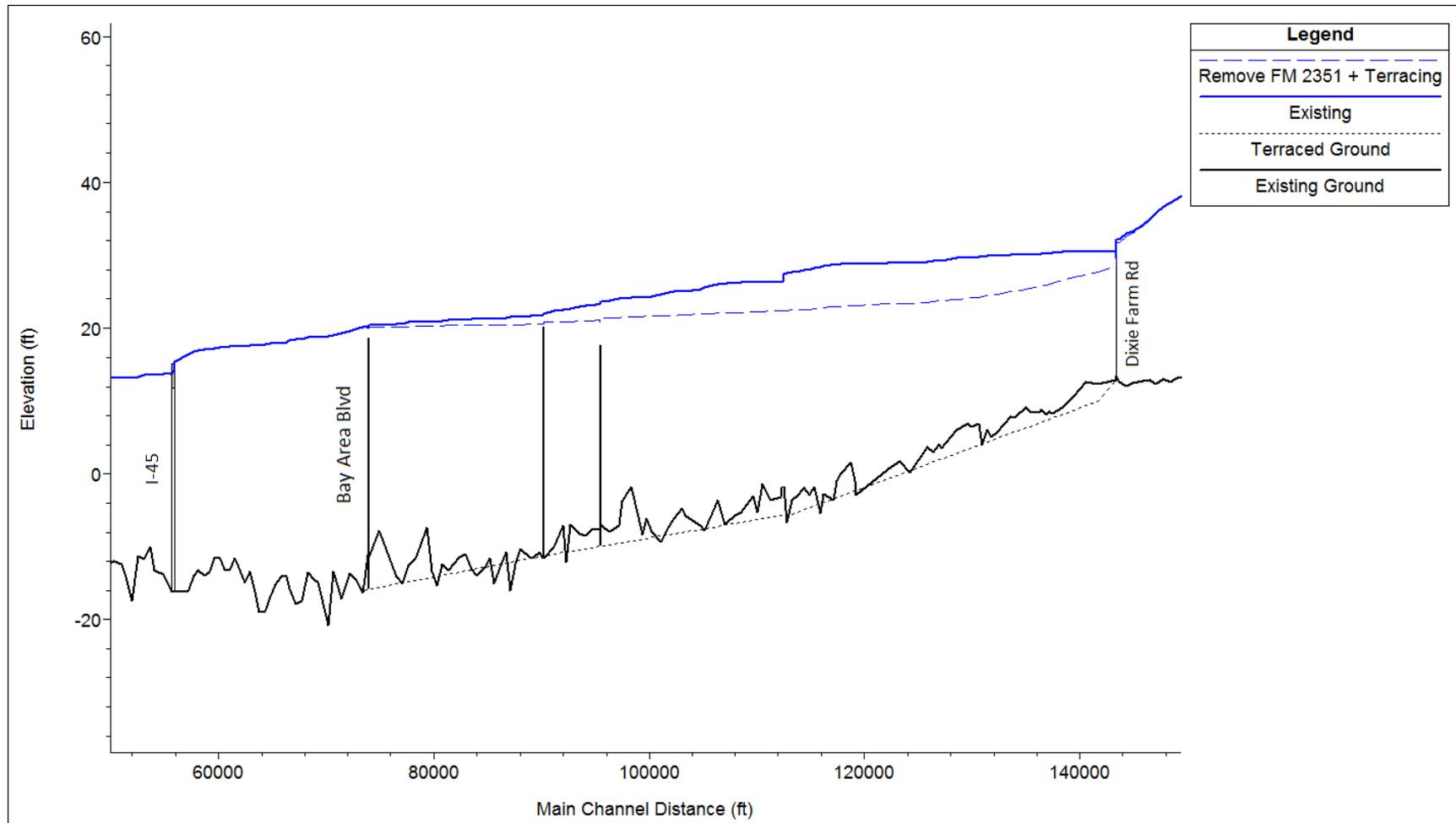
Turkey Creek Diversion to Bay Area Blvd



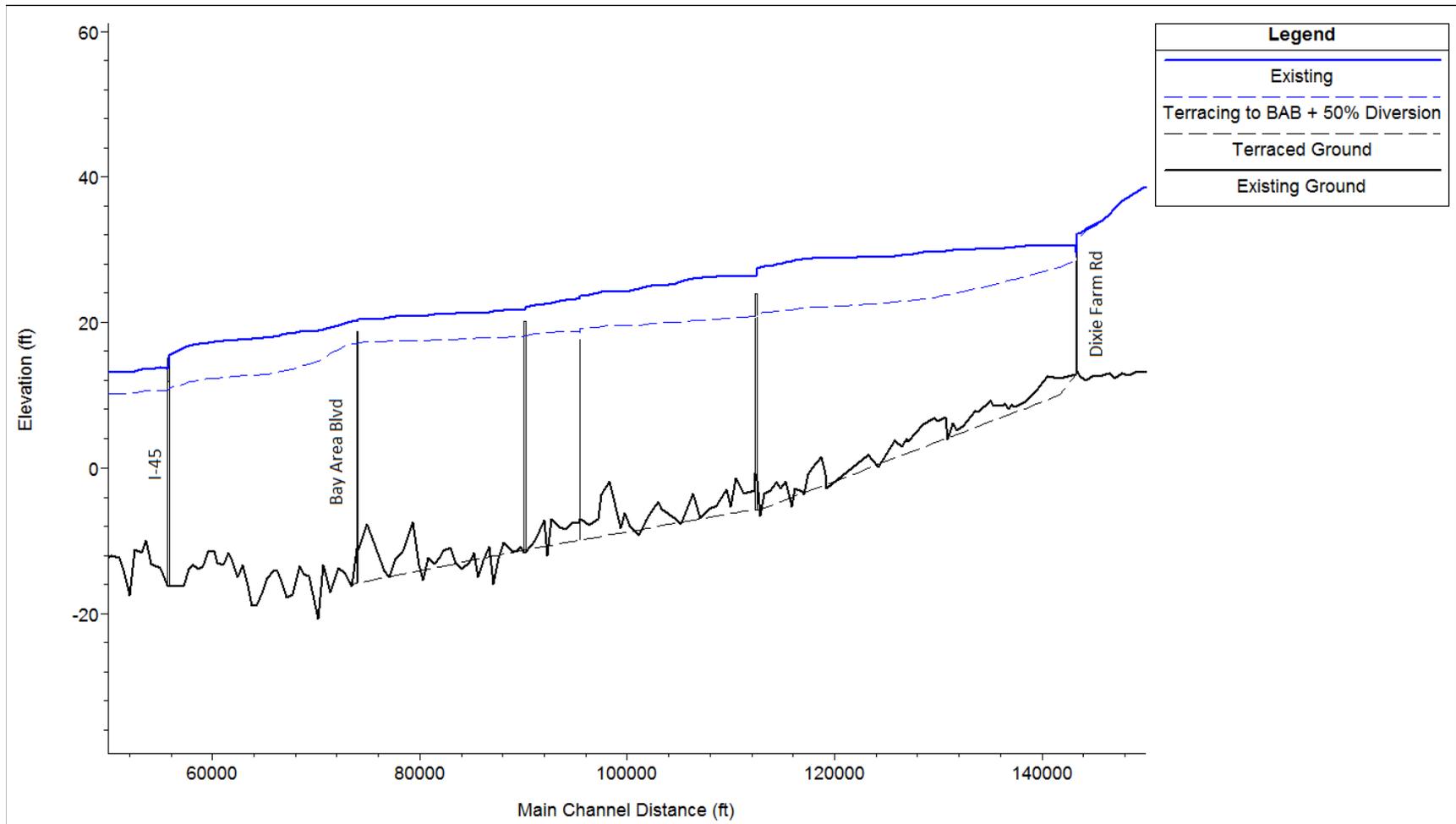
Detention Ponds



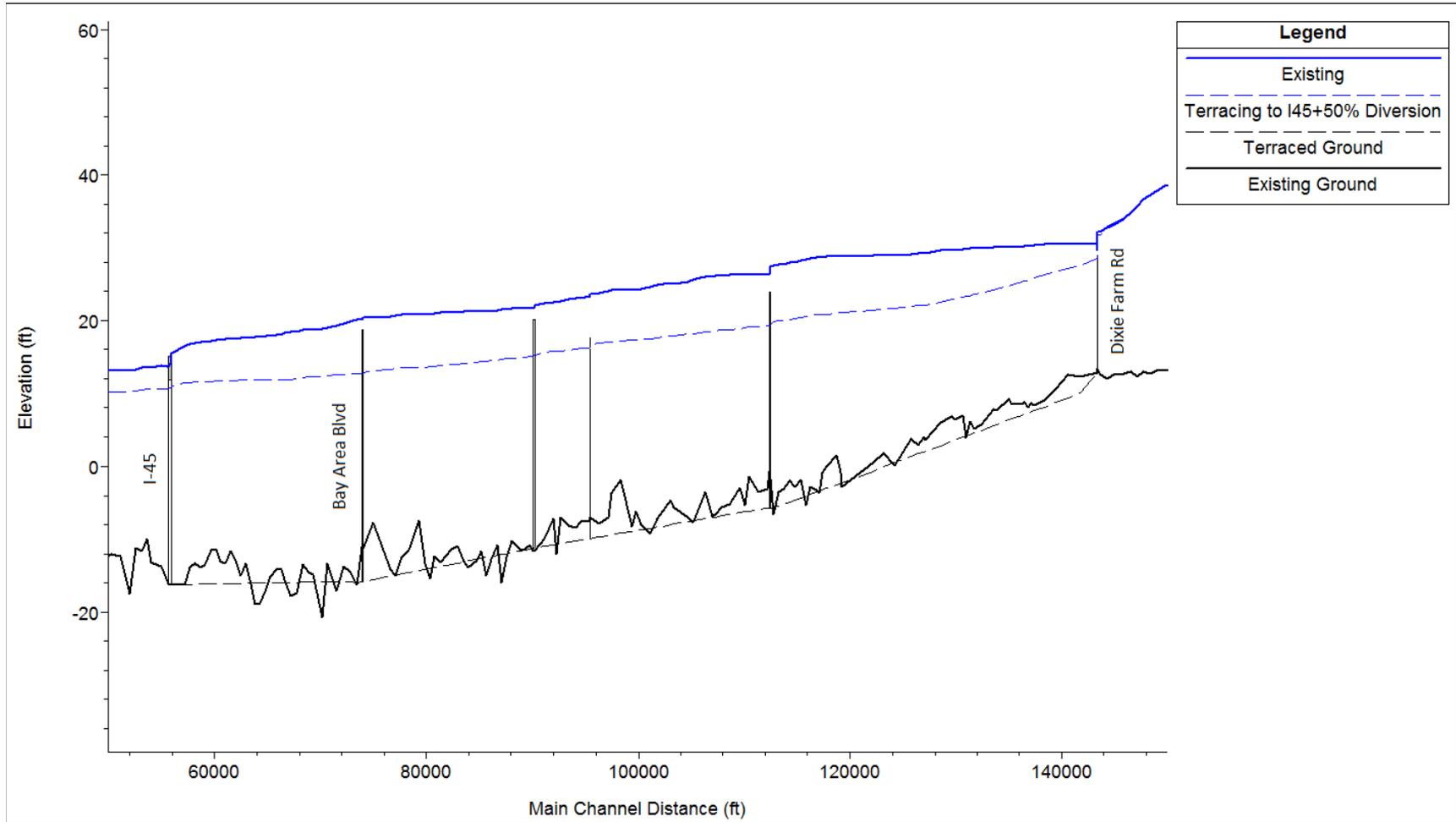
Bridge Removal + Terracing



Terracing to Bay Area Blvd + 50% Diversion at Bay Area Blvd

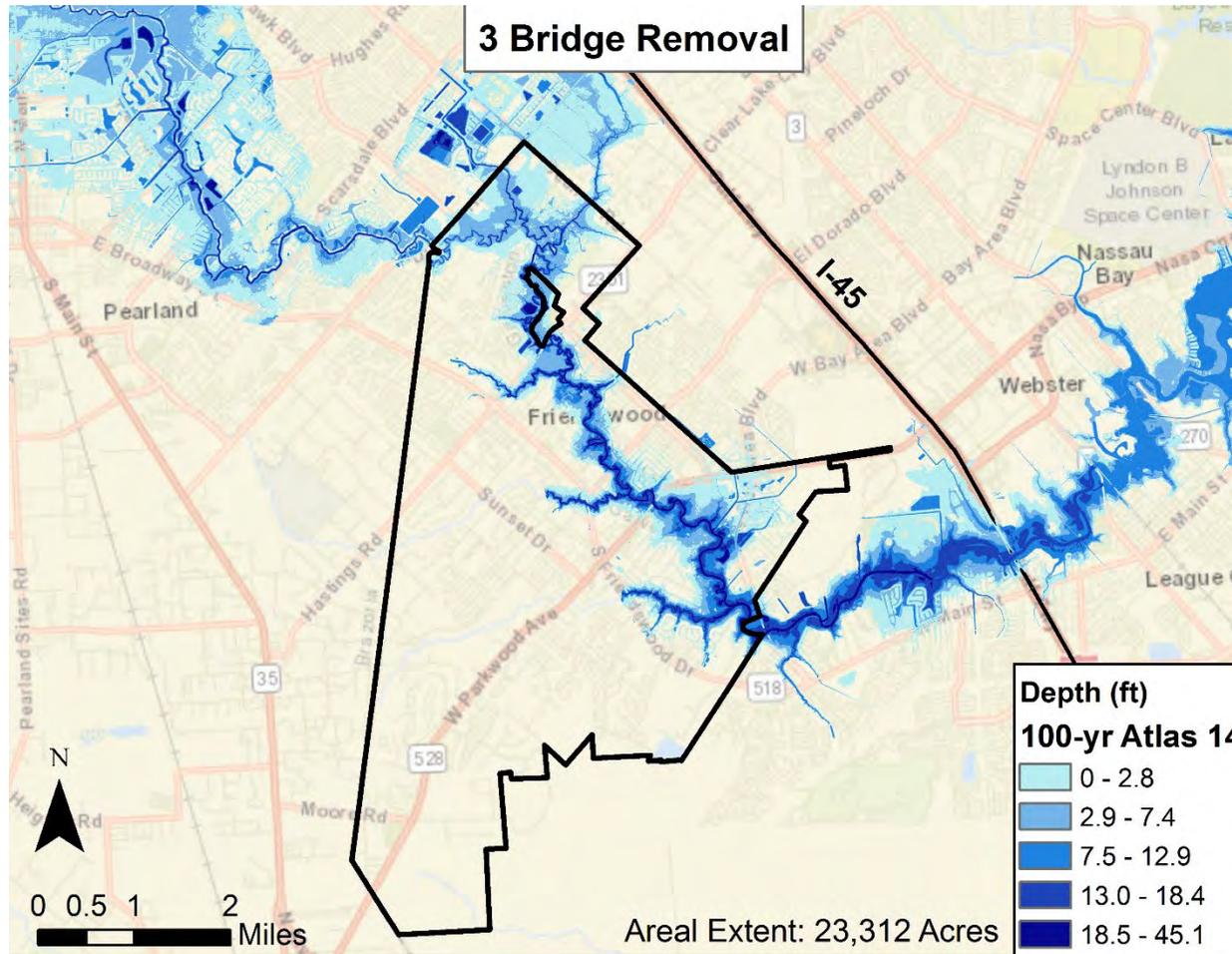


Terracing to I45 + 50% Diversion at Bay Area Blvd

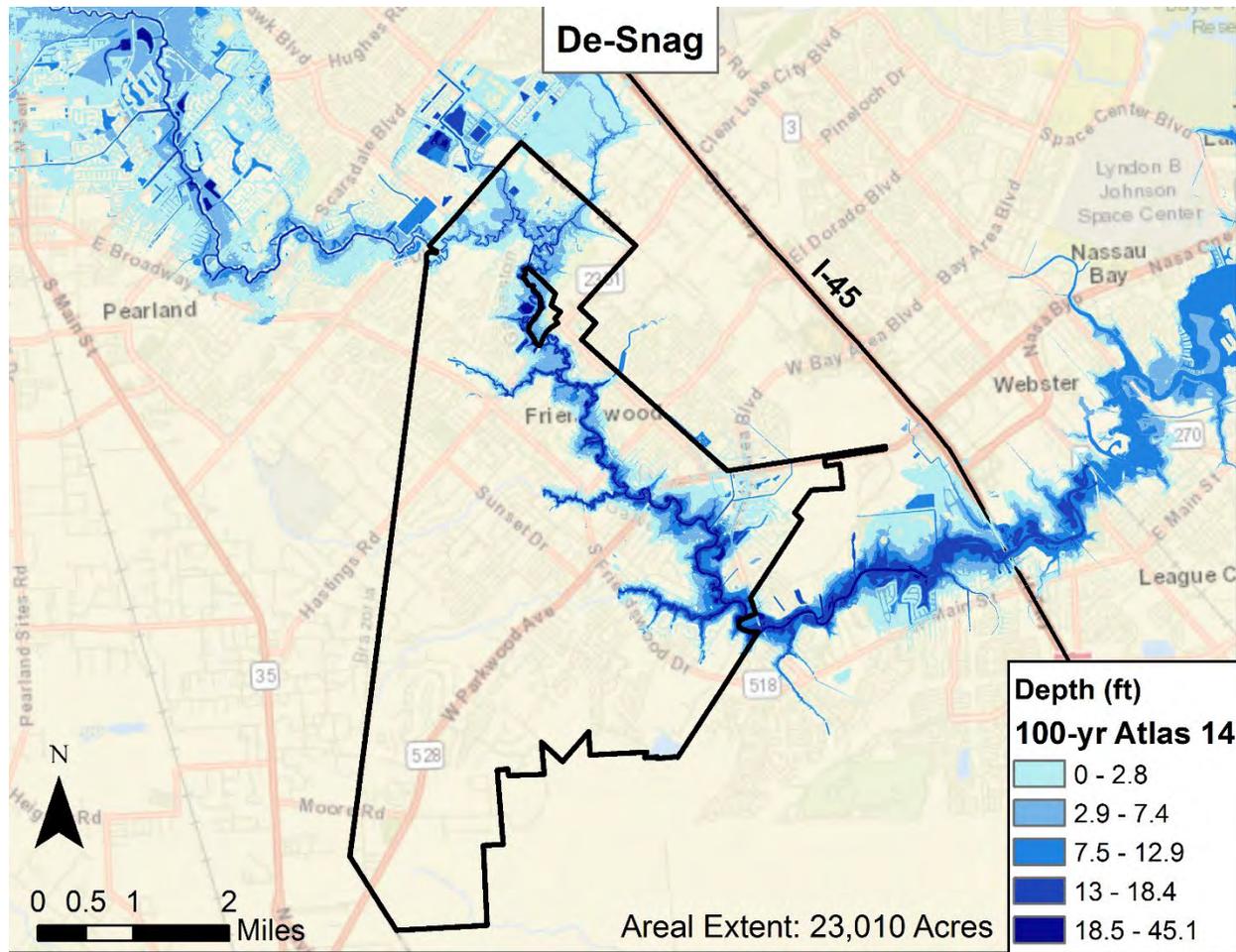


Appendix D: Floodplain Maps

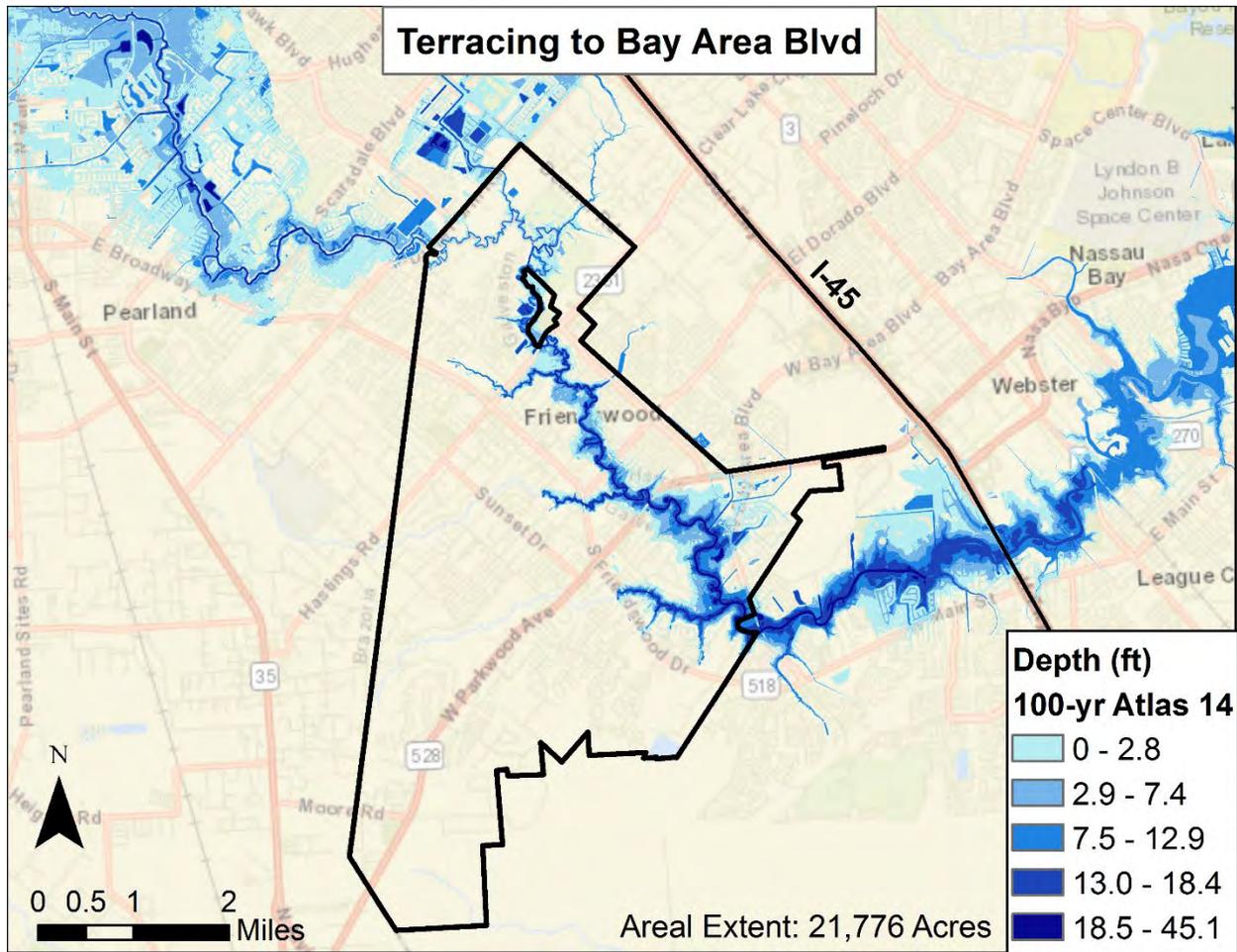
3 Bridge Removal



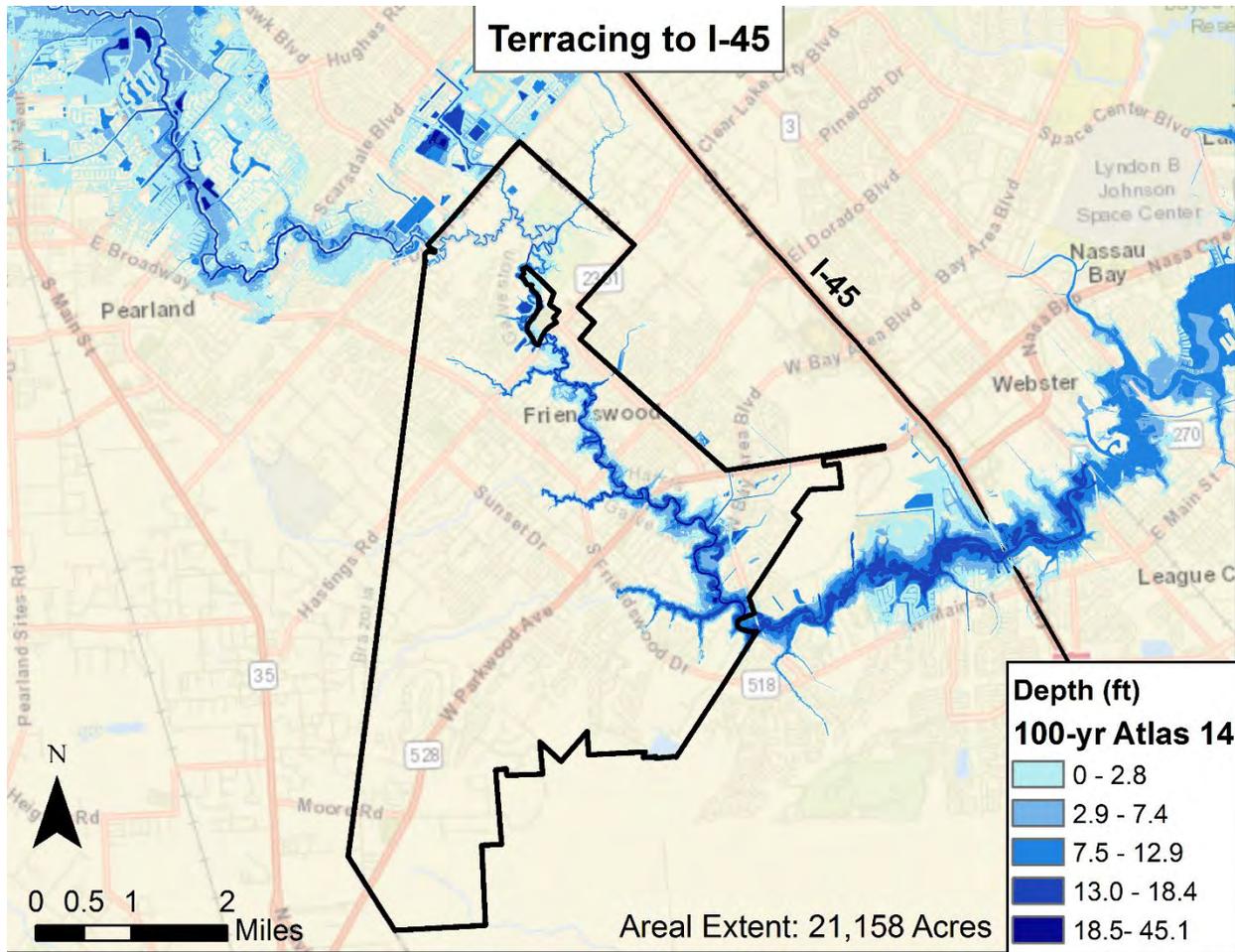
De-Snag



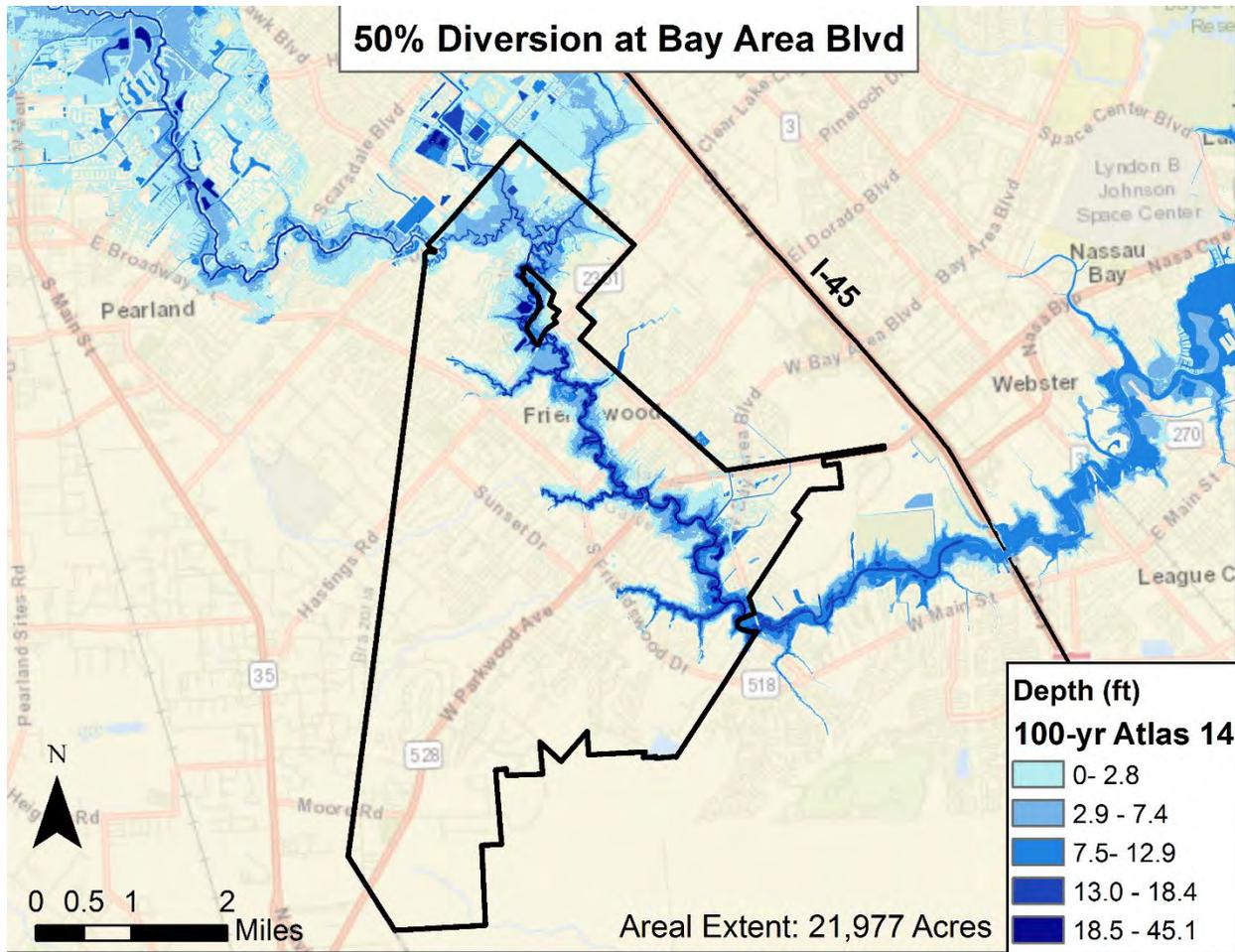
Terracing to Bay Area Blvd



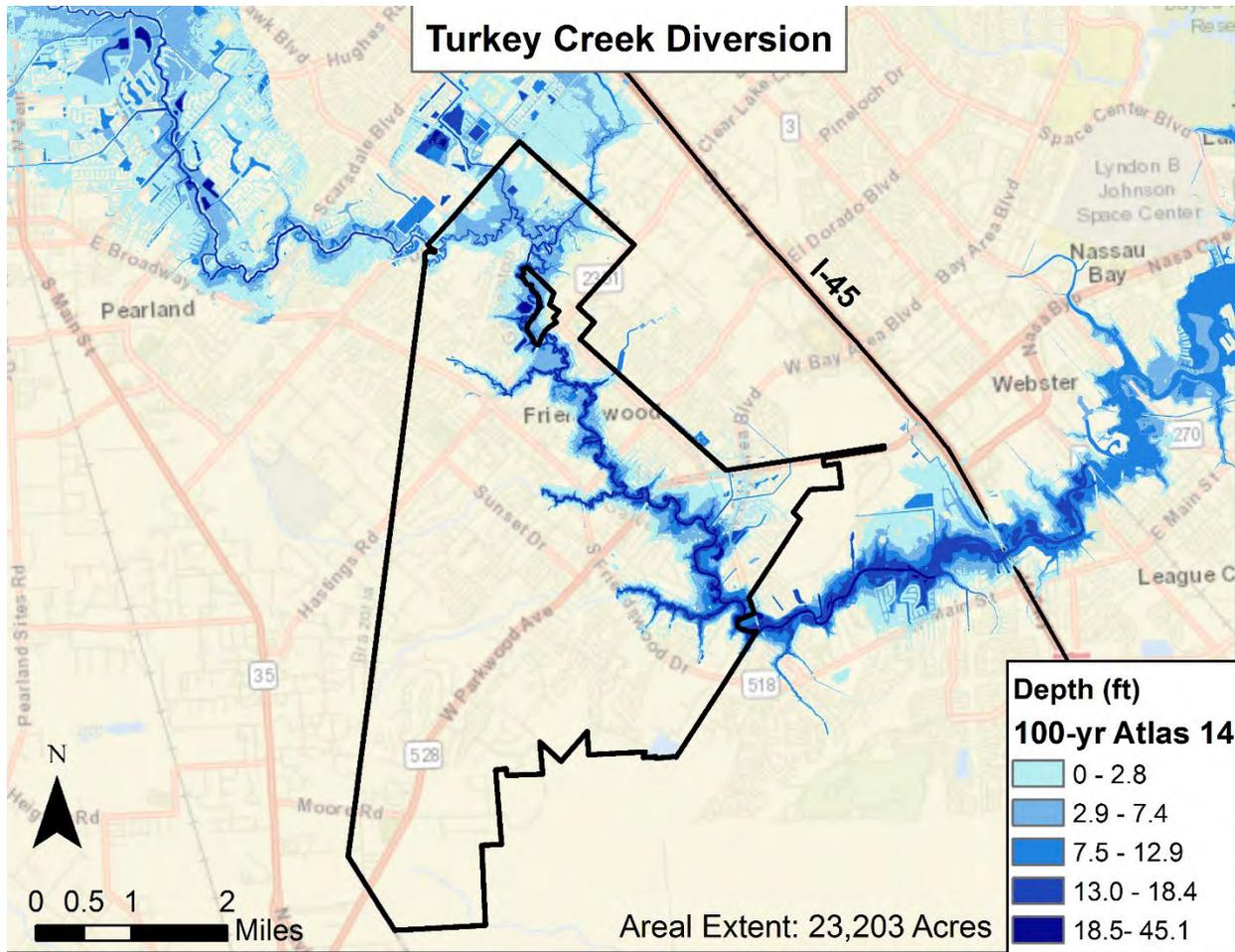
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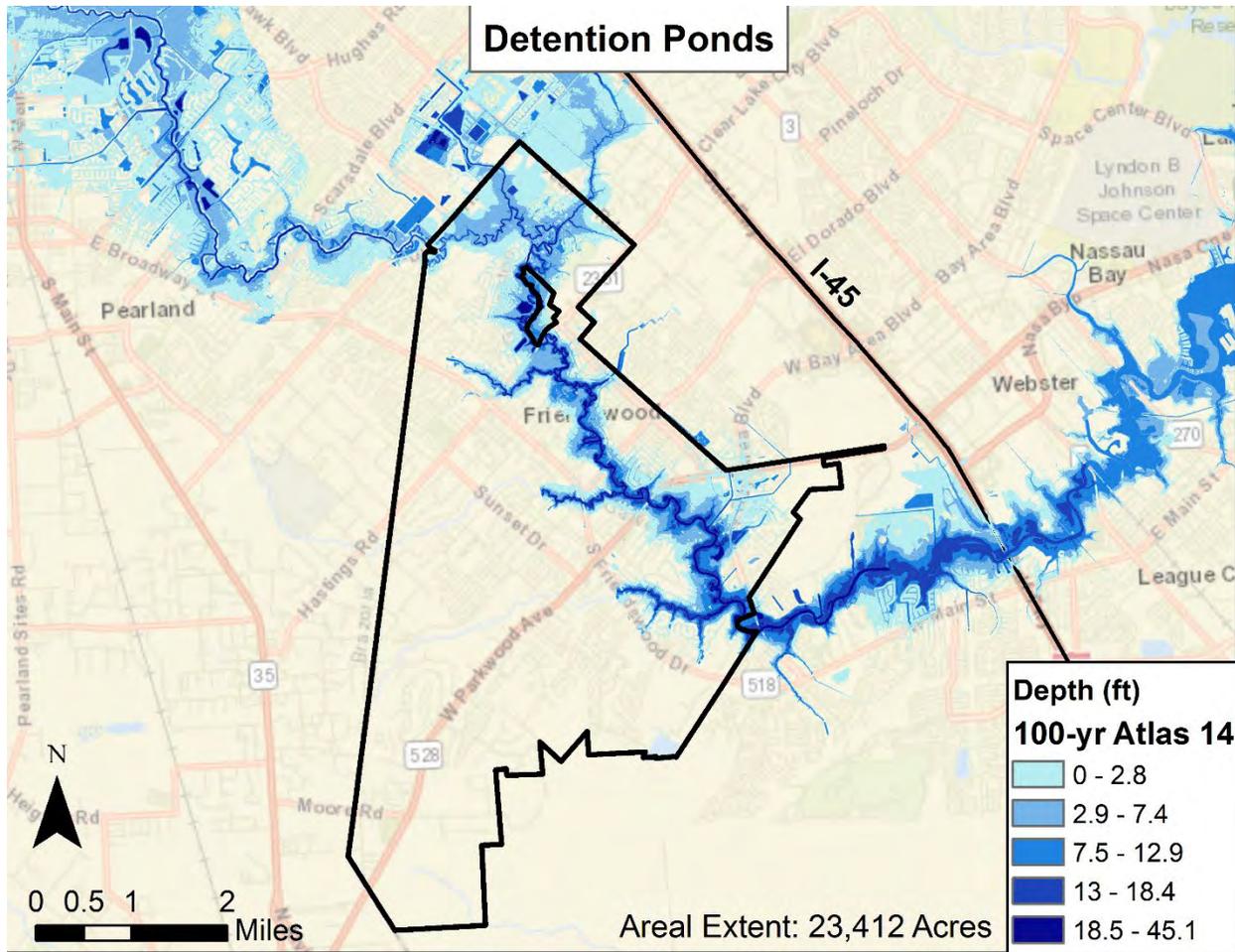
50% Diversion at Bay Area Blvd



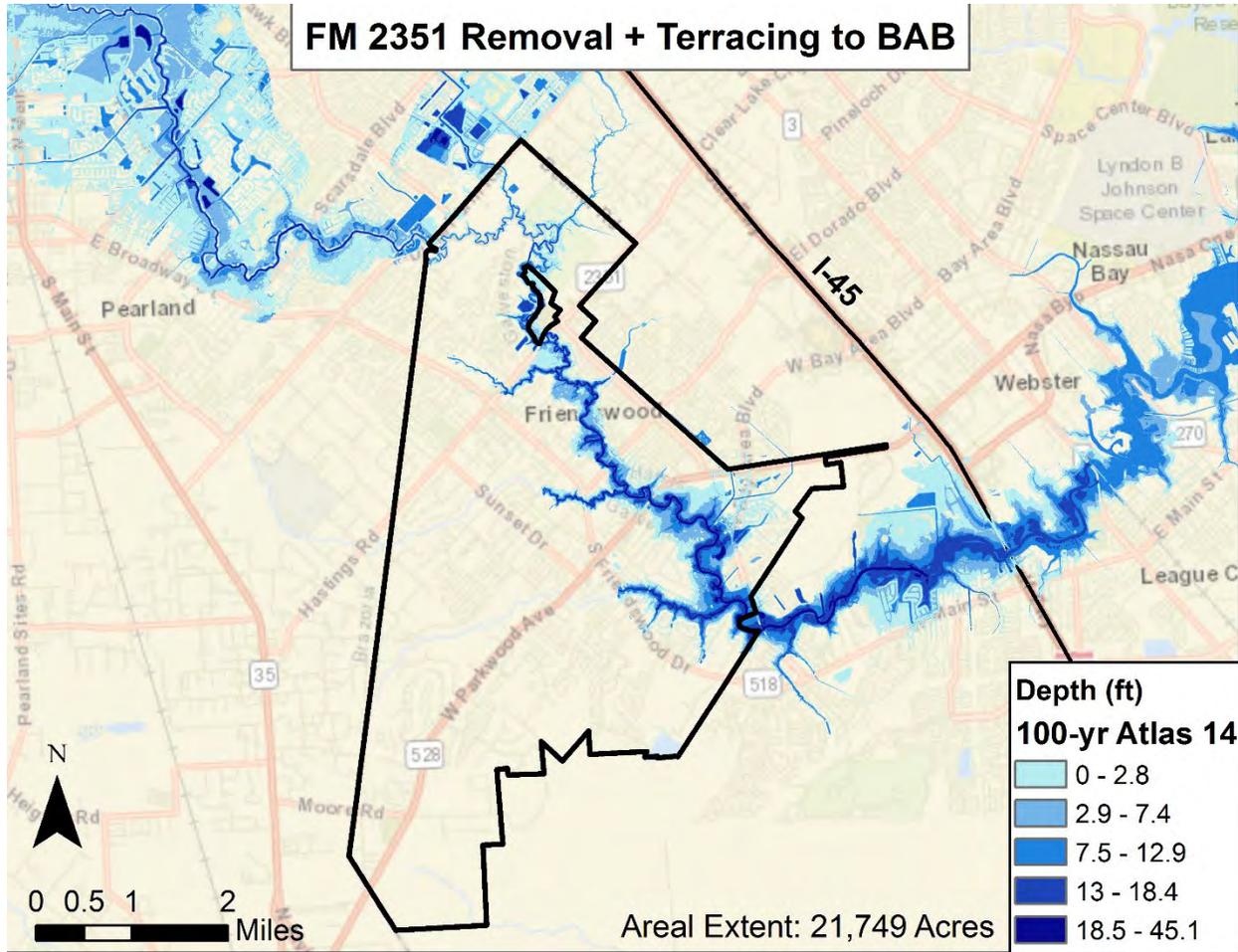
Turkey Creek Diversion



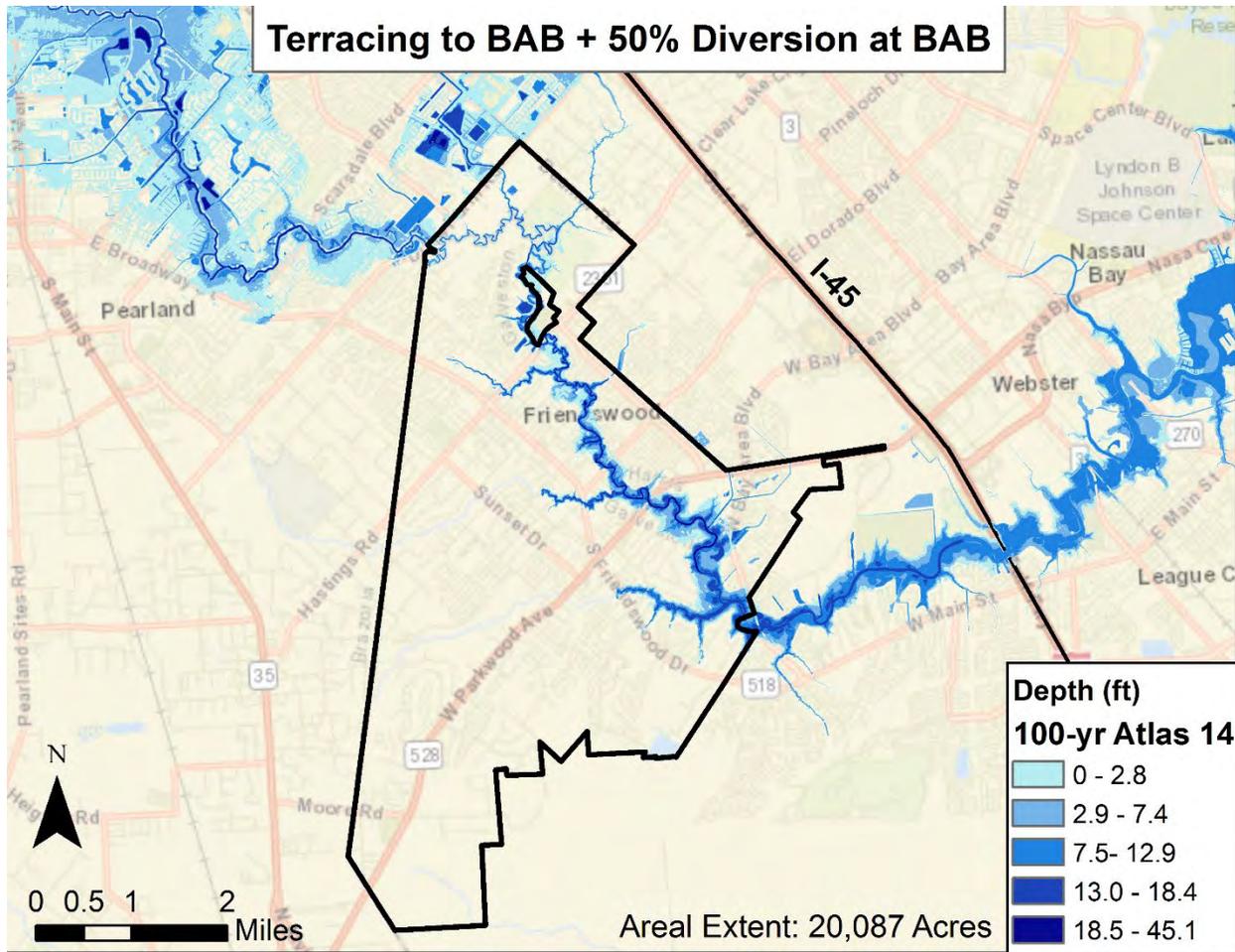
Detention Ponds



Bridge Removal + Terracing



Terracing to Bay Area Blvd + 50% Diversion at Bay Area Blvd



Terracing to I45 + 50% Diversion at Bay Area Blvd

