GREATER HOUSTON FLOOD MITIGATION CONSORTIUM

CYPRESS CREEK WATERSHED: ANALYSIS OF FLOODING & STORAGE OPTIONS

SSPEED Center - Rice University
Texas Southern University

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Definitions and Abbreviations

AEP	Annual Exceedance Probability - the probability of a storm event exceeding a particular flood level in one year.
LID	Low Impact Development

GREATER HOUSTON
FLOOD MITIGATION CONSORTIUM

Since the devastating blow of Hurricane Harvey in the greater Houston region,local jurisdictions have taken a hard look at their flood preparedness, from regulations to structural projects, and regional level projects to site specific solutions. However, significant vulnerabilities remain.

The Greater Houston Flood Mitigation Consortium convened after Hurricane Harvey to advance greater Houston's resiliency and to ensure that all communities benefit from flood mitigation efforts. This independent collaborative of expert researchers and community advocates is committed to compiling, analyzing and sharing a rich array of data about flooding risk and mitigation opportunities; and translating this data into information to engage the public and help guide and support decision-makers at all levels as they direct the Houston region's redevelopment. Consortium members are affiliated with local, regional and statewide universities, research centers and community organizations with deep expertise in hydrology, climate science, engineering, coastal resiliency, energy, community development and urban planning. Houston-based Huitt-Zollars, a planning, engineering and architectural firm, manages the consortium.

The consortium is focusing its work on Harris County's 22 watersheds, several of which extend to surrounding counties. The consortium will complete its work in mid 2019.

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Foreword

By Earthea Nance | Texas Southern University

This report is a hydrological study of the Cypress Creek watershed. Its findings include the ways that development activities upstream have far-reaching flood impacts downstream. This raises equity concerns that are directly related to the report findings and should inform further work in this watershed.

Equity analysis is not usually included in watershed studies of this type. However, equity concerns have arisen for several reasons. The Consortium identified the possibility of inequitable flood impacts in its first report ("Strategies for Flood Mitigation in Greater Houston," April 2018), and this memo translates those general concerns to the specific conditions described in the Cypress Creek Study. Specifically, the Consortium pointed out inequities in benefit-cost methodology that is typically used to assess mitigation projects, and the Consortium suggested tools such as social impact assessment to measure the extent of impact.

Subsequent to the issuance of the Consortium's first report, the Greater Houston population voted overwhelmingly for a $2.5 billion bond measure for flood mitigation investments. Included in the bond measure was a set of "Equity Guidelines" (https://www.hcfcd.org/2018-bond-program/equity-guidelines/) to ensure "equitable expenditure of funds." Harris County Flood Control District is developing methods for prioritizing investments in the bond projects based on the following evaluation criteria: drainage conditions, lack of service, flood risk reduction, maintenance costs, environmental impacts, potential benefits, project efficiency, and partnership funding. While these equity evaluation methods are still in draft form and remain untested, they have opened the door to public debate about how the concept of equity should be applied to flood mitigation in Greater Houston.

Using best available science, the authors of the Cypress Creek study have found disparate impacts in the watershed in terms of flood risk (measured as elevation, flow rate, and storage required under different flood event return intervals). Their main take-home point is that development activities upstream have had far-reaching flood impacts downstream. Additionally, the Consortium's development regulations paper concluded that equity outcomes derive not just from infrastructure but from the policies and regulations that guide development. Both reports lead to the conclusion that these policies and development regulations have produced inequitable impacts.

These impacts likely include differential flood risk impacts based on geography, differential social impacts based on demographics, differential economic impacts based on wealth level, etc. A formal social impact analysis of the Cypress Creek Study findings would be an important and timely addition to public debate and official decision-making. Such an assessment should include the following elements.

Equity Definition – Adopt a practical definition of equity for use in Cypress Creek. There are many such definitions available. For example, types of equity include gender equity (freedom from bias between men and women), intergenerational equity (justice between generations), and racial/ethnic equity (absence of disparities in environmental burden by race and ethnicity). The meaning of equity is broad and can address traditionally disadvantaged groups (e.g., people of color, low income, immigration status, language, cultural discrimination, or geographic/social isolation) as well as other vulnerable groups, such as children and the elderly. Local stakeholders should be involved because context often determines social outcomes. The process itself will be inclusive of those most impacted and those most informed.

Economics – Estimate the cumulative indirect benefits received upstream resulting from policies and development regulations and the dis-benefits incurred downstream to date in the Cypress Creek watershed. Use these findings to prioritize projects, taking into account the known inequities built into federal benefit-cost analysis, which shaped past project decisions and disproportionately and adversely impact lower income areas. The Association of State Floodplain Manager's publication on the inequities built in to benefit-cost analysis will guide this analysis. Analyze the economic dis-benefits of new development to downstream residents, and use this to develop appropriate regulations for new development.

Demographics – Using the flood elevation results of the Cypress Creek study, determine the demographics of populations impacted by past flooding. Also determine the demographics of populations expected to be impacted by future flooding. Focus on people not just properties. The purpose of this analysis is to show the disproportionate burden of flood risk outcomes in the upstream and downstream areas of Cypress Creek. This graphical analysis will be guided by the method of Maantay and Maroko (2009).

The principles of inclusion and interdisciplinarity will be used in forming a team to conduct this assessment. Expertise in environmental justice, environmental sociology, environmental hazards, environmental economics, environmental geography, environmental impact assessment, and urban studies are most relevant.

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Executive Summary

The flooding from Hurricane Harvey in August 2017 was extensive and devastating throughout the greater Houston area. This was especially true in the far western portion of the region, such as the Katy Prairie area, which also includes the watersheds of Addicks, Barker and upper Cypress Creek. Tens of thousands of homes flooded in these watersheds, with most of them being located within the Addicks and Barker reservoirs. The subsequent releases of stored floodwaters from Addicks and Barker reservoirs, when their gates were eventually opened, led to further flooding of thousands of homes downstream along Buffalo Bayou. A significant amount of the floodwaters that entered the Addicks reservoir came from overflows from the upper Cypress Creek watershed. This flood event, with over 30 inches of rain, could have been far worse had it received the more than 50 inches of rain that occurred in the southeastern part of Harris County.

There has been discussion among local stakeholders and agencies of a "third reservoir" or additional storage in this area of Harris County to supplement the storage capacity of the two reservoirs and help relieve some of the flooding issues that were experienced during Harvey, or have the potential to be experienced from a Harvey-type storm event in the future. These discussions and studies also focused on the "overflow" that occurs from the upper Cypress Creek watershed into the Addicks watershed during major rain events. This overflow increases the volume of water entering Addicks reservoir while providing some flood relief in the rest of the Cypress Creek watershed.

The purpose of this study was to investigate the possibility of adding more storage capacity in the western portion of the Greater Houston area (i.e., upper Cypress Creek) not only to reduce the flooding potential for the Addicks and Barker watersheds, but also to potentially help mitigate flows being released into Buffalo Bayou, as well as floodwaters being transported down Cypress Creek.

Over the years, land development has progressed westward/upstream in the Cypress Creek watershed with very little channel improvements or upstream storage added for necessary mitigation controls. Thus, major floods have occurred along the middle and lower portions of this creek, the most noteworthy being the recent damaging floods of both the 2016 Tax Day Flood , with up to 17 inches of rain, and Hurricane Harvey.

The study team obtained and used hydrologic and hydraulic computer models available from the Harris County Flood Control District (HCFCD) covering the Cypress Creek watershed. These models were revised and updated to incorporate more recent data, including the use of two-dimensional capabilities of the HEC-RAS hydraulic model from the U. S. Army Corps of Engineers. These models provide the ability to investigate how this watershed responds to rainfall events, such as Harvey and the flooding along Cypress Creek that results from such rains.

The hydrologic and hydraulic model analyses conducted for this study revealed where the Cypress Creek flooding originates and the difficulties in attempting to reduce or eliminate such flooding. While there are flooding issues all along Cypress Creek, from its outlet into Spring Creek up to the overflow area in the upper portion that spills over into the Addicks watershed, solving these issues would require a combination of alternative concepts. This study focused on the flooding that originates in the upper portion of the Cypress Creek watershed, which contributes significantly to flood flows entering into the Addicks reservoir by diverting these flows away from going downstream along Cypress Creek. Thus, any solution to preventing such flood flows from entering the Addicks reservoir, and eventually into Buffalo Bayou, will require mitigation such that these flood flows do not increase the flooding issues along Cypress Creek.

Various storage options were analyzed in the upper Cypress Creek watershed, along with constructing a levee along the south side of the creek to prevent any overflows from leaving this watershed and entering into the Addicks reservoir. While these options were effective in confining these flood flows within the Cypress Creek watershed, the magnitude of these flows required considerable storage capacity to limit the outflows into the remainder of Cypress Creek to the flow capacity of the creek. Yet, as additional local runoff would continue to enter the creek further downstream, this local runoff would still produce flooding along the creek consistent with the current magnitude seen today. Thus, flood reduction measures would be needed along the entire creek to fully address the existing flooding problems that have been experienced in these areas. Given the extent of the existing development in the middle and lower portions of the Cypress Creek watershed, there are few opportunities for providing storage capacity in these areas without significant buyout of private properties.

Channel improvements or an underground tunnel system may be a more viable option for these lower areas, but even these options would require storage mitigation measures due to the increase in flow rates caused by implementing such options.

While the existing flooding problems along Cypress Creek need to be more fully analyzed and then resolved, there is the need to prevent new development in this watershed from aggravating these existing problems. The watershed's remaining undeveloped lands, which are primarily in the upper portion of the watershed, provide considerable natural detention/retention functions that greatly benefit downstream properties. These functions need to be preserved, either as new development occurs or by conserving and/or enhancing the existing undeveloped lands, especially native prairie lands. Most of the undeveloped lands are located in the upper portion of the Cypress Creek watershed, where considerable development pressure is occurring, especially along the Highway 290 and Highway 99 corridors. There is a need to ensure that any new development is maintaining the existing natural flow rates, leaving the site so that downstream properties are not adversely impacted.

In summary, this study reached the following overall conclusions:

1. An upper Cypress Creek watershed levee and reservoir(s) can reduce or eliminate the overflow to Addicks reservoir; however, these projects will not significantly reduce the major source of downstream flooding along the middle and lower portions of Cypress Creek.

2. There are few viable locations for major detention storage in the middle and lower portions of the Cypress Creek watershed; as a result, other alternatives may need to be pursued, such as buyouts and/or channel improvements in the lower/middle watershed (tunnels may be possible), with appropriate mitigation as needed.

3. To prevent flooding along Cypress Creek and the overflow to Addicks from getting worse, undeveloped land in the upper watershed should be preserved, or at a minimum, increased measures should be taken to prevent new development from increasing downstream flows above existing rates.

Introduction

The flooding from Hurricane Harvey in August 2017 was extensive and devastating throughout the greater Houston area. This was especially true in the far western portion of the region, such as the Katy Prairie area, which also includes the watersheds of Addicks, Barker and upper Cypress Creek. Tens of thousands of homes flooded in these watersheds, with most of them being within the Addicks and Barker watersheds. The subsequent releases of stored floodwaters from Addicks and Barker reservoirs, when their gates were eventually opened, led to further flooding of thousands of homes downstream along Buffalo Bayou. A significant amount of the floodwaters that entered the Addicks reservoir came from overflows from the upper Cypress Creek watershed. This flood event, with over 30 inches of rain, could have been far worse had it received the more than 50 inches of rain that occurred in the southeastern part of Harris county.

For example, there is a real concern as to the potential for even greater catastrophic flooding than during Harvey if either Addicks or Barker dams were to fill high enough so as to release excessive amounts of water over their uncontrolled spillways, or even worse, if these dams were to fail, given the amount of stress put on these dams when they get full. In addition to downstream concerns, there would be an even greater number of homes flooded upstream of these dams than we saw during Harvey if they were to reach full capacity. Furthermore, an "overflow" that occurs from the upper Cypress Creek watershed into the Addicks watershed during major rain events further increases the volume of water entering Addicks reservoir while providing some flood relief in the Cypress Creek watershed. As such, there has been talk of a "third reservoir" or additional storage in this area of Harris County to supplement the storage capacity of these two reservoirs and help relieve some of the flooding issues that were experienced during Harvey, or have the potential to be experienced from a Harvey-type storm event in the future while not increasing flood water levels on Cypress Creek, which has its own flooding problems.

Thus, the purpose of this study was to investigate at a high level the possibility of adding more storage capacity in the western portion of the Greater Houston area (i.e., upper Cypress Creek) not only to reduce the flooding potential for the Addicks and Barker watersheds, but also to potentially help mitigate flows being released into Buffalo Bayou via Addicks reservoir, as well as floodwaters being transported down Cypress Creek.

The scope of work for this study consisted of the following six tasks:

1. Investigating the flood control benefits and potential impacts of building additional detention storage in the upper portion of Cypress Creek, such as a few (e.g. 3) medium sized reservoirs, or a number (e.g. 7) of smaller reservoirs distributed across the region;
2. Studying both current development and future land use conditions (using projections through 2040) in detail in these watersheds, and assessing the benefit of natural land preservation by comparing a status quo future development scenario with a "conservation" scenario that includes large areas of native prairie conservation;
3. Analyzing the following storm events to evaluate benefits of different detention scenarios: 10-year, 100-year, 500-year, 2016 Tax Day flood and Harvey, based on both rain gages and available rainfall-radar information;
4. Running HEC HMS and Vflo® models, described further in the Methodology section, to determine stream flow responses to rainfall in each watershed, along with the proposed reservoirs;
5. Running HEC RAS (both 1D and 2D) models, described further in the Methodology section to simulate the flood inundation dynamics and evaluate overflow issues from Cypress Creek into the Addicks reservoir area; and
6. Preparing a report summarizing the results of the above work and recommending future study that may be needed.

Background

The Cypress Creek watershed is located in northwest Harris County and extends slightly into Waller County, with the watershed's primary channel being Cypress Creek and Little Cypress Creek being its major tributary. The watershed area is shown in Figure 1. Cypress and Little Cypress creeks generally flow from west to east, with the main creek emptying into Spring Creek before it eventually enters into Lake Houston.

The Cypress Creek watershed area covers over 300 square miles and features over 250 miles of open streams (ref. HCFCD). Upper Cypress Creek is considered to be that portion upstream of the confluence with Little Cypress Creek, and consists of approximately 160 square miles. This study did not analyze flooding issues along Little Cypress Creek as it is currently under study by HCFCD

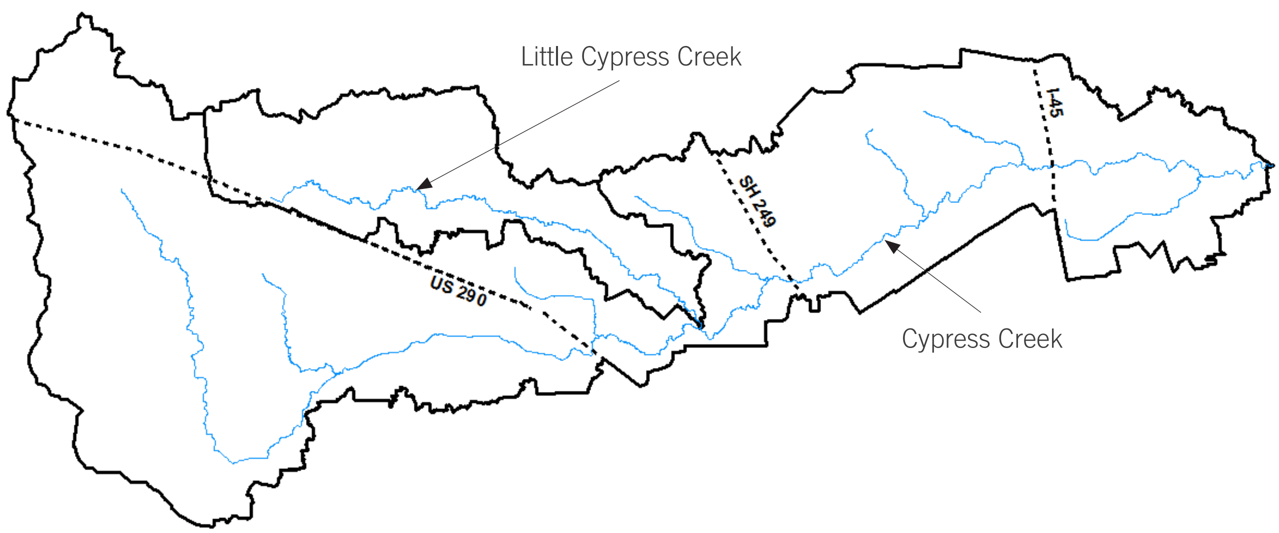


Figure 1: Cypress Creek Watershed Area

Over the years, land development progressed westward/upstream in the watershed with very little channel improvements or upstream storage added for necessary mitigation controls. Thus, major floods have occurred over the years along the middle and lower portions of these creeks, the most noteworthy being the recent damaging floods of April 2016 Tax Day flood with up to 17 inches of rain and Hurricane Harvey, with over 30 inches of rain as described earlier.

Current land use patterns within the Cypress Creek watershed are varied throughout, as shown in Figure 2. For example, the upstream portion mostly consists of agricultural (brown) and prairie/pasture/grasslands (yellow), including lands protected by the Katy Prairie Conservancy (KPC), a nonprofit land trust, while the middle and downstream portions of the watershed have become developed (red/brown/pink) in the last several decades for residential and commercial purposes.

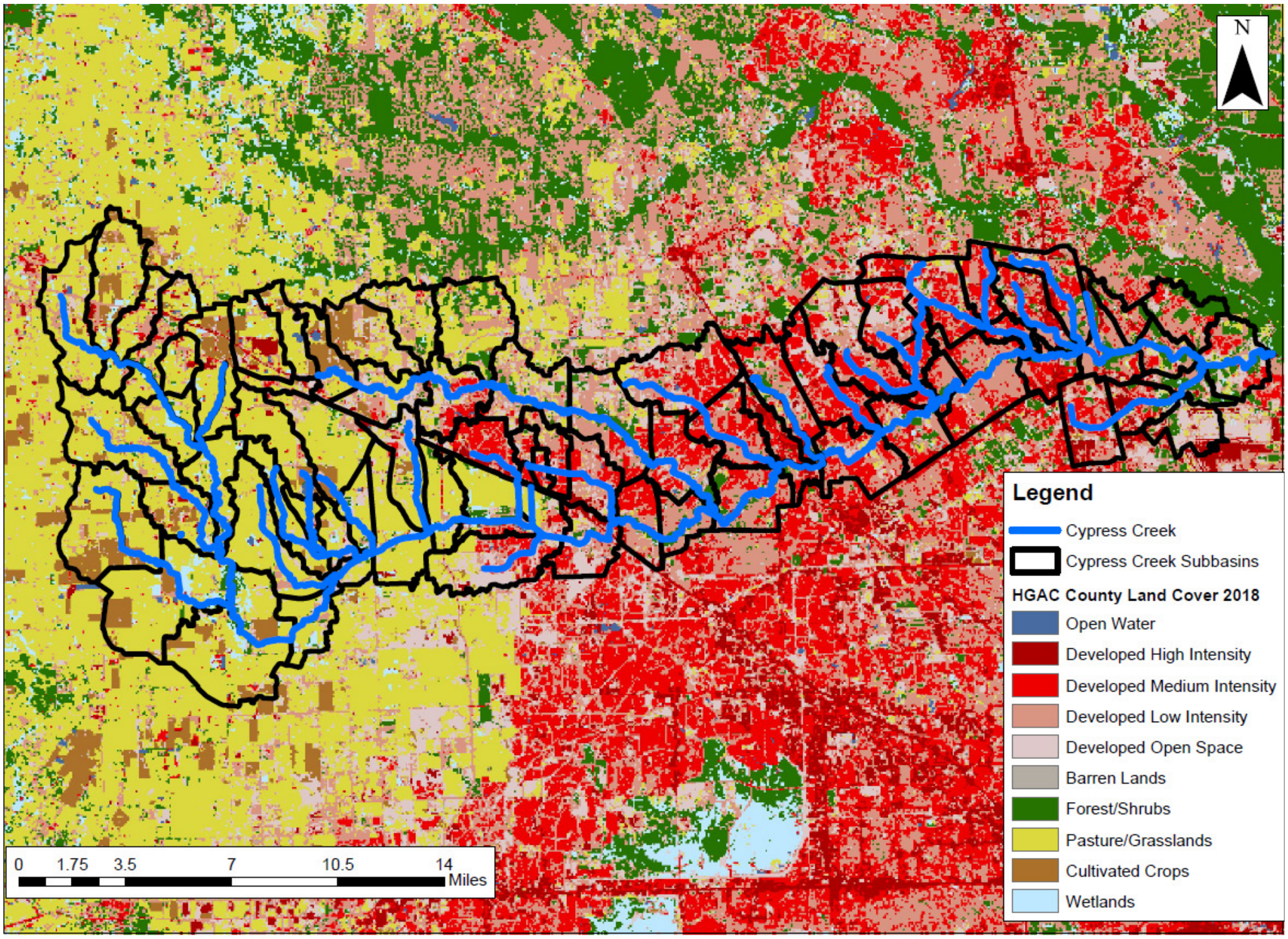


Figure 2: Land Use within the Cypress Creek Watershed (2018)

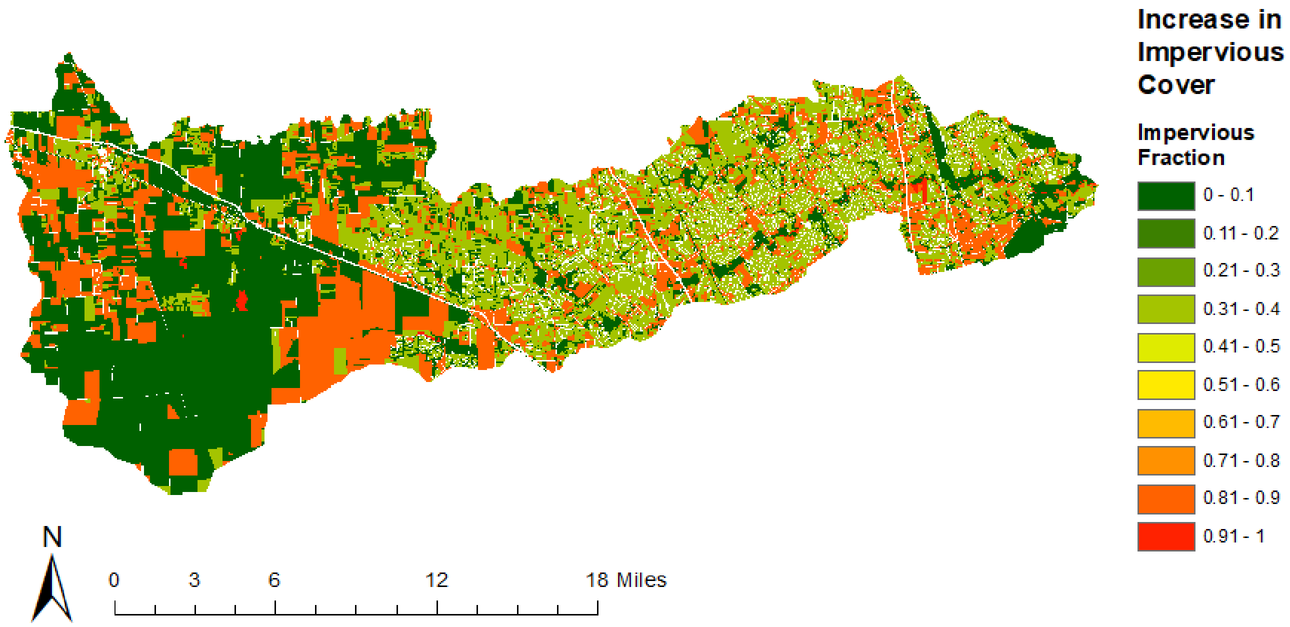


Figure 3: 2040 Impervious Cover within the Cypress Creek Watershed (ref: Rice U. 2018)

However, the upstream portion of the watershed is quickly being developed, aided by the roadway improvements involving Highway 290 and Highway 99 (the Grand Parkway). Based on 2010 census data, the Cypress Creek watershed already contains almost 400,000 residents (ref. HCFCD). By the year 2040, land development is projected to expand further westward/upstream in the Cypress Creek watershed, producing additional impervious cover as shown in Figure 3.

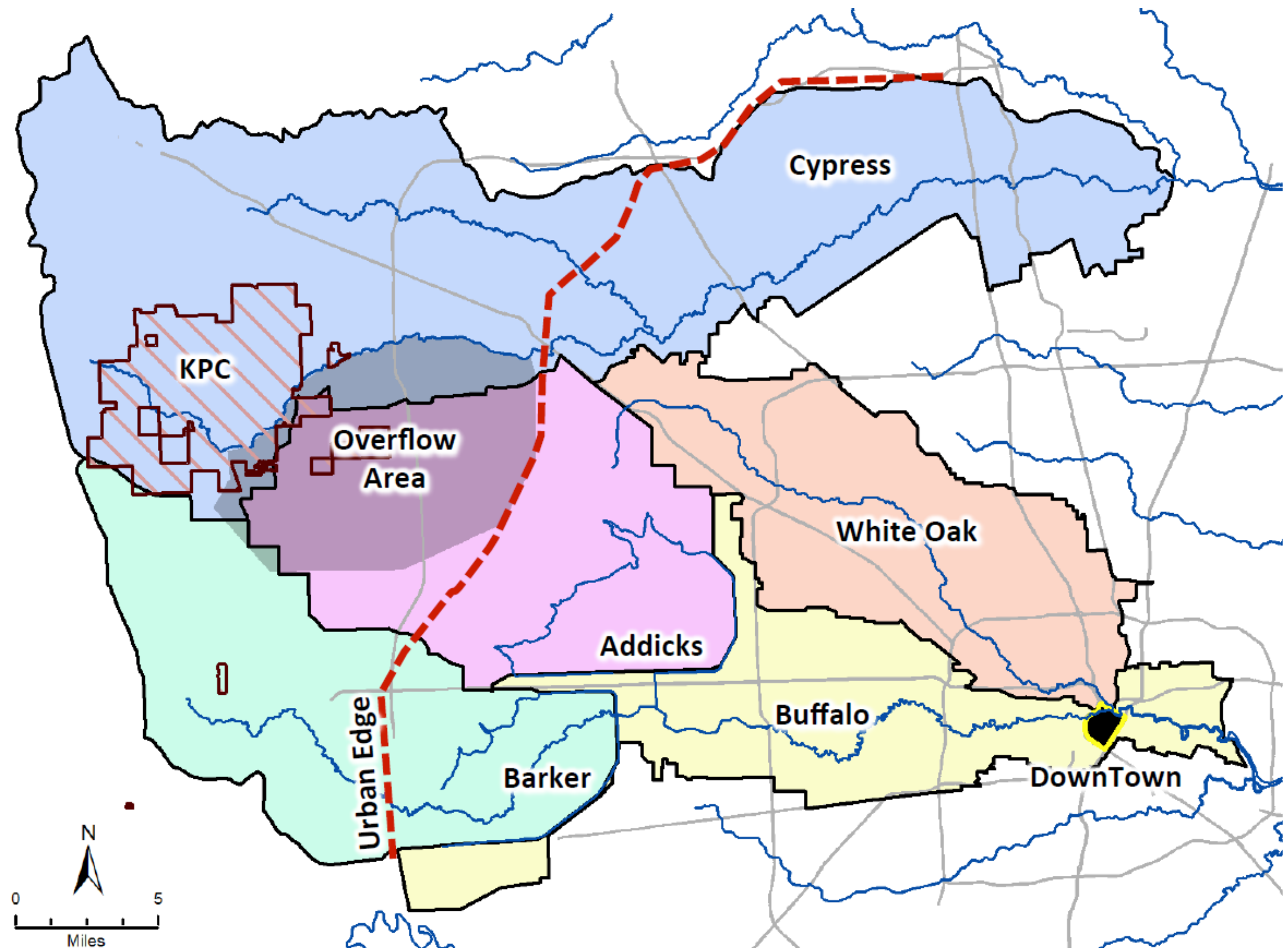


Figure 4. Complexity of the Western Watershed Area

The upper watershed area of Cypress Creek as shown in Figure 4 is quite complex. For example, upper Cypress Creek tends to spill out of its southern banks and overflow into Addicks watershed during heavy rain events (greater than a 5-year return period). The extent of the overflow starts at the upper end of Cypress Creek and can occur downstream as far as Highway 290. The overflows would travel southward into the Addicks watershed, where they enter into the upper ends of South Mayde, Bear, Langham, and Horsepen Creeks, and then into Addicks reservoir. These overflows can contribute a significant amount of water entering into the Addicks reservoir and did so during Harvey. Thus, accurately representing this hydrologic interaction requires a complex hydrologic and/or hydraulic model that links these two watersheds together. In addition, this upper part of Cypress includes the Katy Prairie Conservancy lands and is a unique undeveloped area that provides natural detention/retention storage over vast areas of prairie and agricultural lands. This is an important area for existing and future upstream storage considerations as Houston continues to expand westward.

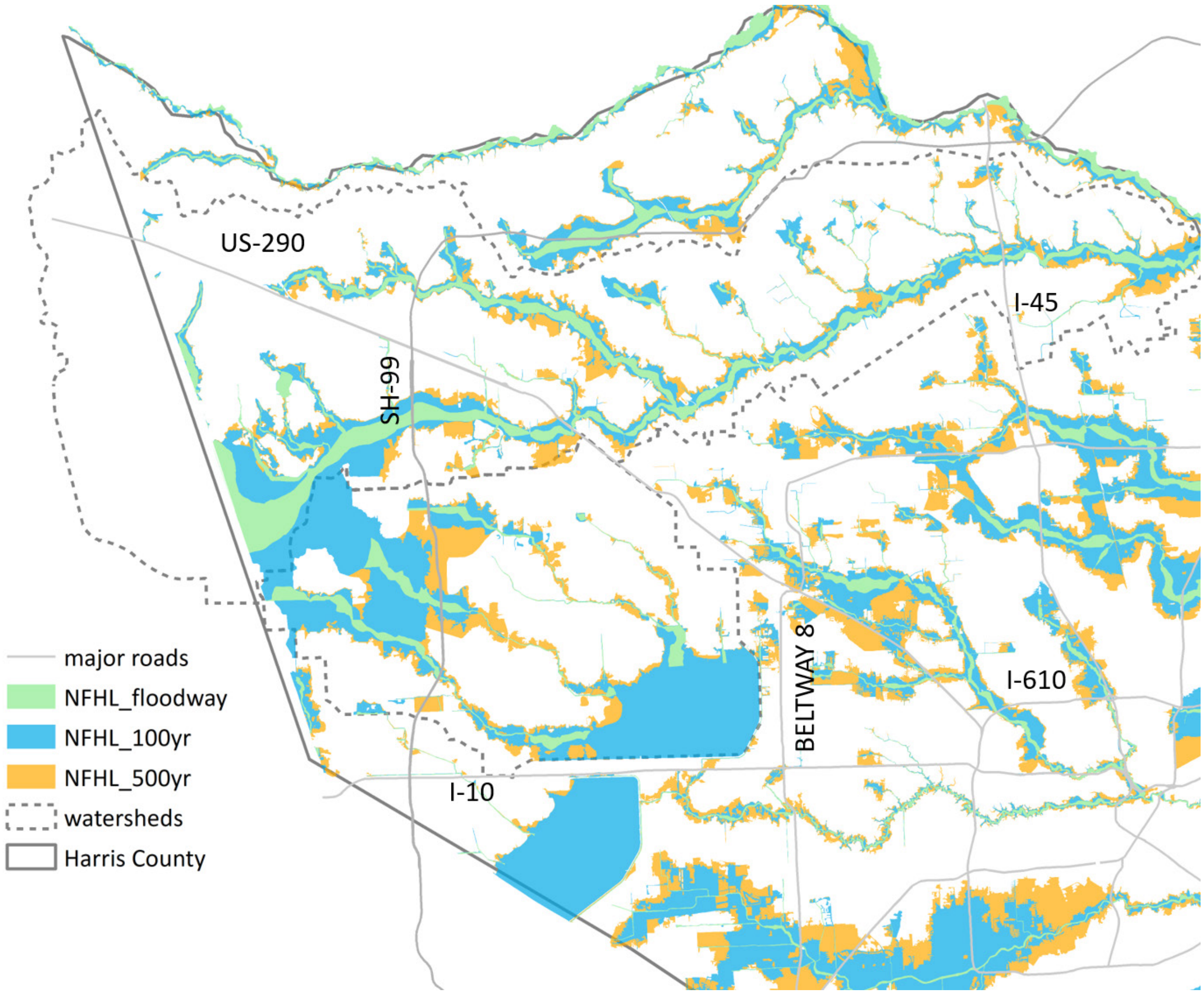


Figure 5. FEMA Floodplain along Cypress Creek and Surrounding Areas

Numerous floods have occurred along Cypress Creek, including major flooding associated with the October 1994 and October 1998 floods, which set record flood levels at various locations in the watershed prior to the most recent flood events (see Appendix A for the flood levels reported by HCFCD for historic floods in the Cypress Creek Watershed). The hydrologic models developed by HCFCD for this watershed as part of the county's recovery project following Tropical Storm Allison in 2001 (known as TSARP), and used for FEMA floodplain mapping, were calibrated to these previous flood events. However, more recent floods, including the 2016 Tax Day Flood and, of course, Harvey in August 2017, suggest that the currently effective FEMA floodplain maps for Cypress Creek need to be updated, especially in light of the new rainfall data issued by the National Weather Service for this area. This new rainfall data (known as Atlas 14) shows the 100-year 24-hour rainfall amounts for this watershed have increased by about 30 percent (from 12.5 inches to 16-17 inches). The currently effective FEMA mapped floodplain for Cypress Creek and surrounding areas, based on the older rainfall data, is shown in Figure 5.

Figure 6. Estimated Harvey Floodplain for Cypress Creek (ref: HCFCD)

The 2016 Tax Day Flood inundated about 2,100 homes in the Cypress Creek watershed – about 1,680 homes in Cypress Creek and 430 homes in Little Cypress Creek (ref: HCFCD). However, Harvey flooded about 9,450 homes in this watershed – 8,750 in Cypress and 700 in Little Cypress, with over 150,000 flooded homes throughout Harris County (ref: HCFCD). Figure 6 shows the Harvey floodplain as estimated by HCFCD.

As is shown in these floodplain maps for Cypress Creek, there are overflows that leave the Cypress Creek watershed upstream of Highway 290 and enter into the Addicks watershed, and eventually flow into the Addicks reservoir. During Harvey, this overflow contributed about 20 percent of the total amount of water that entered the Addicks reservoir, which resulted in over 6,000 homes being flooded in the Addicks watershed, with many more flooded downstream when Addicks Dam released its floodwaters because of rising pool levels behind the dam.

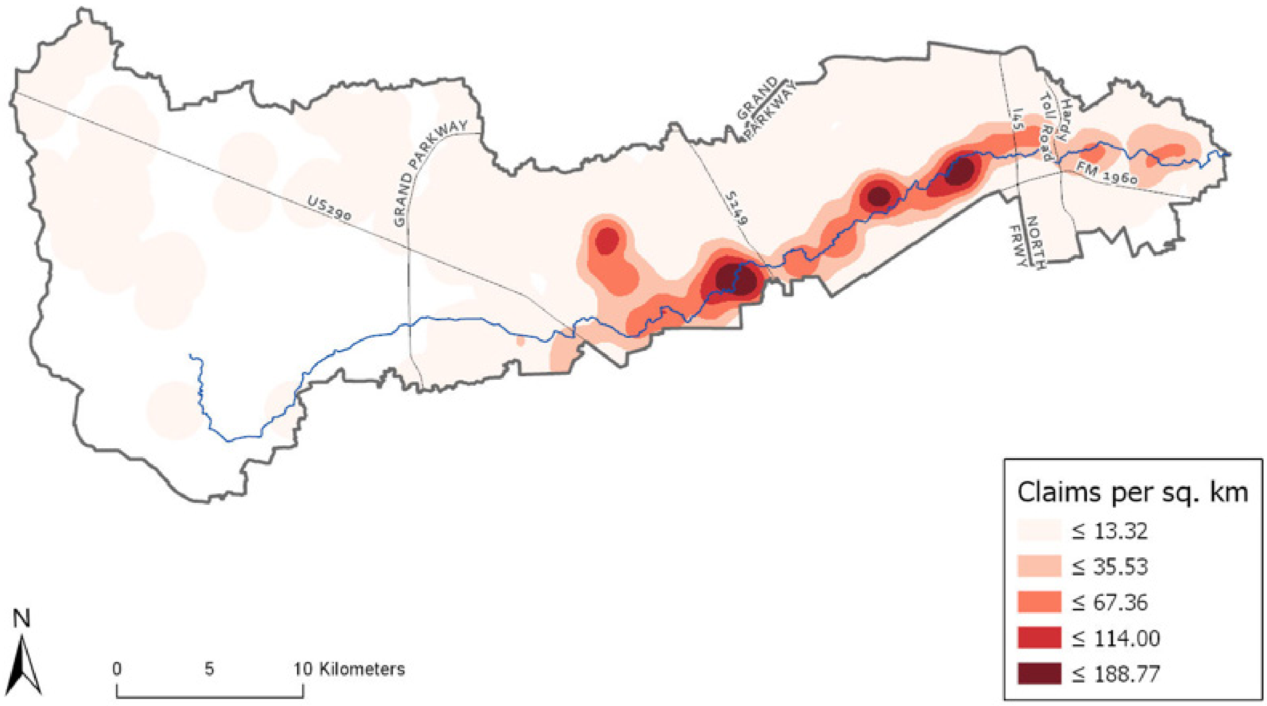


Figure 7. NFIP Claims along Cypress Creek per Square Kilometer (ref: Brody)

Cypress Creek has a history of flooding along its main channel, primarily at certain "hot spots" as depicted in Figure 7, which is based on flood claims filed with FEMA under its National Flood Insurance Program (NFIP). Yet, there has been little public funds spent on trying to reduce this flooding problem.

The floodplain along Cypress Creek tends to be narrower in areas where there has been development, especially in the lower portion of Cypress Creek. These developed areas tended to place fill material on lots in the floodplain to elevate the land so subsequently-built homes would not flood. However, there has been concern over the years that as development continues to proceed further upstream, and generates increased runoff entering the creek, downstream flooding and the associated floodplains are increased. This is especially true for the ongoing development in the upper portions of Cypress Creek upstream of Highway 290. Appendix B presents the current 500-year floodplains at various locations along Cypress Creek.

Thus, this study was performed to investigate the potential for providing regional detention storage in the upper portions of the Cypress Creek watershed to not only address the existing flooding issues along Cypress Creek, including the overflows into Addicks, but also to address future development concerns that may aggravate these existing flooding issues.

Methodology

In order to investigate the current flooding issues along Cypress Creek, including the overflow issue, and evaluate the potential flood reduction benefits of regional detention storage areas in the upper portions of the Cypress Creek watershed, hydrologic and hydraulic computer models were used for these analyses. The hydrologic and hydraulic analyses conducted for this study primarily utilized HEC computer models (HMS, RAS) and the distributed hydrologic model Vflo®. The HEC models have been developed by the U.S. Army Corps of Engineers and serve as the industry standard for modeling and simulating the hydrologic (HMS) and hydraulic (RAS) responses within a riverine watershed. These modeling tools were selected as the ones used to prepare the FEMA floodplains for Harris County as part of the TSARP project in the early 2000s. In addition, the Vflo® model was used in this study to initially provide a more accurate and high resolution analysis of the hydrologic response of the watershed to different storm events, and more realistically model their hydrodynamic effects. Vflo® is valuable for this analysis because it is a physics-based distributive model that uses grid cells to create a checkerboard configuration representing the hydrologic characteristics of a watershed, such as the topography of the land surface, its land cover type and the rainfall and losses associated with it (VAI, 2012).

First, available HMS and RAS models for Cypress Creek were obtained from the HCFCD that represent "existing conditions" within the watershed. These models were then run for various hypothetical and real storm events to establish a baseline of flooding conditions. Then, several detention scenarios were developed in HEC-HMS by examining existing available land areas and the topography of the region, and a suite of runs were generated to evaluate the flood reduction benefit of each scenario for the various storm conditions analyzed. Based on these results, one or two feasible scenarios were selected and modeled in more detail in Vflo®. These scenarios were represented in Vflo® to provide more accurate hydrodynamic modeling based on these high resolution land characteristics. Finally, the overland flows computed from the Vflo® model served as input to a newly created 1D and 2D HEC-RAS models to evaluate the impact along Cypress Creek, including in the overflow area.

Hydrologic Model: HEC-HMS

HEC-HMS is utilized to model a watershed's hydrologic response to a particular rainfall event based on unit hydrograph methodology. The Cypress Creek watershed is divided into sub-basins based on their drainage boundaries (see Figure 8) and each sub-basin has unit hydrograph parameters (Tc and R) assigned to it based on its hydrologic characteristics, such as land use, soil type, storage capacity, slope, length, size, etc. Rainfall is generated over each sub-basin in hourly intervals, and the program generates the associated runoff from each sub-basin. This runoff is transferred into specified channels, and then this channel flow is routed downstream based on available storage in the channel and its overbank/floodplain.

Hydraulic Model: HEC-RAS

HEC-RAS uses channel flows from HEC-HMS (or another hydrologic model such as Vflo®) as input in order to generate water surface elevations throughout the channel. Other inputs include cross-sections of the channel that are extracted from topography contained in a digital elevation model (DEM) and channel roughness values determined on the basis of how the channel is lined (concrete, grass, etc). HEC-RAS typically computes the water surface elevations starting at the most downstream cross-section and moving upstream based on the one-dimensional energy equation. It takes into account friction losses as well as contraction and expansion effects. HEC-RAS can be used for steady flow analyses, which only take into account peak flows, or for unsteady analyses, which provide time series water surface information based on inputted flow hydrographs. FEMA floodplains in Harris County are generally based on steady flow analyses. HEC-RAS 2D is also available to simulate two-dimensional overland flow hydraulics.

We utilized HCFCD's HEC-RAS one-dimensional model for simulating the hydraulics of the main channel of Cypress Creek, and developed a 2-D model component for the overflow area and the upper portion of the Addicks watershed, as shown in Figure 9.

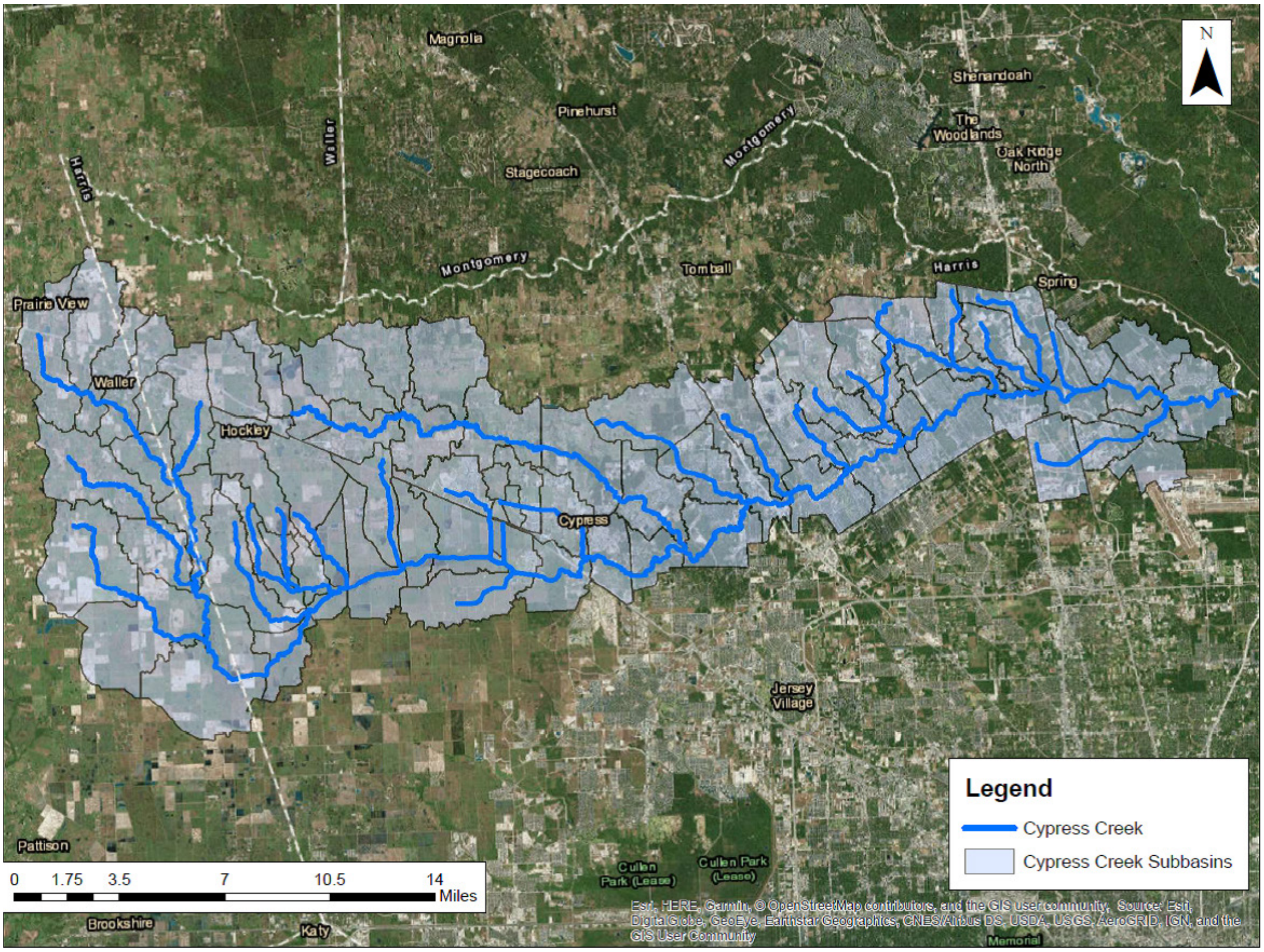


Figure 8. Cypress Creek Sub-basin Map from the HCFCD HEC-HMS Model

Hydrologic Model: Vflo®

Vflo® is a physics-based distributive hydrologic model that was developed at the University of Oklahoma by Dr. Baxter Vieux to represent the hydrologic response of a watershed by using grid cells in a checkerboard configuration to reflect the land use type, soil type, and overland flow roughness of the watershed. This software program has been applied to numerous watersheds in the Houston area and elsewhere, and provides a number of advantages over the HEC-HMS software, including the level of detail that it provides within a watershed and that it is physics-based rather than based on a unit hydrograph to represent a watershed. This model also takes rainfall as input and generates runoff as output for each grid cell, and combines the runoff from each grid cell with the runoff from upstream grid cells as the runoff is transported downstream into and along primary channels.

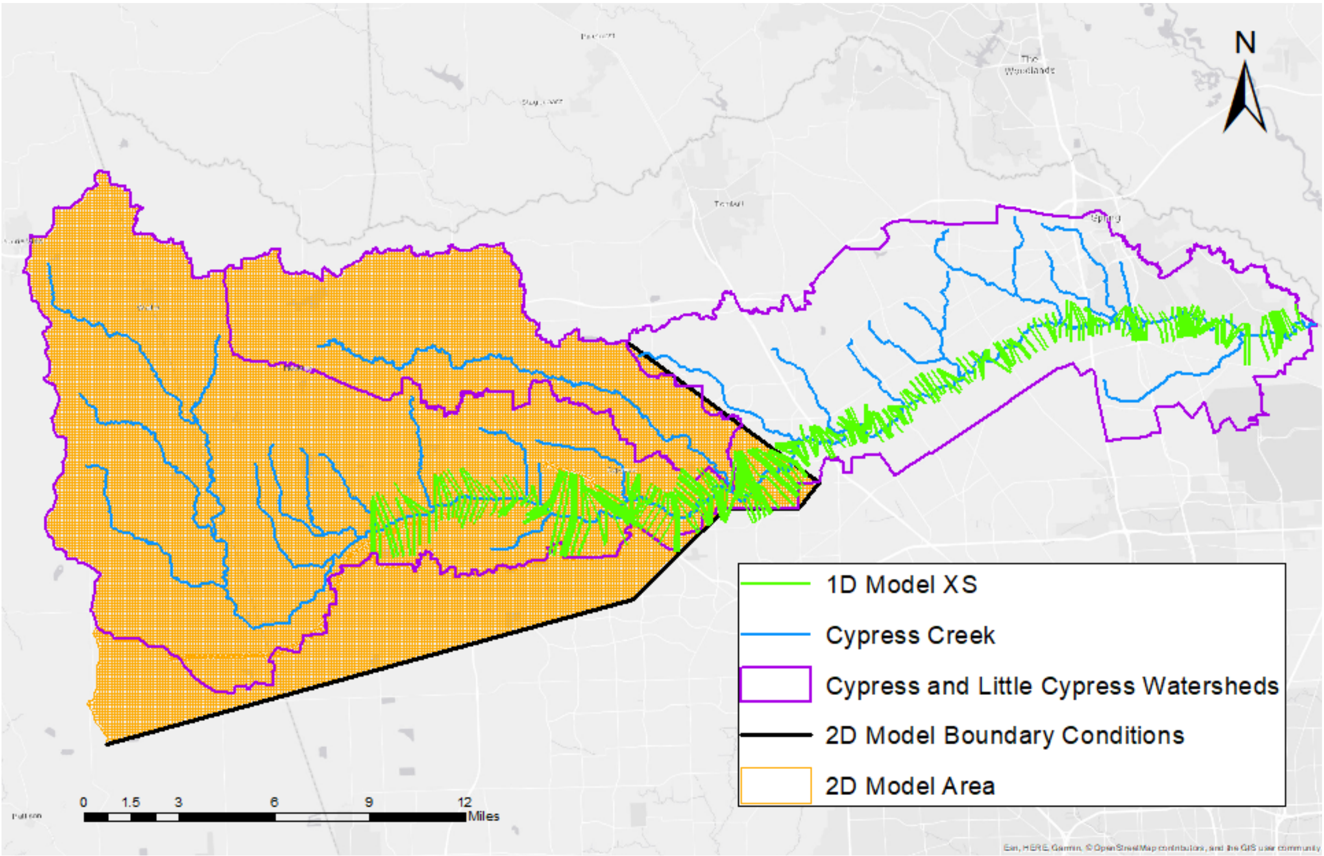


Figure 9. HEC-RAS 1D and 2D Model Layouts for Cypress Creek and the Overflow Area

Data Sources

The HEC-HMS and HEC-RAS models for the various creeks and bayous used in this study were obtained from the HCFCD's M3 Model Library. This is publicly available data and is provided at the website www.m3models.org. These models are the ones that were used to create the currently effective FEMA floodplain maps for this watershed. These models were corrected/updated/re-calibrated around 2007 (and became the effective models in 2013) from the TSARP models that were originally developed around 2004 after Tropical Storm Allison that had been determined to be in error. The Vflo® model was obtained from previous work for the Cypress Creek watershed.

In order to validate the HEC-RAS model, observed high water mark data for the two flood events were obtained from official Harris County flood reports (Lindner and Fitzgerald, 2016 and 2017). These reports provide observed water levels at gauged and un-gauged locations throughout the various watersheds.

Topography data in the form of a DEM file was obtained from the Houston-Galveston Area Council's (HGAC) publicly-available GIS data website, based on the 2008 LIDAR data set for Harris County. The DEM file was used to create the Vflo® model for the Cypress Creek watershed and assess inundation throughout the watershed.

Rainfall data for the two flood events were obtained from several different sources. Radar rainfall was obtained from the National Weather Service (NWS) in 15-minute intervals and averaged over each sub-basin in the various watersheds. Rain gage data was obtained from the HCFCD's Flood Warning System and used to validate the NWS radar-rainfall data.

Analysis

The study team began by updating the HEC-HMS model obtained from the HCFCD to better reflect observed flows for the Tax Day flood of 2016. The team then reran this HMS model for the Cypress Creek Watershed for the various frequency storm events (i.e. 10-year, 100-year and 500-year storms), and for the 2017 Harvey event. The resulting flows for these various storm events were analyzed throughout the Cypress Creek watershed to better understand how this watershed responds to rainfall events and where in the watershed do flood flows along the main channel of Cypress Creek originate. The peak flows computed for the 500-year storm event at certain locations along Cypress Creek are shown in Figure 10.

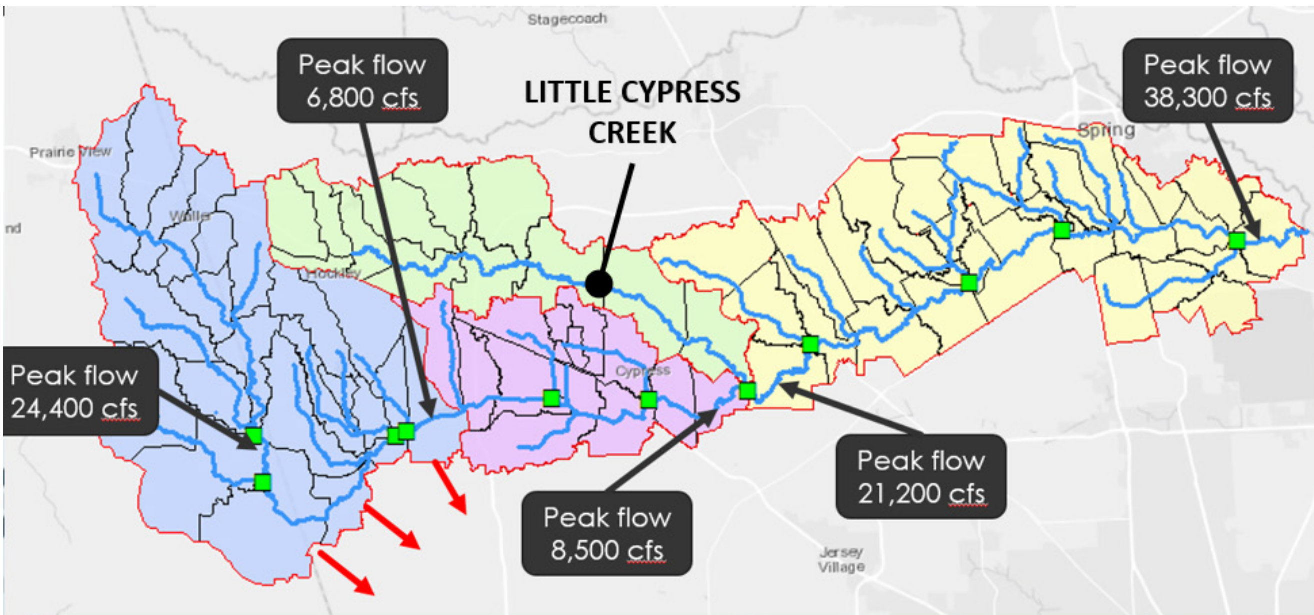


Figure 10. Computed 500-year Peak Flows along Cypress Creek using HEC-HMS

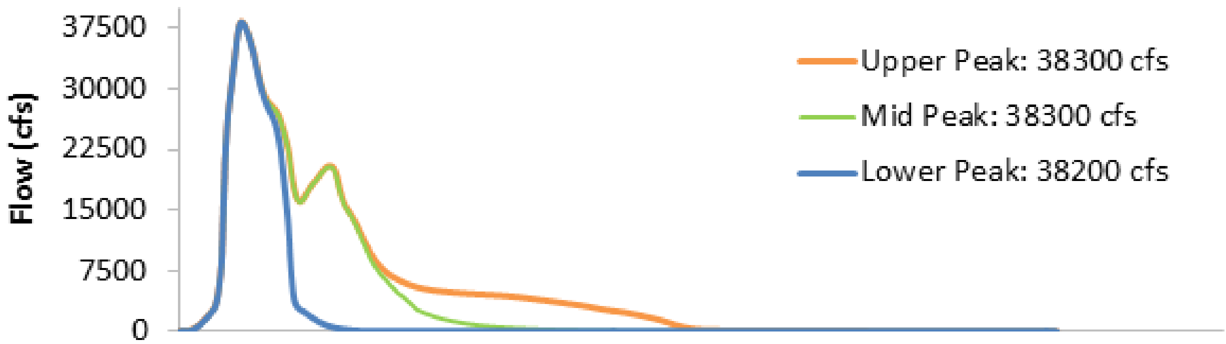


Figure 11. 500-year Flows for Cypress Creek at Outlet

A review of these computed flows for the 500-year storm event revealed multiple peaks were being created along Cypress Creek, as shown in Figure 11. This figure shows the 500-year flow hydrograph at the outlet of Cypress Creek as it enters into Spring Creek, depicting the various flow contributions from different portions of the Cypress Creek Watershed. The highest peak flow of about 38,000 cfs is generated by the lower portion of the watershed and is the initial peak flow experienced at the outlet (purple line). The second peak flow is a little over 21,000 cfs and is generated by the combination of Little Cypress Creek and the middle portion of the Cypress Creek watershed (blue line). The last peak flow of slightly less than 7,000 cfs is produced by the contribution of the upper portion of the Cypress Creek watershed, after the majority of those flows are overflowed into the Addicks watershed (red line). Thus, even without any contribution of flood flows from the upper or middle portions of the watershed, the lower portion of Cypress Creek will still experience significant flooding issues.

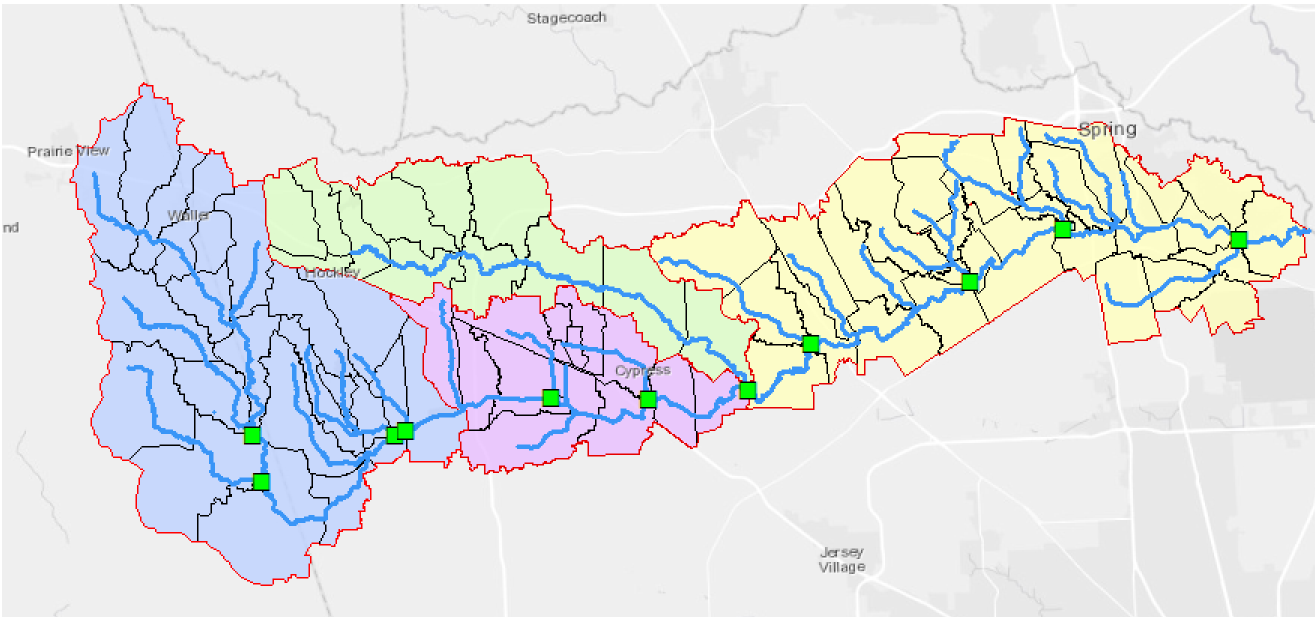


Figure 12. The 4 Sub-watersheds within the Cypress Creek Watershed

This analysis determined that this creek's peak flood flows tend to originate within the local portions of the Cypress Creek watershed. Therefore, the team identified four "sub-watersheds" within the Cypress Creek watershed that contribute to the flooding problems along Cypress Creek, as shown in Figure 12.

The upstream-most sub-watershed (blue area) was labeled the "Upper Cypress Creek Watershed" and covers the upper-most portions of the Cypress Creek watershed from the headwaters of the creek down to about Highway 99. This portion of the creek includes that part of the creek that tends to overflow into the Addicks watershed. The next upstream-most sub-watershed (purple area) was labeled the "Middle Cypress Creek Watershed" and covers the middle portions of the Cypress Creek watershed, starting from Highway 99 and extending downstream to the confluence with Little Cypress Creek. The "Little Cypress Creek Watershed" itself (green area) was labeled as the next sub-watershed and covers the entire watershed of this major tributary to Cypress Creek. Finally, the remainder of the Cypress Creek watershed (yellow area) was labeled the "Lower Cypress Creek Watershed" and covers the rest of the Cypress Creek watershed downstream of the confluence of Little Cypress Creek and Cypress Creek to its outlet into Spring Creek.

In order to identify the flow contribution of each of these sub-watersheds to the flooding problems along Cypress Creek, this HMS model was run multiple times, with each time having eliminated one or more of the sub-watersheds. In other words, the local contributions from the various sub-watersheds were determined by re-running scenarios in the HMS model with all components upstream of a particular cut-off location deleted (e.g. one scenario is everything upstream of the Katy-Hockley Road being deleted from the HMS model run). These various runs confirmed that the peak flood flows along each section of Cypress Creek are generated within the local sub-watersheds themselves, with the other sub-watersheds providing lesser peak flood flows along Cypress Creek (see Appendix C for HMS model results).

For example, the analysis showed that very little floodwater from the upper-most part of the watershed makes its way past the overflow area (that enters Addicks watershed), so as to cause very little flooding downstream on Cypress Creek under existing conditions; however, if overflows were held back from going into Addicks, then the problem will get significantly worse downstream along Cypress Creek without mitigation.

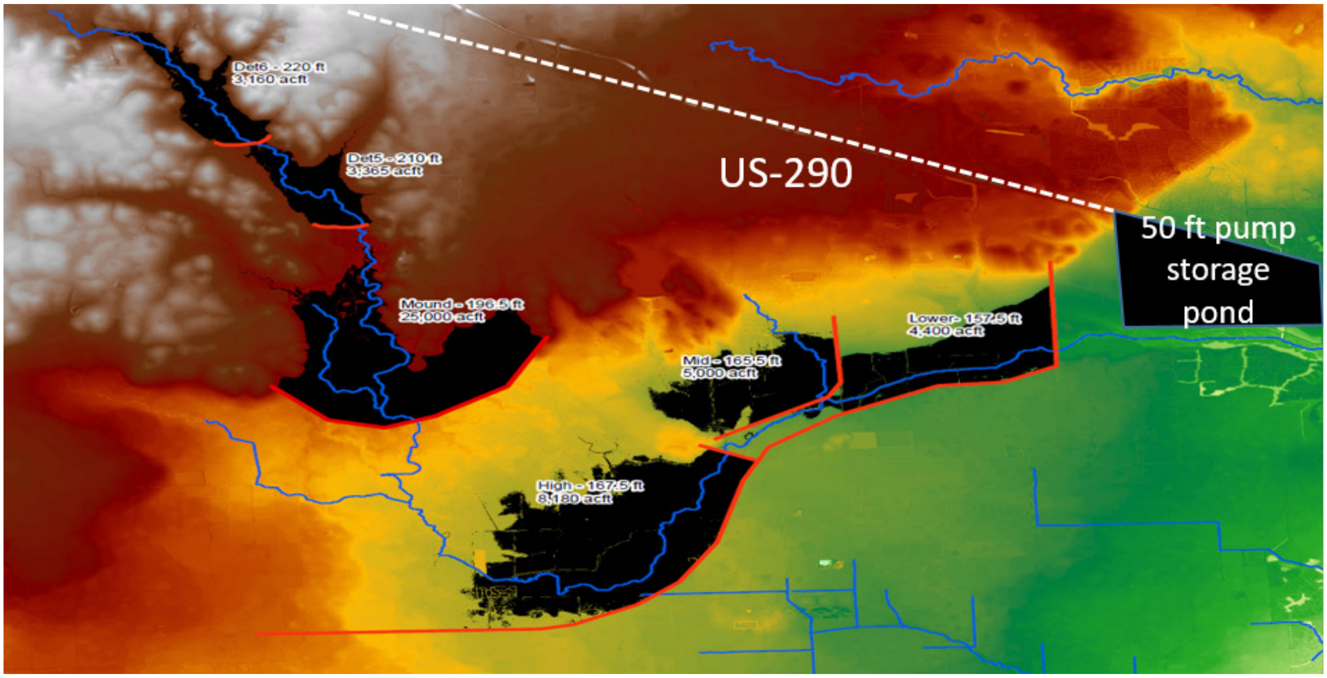


Figure 13. Location of Various Solution Strategies in the Upper Cypress Creek Sub-Watershed

The results of this analysis were used to determine that each sub-watershed required its own flood reduction measure in order to reduce the greatest flooding potential for that area of the Cypress Creek watershed. Thus, the team began to identify if there were any tributaries and/or mainstream locations that could bring the greatest flood reduction potential inside each sub-watershed.

Given the extent of existing development along the middle and lower portions of the watershed, establishing regional detention or storage areas in these portions of the watershed were determined to be not feasible. Other options, such as buyouts, flood proofing and/or elevating structures, channel improvements (with mitigating detention downstream) or an underground tunnel conveyance system were explored and are discussed under the Results section of this report.

Thus, the area where regional detention or storage areas were investigated for addressing the flooding problems caused by the upper portion of the Cypress Creek watershed became the focus of the alternatives analysis for this study. The set of potential locations in the Upper Cypress Creek Sub-Watershed for regional detention or storage areas were identified as “storage option” locations. The set of storage option locations were analyzed topographically with both Google Earth and GIS software to determine a set of feasible locations that still have undeveloped land available for implementing flood reduction and/or mitigation strategies.

By focusing attention on the Upper Cypress Creek Sub-Watershed area, implementing flood reduction measures in this area would likely reduce or eliminate overflows into the Addicks watershed, but also hopefully reduce some of the flood flows traveling downstream along Cypress Creek itself, helping to reduce any flooding being caused by floodwaters originating from this sub-watershed, although not necessarily eliminating the peak flooding issue in the downstream portions of Cypress Creek (that being generated by the downstream portions themselves). Once a few combinations of locations were determined (i.e. solution strategies with one to seven structures), they were sized and geographically determined based on HMS results and GIS LIDAR information. Figure 13 shows the locations of these various solution strategies.

Once the solutions were located and sized, they were put into the hydraulic model (a 2D-HEC RAS model) and run with the frequency storm rainfall events. Since RAS 2D does not directly handle rainfall loss calculations, the team adjusted the total rainfall assuming 25 percent infiltration to get the net rainfall, and the models and the storms were also updated to reflect NOAA's new Atlas 14 rainfall data.

The "existing conditions" run was compared to all the tested solution strategies to determine the flood level changes and associated flood reduction benefits, as discussed below. It was determined that the HEC-RAS 2D modeling in the Upper Cypress Creek Sub-Watershed provided a more accurate indication of the flood reduction due to storage options than the Vflo® model provided, so the HEC-RAS model was selected to use for the remaining analyses.

Results

The results of the HEC-RAS 1D and 2D modeling of the various scenarios are shown below. The various scenarios included (1) a single reservoir on Cypress Creek at Highway 99, (2) a single reservoir (pump storage) north of the creek and just east of Highway 99, with a levee/berm just south of Cypress Creek along the overflow area up to Highway 99, (3) two reservoirs with the levee/berm along the south side of Cypress Creek, (4) five reservoirs with the levee/berm, and (5) seven reservoirs. The Figures 14a-14e below show the difference in the 500-year floodplain with and without these various scenarios in place. The blue areas reflect a reduction in flood levels, while the red/brown areas reflect an increase in flood levels.

As expected, there is a reduction in flood levels immediately downstream of any reservoir area. However, as one moves further downstream, local runoff begins to accumulate in the creek and flooding issues still occur.

The levee across the southern portion of upper Cypress Creek can effectively eliminate any overflows into the Addicks watershed; however, by doing so, these contained flood flows are directed further downstream along Cypress Creek, and would create additional flooding issues downstream without mitigation. This is the primary reason for the pumped storage option located just north of the creek and east of Highway 99.

Hydraulic Model: HEC-RAS Results

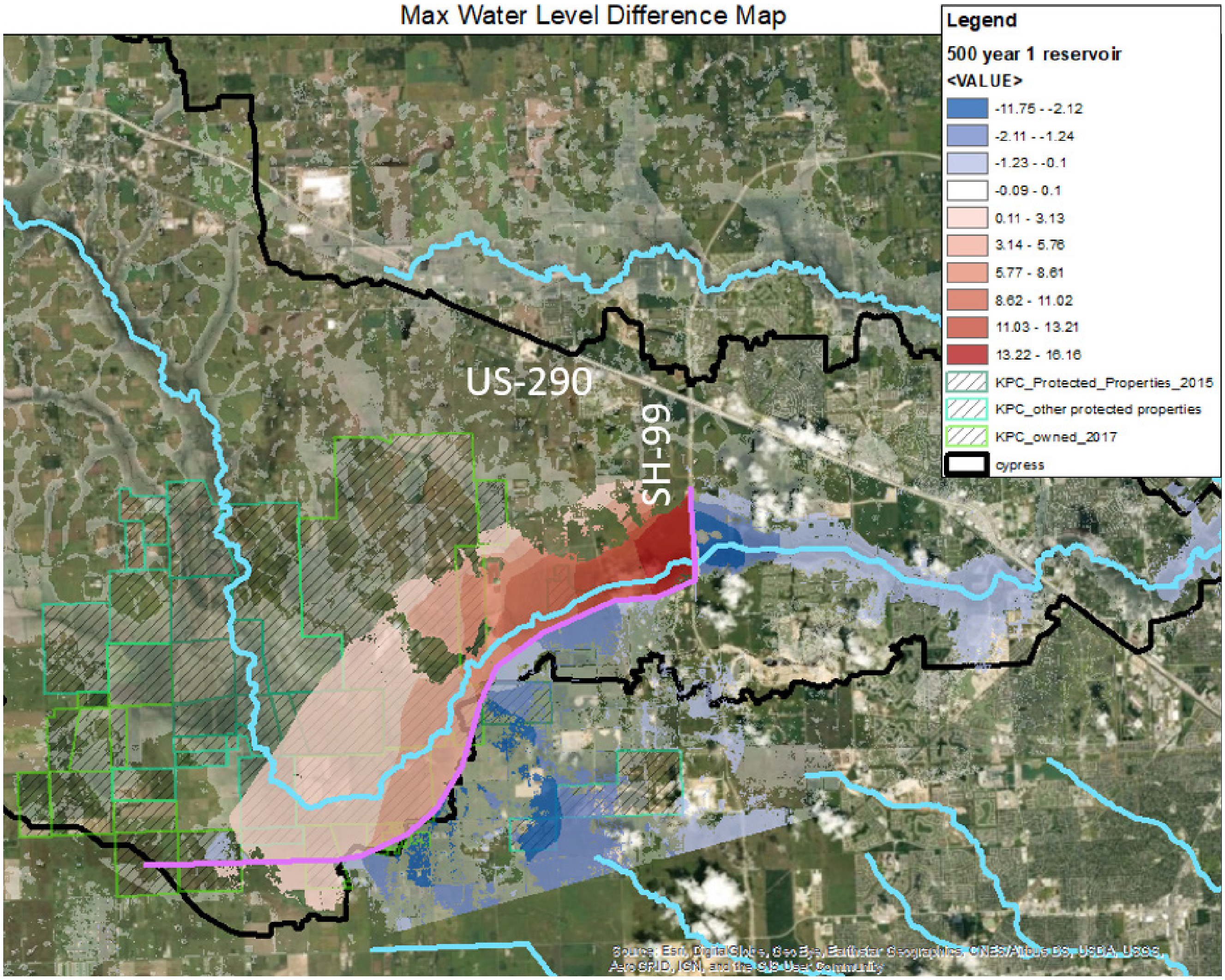


Figure 14a. Maximum Water Level Difference for 500-year Storm Event between Existing Conditions and with a Single Reservoir In-place

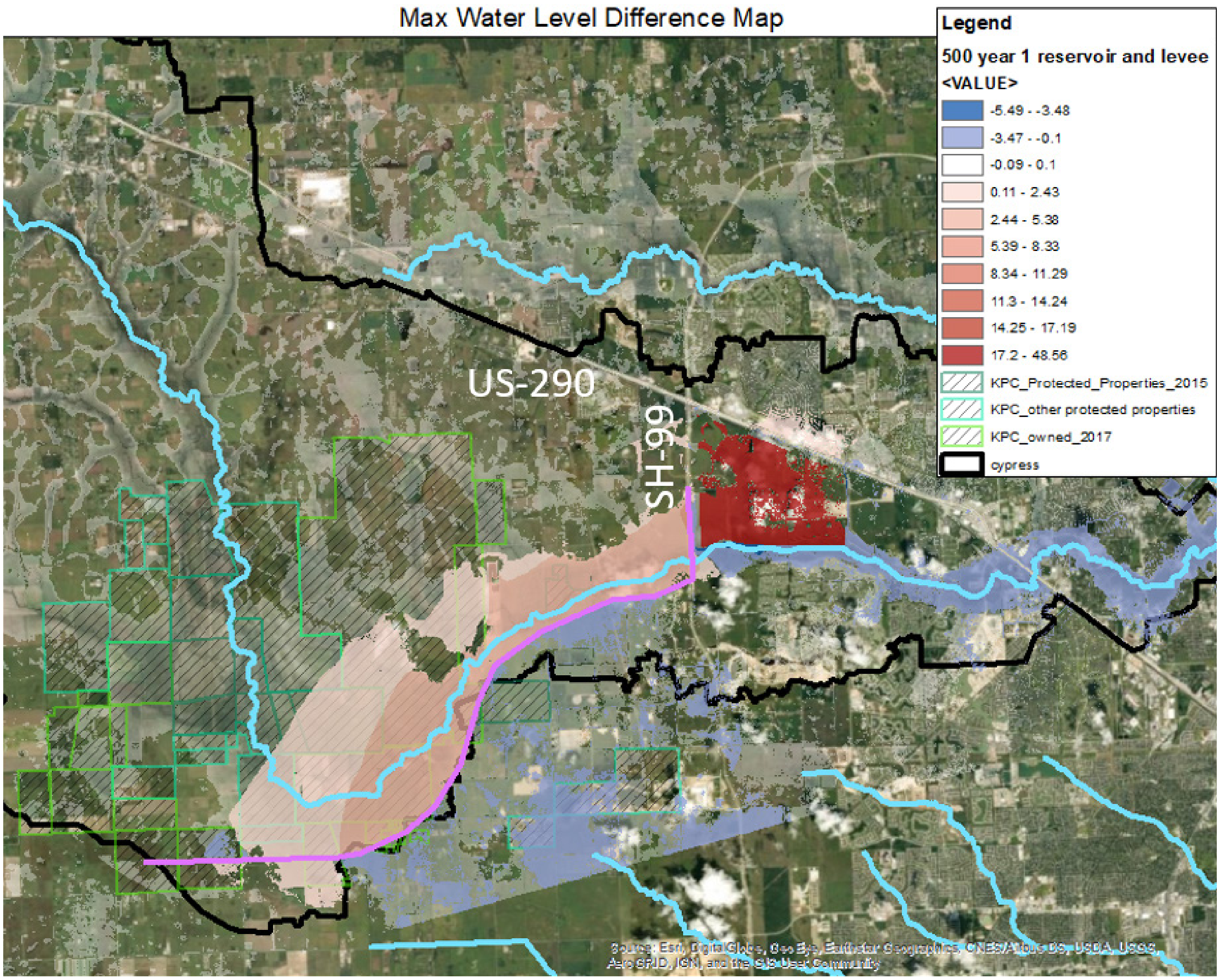


Figure 14b. Maximum Water Level Difference for 500-year Storm Event between Existing Conditions and with a Single Reservoir with a Cypress Creek Overflow Levee In-place

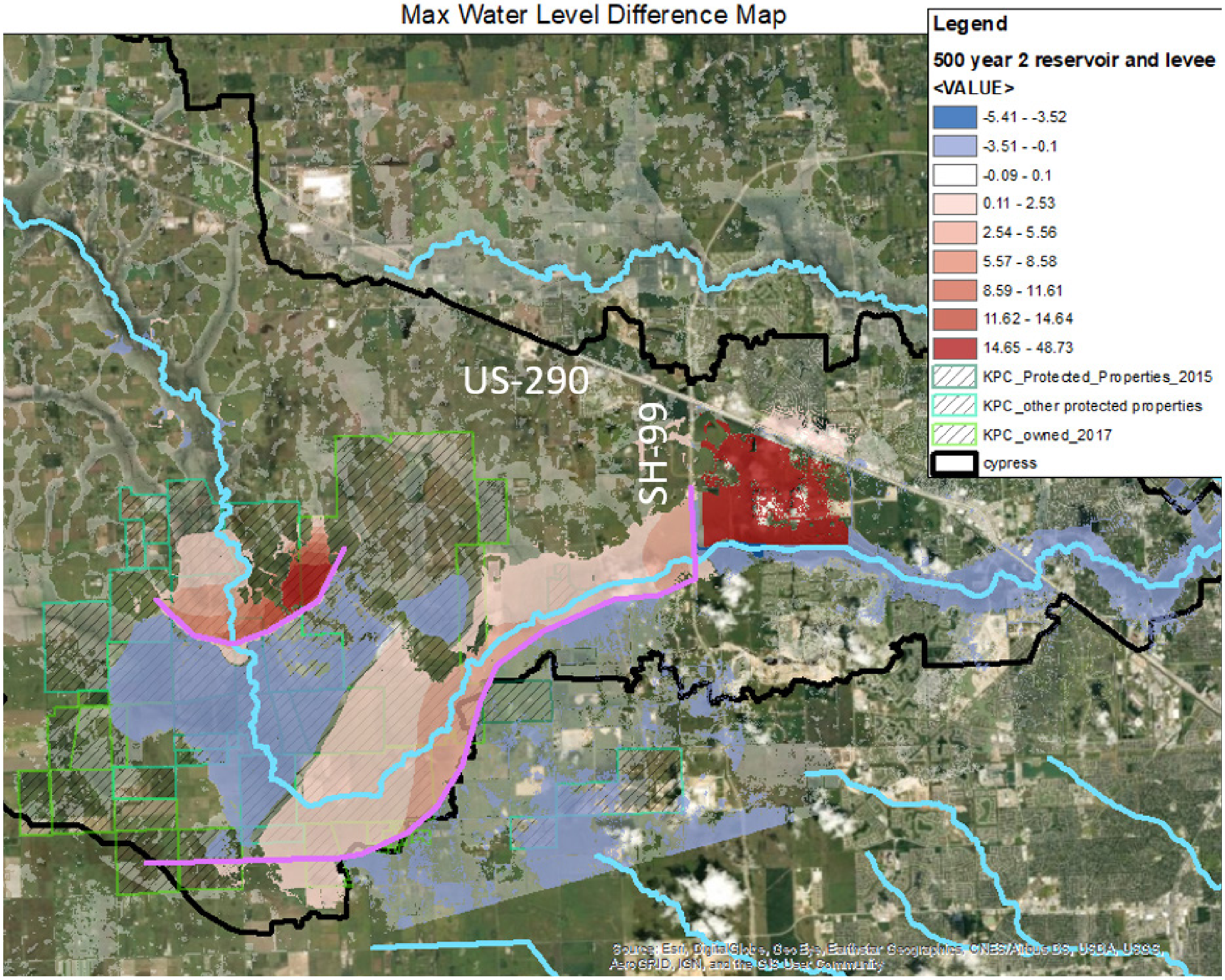


Figure 14c. Maximum Water Level Difference for 500-year Storm Event between Existing Conditions and with Two Reservoirs and the Cypress Creek Overflow Levee In-place

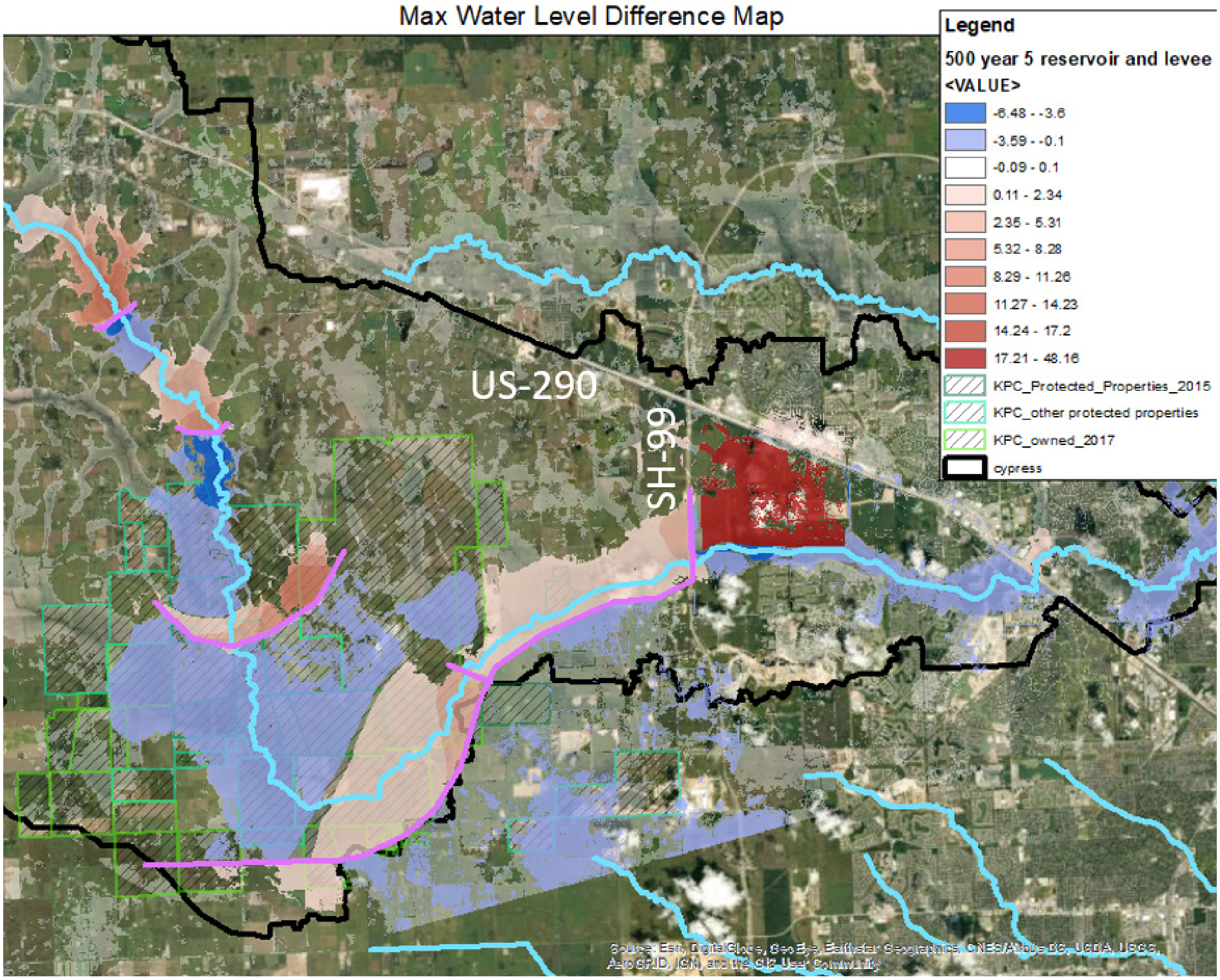


Figure 14d. Maximum Water Level Difference for 500-year Storm Event between Existing Conditions and with Five Reservoirs and the Cypress Creek Overflow Levee In-place

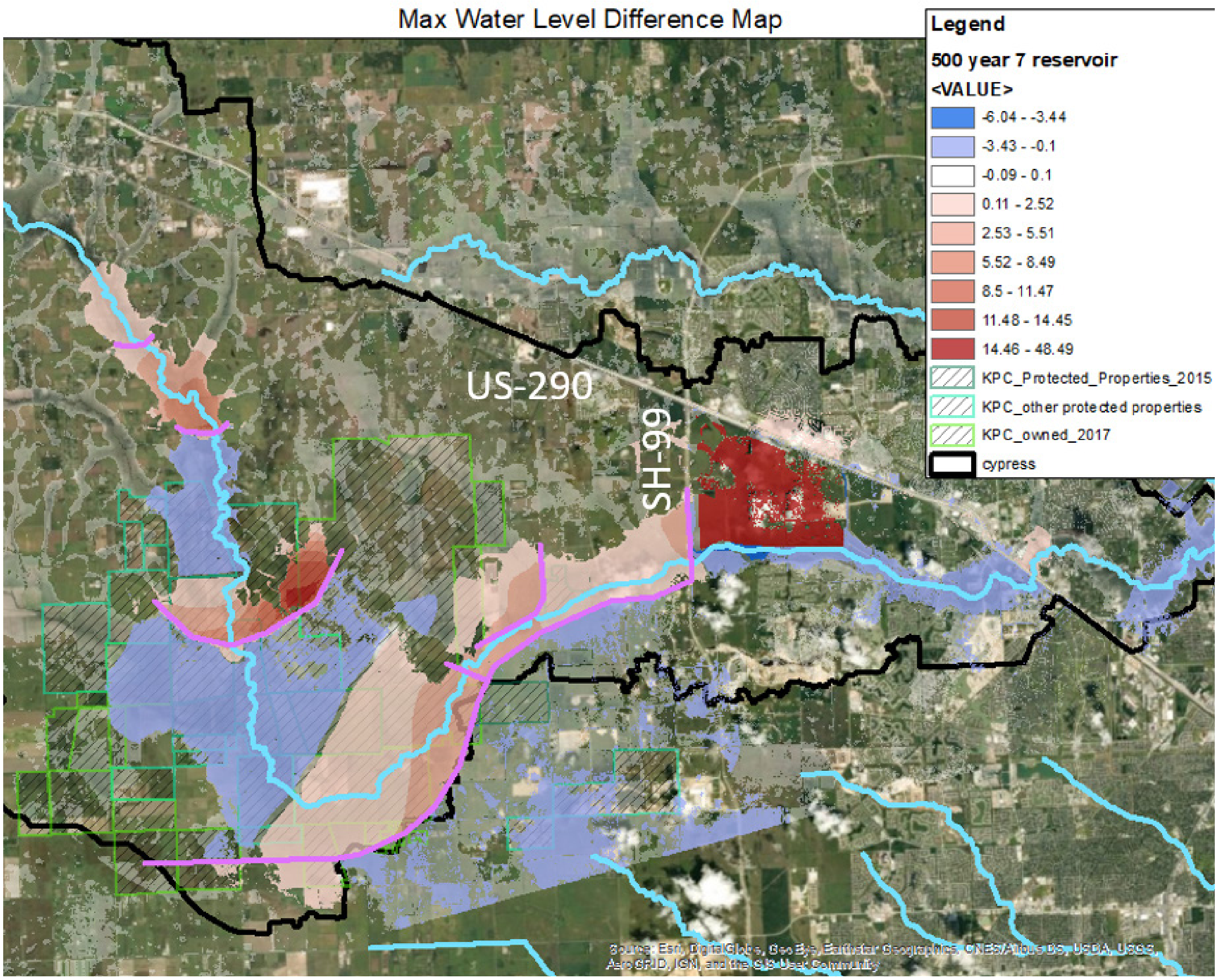


Figure 14e. Maximum Water Level Difference for 500-year Storm Event between Existing Conditions and with Seven Reservoirs In-place

The results of these HEC-RAS model runs for the various storage scenarios analyzed showed that the most efficient approach to eliminating overflows into the Addicks watershed was with a levee along the south side of Cypress Creek extending from the westerly watershed divide to Highway 99. An opening through the levee would be needed as it crosses Cypress Creek from the south side to the north side of the creek to allow floodwaters to continue to flow downstream along Cypress Creek. However, such a confinement of the flows along the creek would result in a significant increase in the flood flows continuing down the creek past the overflow area, and would cause major increased flooding without mitigation. Thus, a large storage area would be needed to provide such mitigation, such as indicated on the various figures above as the pumped storage area just north of the creek and just east of Highway 99. Additional storage areas could be provided upstream of the levee so as to reduce the size of the levee and the pumped storage area.

Middle and Lower Cypress Creek

Any strategies addressing the overflows from upper Cypress Creek into the Addicks watershed will not fully address the flooding issues that face the middle and lower portions of Cypress Creek. Any storage options located in the Upper Cypress Creek Sub-Watershed will not significantly reduce the flooding issues facing the areas downstream, due to the local contribution of storm water runoff into those areas.

The team considered what would be needed to significantly reduce the flooding issues in these downstream portions of the creek, and analyzed the concept of channel improvements as one option. An enlarged channel along Cypress Creek, having a bottom width of about 300 feet, with 3 to 1 side slopes, was modeled in HEC-RAS, as shown in Figure 15.

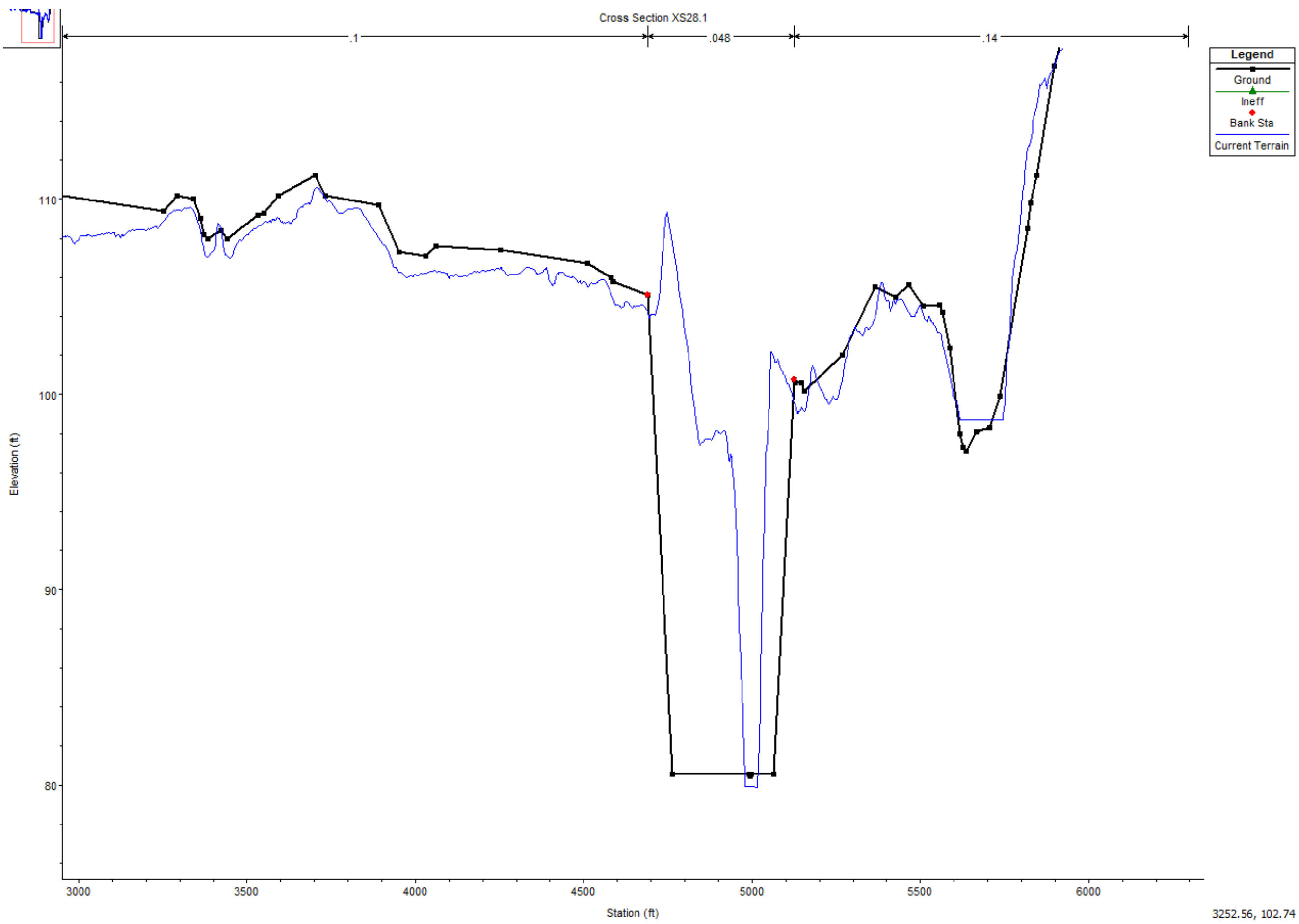


Figure 15. Typical Cross-section of Cypress Creek showing the Enlarged Channel Improvement

The current (old) 500-year flood flows were analyzed, along with the updated (new) 100-year flood flows using Atlas 14 data. In addition, analyses were run with and without the Cypress Creek levee in-place, as well as with and without the channel improvement in-place.

The results of this analysis are presented in the tables below, showing the resulting peak flow rates in cfs, as well as the resulting peak water surface elevations (flood levels) in feet above mean sea level (NAVD ’88, ’01 adjustment).

		Peak flow in cfs			
		Katy Hockley	Pre Little Cyp. confl	Grant Road	Outlet
Original Topography	old 500 year without levee	7206	8985	23380	33757
	new 100 year with levee	11807	9477	23847	33782
Channel Improvement	old 500 year without levee	6724	14573	27187	55778
	new 100 year with levee	11912	15951	28518	57383

		Water Surface Elev. In feet			
		Katy Hockley	Pre Little Cyp. confl	Grant Road	Outlet
Original Topography	old 500 year without levee	163.2	132.7	127.8	71.0
	new 100 year with levee	164.3	132.8	127.9	71.0
Channel Improvement	old 500 year without levee	163.1	127.4	121.3	65.0
	new 100 year with levee	165.2	127.8	121.7	65.3

As seen from the tabulated results above, adding the Cypress Creek levee, with no mitigation, significantly increases the peak flow rate and flood level at the Katy Hockley bridge. However, as one goes further downstream along the creek, the impact of such increases become less and less. The channel improvement concept would also increase peak flow rates in the middle and lower portions of the creek, since the existing floodplain storage capacity would be eliminated by bringing the flood flows to stay within the banks of the improved channel. This increased flood flow would have to be mitigated before it entered into Spring Creek at the outlet. However, the flood levels along the improved channel of Cypress Creek would be significantly reduced, by as much as 5-6 feet, as a result of the channel improvement concept. Another approach would be to provide an underground tunnel system to convey some of the flood flows so as to prevent them from continuing downstream and cause flooding in the middle and lower portions of the creek. A rough estimate of such a tunnel would be $100 million per mile for a 30-40 foot diameter tunnel that would carry about 10,000 cfs (based on an estimate recently given to Cypress Creek residents by a tunnel expert).

To determine the effect that continued land development will have on potential flooding in the watershed in the future, a normalized value of the 100-year peak flow rate (in cfs/acre) was determined for all of the sub-basins contained within the HCFCD's official/calibrated HEC-HMS model for the Cypress Creek watershed (see Figure 16). This analysis shows the existing contribution of each sub-basin's runoff rate to the eventual flooding along Cypress Creek for the 100-year storm event (based on the currently used frequency rainfall data used in the HCFCD's hydrologic models for the county). This information provides an insight into the impact that future land development might have on the flooding in the watershed as developers implement the HCFCD current detention criteria for new development in the Cypress Creek watershed. For the upper Cypress Creek watershed, the current detention criteria for small developments (<640 acres) allows for a release rate of about 0.5-1.0 cfs/acre of new development (depending on the number of acres associated with the new development). This compares to the rest of Harris County, in which the allowable release rate is about 1-2 cfs/acre. However, for any areas of undeveloped land that produce runoff rates less than the HCFCD current release rate criteria, allowing such release rates from new development will tend to increase existing flood flows and associated flooding potential downstream.

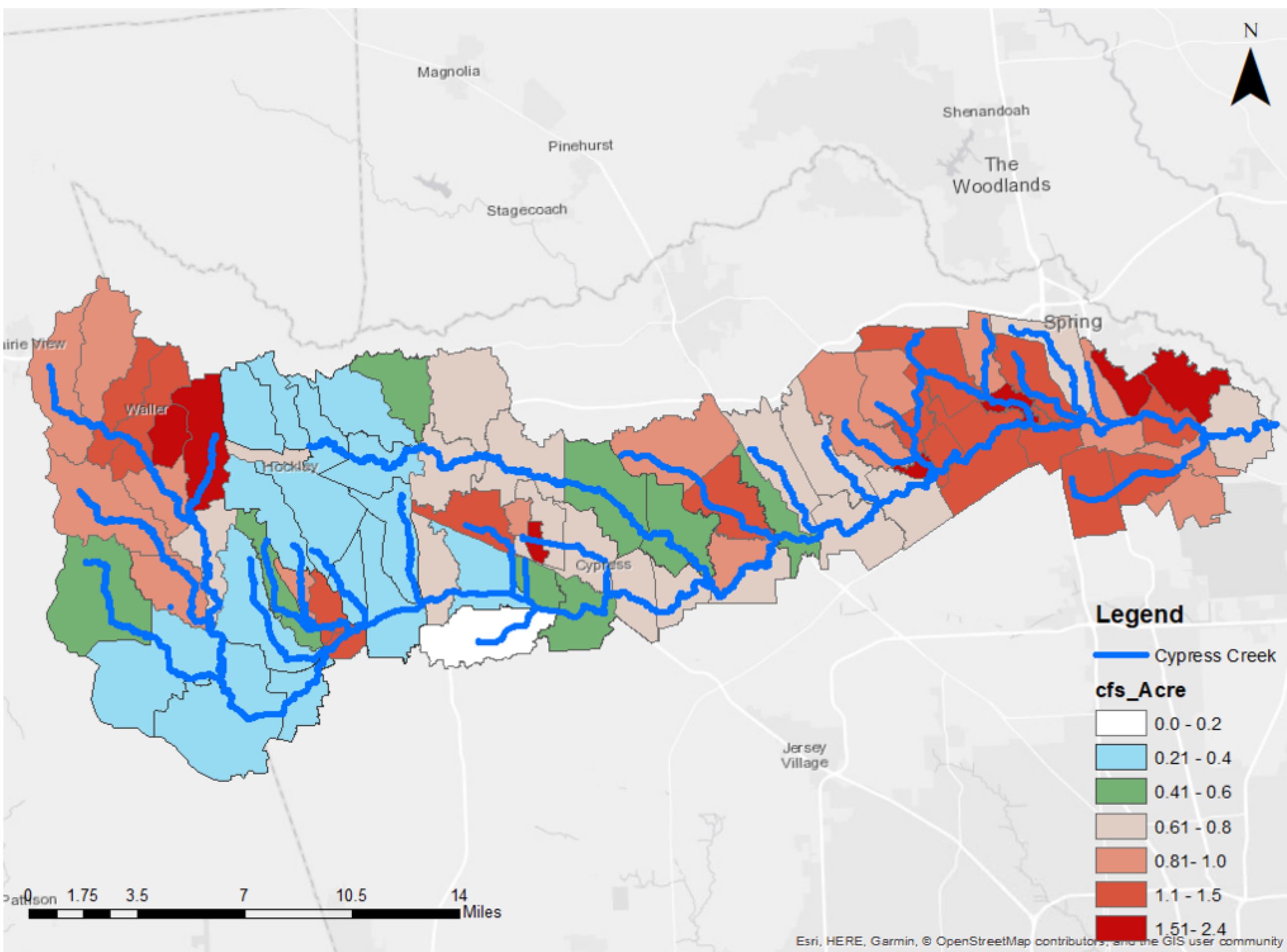


Figure 16. 100-year Flow Rate (in cfs/acre) for Each Sub-Basin in the HEC-HMS Model for the Cypress Creek Watershed

Conclusion

The hydrologic and hydraulic model analyses conducted for this study revealed how the Cypress Creek flooding originates and the difficulties in attempting to reduce or eliminate such flooding. While there are flooding issues all along Cypress Creek, from its outlet into Spring Creek up to the overflow area in the upper portion that spills over into the Addicks watershed, solving these issues will require a combination of a number of alternative concepts. This study focused on the flooding that originates in the upper portion of the Cypress Creek watershed, which contributes significantly to flood flows entering into the Addicks reservoir by diverting these flows away from going downstream along Cypress Creek. Thus, any solution to preventing such flood flows from entering the Addicks reservoir, and eventually into Buffalo Bayou, will require mitigation such that these flood flows do not increase the flooding issues along Cypress Creek.

Various storage options were analyzed in the upper Cypress Creek watershed, along with constructing a levee along the south side of the creek to prevent any overflows from leaving this watershed and entering into the Addicks reservoir. While these options were effective in confining these flood flows within the Cypress Creek watershed, the magnitude of these flows required considerable storage capacity to limit the outflows into the remainder of Cypress Creek to the flow capacity of the creek. Yet, as additional local runoff would continue to enter the creek further downstream, this local runoff would produce flooding along the creek consistent with the current magnitude seen today. Thus, flood reduction measures would be needed along the entire creek to fully address the existing flooding problems that have been experienced in these areas. Given the extent of the existing development in the middle and lower portions of the Cypress Creek watershed, there are few opportunities for providing storage capacity in these areas without significant buyout of private properties. Channel improvements or an underground tunnel system may be a more viable option for these lower areas, but even these options would require storage mitigation measures due to the increase in flow rates caused by implementing such options.

While the existing flooding problems along Cypress Creek need to be more fully analyzed and then resolved, there is the need to prevent new development in this watershed from aggravating these existing problems. The undeveloped lands provide considerable natural detention/retention functions that greatly benefit downstream properties and these functions need to be preserved, either as new development occurs or by conserving and/or enhancing the existing undeveloped lands, especially native prairie lands. Most of the undeveloped lands are located in the upper portion of the Cypress Creek watershed, where considerable development pressure is occurring, especially along the Highway 290 and Highway 99 corridors. There is a need to ensure that any new development is maintaining the existing natural flow rates leaving the site so that downstream properties are not adversely impacted.

Future Work

Results from this study provide valuable information on different scenarios for potential detention in the Upper Cypress Creek Sub-Watershed. By considering both large regional detention ponds as well as smaller distributed systems, this study serves as a step forward in finding an optimal solution to mitigate flooding both in the overflow area and along Cypress Creek as a whole.

Future work building from these results can also incorporate reservoir operations analysis for Addicks and Barker reservoirs to determine appropriate release rates during extreme precipitation events. This reservoir operation planning is vital in order to avoid unplanned releases (such as those during Hurricane Harvey). In addition, future research efforts should consider how urbanization projections for the Cypress region might impact the longevity of current flood mitigation solutions. Specifically, by considering the excess flows from new developments in the watershed, the impact of urbanization can be incorporated within the detention scenario evaluation process. Finally, results from this study and results from future research efforts should be presented to community stakeholders and be modified/adjusted based on community needs. Structured stakeholder outreach programs in the form of community meetings and round table discussions will be developed and implemented during any future phase of this work.

Appendix A - HCFCD Historical High Water Mark Information for Cypress Creek

SUMMARY SHEET - HCFCD HIGH WATER MARKS 10/24/2017

CYPRESS CREEK K100-00-00

								STORM EVENTS											ALLISON		IKE				
ROAD NAME	STAGE GAGE	BRIDGE BM ELEV	78 TO '01 ADJUST	10.0%	2.0%	1.0%	0.2%	10/49	CARLA 9/61	1/19/79	9/19/79	8/31/81	5/21/83	5/19/89	6/26/89	10/18/94	10/19/98	11/14/98	6/9/01	12/14/05	9/13/08	4/28/09	7/12/12	4/18/16	5/27/16
CYPRESSWOOD DR	1110	79.65	-0.5	68.2	75.0	77.8	85.4									79.2	65.5	70.7	72.5	63.2	68.9	66.0	64.5	71.4	73.0
TRESCHWIG		85.39	-1.4	76.4	79.2	80.2	85.4							78.0		78.4	75.3	73.7	78.5	70.8	76.6	74.8	71.8	78.3	75.5
ALDINE WESTFIELD		89.06	-1.4	79.7	83.0	84.2	86.3	85.3				78.9	76.6	83.2	81.5	80.8	78.4	77.9	82.4	73.5	80.5	79.2	74.2	81.7	77.6
HARDY ROAD		94.85	-2.0	84.9	88.1	89.5	91.5	89.8	80.9		81.8		81.6			83.7*	85.4	81.7	86.9	81.6	84.4	84.7	79.5	86.9	83.4
I.H. 45	1120	101.82	-2.1	91.2	93.0	94.4	97.3	95.5	87.5	84.3	87.3	88.6	83.8	92.1	90.7	88.0	89.1	86.8	92.5	84.9	89.3	87.9	83.6	90.6	85.6
KUYKENDAHL	1130	109.01	-1.9	97.1	100.6	102.2	107.0	103.6	95.0	96.5	97.6	97.5	96.4	101.3	99.1	99.4	98.2	97.1	100.9	92.7	97.2	96.8	96.5	101.4	96.5
TC JESTER		NA																						105.4	100.7
STUEBNER-AIRLINE RD	1140	115.95	-1.7	104.9	108.5	109.6	112.3	110.7		105.6	104.0		102.4	108.0	105.3	107.9	106.8	104.9	109.7	101.8	104.3	104.6	103.7	110.3	104.2
CHAMPION FOREST DR		110.31	-1.5	108.7	112.0	113.0	115.5						105.2	108.5		110.3	109.5	107.3	109.5	102.2	106.9	107.4	108.9	112.4	105.3
CYPRESSWOOD DR		120.21	-2.2	112.2	114.8	115.8	118.1										112.7	110.8	114.8	111.5	110.6	111.2	111.7	115.5	111.7
CUTTEN		121.47	-2.1	113.8	116.3	117.4	119.9									114.6	117.6	112.2	114.6	107.7	111.4	112.7	114.6	117.4	112.5
SH 249	1150	128.69	-1.4	115.7	118.9	120.1	122.5	123.7		119.3	118.5		116.8	114.2	113.7	119.4	120.1	116.3	120.5	N/A	N/A	116.5	119.2	120.3	116.8
JONES		126.98	-1.2	118.3	121.1	122.3	125.1									121.0	122.1	119.8	121.2	109.2	116.3	119.0	121.5	122.5	119.8
CYPRESSWOOD 369B		128.42	-1.1	119.5	122.2	123.4	126.2										123.5	121.1	122.9	109.5	117.4	120.3	122.8	125.3	121.2
GRANT ROAD	1160	127.25	-2.2	122.3	124.3	125.2	127.6	123.4		122.6	122.7	120.4	120.6		115.3	125.4	124.3	122.9	123.8	112.6	119.0	123.1	124.6	127.4	124.2
N. ELDRIDGE PARKWAY	1165	134.31	-2.4	124.3	126.3	127.3	129.7									126.1	125.4	123.5	125.9	113.8		124.5	125.0	128.6	125.4
HUFFMEISTER ROAD	1170	134.24	-1.6	128.4	130.4	131.4	133.7			123.5	128.1		127.4			130.0	131.6	129.6	129.8			129.6	130.7	132.9	129.8
TELGE ROAD		139.71	-1.6	132.1	134.2	135.2	137.5		131.9	132.4			131.8			134.5	135.4	134.4	N/A			132.7	133.2	136.9	132.3
BARKER CYPRESS		144.00	-2.4	136.1	138.2	139.1	141.2										138.8	137.2	137.5			135.8	137.4	138.9	136.3
U.S. 290	1175	147.52	-1.0	137.0	139.3	140.2	142.4	137.7	131.0		136.8	135.0	136.2			143.5	138.7	137.4	138.2			137.3	138.9	141.7	n/a
FRY ROAD		150.20	-1.0	142.8	143.8	144.3	145.8																	147.5	
HOUSE HAHL ROAD		149.00	-1.0	144.7	145.8	146.4	148.0						144.8			145.7	147.0	142.0	145.1			145.0	145.1	148.4	147.7
KATY HOCKLEY ROAD	1180	162.20	-0.4	161.5	162.5	162.9	164.0			160.5			160.8			163.0	162.9	161.3	160.6			159.9	159.8	162.3	160.5
SHARP ROAD		164.42	-0.1	167.6	169.2	169.9	171.7			166.5						168.9*	166.8	163.5	164.9			165.8	166.7	168.9	168.0

NOTE: BRIDGE AND HIGH WATER ELEVATIONS ARE ON 1988 NAVD; 2001 ADJ

(?) = Survey Dept research needed to confirm elevation

All K100 exceedance probability elevations based on PMR issued 3/22/2010. High water marks are approximate. HCFCD assumes no responsibility for their accuracy.

SUMMARY SHEET - HCFCD HIGH WATER MARKS 10/24/2017

CYPRESS CREEK K100-00-00

								STORM EVENTS															
ROAD NAME	STAGE GAGE	BRIDGE BM ELEV	78 TO '01 ADJUST	10.0%	2.0%	1.0%	0.2%	HARVEY 8/27/17															
CYPRESSWOOD DR	1110	79.65	-0.5	68.2	75.0	77.8	85.4	80.5															
TRESCHWIG		85.39	-1.4	76.4	79.2	80.2	85.4	82.6															
ALDINE WESTFIELD		89.06	-1.4	79.7	83.0	84.2	86.3	86.3															
HARDY ROAD		94.85	-2.0	84.9	88.1	89.5	91.5	92.1															
I.H. 45	1120	101.82	-2.1	91.2	93.0	94.4	97.3	97.0															
KUYKENDAHL	1130	109.01	-1.9	97.1	100.6	102.2	107.0	106.5															
TC JESTER		NA						110.5															
STUEBNER-AIRLINE RD	1140	115.95	-1.7	104.9	108.5	109.6	112.3	113.8															
CHAMPION FOREST DR		110.31	-1.5	108.7	112.0	113.0	115.5	116.4															
CYPRESSWOOD DR		120.21	-2.2	112.2	114.8	115.8	118.1	119.03															
CUTTEN		121.47	-2.1	113.8	116.3	117.4	119.9	120.9															
SH 249	1150	128.69	-1.4	115.7	118.9	120.1	122.5	123.4															
JONES		126.98	-1.2	118.3	121.1	122.3	125.1	126.3															
CYPRESSWOOD 369B		128.42	-1.1	119.5	122.2	123.4	126.2	127.6															
GRANT ROAD	1160	127.25	-2.2	122.3	124.3	125.2	127.6	129.8															
N. ELDRIDGE PARKWAY	1165	134.31	-2.4	124.3	126.3	127.3	129.7	130.8															
HUFFMEISTER ROAD	1170	134.24	-1.6	128.4	130.4	131.4	133.7	135.3															
TELGE ROAD		139.71	-1.6	132.1	134.2	135.2	137.5	137.6															
BARKER CYPRESS		144.00	-2.4	136.1	138.2	139.1	141.2	141.5															
U.S. 290	1175	147.52	-1.0	137.0	139.3	140.2	142.4	142.0															
FRY ROAD		150.20	-1.0	142.8	143.8	144.3	145.8	147.2															
HOUSE HAHL ROAD		149.00	-1.0	144.7	145.8	146.4	148.0	147.5															
KATY HOCKLEY ROAD	1180	162.20	-0.4	161.5	162.5	162.9	164.0	162.8															
SHARP ROAD		164.42	-0.1	167.6	169.2	169.9	171.7	169.8															

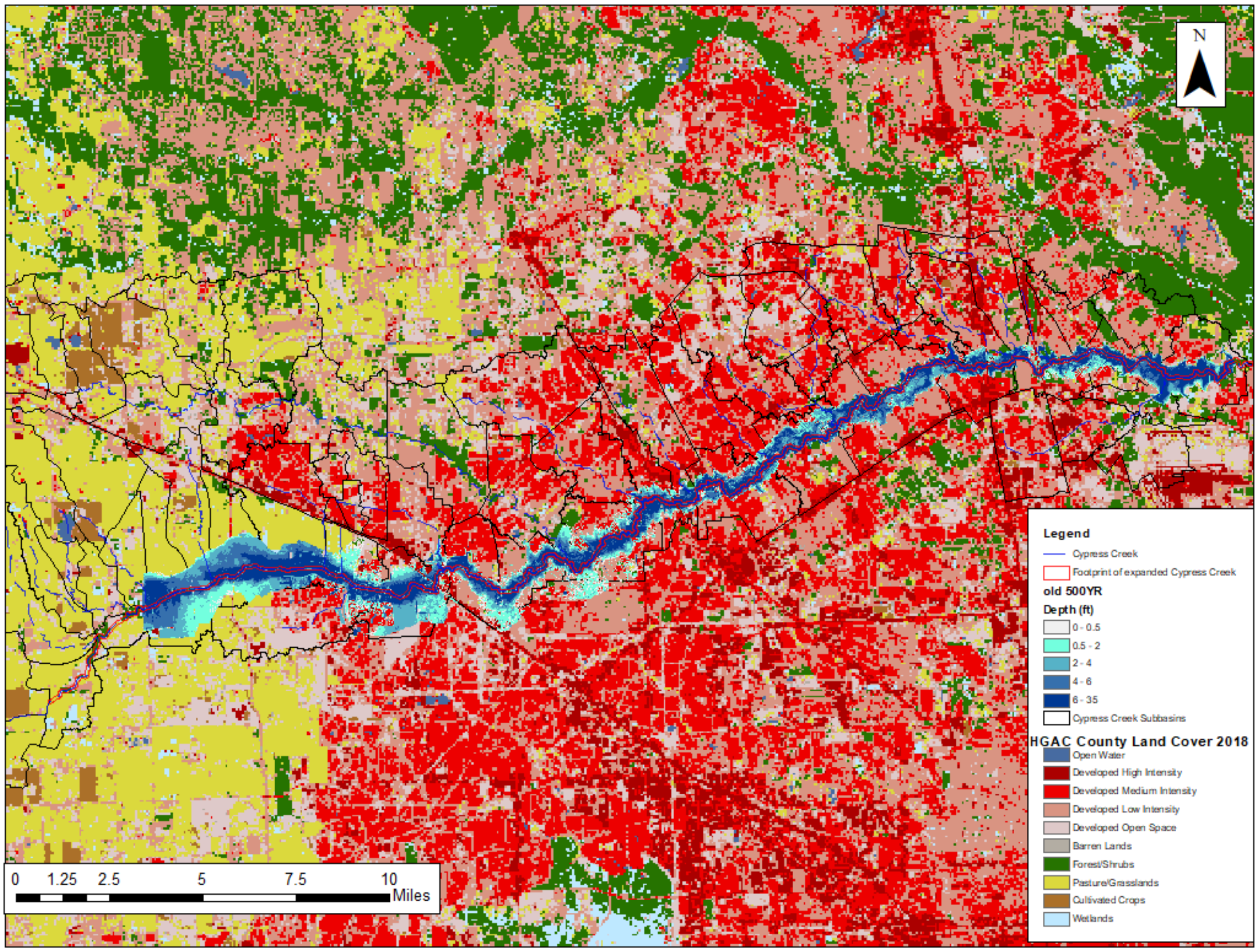
NOTE: BRIDGE AND HIGH WATER ELEVATIONS ARE ON 1988 NAVD; 2001 ADJ

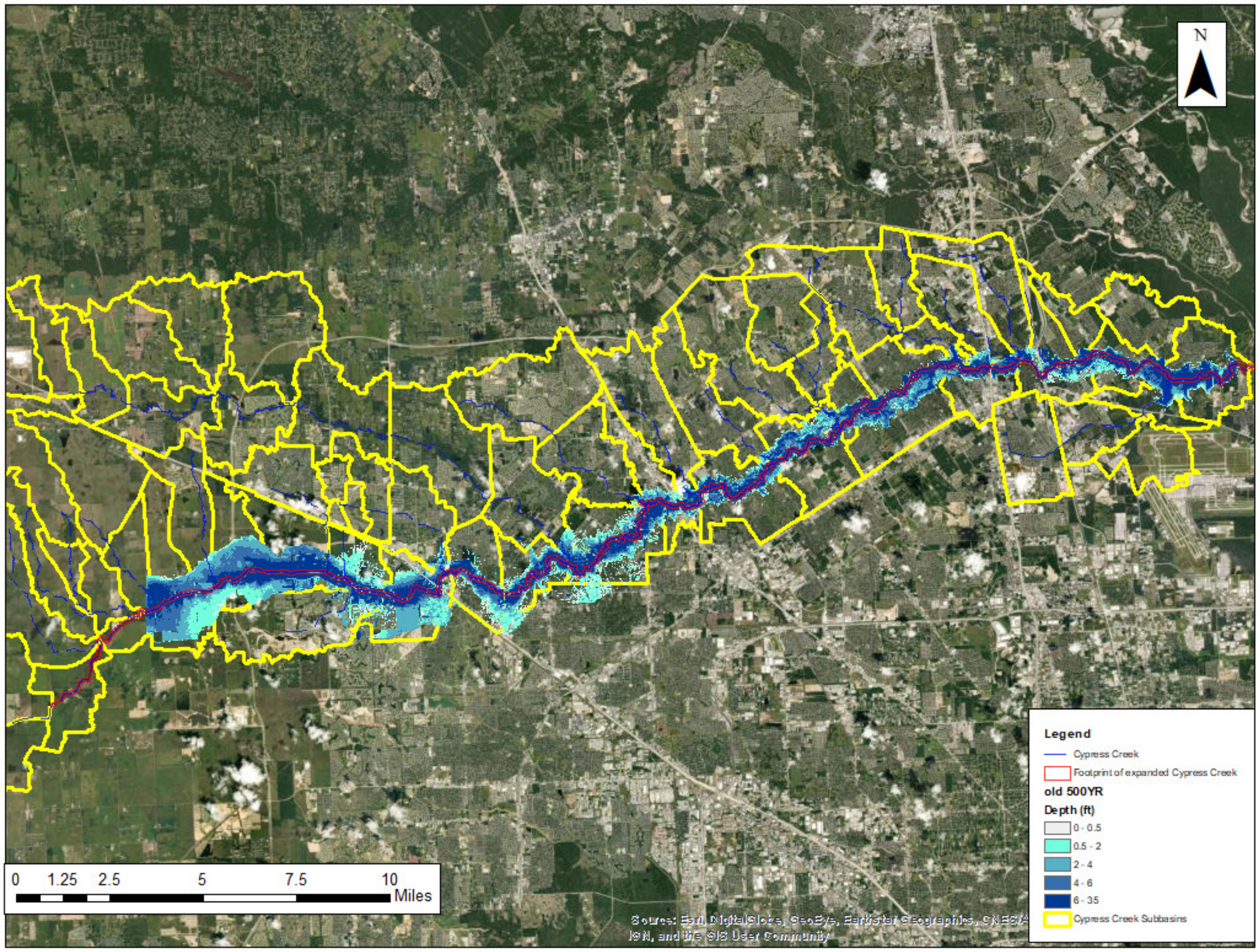
(?) = Survey Dept research needed to confirm elevation

All K100 exceedance probability elevations based on PMR issued 3/22/2010. High water marks are approximate. HCFCD assumes no responsibility for their accuaracy

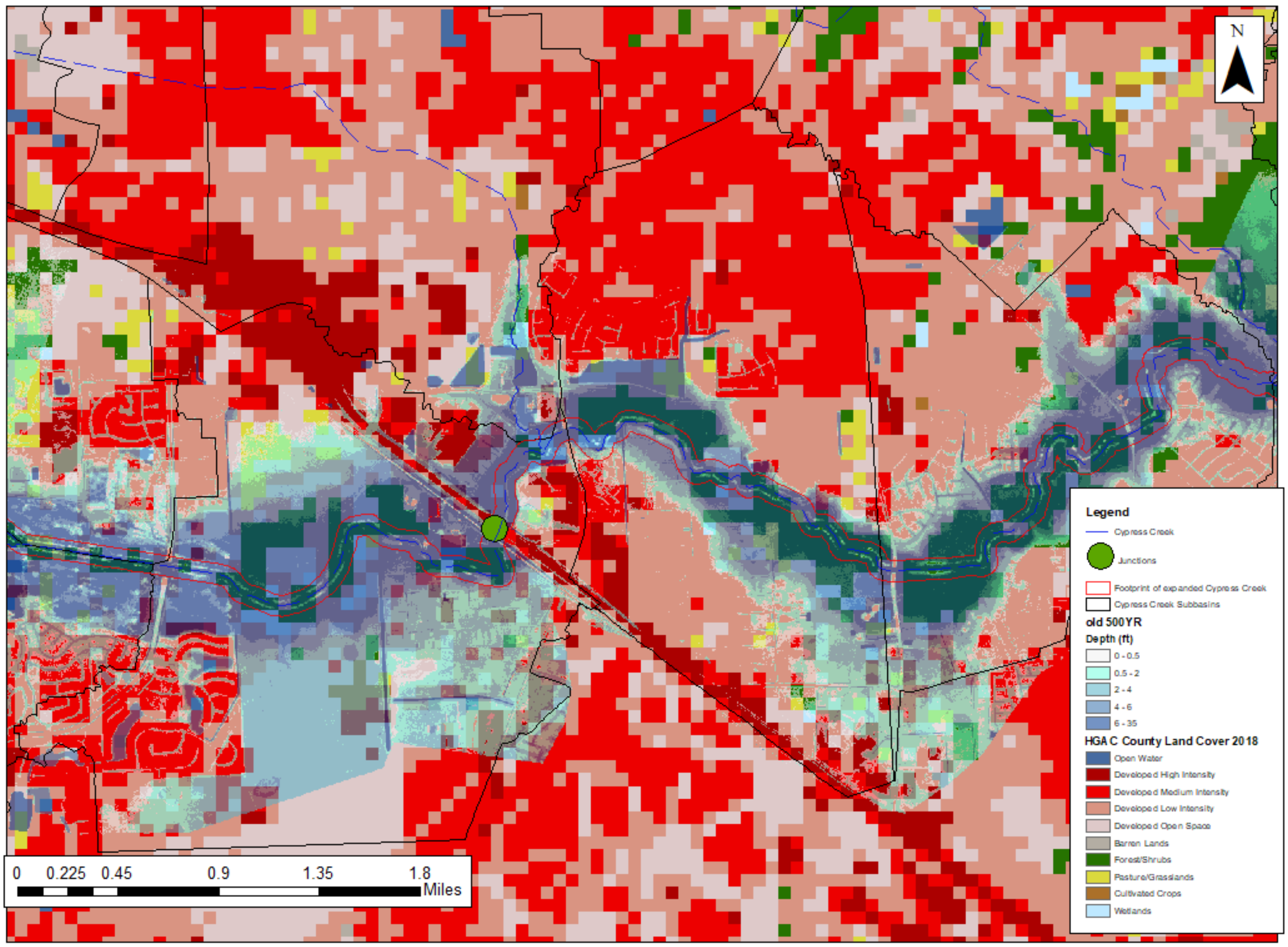
Appendix B - 500-year Floodplains at Various Locations along Cypress Creek

Grand Parkway (Highway 99) to the Outlet

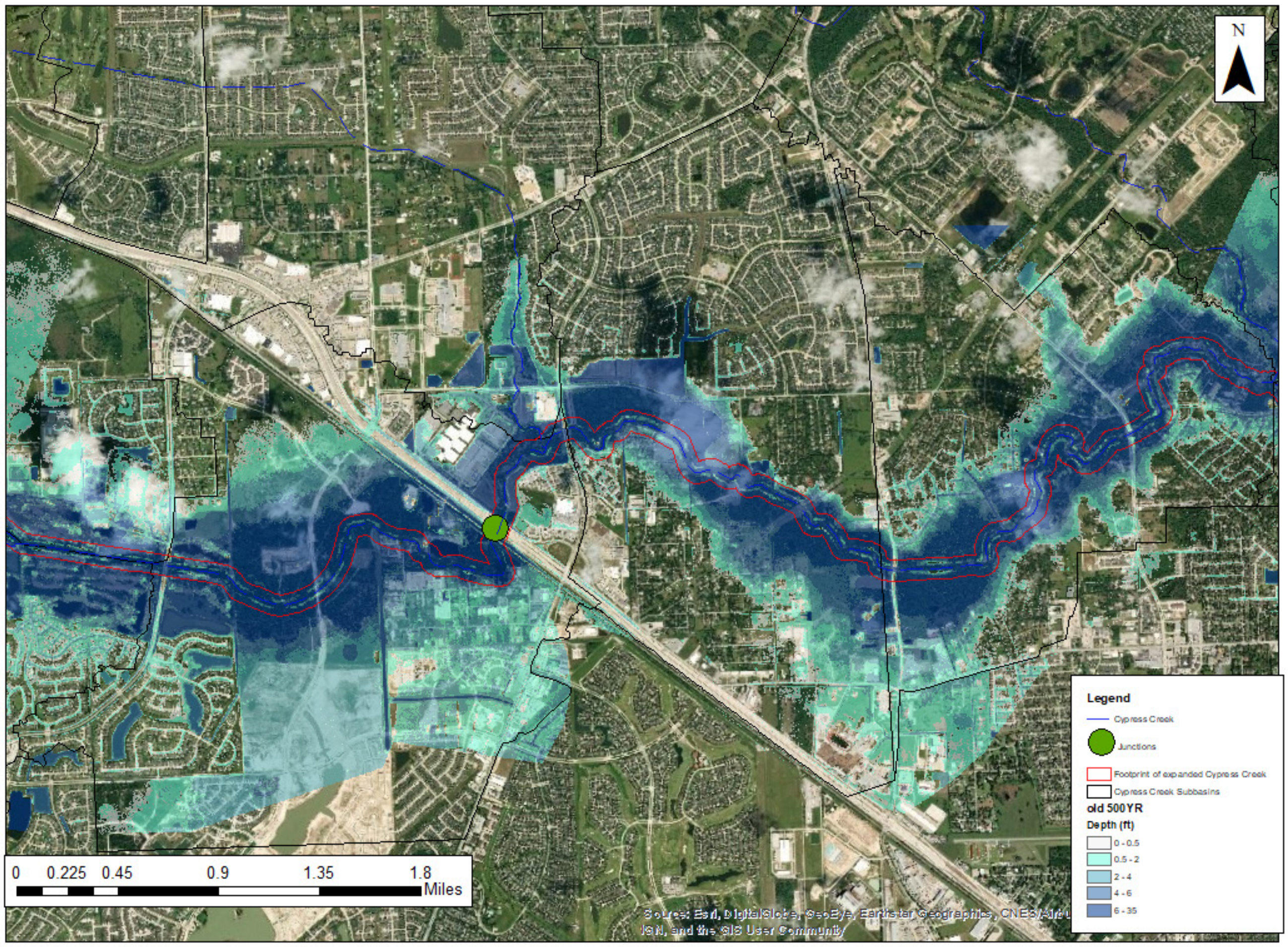



N
Legend
Cypress Creek
Footprint of expanded Cypress Creek
old 500YR
Depth (ft)
0 - 0.5
0.5 - 2
2 - 4
4 - 6
6 - 35
Cypress Creek Subbasins
0
1.25
2.5
5
7.5
10
Miles

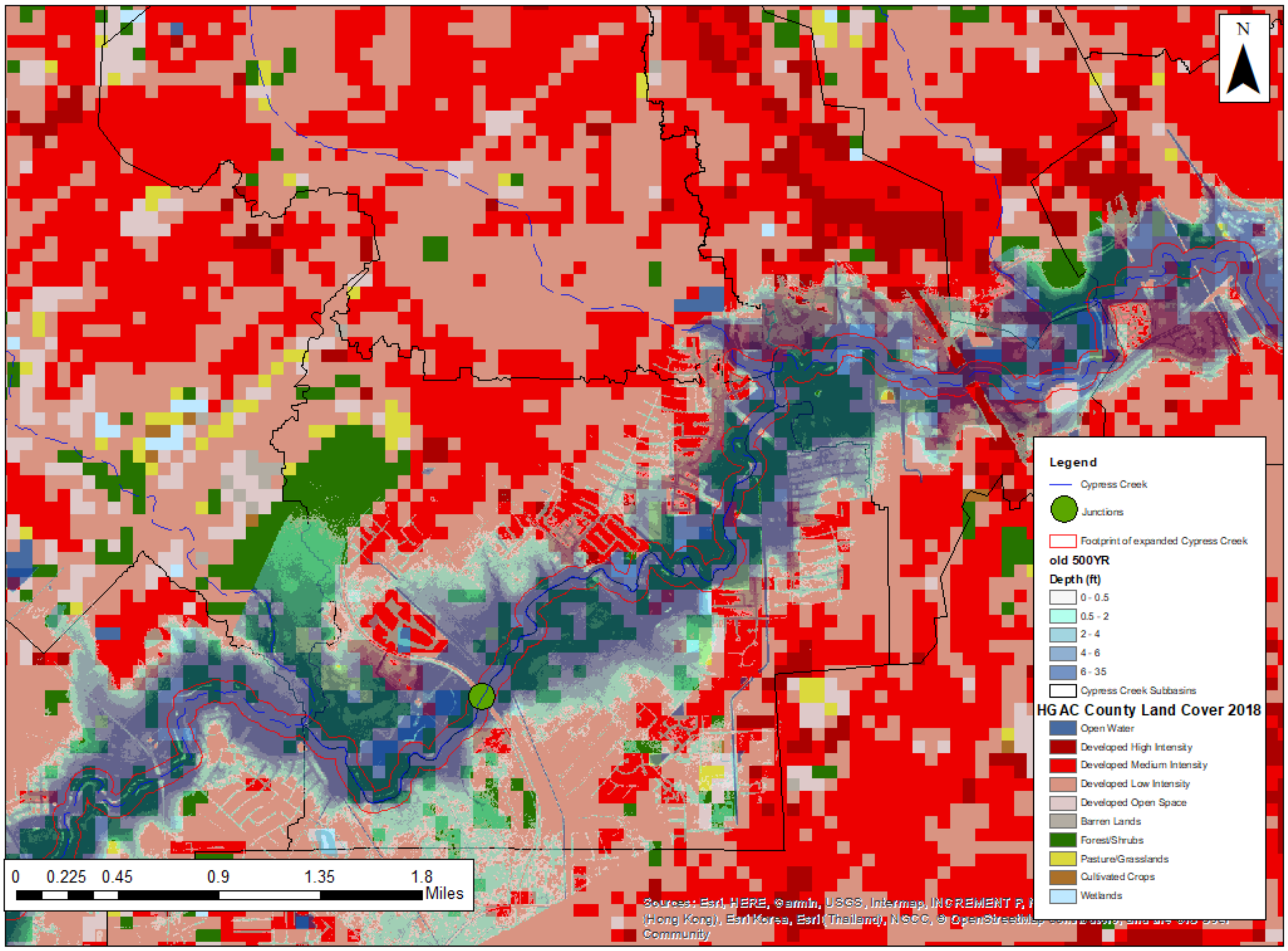
US290 and Cypress Creek



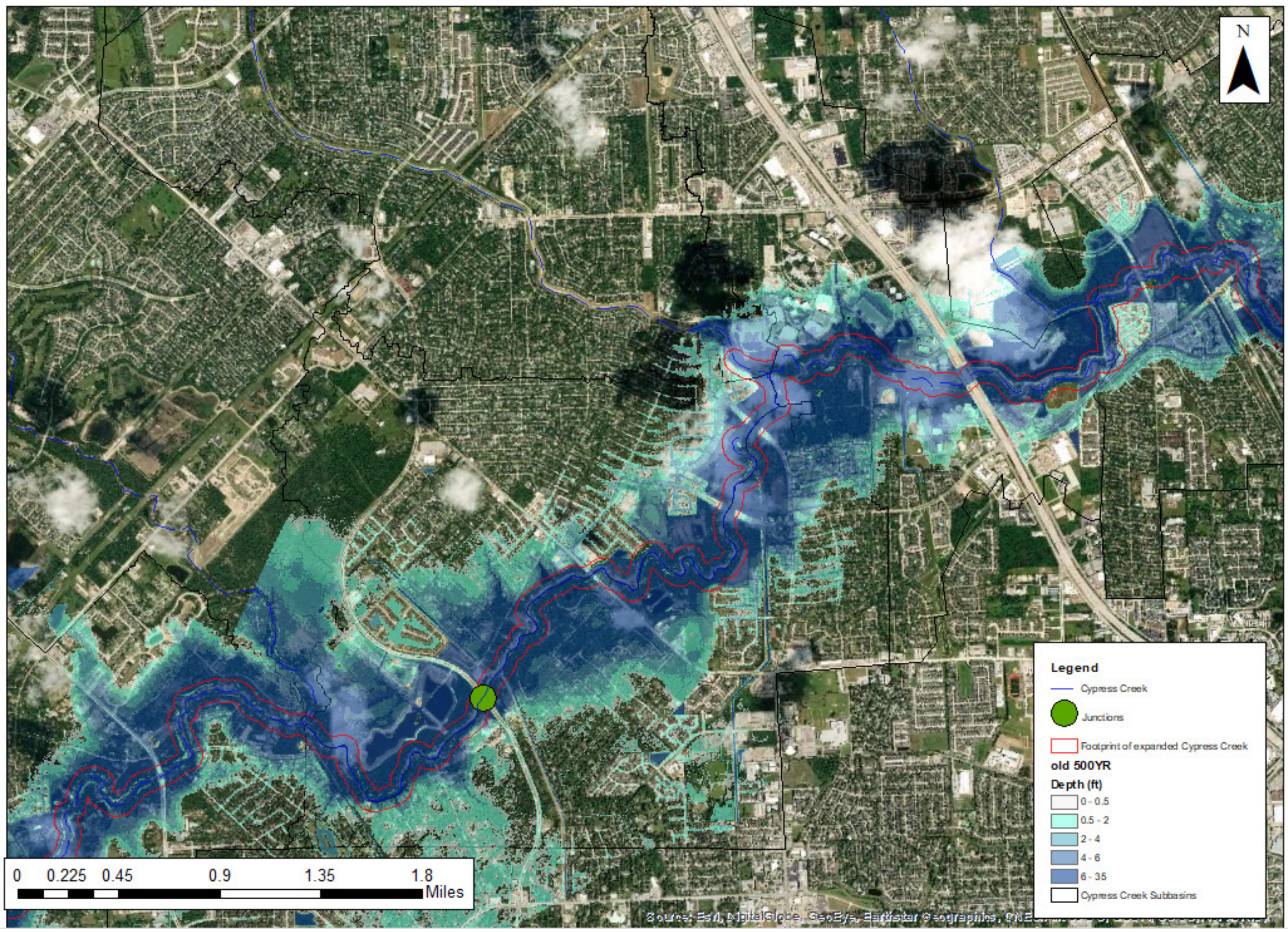
US290 and Cypress Creek



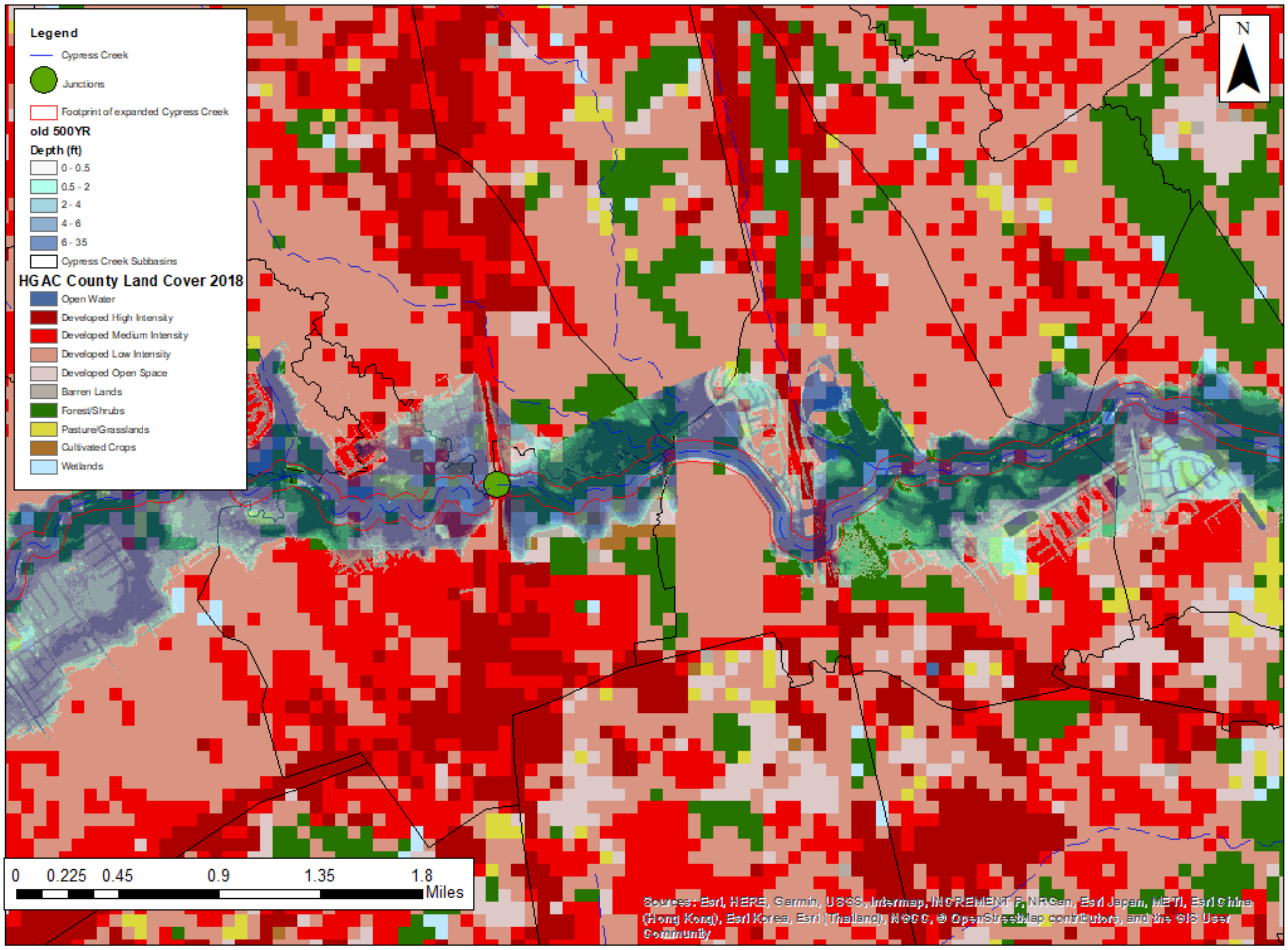
North Eldridge Pkwy and Cypress Creek



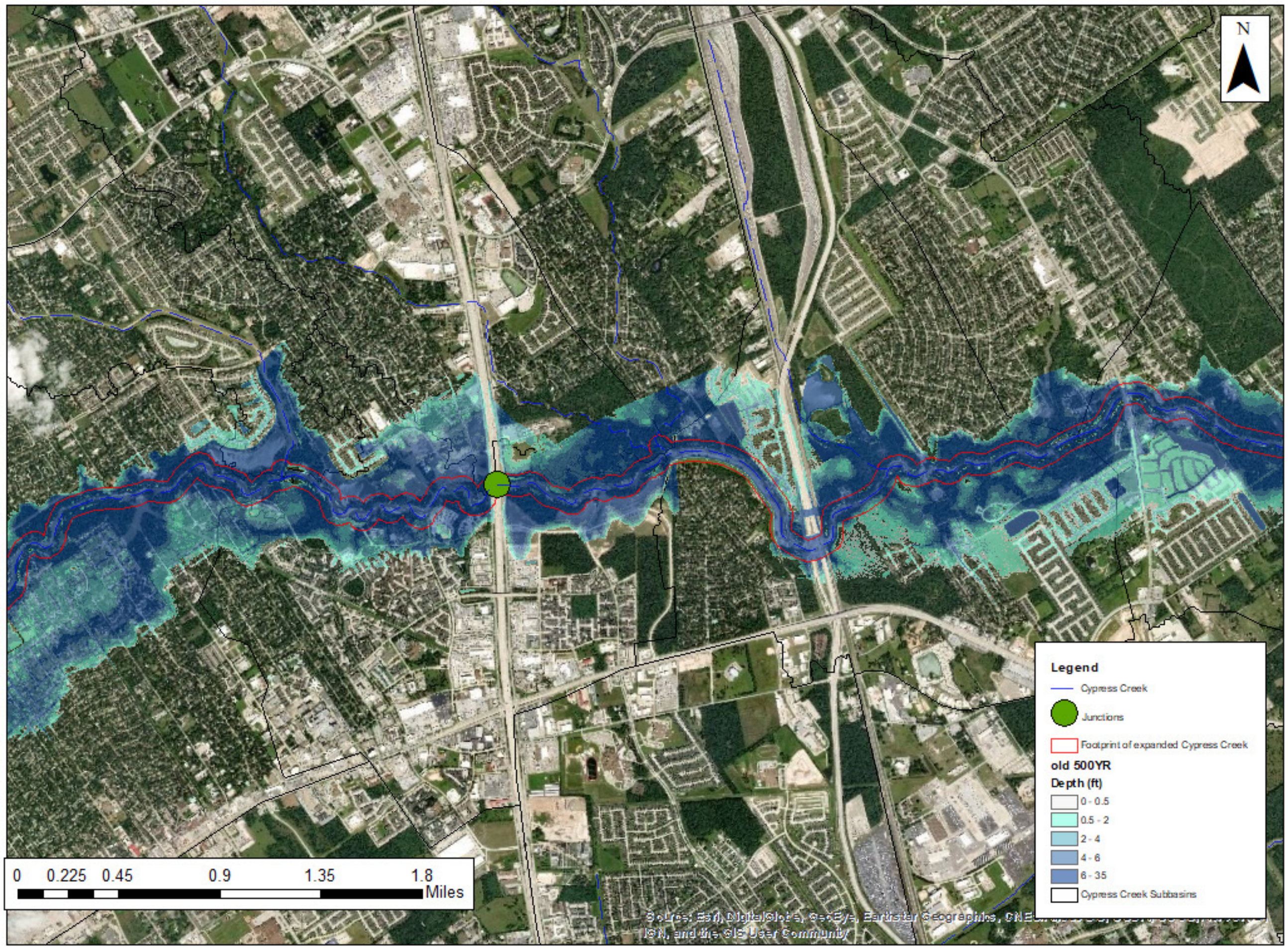
North Eldridge Pkwy and Cypress Creek



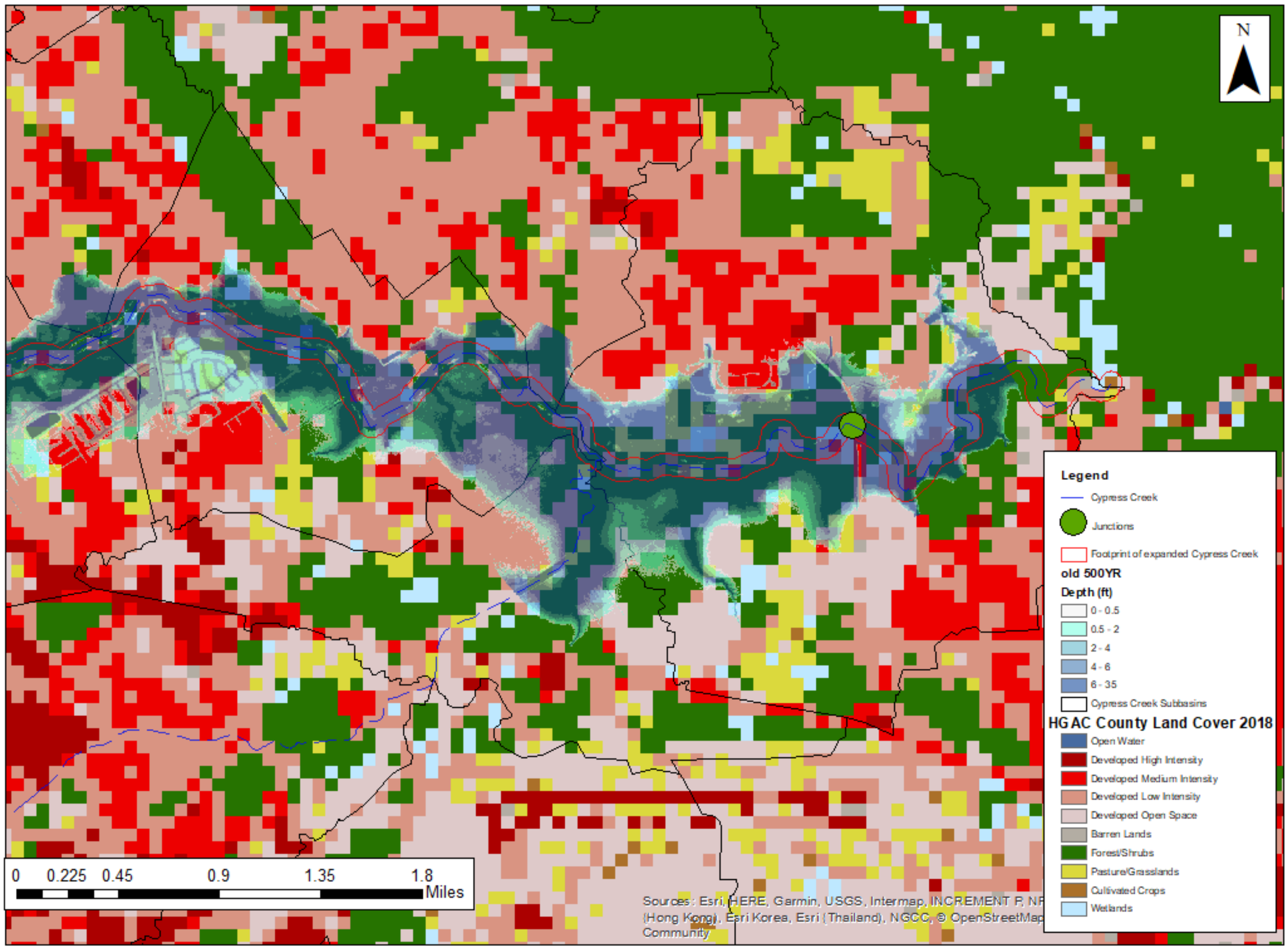
I45N and Cypress Creek



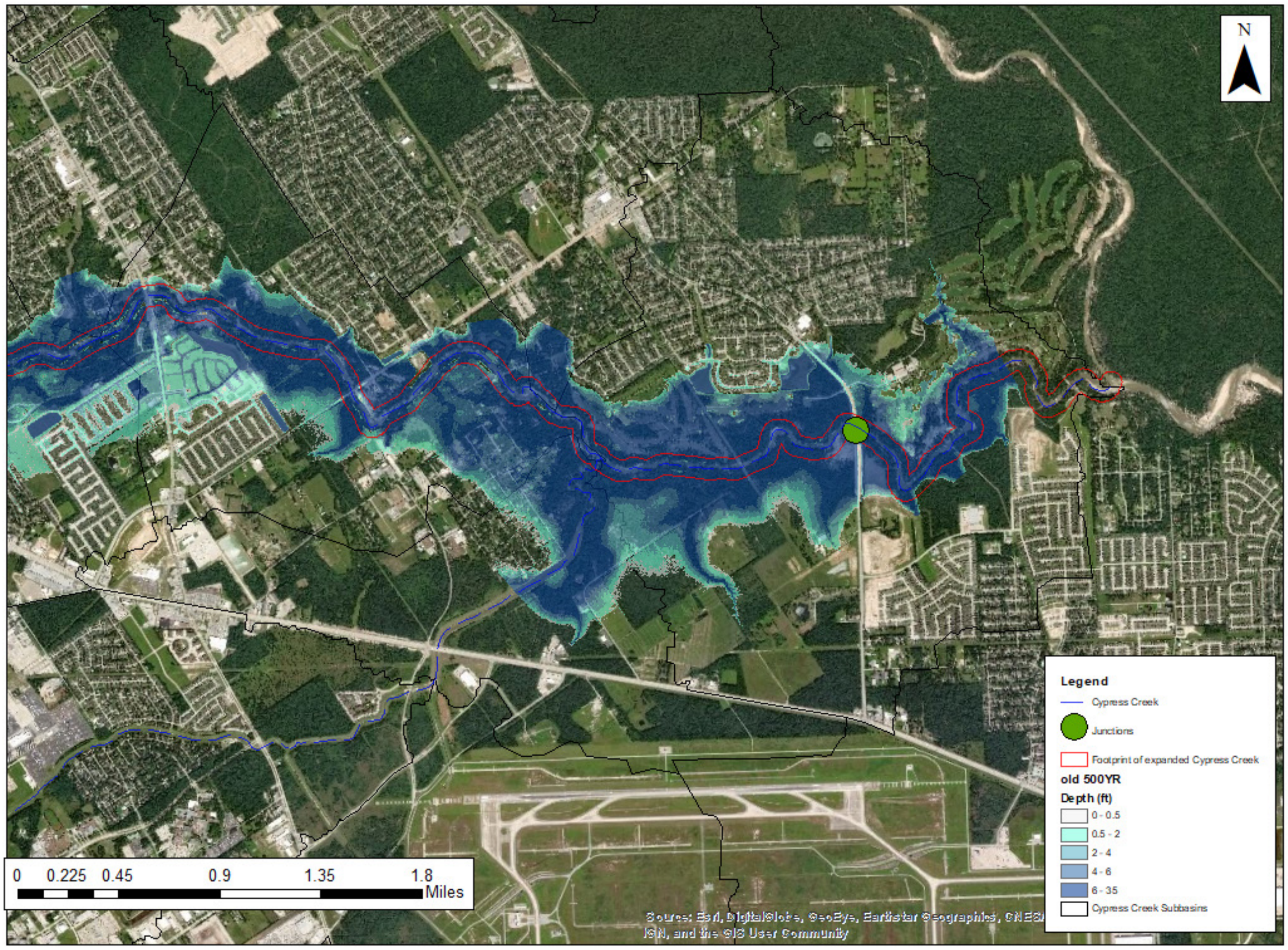
I45N and Cypress Creek



Cypresswood Dr and Cypress Creek

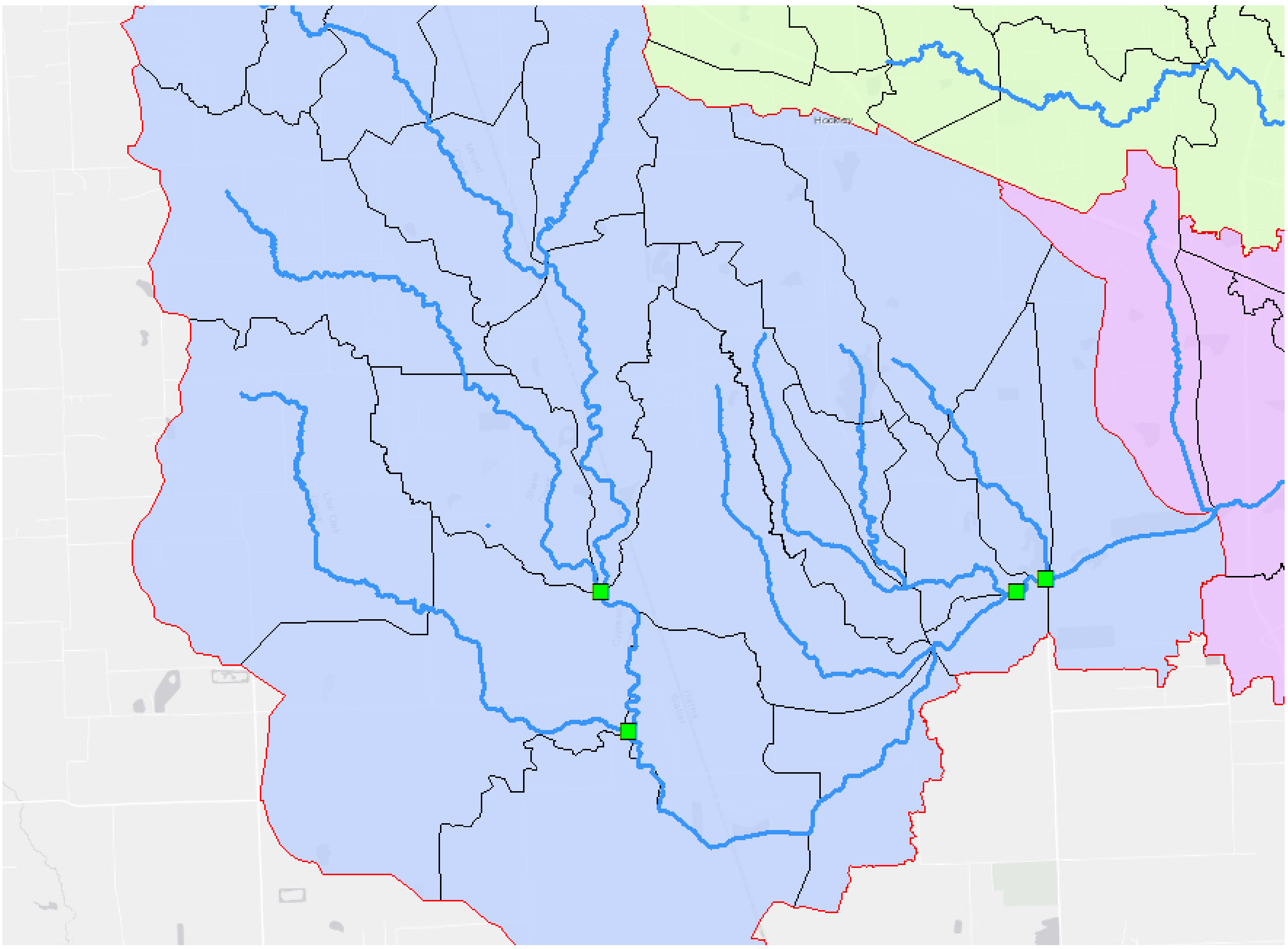


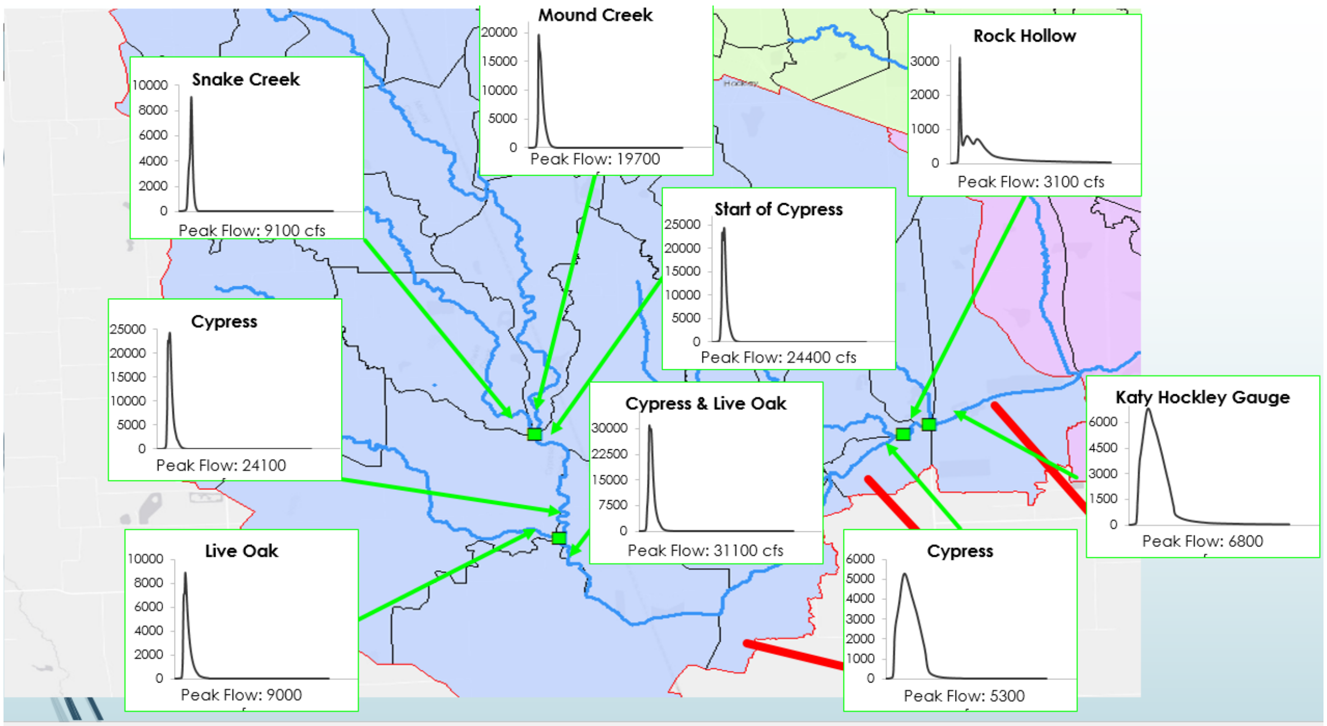
Cypresswood Dr and Cypress Creek



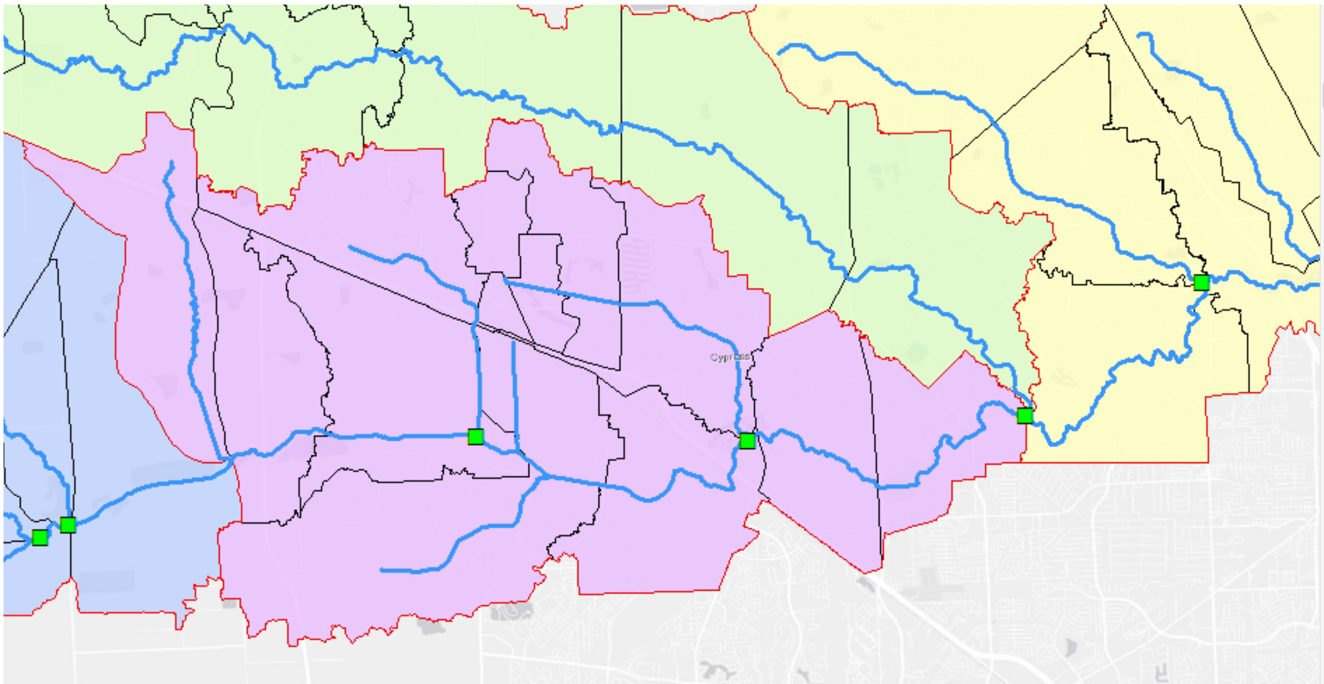
Appendix C - HMS Flow Hydrographs for the 500-year Storm Even for each Sub-Watershed Contribution

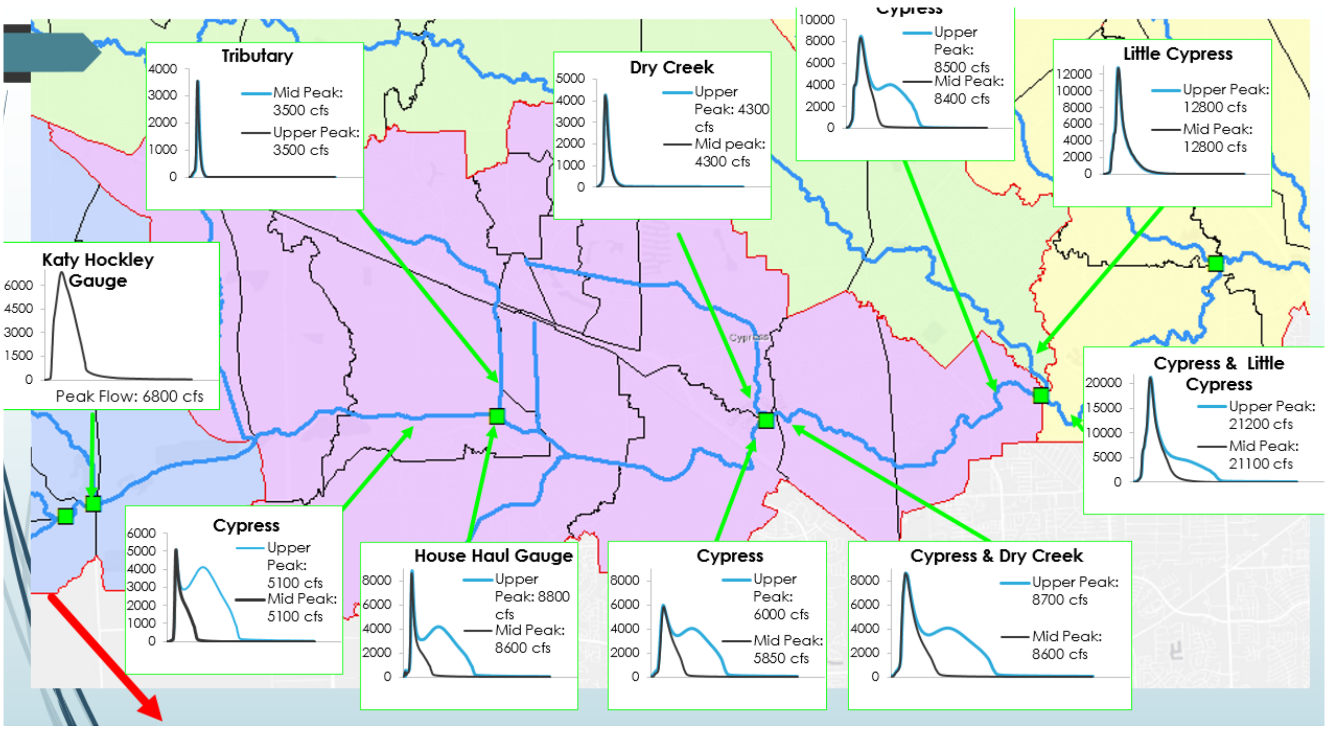
Upper Watershed




Mound Creek
Peak Flow: 19700
Rock Hollow
Peak Flow: 3100 cfs
Snake Creek
Peak Flow: 9100 cfs
Start of Cypress
Peak Flow: 24400 cfs
Cypress
Peak Flow: 24100
Cypress & Live Oak
Peak Flow: 31100 cfs
Katy Hockley Gauge
Peak Flow: 6800
Live Oak
Peak Flow: 9000
Cypress
Peak Flow: 5300

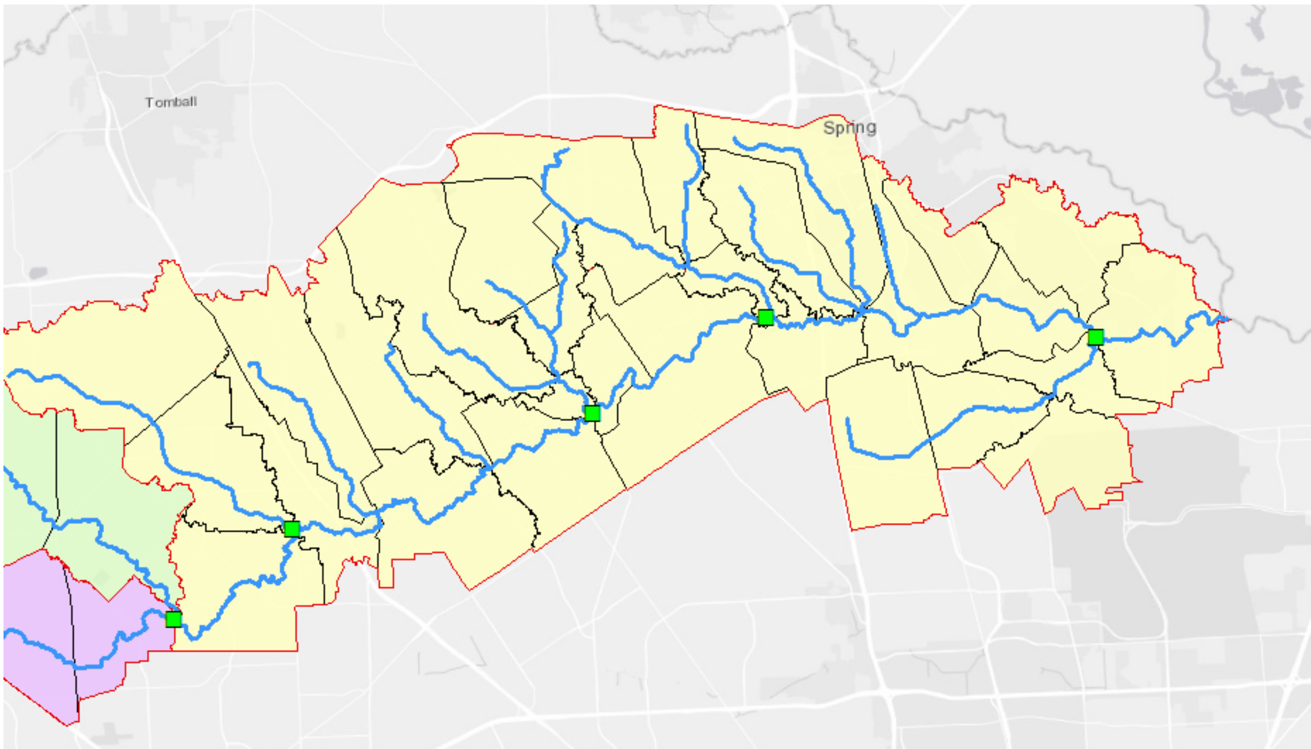
Middle Watershed

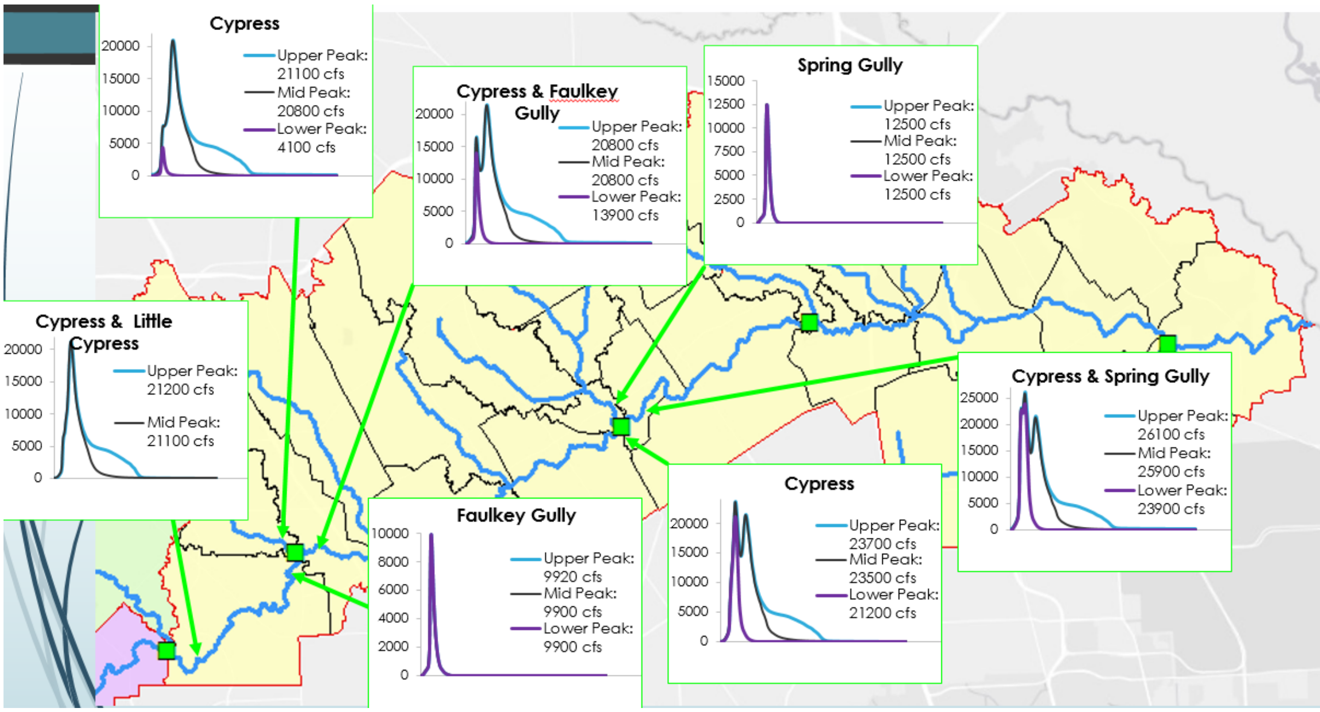


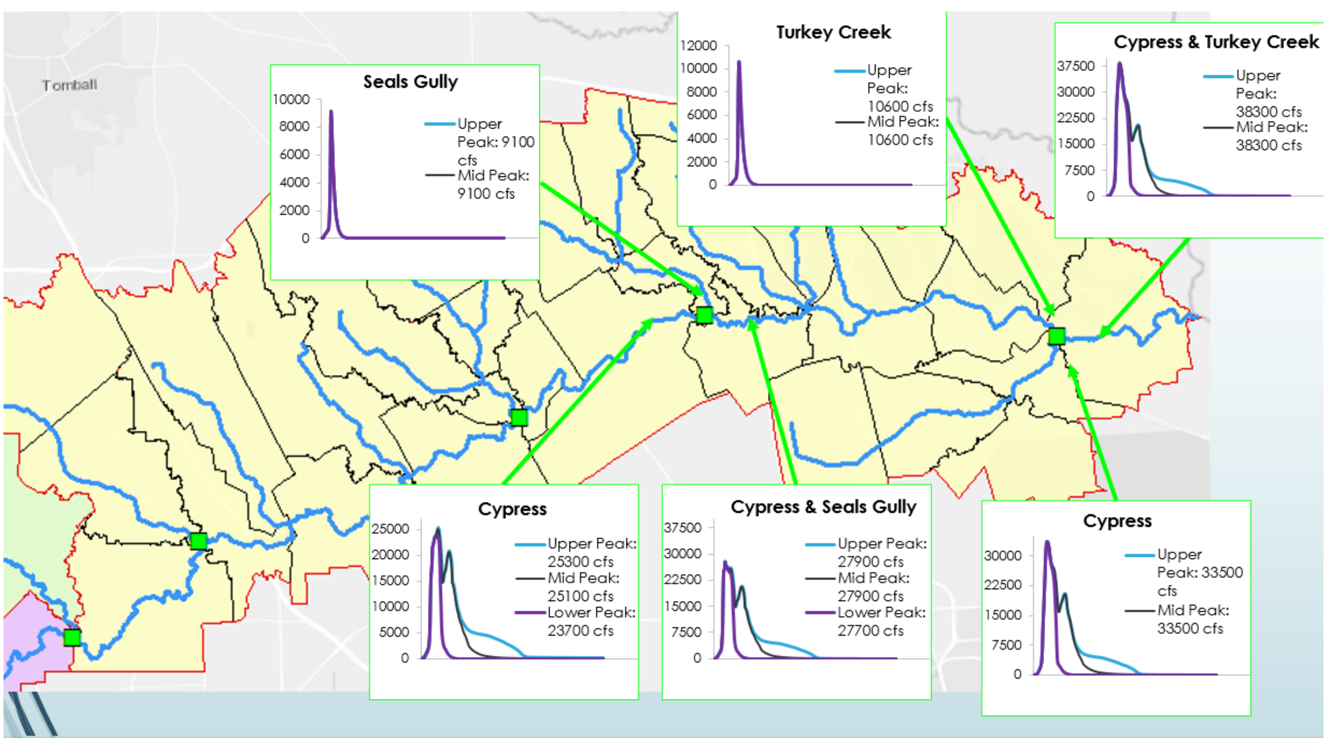


Tributary
Mid Peak: 3500 cfs
Upper Peak: 3500 cfs
Dry Creek
Upper Peak: 4300 cfs
Mid peak: 4300 cfs
Upper Peak: 8500 cfs
Mid Peak: 8400 cfs
Little Cypress
Upper Peak: 12800 cfs
Mid Peak: 12800 cfs
Katy Hockley Gauge
Peak Flow: 6800 cfs
Cypress & Little Cypress
Upper Peak: 21200 cfs
Mid Peak: 21100 cfs
Cypress
Upper Peak: 5100 cfs
Mid Peak: 5100 cfs
House Haul Gauge
Upper Peak: 8800 cfs
Mid Peak: 8600 cfs
Cypress
Upper Peak: 6000 cfs
Mid Peak: 5850 cfs
Cypress & Dry Creek
Upper Peak: 8700 cfs
Mid Peak: 8600 cfs

Lower Watershed




Cypress
Upper Peak: 21100 cfs
Mid Peak: 20800 cfs
Lower Peak: 4100 cfs
Cypress & Faulkey Gully
Upper Peak: 20800 cfs
Mid Peak: 20800 cfs
Lower Peak: 13900 cfs
Spring Gully
Upper Peak: 12500 cfs
Mid Peak: 12500 cfs
Lower Peak: 12500 cfs
Cypress & Little Cypress
Upper Peak: 21200 cfs
Mid Peak: 21100 cfs
Cypress & Spring Gully
Upper Peak: 26100 cfs
Mid Peak: 25900 cfs
Lower Peak: 23900 cfs
Faulkey Gully
Upper Peak: 9920 cfs
Mid Peak: 9900 cfs
Lower Peak: 9900 cfs
Cypress
Upper Peak: 23700 cfs
Mid Peak: 23500 cfs
Lower Peak: 21200 cfs


Tomball
Turkey Creek
Upper Peak: 10600 cfs
Mid Peak: 10600 cfs
Cypress & Turkey Creek
Upper Peak: 38300 cfs
Mid Peak: 38300 cfs
Seals Gully
Upper Peak: 9100 cfs
Mid Peak: 9100 cfs
Cypress
Upper Peak: 25300 cfs
Mid Peak: 25100 cfs
Lower Peak: 23700 cfs
Cypress & Seals Gully
Upper Peak: 27900 cfs
Mid Peak: 27900 cfs
Lower Peak: 27700 cfs
Cypress
Upper Peak: 33500 cfs
Mid Peak: 33500 cfs