City of Houston Stormwater Master Plan

Clear Creek Final Report

February 22, 2024

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Executive Summary

This report describes the development of a 31.4 square mile, two-dimensional (2D) rain-on-mesh InfoWorks ICM model of the portion of Clear Creek watershed located within the City of Houston limits. The model integrates the storm sewer network, roadside ditches, channels, and bayous that form the 191.5-mile-long conveyance system.

The Clear Creek watershed is in the south region of the City of Houston. The watershed was modeled following guidance from the City through white papers and workshops which are detailed in Appendix A and Section 1.7 respectively.

Available data was reviewed and updated to ensure its adequacy for model development. Various datasets were provided by the City of Houston, the Federal Emergency Management Agency (FEMA), the Harris County Flood Control District (HCFCD), the Houston Galveston Area Council (HGAC), the Texas Natural Resources Information System (TNRIS), the Texas Department of Transportation (TxDOT), and the Texas Water Development Board (TWDB). The data included impervious cover, storm sewer network, roadside ditches, culverts, inlets, manholes, finished floor elevations, open channels, unstudied channels, as-builts, LiDAR, land parcels, building footprints, and historical flood claims. All data was reviewed and adjusted to reflect the existing conditions and improve the quality of the data. To fill any gaps in the desktop datasets, field reconnaissance was performed. The field reconnaissance teams collected dimensions of key culverts, bridges and manholes along storm lines. Data was collected in the field using a mobile application that enabled the project team to review all data in real time.

Development of the model's hydrology was based on two methods: the rainfall-on-mesh method for areas within the City limits and the BDF and Clark Unit Hydrograph method for areas outside the City limits. Event rainfall depths and temporal distributions for the frequency events were based on NOAA Atlas 14 and MAAPNext data. Radar rainfall was applied for historic storm events. The Green & Ampt loss method was used to model infiltration using an average impervious cover percentage for the watershed.

A hydraulic model was developed using one-dimensional (1D) and 2D components to represent the storm sewer network, roadside ditches, unstudied channels, culverts, bridges, major channels, and bayous that form the 191.5-mile-long conveyance system within the watershed. Boundary conditions from the HCFCD MAAPNext model provided the discharge and stage hydrographs for the major bayous and creeks that interact with the storm sewer system.

A validation process used to confirm the model's accuracy in depicting stormwater system capacity. Three historical rainfall events were selected for model validation: Hurricane Harvey (2017), Memorial Day (2015), and Tax Day (2016). Storm events were selected based on the availability of rainfall data, number of flooding claims, and the flows and stages along Clear Creek from the available HCFCD models. The model met the City's validation criteria of 50% model flooding match to historic flooding claims at structures and 75% at parcels. The model validation process is detailed in Appendix H.

As the simulations were run, different items were adjusted and improved to allow the simulations to run smoothly and to completion. The model results show the percentage of storm sewer and roadside ditch systems that meet the system capacity of each storm event, defined as having a hydraulic grade line below ground for the 2-year event and within 1.5 feet above ground for all other events. Level of service results showed most of the system in general meet at least a 5-year level of service. The water surface elevations along the main channels and the water level in Clear Creek are the driving factor for the flooding that the model is showing especially in the area south of the Sam Houston Tollway and west of I-45. The majority of the roadside ditches are performing well during the 2-, 5-, and 10-year storms, with a significant decrease in capacity starting at the 25-year storm.

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1 Introduction

1.1. Background

Since Houston was founded, the City has encountered challenges with managing stormwater and flood resilience. Notable storms throughout the City's history have produced record rainfalls that have impacted residents in all parts of the City.

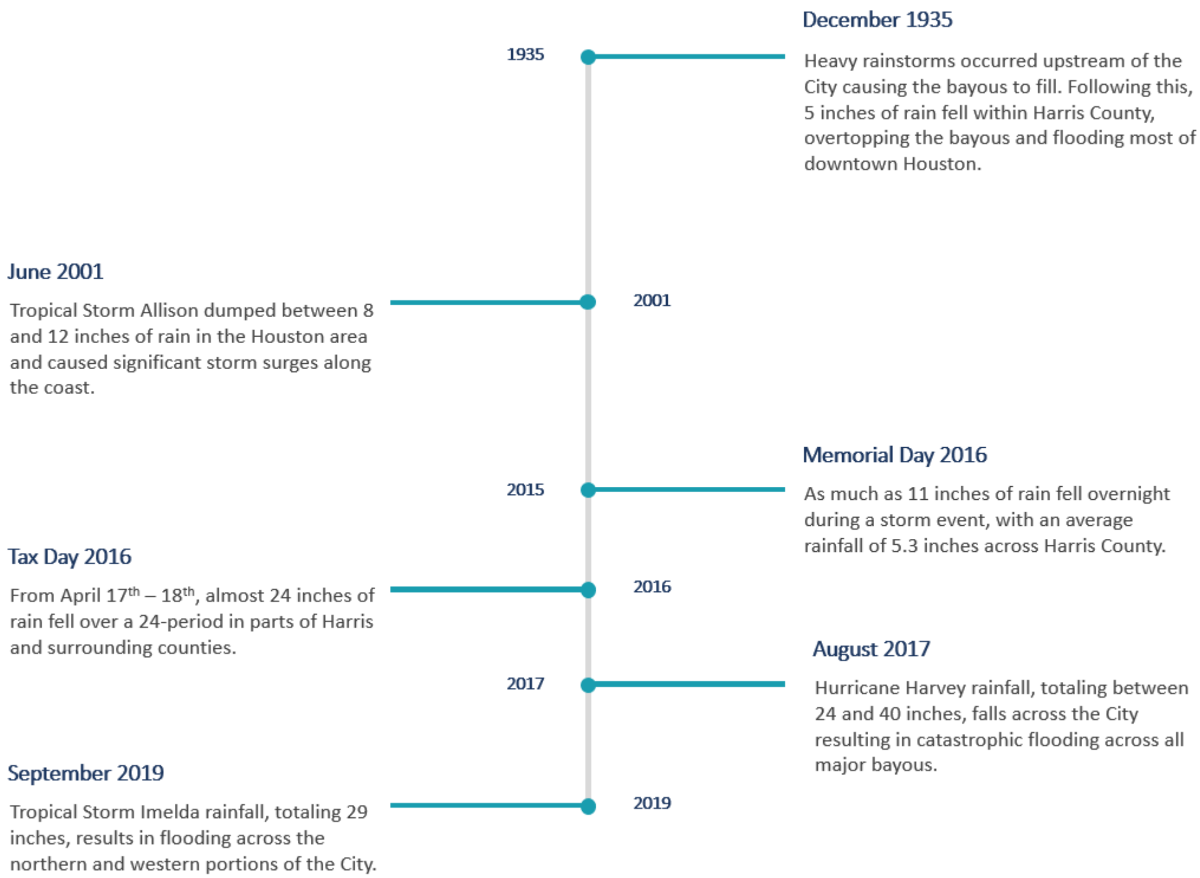


Figure 1-1: Major Historical Storm Timeline

Drainage planning has become an essential part of the project lifecycle to understand the extent of flood related issues and identify areas with the most need. The City has undergone drainage planning since the 1990s with major milestones shown below:

- ***Comprehensive Drainage Plan (1999)*** – First analysis of the City drainage infrastructure utilizing a robust GIS analysis of the storm sewer system. Used the Rational Method to calculate peak discharges and compare results to the capacity of the system. Identified the adequacy or inadequacy of each system. Has been used since its development to identify and target capital improvement projects.
- ***ReBuild Houston (2010)*** – The City launched an infrastructure program and drainage impact fee to address the aging roadway and drainage system. As part of the initiative, neighborhood planning studies were conducted at various locations within the City based on historical losses and capacities identified within the CDP. Projects identified were programed into the CIP.

- ***Roadside Ditch Drainage Planning (2016)*** – In 2016 the City added the roadside ditch system, which accounts for approximately 30% of the infrastructure, into the CDP. The City surveyed the ditches as well as included LiDAR for the first time in the assessment of the drainage infrastructure. This allowed for additional identification of need areas within neighborhoods served by roadside ditches.

1.2. Project Goal

The City of Houston is developing its first comprehensive city-wide drainage model to better understand the City's stormwater infrastructure. The goal of the Stormwater Infrastructure Model effort is to model the main drainage infrastructure throughout the City to better understand the capacity of the storm sewers, overland flow routes, and interaction with the channels and bayous. These models will allow the City to communicate flood risk to existing residents and improve planning for capital projects.

1.3. Preparation Efforts

Two efforts were conducted prior to the initiation of the city-wide study to determine what modeling approaches would be most beneficial. The first analysis included a software evaluation and selection. This process evaluated over 20 software packages to identify the software that would be most appropriate for the comprehensive analysis. InfoWorks ICM was selected due to its capability to perform both 1D and 2D modeling and its quick performance speeds for large complex systems.

The second analysis included identifying the level of detail needed to accurately model storm sewer within the City. The analysis concluded that in most cases, modeling trunk lines 36-inch in diameter and higher would provide similar results to modeling all storm sewer within the City. Exceptions to this include neighborhoods fully served by less than 36-inch trunklines and roadside ditch neighborhoods.

1.4. Project Scope

Six consulting teams were selected to model the 11 watersheds within the City. The watershed responsibilities of each consulting team are listed below.

- Sims Bayou – Halff Associates, Inc.
- Brays Bayou – LAN, Inc.
- Buffalo Bayou – Gauge Engineering, Inc.
- White Oak Bayou – HDR, Inc.
- Greens Bayou & Hunting Bayou – Black & Veatch, Inc.
- San Jacinto, Clear Creek, Armand, Luce, and Greens (IAH) Bayous – Arcadis, Inc.

The scope for all consulting teams included four main tasks. These are summarized below:

1. Project Management – In conjunction with the GLO grant, consulting teams were required to develop a project management plan, conduct monthly progress meetings, attend workshops, and provide monthly invoices.
2. Data Collection – Teams were to obtain, review, and confirm information from a variety of sources prior to model development. Tasks included data review, adjustment of storm sewer network, and field reconnaissance to confirm accuracy base data.
3. Model Development – Teams were to develop an Innovyze InfoWorks ICM model for their entire watershed within the City of Houston including storm sewers, roadside ditches, and channels within the watershed. Tasks included model development, validation, simulations, and quality control.
4. Project Delivery – Model development would be summarized within a draft and final report to the City, as well as all electronic deliverables including the ICM models.

In addition to modeling Sims Bayou, Halff served as the Program Manager (PM) on behalf of the City of Houston. The role of the PM was to establish standards to be followed by all consulting teams, track schedule to accommodate project delivery, review submittals provided by the consulting teams, and respond to questions and comments throughout the project lifecycle.

1.5. Technical White Papers

The City developed modeling guidance through a series of technical "white papers." The white papers were prepared both prior to and during the modeling process. In addition, during the modeling process, white papers were revised where needed based on specific applications and consultant feedback. The purpose of these documents was to provide consistent modeling approaches and standards for all watershed teams. The technical white papers are included in Appendix A.

Data Collection

The data collection white paper outlined the process to obtain and edit the baseline data that was used for stormwater modeling. Data was provided from a variety of sources and then modified as directed for model development. Additional guidance was also provided to summarize the field reconnaissance (survey) efforts recommended for the task. The paper included recommended processes for manual adjustments to storm sewer data to account for inaccuracies where field reconnaissance was used. Information collected as part of this task was submitted in a Data Collection memorandum.

Naming Conventions

The purpose of the naming conventions white paper is to outline the required naming conventions for model components within the Stormwater Infrastructure Model. Consistent nomenclature is necessary to provide clear documentation and information to the City for all studied watersheds. The white paper outlined naming conventions for all components within the delivered models.

Hydrology

The purpose of the hydrology white paper is to present the hydrologic methods that were applied in the Stormwater Infrastructure Model. Data and discussion are provided to support the recommendations. The NOAA Atlas 14 rainfall depths determined for Harris County Flood Control District's (HCFCD) hydrologic Region 3 were applied throughout the Stormwater Infrastructure Model according to City criteria. The Green & Ampt loss method was used to model infiltration, and rainfall was applied to the surface instead of at discrete nodes. The hydrologic method for areas outside of City limits but within the watershed was approached differently.

1D Model Development

The 1D model development white paper defines what systems should be modeled using 1D hydraulic capabilities for the City of Houston Stormwater Infrastructure Modeling effort. The City of Houston drainage system consists of underground storm sewer, open channels, and roadside ditches. The capacity of these hydraulic components influences ponding and flooding throughout the City. This infrastructure was modeled using 1D calculations to evaluate flow, water surface elevations, and capacity of the entire drainage system.

2D Model Development

The 2D model development white paper outlines where 2D analysis are required for the City's Stormwater Infrastructure Modeling effort. Due to the flat topography within the City of Houston and the potential for stormwater to overflow from neighborhoods and streets, a two-dimensional (2D) model was needed to account for overland flow. The 2D model can more accurately model shallow flow over a flat surface and therefore better represents the conditions prevalent in Houston.

Roadside Ditches

The roadside ditch white paper outlines what approaches were to be used in modeling roadside ditch networks within neighborhoods and along roadways within the City. There are approximately 2,500 miles of roadside ditches within the City limits. Detailed hydraulic modeling of these networks on a regional scale can be challenging due to the size of the ditches and the presence of driveway culverts. Multiple modeling approaches were tested alongside a fully detailed model to identify the approach that mimics results from a detailed model while balancing model build and simulation time for regional models.

Boundary Conditions

Boundary conditions are set within the model to mimic the watershed-wide response on a truncated area within the watershed. Boundary types include flow and stage hydrographs. The use of these boundary conditions allows the modeling to closely resemble previous InfoWorks studies of the watershed. The boundary conditions white paper outlines the specified boundary conditions to use for the City's Stormwater Infrastructure Modeling effort.

Validation

The models developed for each watershed within the City of Houston require validation with historical storm events to ensure confidence in the model assumptions and results. The validation white paper describes the steps for model validation including data, rainfall, simulation, and results. The white paper also includes information on when models would be considered 'validated' based on meeting particular criteria or metrics.

2D Flow Exchanges

The hydraulic models developed for each watershed consist of a series of small models to be more manageable with model development, runtimes, and future use. Due to the model truncation, there are instances where these models will interact with each other outside of the HCFCD studied bayou or channels. The 2D flow exchanges white paper describes the recommended process for conveying 2D flow between adjacent models.

1.6. Watershed Overview

The entire Clear Creek watershed is 201 square miles, of which 32 square miles is located within the City limits. The southern edge of the watershed includes the cities of Pearland, Friendswood, Deer Park, and League City. The watershed is bounded by Sims Bayou watershed to the north and Armand Bayou watershed on the east side. Exhibit 1 includes the extents of the watershed.

The terrain is generally flat throughout the watershed. The watershed drains in an easterly and southerly direction towards Clear Creek Bayou.

The watershed within the City limits is mostly developed, consisting primarily of small-lot, single-family residential development. There are areas of commercial land use in the north and southeast portions of the City limits, especially along 2nd Street where the Lyndon B Johnson Space Center is located. The City limits include undeveloped and developed open spaces. The northern part in the middle of the City limits includes medium-lot, residential areas that are primarily drained through roadside ditches. A summary of the land uses throughout the Clear Creek watershed within the City limits is provided in Table 1-1.

Table 1-1: Clear Creek Watershed Land Use Summary (within City Limits)

Land Use[1]	Area (sq. mi.)	Percentage (%)
Undeveloped	10.27	32%
Developed Open Space	1.59	5%
Residential	7.1	22%
Commercial	8.44	26%
Right of way and channels	4.68	15%

[1]Source: Houston Galveston Area Council 2018

Table 1-2 shows the storm sewer mileage and size distribution of the conveyance systems in the watershed within the City limits. Roadside ditches are predominant in the center of the watershed, near the Skyscraper Shadows Ditch area. Localized areas of roadside ditch also appear in the western and eastern regions of the watershed. Approximately, 44% of the channels within the watershed are studied by the HCFCD.

Table 1-2: Conveyance Infrastructure Distribution in Clear Creek Watershed (within City Limits)

Description	Length (mi.)	Percent of Total Conveyance System
Pipe Diameter < 36”	75	32%
36’’ ≤ Pipe Diameter < 60”	28	12%
Pipe Diameter ≥ 60”	12	5%
Roadside Ditch	84	36%
Studied Channel	15	6%
Unstudied Channel	19	8%

Table 1-3 provides the area covered by each type of Special Flood Hazard Area (SFHA) and the number of structures in each SFHA within the watershed (within the City limits).

Table 1-3: Clear Creek Watershed Floodplain Summary (within City Limits)

Floodplain Classification	Area (sq. mi.)	Structures[1]
Within 1% ACE Floodplain (Zone AE)	5.7	3,270
Additional within 0.2% ACE Floodplain	7.2	7,300
Outside the 0.2% ACE Floodplain	19.2	10,830

[1]Source: Houston-Galveston Area Council 2018

Based on data from the City, HCFCD, and FEMA, Table 1-4 summarizes the historical flood claims in the Clear Creek watershed within City limits since 2015.

Table 1-4: Clear Creek Watershed Flood Claims

Source	Claims	Percent of Total[1]
FEMA Flood Claims (since 2015)	1,165	18%
Other Flood Claims (since 2015)	5,266	82%

[1] Percentages are based on total number of claims.

Historical flooding reports are widespread across Clear Creek (see Exhibit A.18 in Appendix E), 20% are outside the 500-year floodplain. There are two hotspots outside the 500-year floodplain. The first hotspot is the Skyscraper Shadows neighborhood which is mainly serviced by roadside ditches. The majority of this neighborhood ROW flooding reports have not occurred during major flood events which may indicate that the capacity of the drainage system and not the bayous is the cause of the ROW flooding (see Figure 16 in Appendix E). The second hotspot is the Clear Lake City area (shown in Figure 17 in Appendix E). The majority of 311 ROW flooding calls for Clear Lake City area were associated with general flooding, with only 11% associated with Harvey (2017). It is noted that most of the historical flooding report locations are outside of the FEMA effective 500-year floodplain indicating that the capacity of the drainage system could be a source of flooding.

1.7. Meetings/Workshops

Regular progress meetings were held during the project to convey progress and discuss modeling challenges. Minutes from these progress meetings are included in Appendix B.

Three workshops were also hosted by the City and included all watershed teams. Photos from the workshops can be found in Figure 1-2.

- Workshop #1 occurred on September 27, 2022, and covered the general modeling process, introducing the guidance provided in the initial white papers and the general project management approach.
- Workshop #2 occurred on May 5, 2023, and covered updates to procedures as well as the recommended validation process.
- Workshop #3 occurred on October 4, 2023, and covered validation, the draft report outline, and model submission.

Figure 1-2: Workshop Photos

1.8. QA/QC

Quality Control occurred at the consultant level as well at the City program level. The purpose of these review processes was to produce consistent and accurate models.

1.8.1. City and Program Review

The City conducted six checkpoint reviews for each watershed to confirm model quality at key development stages. Those stages are detailed below in Figure 1-3.

At each quality control stage, the expected submittal data was outlined by the Program Management Team and a comprehensive review form was developed to standardize the reviews. Submitting Consultant Teams provided the requested data to the Program Management Team and received QC checklists detailing the items reviewed and comments in return. Consultant Teams then provided comment responses to confirm revisions or provide explanations for variances and returned to the Program Management Team. These completed forms for each checkpoint for the watershed are included in Appendix C. Meetings were held to discuss comments and responses as necessary to ensure both teams agreed on the appropriate revisions.

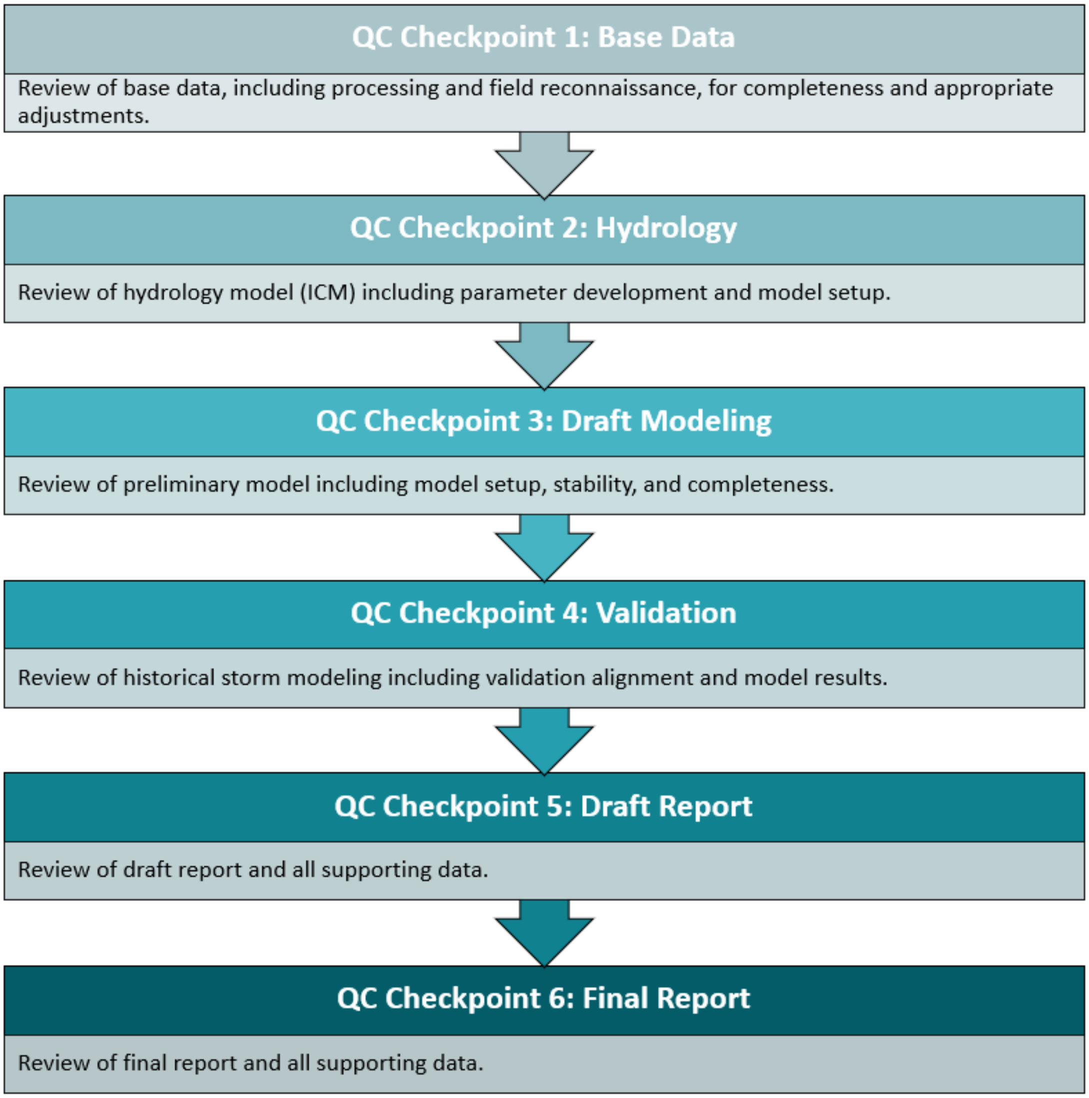


Figure 1-3: QC Checkpoints

1.8.2. Watershed Team Review

From data collection through to the final model delivery, QA/QC checks were performed and summarized in Appendix D. The QA/QC process that was followed during the project was mainly to ensure that the model provides an accurate representation of the storm system. The process included reviewing storm pipe network directions and profiles. As-built drawings were used to confirm connectivity and update network diameters and slopes. As-built drawings with aerial imagery were used to identify locations where LiDAR changes were needed along channels. To verify channel depths, LiDAR data was reviewed starting at the most upstream portion of the channel. The channel depths were estimated from as-built drawings and compared with the depth observed from the LiDAR. Adjustments to the channels based on the data review was completed using HEC-RAS to ensure smooth transition along each channel.

Structure data were reviewed, and missing data was completed using as-built drawings and field recon. Clear Creek watershed has six offsite areas. Offsite area boundaries were delineated and reviewed against available network data, LiDAR, and previous MAAPNext studies.

Once data review was completed, another round of QA/QC started inside the model to ensure that the junction relocation was done correctly, and that no shallow storm lines existed in the model. Additional breaklines were added along the bottom of the specific channels to provide better representation as well.

Compared to the initial schedule developed at project kickoff, there were some deviations throughout the project. Additional time was needed during data collection due to the amount of effort that was required to review as-builts and prepare existing storm sewer and roadside ditch GIS datasets for model input. Additionally, the schedule was adjusted to accommodate the time needed to develop a stable baseline model and validated model. Model instability, especially along 1D river reaches was the greatest contributor to the need for additional time to stabilize the models. Submittal dates for each milestone are shown in Table 1-5.

Table 1-5: Clear Creek Submittal Dates

Clear Creek Deliverables	Submittal Date
Data Collection	4/7/2023
Hydrology	5/26/2023
Base Hydraulics Model	9/25/2023
Validation Model	11/18/2023
Final Model and Draft Report	1/8/2024
Final Report	2/22/2024

Throughout the project, when schedule adjustments were identified, the revised submittal dates were closely coordinated with the program manager and with the City. Critical final deliverable dates were kept fixed, even if internal schedule adjustments were made.

2 Data Collection

Data collection was the first major task of the modeling effort. The purpose of this task is to ensure the information used for subsequent hydraulic and hydrologic modeling is consistent, reliable, and manageable across the watershed. Details regarding the data collection process can be found in Appendix E.

2.1. Data Summary

Most of the data used for model development was gathered by the City from multiple sources and provided to the consultant teams. The City of Houston developed a SharePoint website to distribute data to the consulting teams. This data includes files in GIS format. Plan sets and reports were provided in PDF format. All digital data were either downloaded from the SharePoint site or obtained through other electronic means, including City of Houston GeoLink. Table 2-1 summarizes the data provided to consultants through the SharePoint website.

Table 2-1: City Data

Source	Data	Type
City of Houston	2013 Impervious Cover	Raster
	311 Flood Complaints	Point shp
	Culverts	Point shp
	Roadside Ditches	Polyline shp
	Storm Sewer	Polyline shp
	Inlets	Point shp
	Manholes	Point shp
	Finished Floor Elevation	Point shp
	City of Houston Limits	Polygon shp
	Edge of Pavement	Polyline shp
	Flood Claims (2015-2019)	Point shp
	Open Channels	Polyline shp
	Unstudied Channels	Polyline shp
	As-builts and Plans	PDF
	SWEET Roadside Ditch Technical Report	PDF
	SWEET Storm Sewer Technical Report	PDF
FEMA	Imelda Losses	Point shp
	Repetitive Losses	Point shp
	Single Losses	Point shp
HCFCD	Stream Centerlines	Polyline shp
	Bridges & Culverts (approximate survey)	Point shp
	Impervious Cover	Raster
Halff	Revised Watershed Boundaries	Polygon shp
	2D Roughness Zones	Polygon shp
HGAC	2018 LiDAR	Raster
TNRIS	2021 Land Parcels	Polygon shp
TxDOT	TxDOT Roadways	Polyline shp
TWDB	Building Footprints	Polygon shp

The projected coordinate system for all GIS and model files is:

NAD_1983_2011_StatePlane_Texas_South_Central_FIPS_4204_FtUS.

2.2. Field Reconnaissance

Field reconnaissance was performed for the several locations within the Clear Creek watershed. Bridges, culverts on unstudied channels and manholes along storm sewers were surveyed to improve the accuracy of the stormwater collection model network.

Generally, dimensions of sewers and structures along unstudied channels were obtained through a dataset which included GeoLink shapefiles, as-builts, and HCFCD structure reconnaissance provided by HCFCD and thus did not require survey. Those locations that were not included in those datasets but were key to model development were identified for field reconnaissance. There were three phases for the field reconnaissance activities. For Clear Creek watershed, location selection focused on missing dimensions for culverts and bridges located on unstudied channels. Under Phase 3A, pond outfall piping and select storm sewer network data was also collected in areas where as-builts and GeoLink data was inconsistent or missing.

Some of the selected locations could not be accessed by the surveyors due to site restrictions. Table 2-2 below summarizes the survey type performed in Clear Creek during each phase of the field reconnaissance task and identifies the number of structures where data was able to be collected.

Table 2-2: Structures Collected in Clear Creek Watershed

Phase	Type	Number of Structures Collected
Phase 1	Bridge	1
	Culvert	13
Phase 2	Bridge	3
	Culvert	1
Phase 3A	Bridge	7
	Culvert	21
	Storm Sewer Manholes	31
	Ponds	2
Total		79

2.3. Watershed Adjustments

In general, GeoLink storm sewer data contained correct flow directions and was hydraulically connected. A verification process was completed in ArcMap to verify storm sewer network connectivity. This process included a visual check of each storm sewer system by adding arrow symbols to the downstream endpoints of each storm sewer segment so that incorrect flow directions and disconnections could be identified. Incorrect flow directions or disconnections were manually corrected in ArcMap as needed. Once the GIS data was imported into InfoWorks ICM, profiles, slopes, and pipe diameters were reviewed in detail, compared to available as-builts and/or field reconnaissance data, and edited accordingly. A comment was added in the model to document any changes and the source of information used to make the change.

Some of the storm sewer data gaps were seen in areas of newer developments, which may have not yet been incorporated into the GeoLink database. Often, the topography of these developments is newer than the 2018 LiDAR. When plans and updated LiDAR become available, the model should be updated with the most recent information. Exhibits 1 and 4 in Appendix H include a red box to highlight locations future updates should be done when data is made available.

In other instances, the GeoLink storm sewer network was missing in areas of established development. These areas were identified by manual inspection of satellite imagery overlaid with the GeoLink storm sewer network. Some of the storm sewer lines were collected during field reconnaissance as indicated in Table 2-2. Any areas where curb-and-gutter drainage systems were seen in satellite imagery were verified in Google Street View to determine the presence of curb-and-gutter drainage systems. The missing storm sewer network was then manually added to the working storm sewer shapefile.

These cases were reviewed with the PM team on a case-by-case basis. The following locations had missing storm sewer networks that were added to the model network (Figure 2-1):

- Gulf freeway: The size of this line was surveyed and the slope was assumed.
- Dixie Farm Road: The connection size was estimated based on information in as-built drawings and GeoLink data. The slope was estimated based on the upstream elevation and the elevation of the receiving water body at the downstream end of the network.
- South Sam Houston Parkway (between Old Chocolate Bayou and Cottingham Street): The slope of the sewer line was estimated using on the slopes for other storm lines in the vicinity with similar pipe diameters.
- Telephone Road: The connections between the ditches and the sewer lines were estimated based on aerial imagery and street view maps. The diameter and slope for the sewer line along Telephone Road was estimated based on the size and slope of the section noted in the as-built drawings.

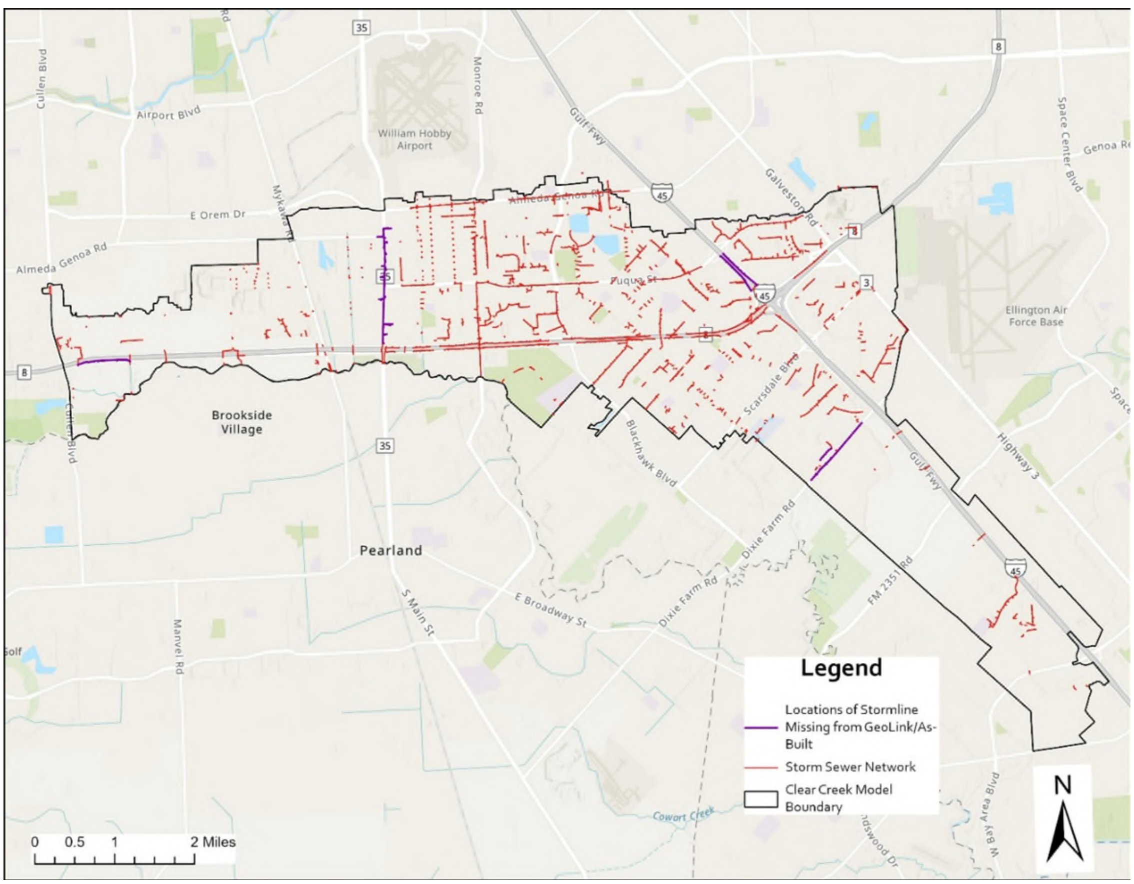


Figure 2-1: Locations of Missing Storm Lines from GeoLink/As-Built Drawings

Updates to the storm sewer network are constantly ongoing throughout the City of Houston due to construction projects. The program management team performed a review of Capital Improvement Projects (CIPs) where the design is completed or close to completion (90% or greater) and the projects are funded. The review did not find any CIPs meeting the criteria within the Clear Creek watershed.

Pond depths and studied and unstudied channel depths were reviewed as well and LiDAR was updated along many channels using the as-built drawings. This step was essential to ensure accurate representation for the channels and ponds and to avoid shallow storm lines in the model. Figure 2-2 shows the locations where LiDAR adjustments were made along channels or ponds.

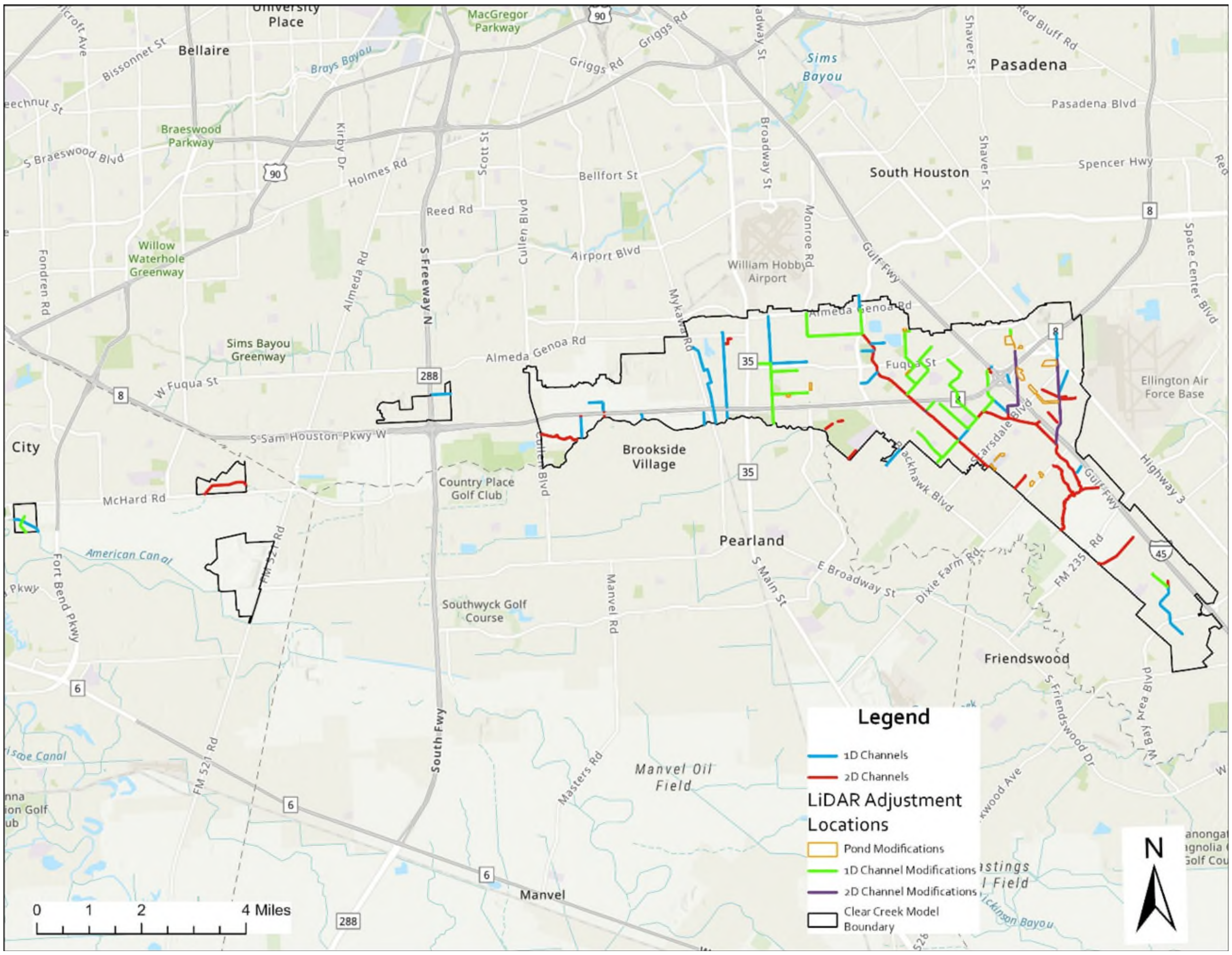


Figure 2-2: LiDAR Adjustment Locations

Based on the 2D Model Development White Paper, all pavement edge lines located in areas drained by roadside ditches were deleted. This information was not needed since the roadside ditch modeling methodology stipulates the use of five breaklines to define the centerline, toe, and banklines of each ditch.

In several instances, the edge of pavement spatial files did not match recent satellite imagery. Often these were in locations near thoroughfares or where recent street improvements had been constructed. In such cases, the pavement edge lines were manually edited according to satellite imagery or LiDAR. Pavement edge lines that had minor misalignment issues (i.e., by a few feet) were not adjusted. This effort was performed to enhance roughness zone boundaries and to align flood results to pavement boundaries.

Roadside ditches were reviewed against aerial imagery and updates were made where the layer was found to be outdated by adding or removing ditch lines. In all of those cases, the LiDAR data showed that there was a ditch but the ditch centerline was missing from the shapefile. Aerial imagery and street views were used to confirm the connectivity between the roadside ditches and the storm system.

2.4. Base Data

The data collection, review, and field reconnaissance efforts provided consistent and accurate base data that was used for the development of the ICM model. Table 2-3 summarizes the final data that was used to create the ICM model.

Table 2-3: ICM Model Components

Model Component	Value
Storm Sewer	64 miles
Roadside Ditch	89 miles
Unstudied Channels	21 miles
Manholes	1,945
Breaklines	850 miles
Building Footprints	20,990 buildings
Roughness Zones	2,364 zones

3 Hydrology

The hydrologic analysis provided the rainfall and discharge rates that were used within the ICM model. An approach to the analysis was provide in a technical white paper. Specific steps and modifications are described below.

3.1. Methods

Two distinct methods were used within the ICM model to account for the complexity of drainage within the Houston area. These two methods are summarized below, and details can be found within the Hydrology White Paper.

- For all areas within the City limits, rainfall was applied directly to the terrain to identify overland drainage patterns and stormwater runoff as it flows towards drainage infrastructure. For these areas, precipitation losses were applied prior to inclusion in the InfoWorks model.
- For areas outside the City limits that contribute to the City's drainage network, discharges were calculated using the Clark Unit Hydrograph method utilizing the Basin Development Factor as prescribed by the HCFCD. For these areas, precipitation losses were applied within the InfoWorks model.

3.2. Rainfall

Rainfall depths shown in Table 3-1 were obtained from the MAAPNext White Paper 1a: Rainfall Depths and Intensities in Harris County (revised 5/31/2019). The 2-, 5-, 10-, 25-, 50-, 100-, and 500-year storm events were modeled as part of this effort.

Table 3-1: Annual Exceedance Probability Rainfall Data for Harris County Region 3

Duration	50% AEP	20% AEP	10% AEP	4% AEP	2% AEP	1% AEP	0.2% AEP
	2-Year	5-Year	10-Year	25-Year	50-Year	100-Year	500-Year
15-min	1.20	1.50	1.76	2.13	2.42	2.72	3.48
30-min	1.72	2.14	2.50	3.01	3.40	3.81	4.95
60-min	2.29	2.88	3.38	4.09	4.65	5.25	6.98
2-hr	2.87	3.72	4.49	5.63	6.58	7.64	10.6
3-hr	3.23	4.26	5.23	6.71	7.98	9.42	13.4
6-hr	3.87	5.22	6.55	8.59	10.4	12.5	18.2
12-hr	4.56	6.24	7.88	10.4	12.6	15.2	22.8
24-hr	5.30	7.33	9.30	12.3	15.0	18.0	27.2

Rainfall runoff was calculated using HEC-HMS version 4.10 for all storm events. Specific details regarding how rainfall was applied can be found in Appendix A.

3.3. Impervious Cover

Green & Ampt losses were used to calculate the infiltration within the watershed for areas both within and outside the City. Within the City, infiltration was calculated prior to applying a constant rainfall to the watershed. Therefore, a composite impervious percentage was calculated for the watershed within the City using the impervious cover raster provided by the City. For the Clear Creek watershed, the impervious percentage was calculated to be 27.2%. This percentage was applied to the Green & Ampt parameters to calculate the infiltration and excess precipitation for the watershed. The 100-year frequency storm event total and excess rainfall hyetographs are shown in Figure 3-1.

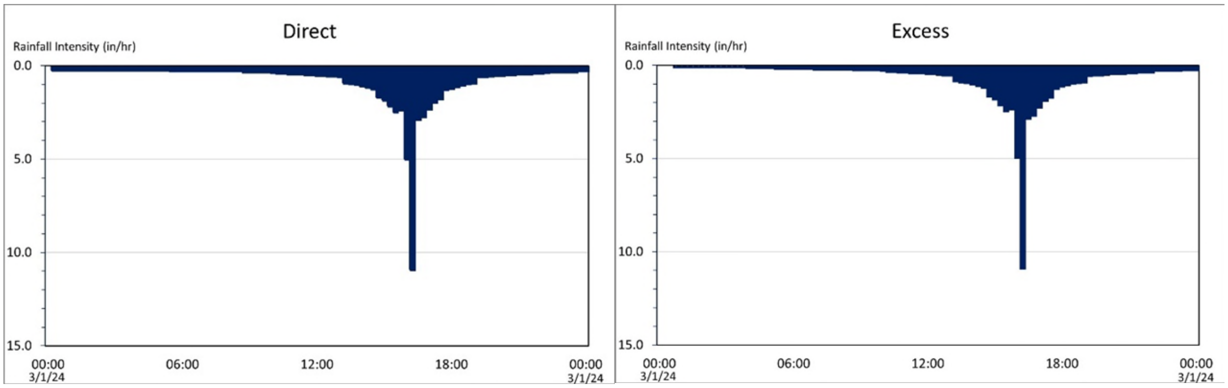


Figure 3-1: Rainfall Hyetographs for Clear Creek (Left – Total Rainfall; Right – Excess Rainfall)

3.4. Offsite Hydrology

Areas that are outside of the City limits were not modeled in detail in ICM due to data and scope limitations. However, most watersheds have areas outside City limits that flow into City drainage infrastructure. These "offsite" areas were modeled using standard drainage areas and traditional hydrology within ICM. Offsite areas were modeled with the Basin Development Factor (BDF) hydrologic method as developed by the HCFCD to develop Clark Unit Hydrograph parameters for the ICM model.

Drainage areas were delineated for areas within the watershed, but outside City limits. Information from the HCFCD MAAPNext efforts were used to inform drainage area delineation, methodology, and discharge hydrographs as available. BDF, Rational Method, and HCFCD Site Runoff Curve methodologies were applied to the offsite basins, and the resulting discharges were compared to the MAAPNext discharges. Based on the comparisons, it was determined that BDF method should be used for areas greater than 100 acres and the Rational Method for areas less than 100 acres.

3.5. Watershed Considerations

There were no changes made to the Clear Creek watershed.

3.6. Results

The Clear Creek watershed had 6 contributing drainage areas outside the City. The drainage area delineations are shown in Exhibit 2**.** Flows from these drainage areas were applied as sub-catchments within ICM with parameters calculated using either the Rational Method or Clark-BDF method. Detailed parameter tables are included in Appendix F.

4 Hydraulics

The hydraulic model is the final product of the stormwater infrastructure modeling effort. The model provides details for all drainage components within the watershed incorporating the rainfall, overland flow patterns, roadside ditches, open channels, and flows from other watersheds into a single, comprehensive resource.

4.1. Model Division

The hydraulic modeling developed for the Clear Creek watershed covers 31.4-square miles of the entire 201-square mile watershed. The model includes five different 2D zones. Four are small 2D zones that cover the discrete areas on the west side of the part of the watershed within the City limits. Zone 5 covers most of the modeled area as shown in Exhibit 3. Table 4-1 summarizes the drainage infrastructure within the model for the Clear Creek watershed. Model extents are included as Exhibit 3.

Table 4-1: Model Division Summary

Model Name	Area	# Nodes	Storm Sewer	Roadside Ditches	River Reaches	Studied Channels	Offsite Basins	Structures
	(sq. mi.)		(miles)	(miles)	(miles)	(miles)	(sq. mi.)	(#)
A_10	31.0	2,838	64	89	21	17.5	0.6	20,989

The hydraulic model includes approximately 56% of the City limits storm sewer infrastructure located within the Clear Creek watershed. The breakdown of the infrastructure included in the model is shown in Table 4-2. The model mainly included storm lines with diameters 36-inches and greater. Sewer lines smaller than 36-inches were included for roadside ditch connections to the storm network, road crossing culverts between roadside ditches, and outflow pipes from ponds. Smaller sewer lines were also modeled to mitigate unrealistic peak flows from smaller diameter sewer networks (less than 36-inches) that could cause inaccurate ponding in downstream receiving channels. The model was extended as well beyond City limits in some cases for modeling purposes like modeling a channel that starts inside the City limits then goes outside the City limits before coming back inside the City limits again, see Figure 4-1 for an example.

Table 4-2: Modeled Storm Sewer

Watershed Storm Sewer (miles)	Modeled Storm Sewer (miles)	Modeled Storm Sewer (%)
115	64	56%

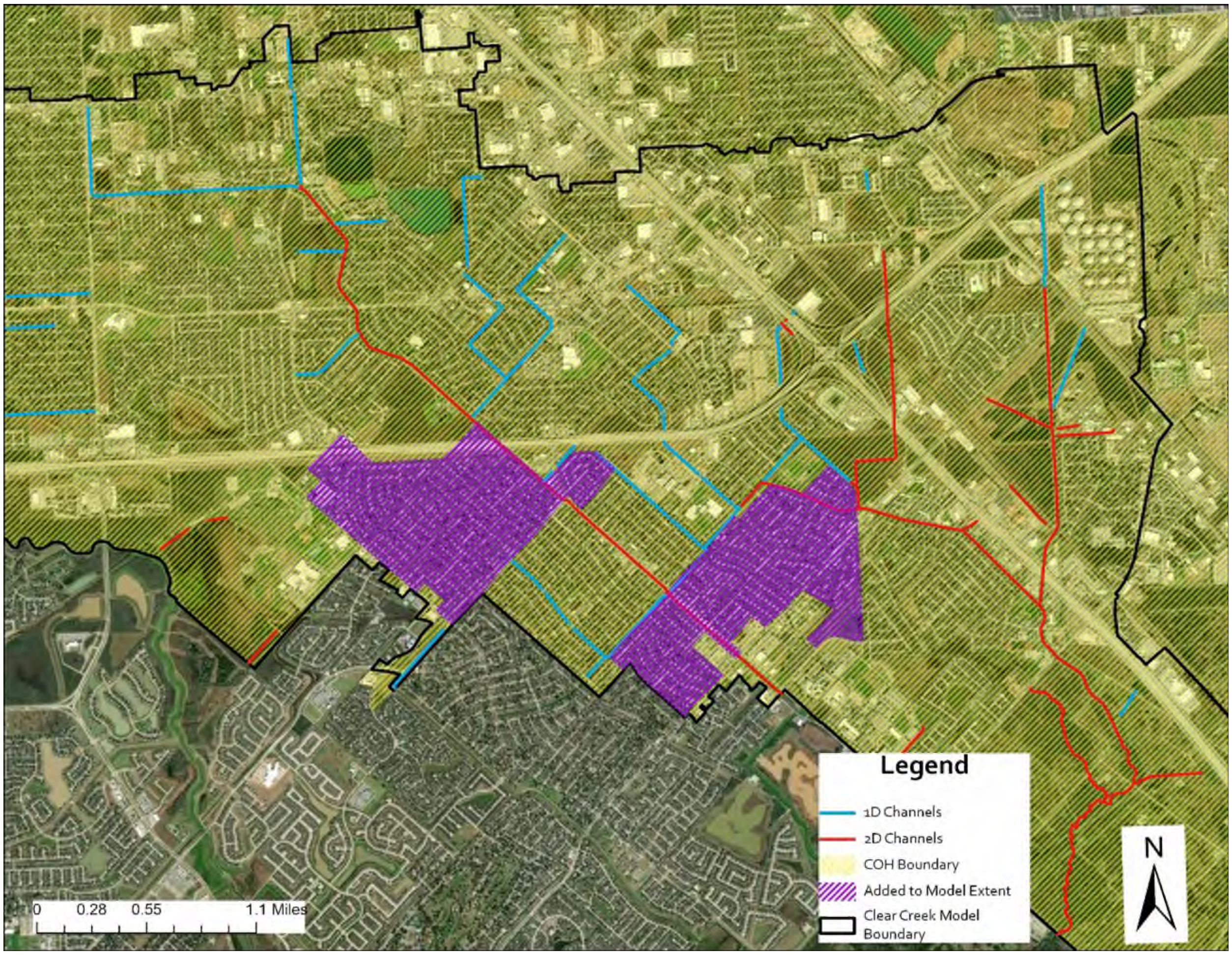


Figure 4-1: Example of Model Extension Boundary beyond the City Limits for Modeling Purposes

4.2. Methods

Within the InfoWorks ICM models, two methods were utilized to model the drainage network. 1D components were used for the drainage systems and 2D components were used to model above-ground flow patterns. Methods for developing and assigning values to these components were prescribed within the technical white papers provided in Appendix A.

- The 1D model components include the storm sewers, unstudied channels, culverts, and bridges within the watershed. These components utilize traditional calculations for conveying flow through the network.
  - Storm sewers were modeled as a combination of nodes and links with information obtained from the City GIS network and supplemented with field reconnaissance and plan drawings.
  - Unstudied channels were modeled as river reaches consisting of cross sections and bank lines with information obtained from the LiDAR.
  - Culverts and bridges were modeled as culvert links or bridge links with information provided by HCFCD and field reconnaissance.
- Much of the City's drainage system consists of overland flow through streets and bayous. This portion of the system was modeled using a two-dimensional (2D) model.
  - The provided LiDAR was divided into small "mesh" elements throughout the watershed.
  - Overland roughness values were delineated by Halff and provided to all watershed teams.

- Major channels and bayous were modeled within the 2D portion of the model.
- Breaklines were added to define City streets, major channels, and significant terrain changes such as highway embankments and detention basins.
- 2D conduits were used to model roadway cross-culverts with information obtained from 2014 SWEET Roadside Ditch Evaluation, as-builts, and field reconnaissance.

4.3. Boundary Conditions

The watershed model terminates at Clear Creek Bayou. As specified in the Boundary Conditions white paper, discharge and stage hydrographs from major studied bayous and creeks were incorporated into the hydraulic model. Discharge hydrographs were used at the upstream end of the model to simulate inflows from Clear Creek to the model network. Stage hydrographs were used at the downstream end of the model network to simulate the downstream stage from Clear Creek Bayou. The hydrographs were derived from the provided HCFCD MAAPNext hydraulic model. The locations derived for each of the models is included in Appendix G

4.4. Watershed Considerations

For the Clear Creek hydraulic model, there was one deviation from the guidance issued in the white papers. The variation was made to improve hydraulic model stability in the longer validation storm simulations. Deviations are described in detail in the following report section.

4.4.1. 1D River Reach Conversion to 2D Channels

Deviations from the 1D and 2D Model Development white papers were made to alleviate issues with model stability during the frequency storm simulations. The primary change to the model was the conversion of unstudied channels from 1D to 2D at three locations as shown in Figure 4-2. Additional breaklines were added along the bottom of the channel for better and more accurate representation of the converted river reaches.

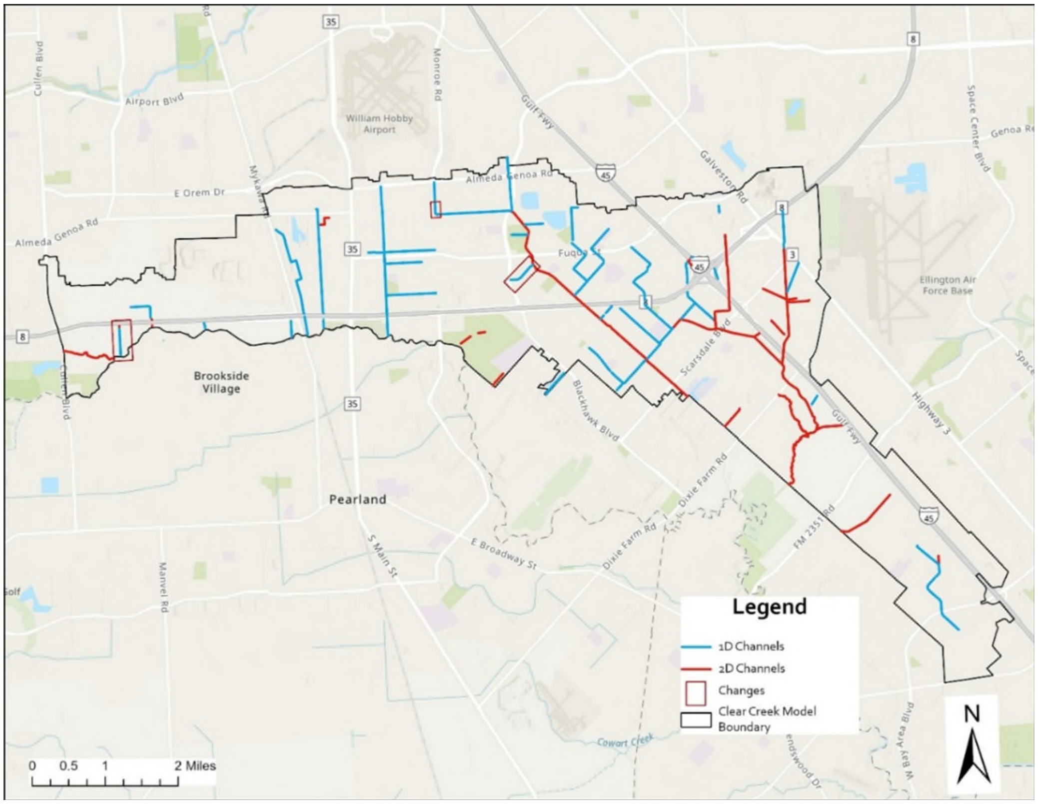


Figure 4-2: Locations of Unstudied Channels Modeled as 2D Channels

5 Validation

The models developed for each watershed within the City of Houston required validation against historic storm events to obtain confidence in reasonableness of assumptions and results. Detailed model validation information for the Clear Creek watershed is included as Appendix H.

5.1. Validation Goals

As outlined in the Model Validation Technical White Paper, the goal for each watershed was to match the number of flooded structures for each historical event as closely as possible. The metrics analyzed for each watershed are discussed below:

- Models should show at least a 50% match between flooded structures modeled and recorded information. For example, if 500 structures show flooding in the recorded information, at least 250 of those structures should be flooded in the ICM model. A structure will be considered flooded when the water surface elevation of the modeled event is within 1 foot of the estimated FFE of the structure.
- Additionally, the model should show at least a 75% match between flooded parcels modeled and recorded information. For example, if 500 structures show flooding in the recorded information, at least 375 of those parcels should be flooded in the ICM model. A parcel is considered flooded when depths of at least 0.25 feet are recorded on the parcel.
- Models were also reviewed for excessive flooding in areas without flooded structures. This review was performed qualitatively.

5.2. Historical Storm Selection

The Clear Creek watershed has been subject to frequent storms over the past few decades. Three storms were selected for the watershed based on the availability of rainfall data, number of flooding claims, and the flows and stages along Clear Creek from the available HCFCD models. Per City directive, Hurricane Harvey was one of the validation storms due to its magnitude city-wide.

For the other two events, historic storms were ranked based on the best available historical flood claims data. The FEMA single loss claims took precedent due to their reliability, but City of Houston collected claims data (non-FEMA) and 311 flooding reports were used as well. Among these two storms, the City requested that one of the two be an in-bank event. The HCFCD stream gage network was used to determine if the historic storms were in or out of bank. Based on the available claims data and applicable stream gage data, Tax Day 2016 was selected to represent the in-bank event. Table 5-1 summarizes the three historical storms selected for validation of the Clear Creek model.

Table 5-1: Summary of Historical Storm Events

Historical Storm Event	Maximum Total Rainfall (in)	Number of Flood Claims
8/25/2017 (Harvey)	40.27	6,419
5/25/2015 (Memorial Day)	9.77	8
4/17/2016 (Tax Day)*	7.68	2

*in-bank storm event

5.3. Model Adjustments

No model network adjustments were needed to meet the validation criteria. To mitigate the need for multiple iterations to meet validation criteria, the modeling development team focused on ensuring that the network and connectivity between the ditches, ponds, and channels were reviewed and any missing connections were added so that the flow from the ditches and the ponds could reach the applicable main channel. The culverts along the channels were reviewed in detail as well. As noted in Section 4.4, to improve model stability during simulations, three river reaches were converted to 2D channels (Figure 4-2). Appendix H shows the locations where the river reaches were modified.

5.4. Model Evaluation

The model was simulated and evaluated against the validation criteria. The model meets the validation criteria as shown in Table 5-2 for both Harvey and Memorial day storm events. The validation criteria is not met for the very limited claims data for the Tax Day event. MAAPNext data for the Tax Day boundary conditions were not available. However, with the location of the two claims being upstream in the storm network, significant impact from the boundary conditions were not expected.

The limited number of Tax Day claims made it difficult to meet the criteria but the model in general did not show widespread flooding in areas without claims.

Table 5-2: Model Validation Results

Storm Event	Flood Claims	Model Flooded Structures	Model Flooded Parcels	Structure Percent Difference	Parcels Percent Difference
8/25/2017 (Harvey)	6,419	4,303	5,724	69%	91%
5/25/2015 (Memorial Day)	8	7	7	88%	88%
4/17/2016 (Tax Day)	2	0	0	0%	0%
Total	6,429	4,310	5,731	67%	89%

6 Results

The completed and validated models were simulated for the 2-, 5-, 10-, 25-, 50-, 100-, and 500-year storm events to provide a wide range of flooding information across the City. Each storm event was simulated for 48 hours and included the local rainfall, offsite hydrology, and the discharges and stages from the HCFCD models.

6.1. Stormwater Infrastructure Results

The overall scope of the project includes the development of the hydraulic models for the watershed; however, the City provided scripts were used to analyze the capacity of the infrastructure model.

6.1.1. System Capacity

Using the City's data query, the percentage of storm sewer and roadside ditch systems that meet the system capacity of each modeled storm event was determined and is listed in Table 6-1. For this Citywide analysis, the "meeting capacity" is defined as having a hydraulic grade line below ground for the 2-year event and within 1.5 feet above ground for all other storm events. These values were chosen as an approximate representation of the standard right-of-way elevation across the City.

Table 6-1: Clear Creek System Capacity

Storm Event	Storm Sewers Meeting Capacity	Roadside Ditches Meeting Capacity
2-year	48%	83%
5-year	72%	76%
10-year	64%	71%
25-year	50%	63%
50-year	44%	58%
100-year	36%	52%
500-year	25%	41%

Results in table 6-1 show that in general the system meets the level of service during the 2-, 5-, and 10-year storms, with significant decreases in available capacity for events greater than the 25-year storm. The storm lines that do not meet the level of service seem to be driven by the conditions along the receiving channel which in most of the cases is controlled by the water service elevation in the main bayou.

During the 2-, 5-, and 10-year storms, the roadside ditches seem to perform well. However, for events greater than the 25-year storm, the capacity reduces significantly, with less than 50% having adequate capacity for the 500-year storm.

6.1.2. Flooded Structures

Flooded structures within the model were identified using a query to select any buildings that had more than 1 inch of ponding within them.

Table 6-2: Flooded Structures

Storm Event	Flooded Structures
2-year	559
5-year	1,154
10-year	1,880
25-year	2,882
50-year	3,748
100-year	4,700
500-year	7,115

Model results show limited number of flooded buildings during the 2-year storm, many of those are concentrated in newly redeveloped areas where no storm network is in the model due to the lack of network data and outdated LiDAR. More than one third of the those flooded buildings are concentrated in the redeveloped area west of Mykawa Road and bounded by Alisson Road from the north and Fuqua Street from the south.

The number of flooded buildings during the 5-year storm is more than double and continues to increase until more than 30% of the buildings are flooded during the 500-year event. The majority of the flooded buildings are concentrated in the area south of the Sam Houston Tollway and west of I-45 and could be driven by the conditions along Clear Creek as explained in section 6.1.1.

6.1.3. Major Channels

All major channels within the model boundary contain the flow during the 2- and 5-year except for one location that shows capacity issues during the 5-year storm along the a channel starting from Sagecreek Dr (South of Stuchbery Elementary School) all the way to the intersection between the channel and Scarsdale Blvd. Starting from the 25-year storm, more capacity issues along the downstream part of the channel start to appear which seems to be impacted by the water service elevation in the main channel outside of the model boundary.

During the 500-year event, most of the channels show significant flooding especially along the channels south of the Sam Houston Highway.

6.1.4. Area west of Gulf Freeway and south of Sam Houston Tollway

The area west of the Gulf Freeway and south of the Sam Houston Tollway start to show significant flooding starting from the 25-year storm due to storm system capacity and water surface elevation in the receiving channel. The major reason seems to be the impact of the water surface elevation in the receiving channels which is controlled by the water surface elevation in the main channel outside of the model.

6.1.5. Area west of Telephone Rd, bounded by Greenswarth Ln from the north and Catalina Ln from the south

This area is mainly serviced by roadside ditches which are under capacity even during the 2-year storm event especially the ditches along Manning Ln.

6.1.6. Area near Blackhawk Park, bounded by Fonville Dr to the north and Mango St to the south

This area shows significant flooding starting from the 5-year storm event. The pipes in this area are 24-inches, which appears to be undersized for the service area.

6.1.7. Watershed Summary

Beyond the areas discussed, significant ponding was also noted in newly developed areas where as-built drawings were unavailable so the model is inaccurate or the area is serviced by sewers less that 36-inches which were not included in the scope of this study.

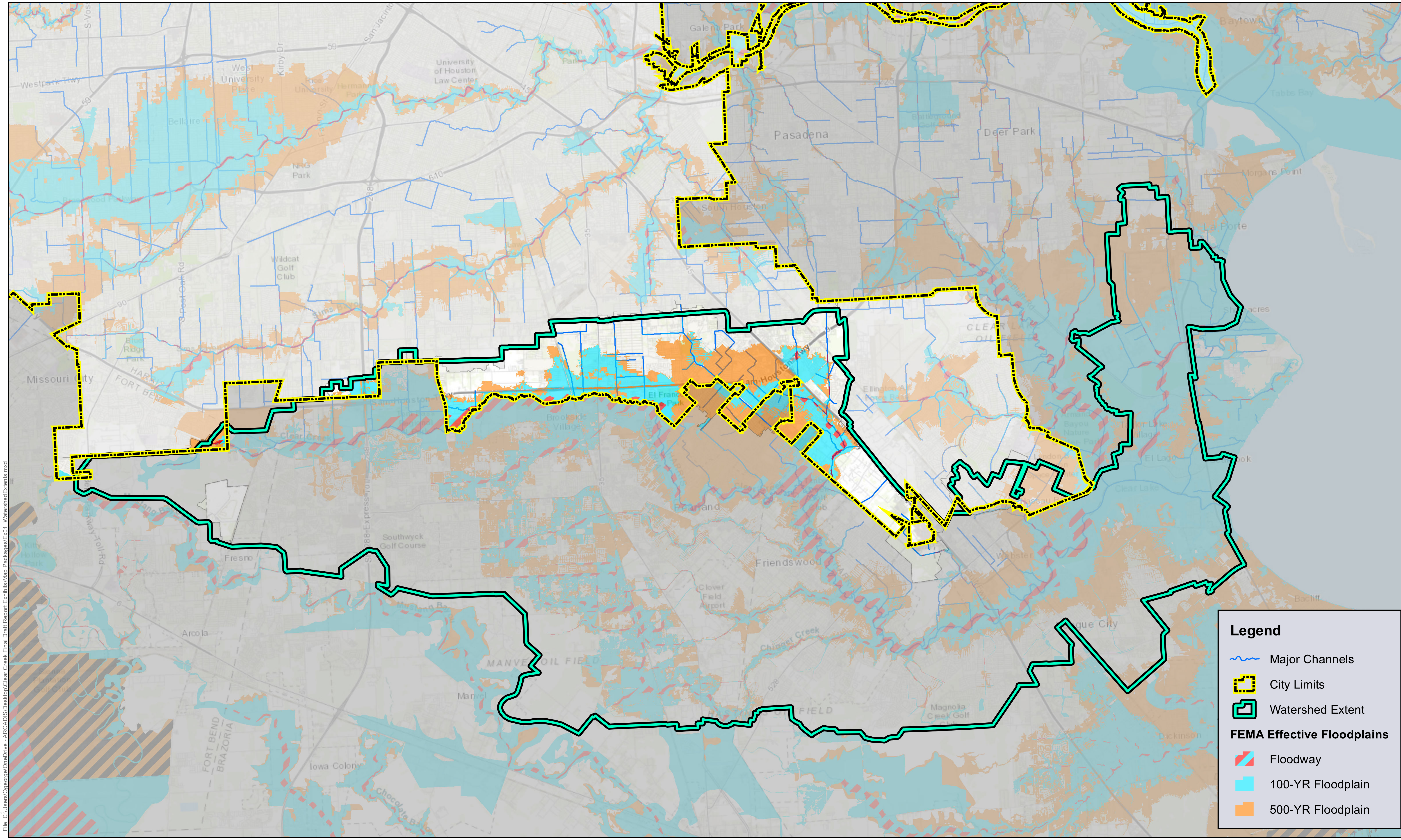
7 Future Considerations

The development of the models for the Clear Creek watershed provides the first comprehensive stormwater model that includes the storm sewers, roadside ditches, open channels, and bayous within the City limits. This modeling effort will provide extensive information in ponding elevations, overflow patterns, and discharge rates for many aspects of the drainage system.

As with any study, there are limitations to the available information, schedule, and scope of the study. Efforts throughout the model development were geared towards a citywide effort using readily available information. Below is a list of considerations that can should be considered for future updates to the Clear Creek models.

- Newly developed areas that were not modeled because of the outdated LiDAR and due to the lack of as-built drawings and/or shapefiles for the new storm system will need to be considered in future updates (see Exhibits 1 and 4 in Appendix H). Flooding was noted in some of these areas, adding detail to the model when the data is available will enable the City to determine the veracity of the current model results.
- Collection of high-water marks and other drainage observations during rainfall events should be prioritized to make available more information to further validate the model.
- Adding new and future CIP projects or HCFCD projects to the model
- Verify the information for the lines that were stated in section 2.3.
- Review the modeled storm system in neighborhoods that are currently serviced by less 36” storm lines. The team in general added the most downstream parts of the storm lines in these areas but in some cases, it may need to be extended further upstream.

EXHIBITS



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HOUSTON PUBLIC WORKS

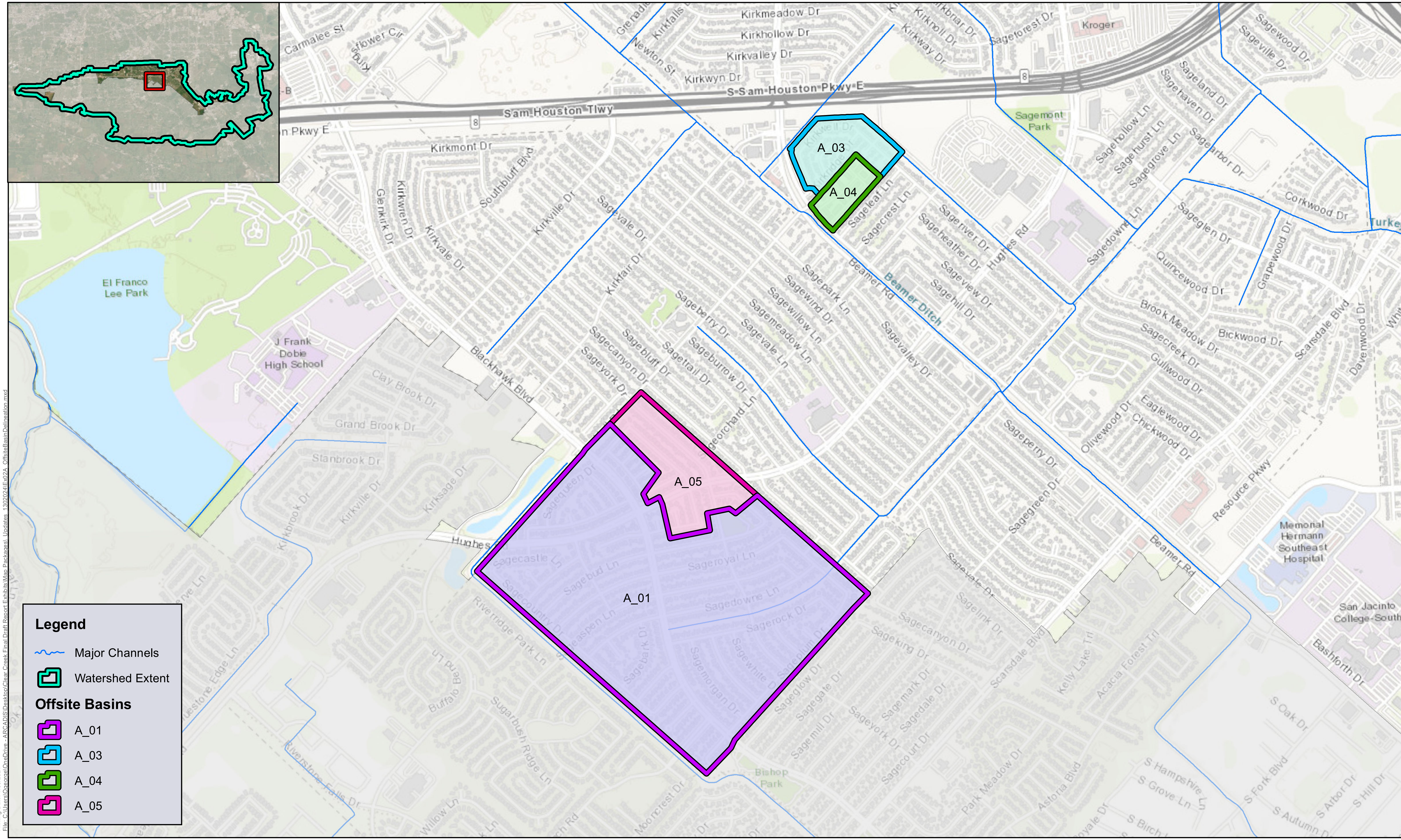
N W E S

CLEAR CREEK WATERSHED EXTENTS

0 1 2 Miles

Stormwater Infrastructure Model

Exhibit 1



ARCADIS

HOUSTON PUBLIC WORKS

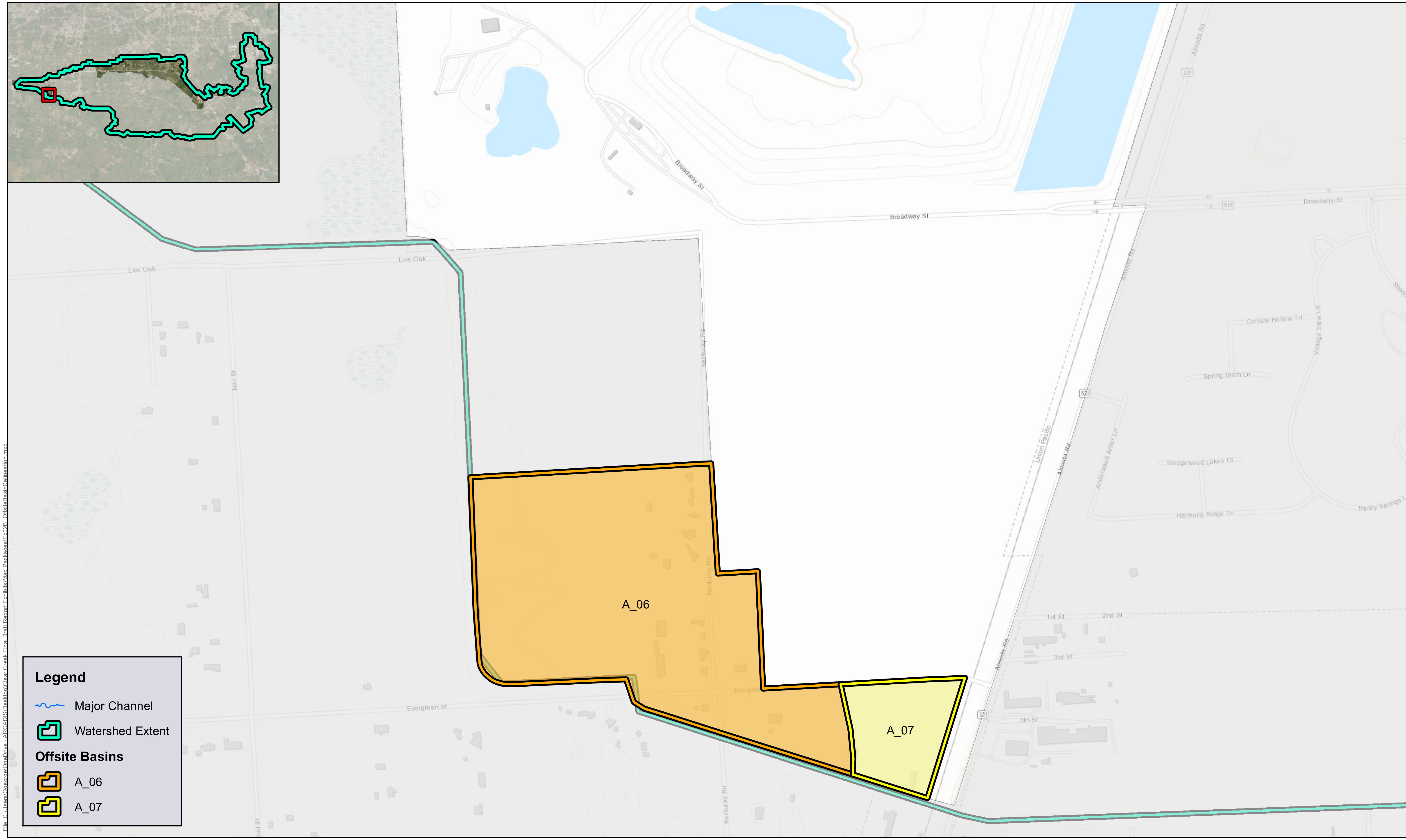
N W E S

CLEAR CREEK OFFSITE DRAINAGE AREAS

0 0.15 0.3
Miles

Stormwater Infrastructure Model

Exhibit 2A



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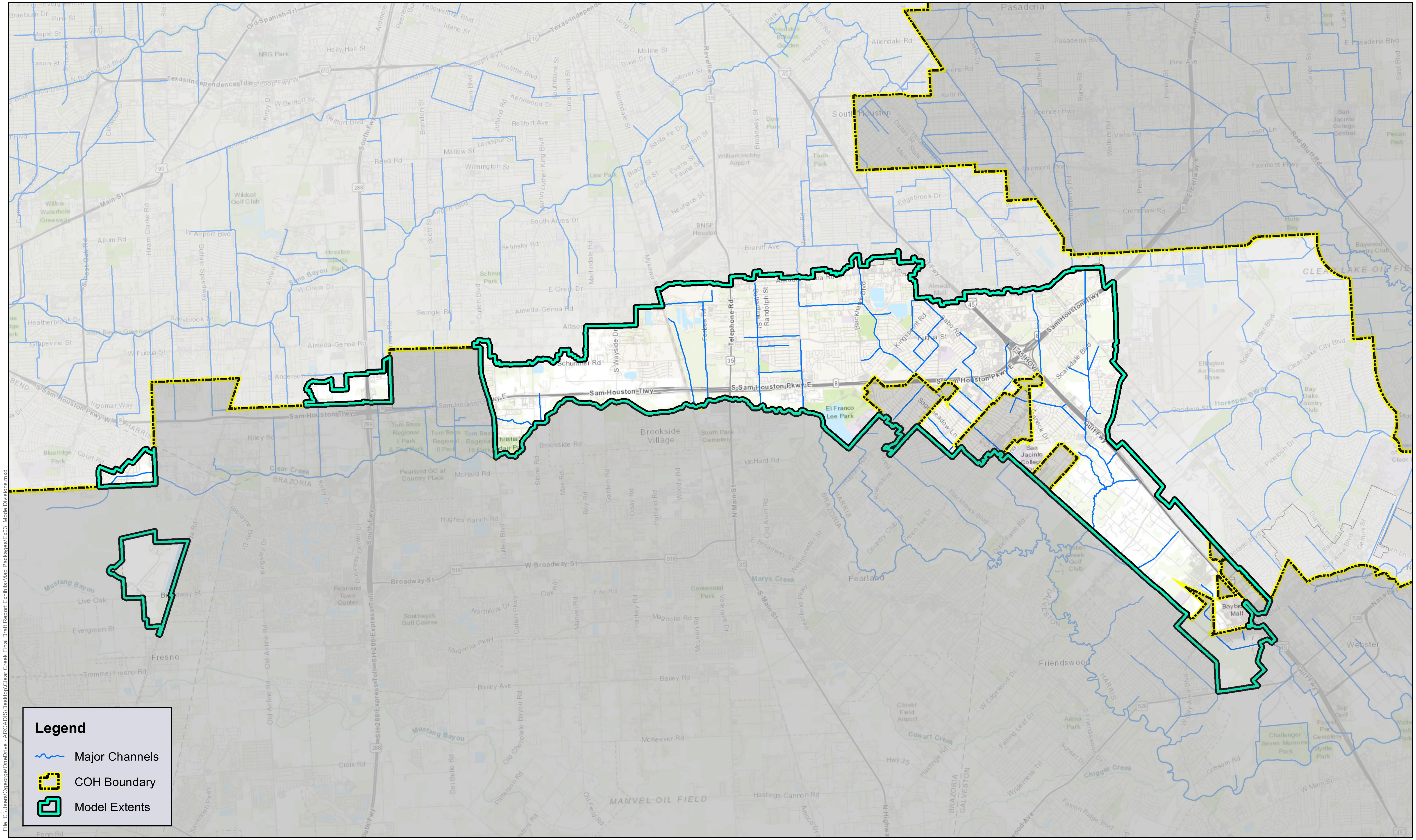
HOUSTON PUBLIC WORKS

CLEAR CREEK OFFSITE DRAINAGE AREAS

0 0.05 0.1 Miles

Stormwater Infrastructure Model

Exhibit 2B



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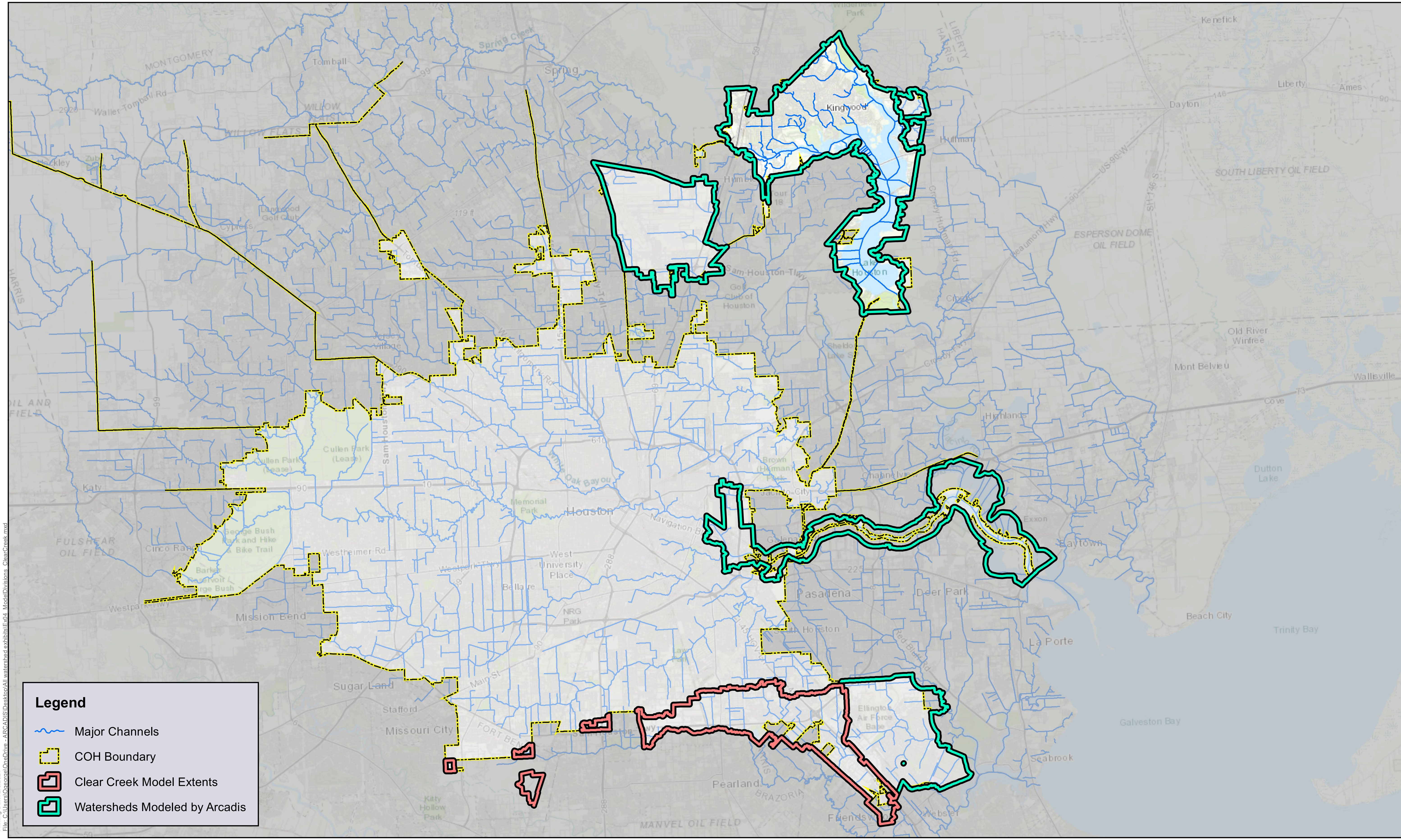
CLEAR CREEK MODEL EXTENTS

Stormwater Infrastructure Model

Exhibit 3



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N W E S

CLEAR CREEK MODEL EXTENTS

0 1.5 3
Miles

Stormwater Infrastructure Model

Exhibit 4