City of Houston Stormwater Master Plan

IAH Airport Draft Final Report

February 26, 2023

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Executive Summary

This report describes the development of a 27.1 square mile, two-dimensional (2D) rain-on-mesh InfoWorks ICM model of the portion of the IAH Airport watershed within the City of Houston. The model integrates the storm sewer network, roadside ditches, channels, and bayous that form the 170.7-mile-long conveyance system within the watershed. The IAH Airport watershed is predominantly roadside ditch with it making up 50% of the conveyance system.

The IAH watershed is located in the north region of the City of Houston within the Greens Bayou watershed. The watershed was modeled given the guidance from the City through white papers and workshops which are detailed in Appendix A and Section 1.7 respectively.

Developing the model required collecting available data and modifying it to make it reliable. The data sources included 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. The data was reviewed and adjusted to reflect the existing conditions and improve the quality of the data. To fill gaps in the desktop datasets, field reconnaissance collected dimensions of select culverts and bridges using a mobile application. The data collection process is detailed in Appendix E.

Data gaps were also filled using as-builts from the City of Houston. The as-builts were most useful in filling gaps in the elevation, slope, and size of the stormwater pipes and outfalls. LiDAR was also used to verify that the stormwater network had accurate elevations and that stormwater system elements such as pipes, outfalls, culverts, and roadside ditches smoothly integrated with the 2D terrain or mesh.

The development of the model's hydrology was developed using 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 two-dimensional (2D) components to represent the storm sewer network, roadside ditches, unstudied channels, culverts, bridges, major channels, and bayous that form the 170.7 mile long conveyance system within the City limits of the IAH (Greens Bayou) watershed. The model utilized the HCFCD MAAPNext models to represent the discharge and stage hydrographs for the major bayous and creeks that interact with the storm sewer system.

Three historical rainfall events were selected for model validation: Hurricane Harvey (2017), Tropical Storm Imelda (2019), and Tax Day (2016). The validation revealed that making adjustments to the Manning's n for the roadside ditches enabled the model results to better align with historical flooding data. After making these parameter adjustments, 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.

After validating the model, the frequency events up to the 500-year event were simulated. As the simulations were run, different items were adjusted and improved to allow the simulations to run smoothly and to completion. Due to the unique characteristics of the IAH watershed, the model required hydraulic variations to allow for smoother runs. This includes the addition of 1D river reach inflows to prevent simulation failures. 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. The model results also show the number of structures that have more than 1 inch of ponding within them for each storm event. The capacity results are presented in section 6 of the report.

For the IAH watershed, the storm sewer system and the roadside ditch system are unable to meet the 2-year level of service. There does not seem to be enough capacity in the channels to support storms larger than the 2-year event as they overtop and contribute to flooding in their surrounding neighborhood and streets. Many residential areas throughout the sub-watershed are serviced by relatively low-capacity roadside ditches, which impacts several homes.

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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.

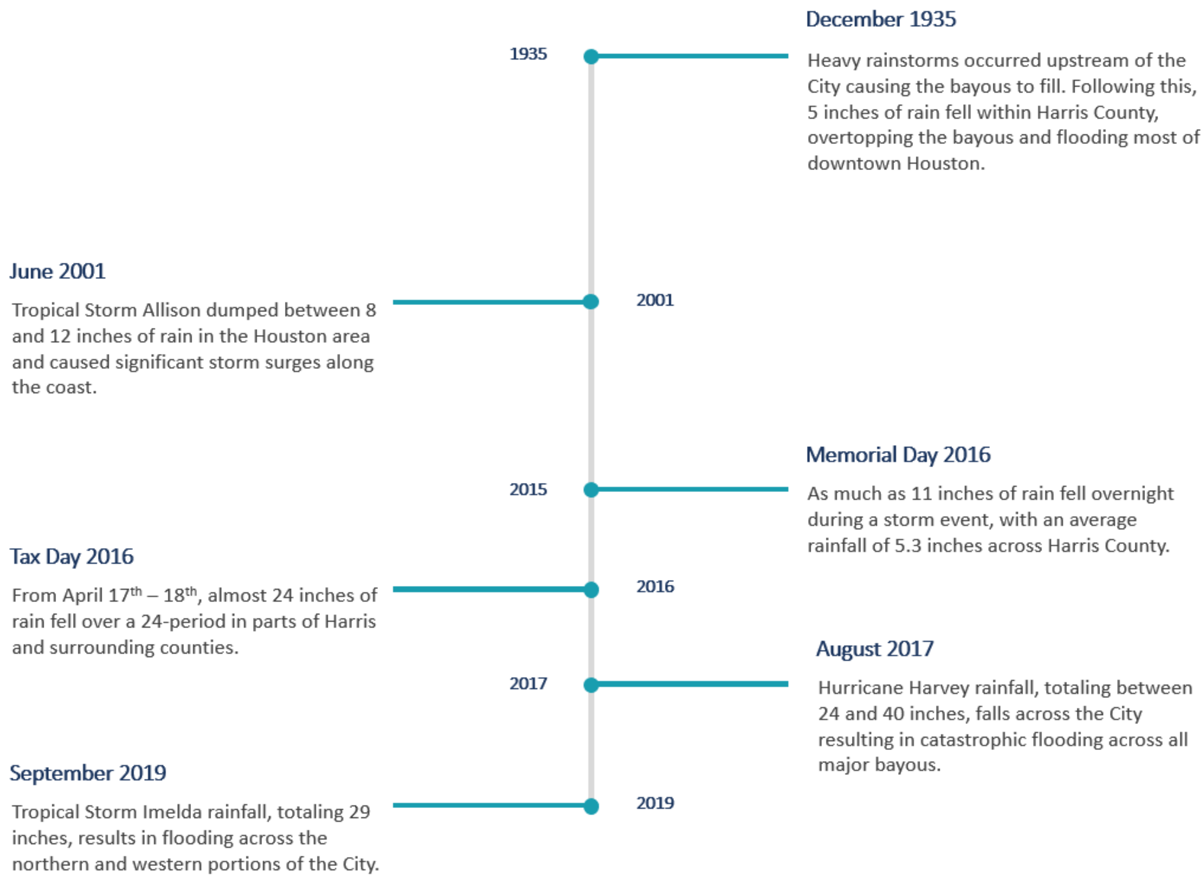


Figure 1-1: Major Historical Storm Timeline

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 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 IAH Airport watershed is 27.1 square miles located in the north region of the City within the Greens Bayou watershed. The entire watershed is located within the City limits. Exhibit 1 includes the extents of the watershed.

The terrain is generally flat throughout the watershed. The inflows come from Hoods Bayou, Greens Bayou, Garners Bayou, and Turkey Creek. The watershed drains in a south-easterly direction to Greens Bayou which eventually discharges into the Houston Ship Channel.

The watershed is mostly developed, consisting primarily of the airport. There are areas with small-lot, single-family residential development and other areas of commercial land use around the watershed, especially around the IAH airport. The watershed includes undeveloped and developed open spaces. The southeastern edge of the watershed includes residential areas that are primarily drained through roadside ditch. A summary of the land uses throughout the IAH Watershed is provided in Table 1-1.

Table 1-1: IAH Watershed Land Use Summary

Land Use[1]	Area (sq. mi.)	Percentage (%)
Undeveloped	7.5	27.8%
Developed Open Space	5.2	19.1%
Residential	9.2	34.1%
Commercial	5.1	18.9%

[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 City limits and IAH airport. Storm sewers are predominant in the southern area of the watershed. Unstudied channels act as the main conveyance system within the airport. Areas of roadside ditch predominantly appear in the southeastern region of the watershed in residential areas. Throughout the IAH watershed, the main conveyance features are the studied channels that provide drainage to the airport and the areas outside the airport.

Table 1-2: Conveyance Infrastructure Distribution in IAH Watershed

Description	Length (mi.)	Percent of Total Conveyance System
Pipe Diameter ≥ 24”	3.0	2%
Pipe Diameter ≥ 36”	21.1	12%
Pipe Diameter ≥ 60”	18.1	11%
Roadside Ditch	100.3	59%
Studied Channel	13.8	8%
Unstudied Channel	13.7	8%

Table 1-3 provides the area covered by each type of Special Flood Hazard Area (SFHA) within the watershed. Additionally, estimates for the number of buildings within the City limits in IAH are provided per SFHA zone type.

Table 1-3: IAH Watershed Floodplain Summary

Floodplain Classification	Area (sq. mi.)	Structures[1]
Within 1% ACE Floodplain (Zone AE)	3.01	358
Additional within 0.2% ACE Floodplain	5.86	538
Outside the 0.2% ACE Floodplain	20.5	1,951

[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 IAH watershed since 2015.

Table 1-4: IAH Watershed Flood Claims

Source	Claims	Percent of Total[1]
FEMA Flood Claims (since 2015)	35	17%
Other Flood Claims (since 2015)	173	83%

[1]Percentages based on total number of claims.

Several flood mitigation projects have been constructed in the IAH watershed over the years. The mitigation projects address drainage improvements to parallel facility developments. The recent airport terminal D expansion project was mitigated by building a 60-acre pond downstream along Garners bayou.

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.

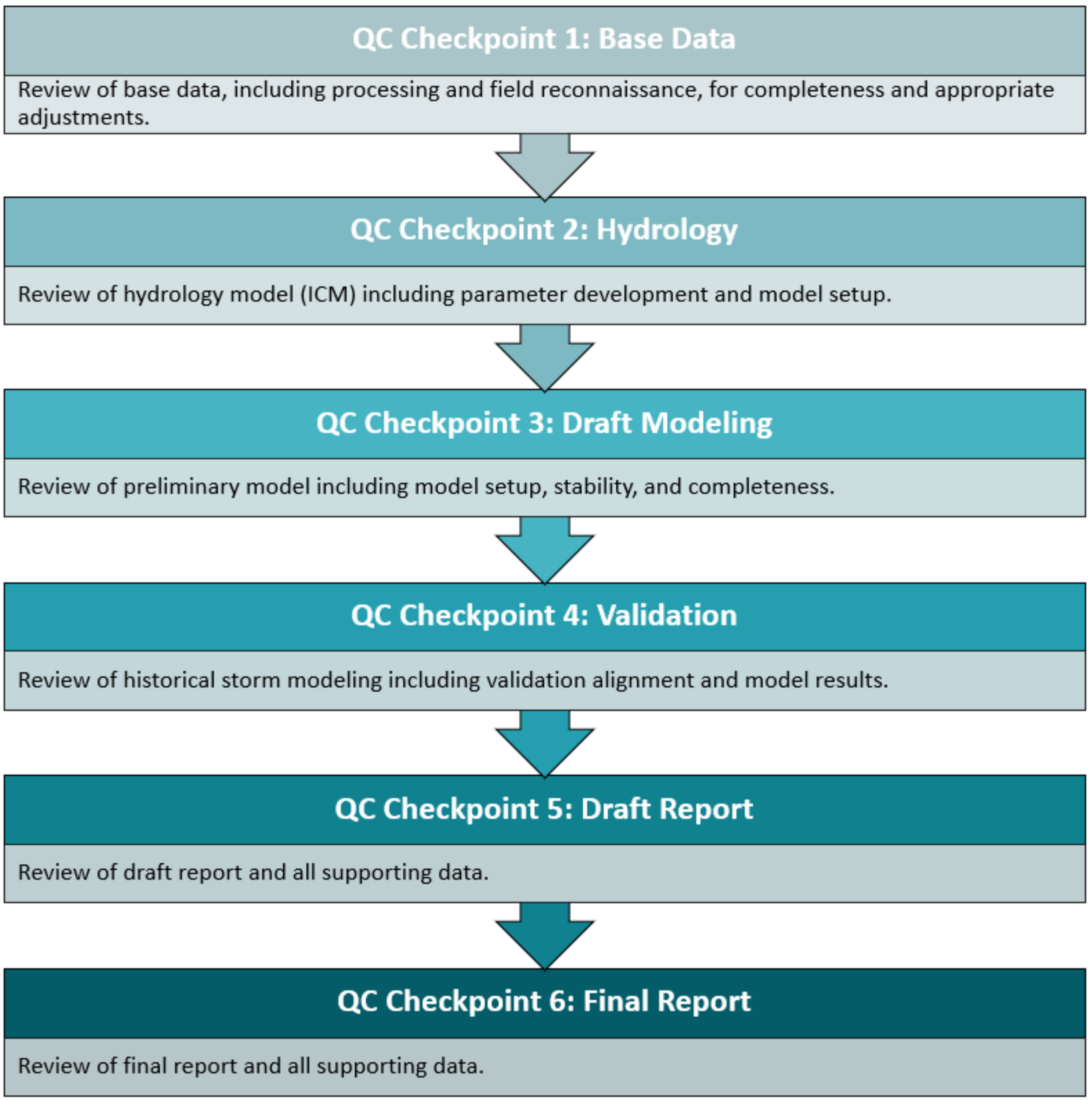


Figure 1-3: QC Checkpoints

1.8.2. Watershed Team Review

Quality assurance and quality control (QA/QC) was an important aspect of project delivery. 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 size and slopes.

As built drawings with aerial imagery were used to identify locations where LiDAR changes are needed especially along channels. Structure data were reviewed and missing data was completed using as-built drawings and field reconnaissance.

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: IAH Airport Submittal Dates

IAH Airport Deliverables	Submittal Date
Data Collection	4/7/2023
Hydrology	5/26/2023
Base Hydraulics Model	10/6/2023
Validation Model	11/22/2023
Final Model and Draft Report	12/29/2023
Final Report	2/26/2024

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. The projected coordinate system for all GIS and model files is: *NAD 1983 2011 StatePlane Texas South Central FIPS 4204 FtUS.*

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

2.2. Field Reconnaissance

A limited amount of field reconnaissance was performed for the IAH Airport watershed. The dimensions of select culverts were obtained through a preliminary dataset which included shapefiles, as-builts, and HCFCD structure reconnaissance provided by the HCFCD. Non-COH owned structure gaps were prioritized over owner entity as-built requests to manage the project schedule.

Field observation reports were completed for each site visit, documenting the visit with photos and descriptions of each drainage feature. For culverts upstream and downstream inverts were measured, shape, size, material, and structure condition were noted. For bridges, deck thickness, deck span, number of piers, and structure condition were documented. Arcadis developed a mobile application that was utilized on phones and/or tablets to collect data in the field. The data was uploaded to the project GIS portal as it was collected allowing for the team to review on-site and minimize the need for re-visits.

The field observation reports for Phase 1 and Phase 2 are provided in Appendix E. Table 2-2 below summarizes the survey type performed in IAH Airport during the phases of the field reconnaissance tasks.

Table 2-2: Structures Collected in the IAH Watershed

Phase	Type	Number of Structures Collected
Phase 1	Culvert	5
Phase 2	Culvert	1
Total		6

2.3. Watershed Adjustments

A key source of base model information was storm sewer data from the City's GeoLink database. 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. The polygons and roughness values were updated based on aerial imagery. Structures were adjusted as detailed in the 2D Model Development white paper and workshop.

Studied and unstudied channel depths were reviewed using LiDAR and as-built drawings. 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. This step was essential to ensure accurate representation for the channels and ponds and to avoid shallow storm lines in the model.

In some 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. 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. Each of these cases was reviewed with the PM team on a case-by-case basis. The missing storm sewer data was taken from available as-built drawings and estimations based on LiDAR and aerial imagery and Google Streetview. The following neighborhoods had missing storm sewer networks that were added to the network.

- East of I-69 and south of Beltway 8, along Old Humble Road
- Scattered locations within the airport

Likewise, TxDOT and HCTRA right-of-way, and the infrastructure owned by these entities is not regularly integrated into the City's database. Because of this, the GeoLink storm sewer network contains outdated information, which does not align with present day conditions. Where storm sewer information did not agree with current roadway alignments, LiDAR elevations, and Google Street View, an attempt was made to adjust the GeoLink storm sewer network. However, in limited cases, storm sewer lines could not be adjusted enough to reasonably function in the model and were removed. The following areas had storm sewer networks that were removed.

- Beltway 8 Frontage Road between I-69 and P133-02-01
- Beltway 8 Frontage Road between Old Humble Rd and Old North Belt Dr

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. Plan sets for each of the projects meeting those criteria were collected and provided to the respective watershed teams. No CIPs meeting the criteria were located within the IAH watershed at the time of this effort.

Based on the 2D Model Development white paper, all pavement edge lines located in areas drained by roadside ditch were deleted. This information was not needed since the roadside ditch modeling methodology prescribes the use of three breaklines to define the centerline and banks of the 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.

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 collected data that was used to create the ICM model.

Table 2-3: ICM Model Components

Model Component	Value
Storm Sewer	42.9 miles
Roadside Ditch	100.3 miles
Unstudied Channels	13.7 miles
Manholes	865
Breaklines	655 miles
Building Footprints	2,847
Roughness Zones	2,579

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 IAH Watershed, the impervious percentage was calculated to be 30.0%. 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.

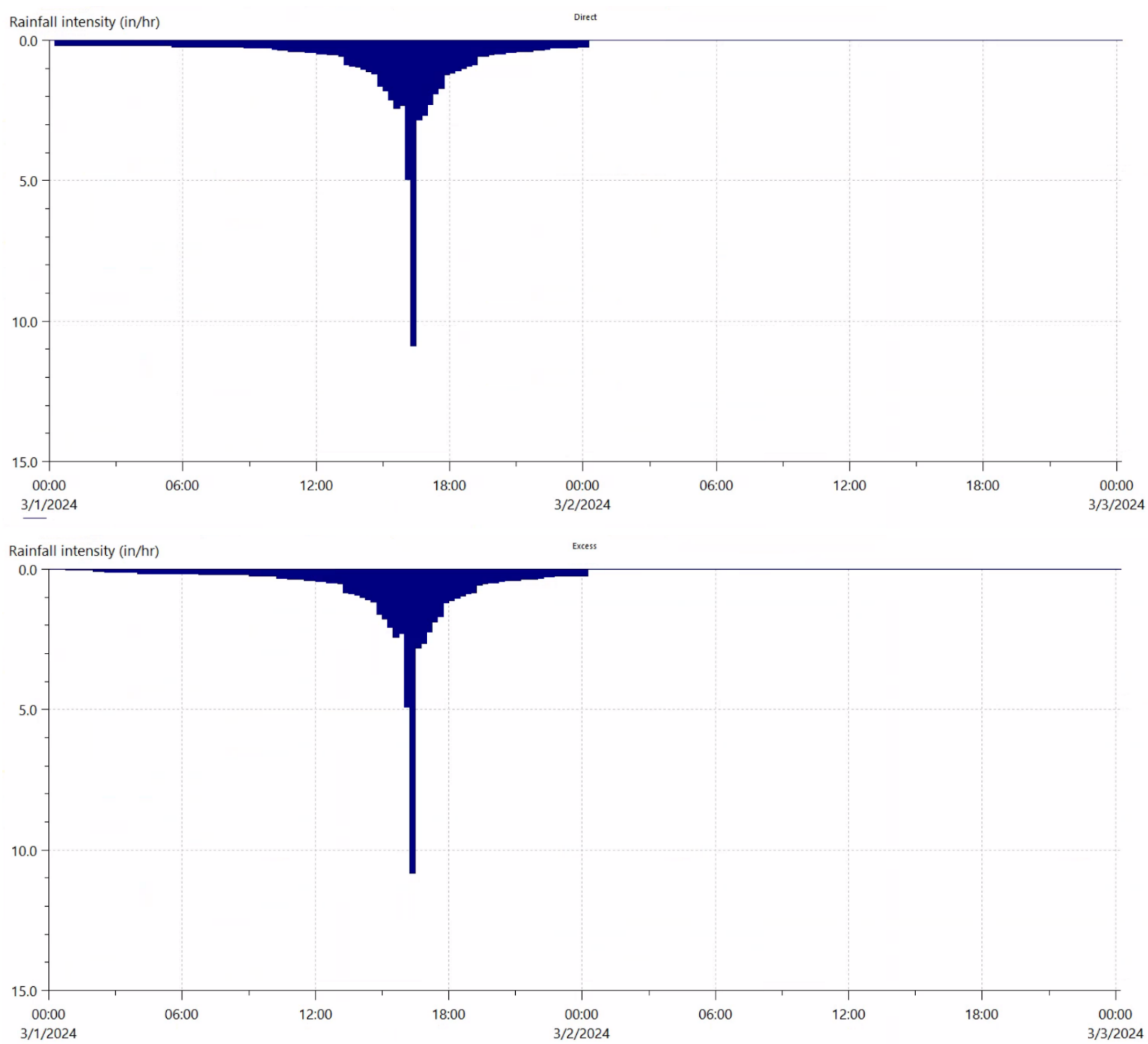


Figure 3-1: Rainfall Hyetographs for IAH (Top – Total Rainfall; Bottom – Excess Rainfall)

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 are no variations from the hydrologic modeling guidance in the IAH watershed model.

3.6. Results

The IAH watershed had 18 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 model developed for the IAH watershed consists of one submodel due to the relatively small size of the watershed. Table 4-1 summarizes the drainage infrastructure included for the IAH Watershed and the model extent is shown in 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.)	(#)
P_10	27.1	1,703	42.9	100.3	13.7	13.8	18	2,847

The hydraulic model includes approximately 50% of the storm sewer infrastructure within the IAH watershed within City limits. The main reason the model only includes 50% of the existing storm sewer in the watershed is due to the simplification of the modeled network, which avoids modeling pipes less than 36 inches that are not culverts. The breakdown of the infrastructure included in the model(s) is shown in Table 4-2.

Table 4-2: Modeled Storm Sewer

Watershed Storm Sewer (miles)	Modeled Storm Sewer (miles)	Modeled Storm Sewer (%)
85.2	42.9	50%

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 models terminate at major bayous and creeks within the City. As specified in the Boundary Conditions Technical 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 each model to simulate flows coming from the upstream major bayous. Stage hydrographs were used at the downstream end of each model to simulate the downstream stage. The hydrographs were derived from the provided HCFCD MAAPNext hydraulic model. No external boundaries exist for this watershed. The locations derived for each of the models is included in Appendix G.

4.4. Watershed Considerations

Variations in hydraulic modeling were required for the IAH watershed model due to its unique characteristics. Two adjustments were made to the model based on necessity. As the model was being further developed and the model became unstable in other locations, the second adjustment was made. These adjustments do not impact the validation results in a negative way, as the model meets validation.

4.4.1. Removal of 1D River Reaches within IAH Property

Throughout the IAH model, many 1D river reaches were causing simulations to fail immediately at the start of the rainfall events. The model was sent to Innovyze for analysis. Because the channel infrastructure in and around IAH is generally larger than what is typical in Houston, and ICM struggles to calculate low flows in large 1D river reaches; Innovyze advised converting the 1D river reaches to 2D channels.

This recommendation was presented to Halff on October 25, 2023. Since IAH is a well-studied area and HCFCD and the IAH Drainage Master Plan models are both being updated using Atlas-14 precipitation data; the conversion of 1D river reaches to 2D channels was deemed acceptable. The conversion eliminated 1D river reach failure in this portion of the model. The few 1D river reaches that were converted to 2D channels still represent the existing channels, just in a different way due to the simulation failures.

4.4.2. Addition of 1D River Reach Inflows

Throughout the IAH model, many 1D river reaches were causing simulations to fail at the start of the rainfall event. This was observed at multiple 1D river reaches throughout the watershed inside and outside of the airport. The model was sent to Innovyze for analysis. Because the channel infrastructure in and around IAH is generally larger than what is typical in Houston, and ICM struggles to calculate low flows in large 1D River reaches; Innovyze recommended adding inflows to prevent the 1D river reaches from having to move from a state of being completely dry to receiving low flows and failing.

Rather than using an inflow file to accomplish this; constant inflows were applied in the 1D river reach properties. Inflows were applied to the most upstream node of each run of 1D river reaches. For small 1D river reaches, an inflow of 10 cfs was applied, and for larger 1D river reaches, an inflow of 20 cfs was applied. These inflows were applied as baseflows. Due to the size of the infrastructure and model, the inflows have little to no measurable effect, and the constant flow within the 1D river reaches prevents them from having to move from a state of being completely dry to receiving low flows and failing. The addition of inflows alleviated this cause of simulation failure.

Figure 4-1 below outlines the river reaches that were converted to 2D channels and all modeled river reaches that have inflow applied.

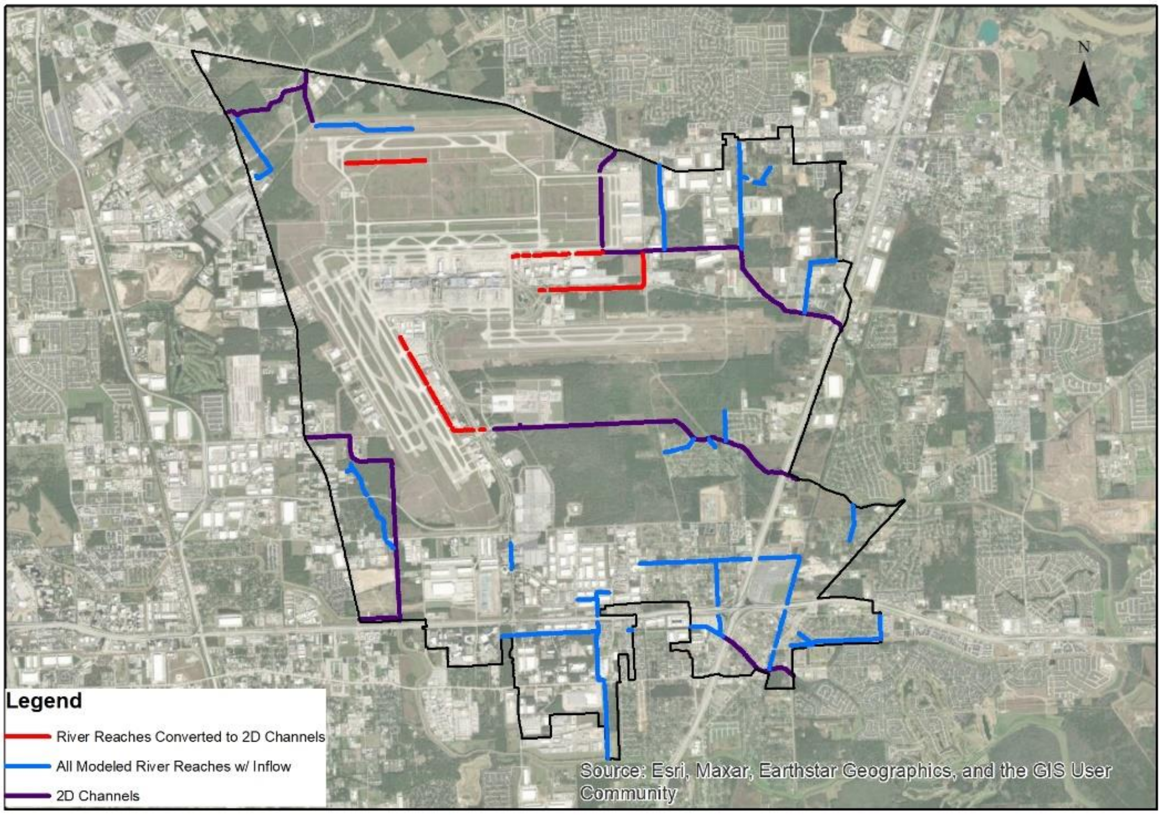


Figure 4-1: River Reach Adjustments

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 IAH 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 IAH watershed has been subject to frequent storms over the past few decades. These events were used to select three storm events for validation of the model. 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 the 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 chosen in-bank event was tropical storm Imelda. Table 5-1 provides a summary of the maximum total rainfall and number of flood claims for each historical event.

Table 5-1: Summary of Historical Storm Events

Historical Storm Event	Maximum Total Rainfall (in)	Number of Flood Claims
8/25/2017 (Harvey)	42	208
9/17/2019 (Imelda)	11.8	7
4/17/2016 (Tax Day)	8.4	0

5.3. Model Adjustments

Upon initial simulation of the historical events, models were adjusted to better reflect the flooded structures provided in the data. The validation criteria were not satisfied initially, so adjustments to the model were required to meet the criteria. The resulting inundation rasters from these parameter changes were tested against the claim locations and provided better validation results. Further details of the model adjustments are included in Appendix H; however, the following changes were made in general:

- The Manning's n value of the roadside ditch layer was increased from 0.15 to 0.2 for all roadside ditches. This was applied universally to keep the ditch roughness value assumption uniform and consistent throughout the model. This adjustment provided more realistic flooding results.
- The flooding discharge coefficient at storm sewer manholes was set to 3.0 at most manholes. Certain manholes with shallow cover depths were set to 0.5 to improve model stability that was not achievable with a coefficient of 3.0. Setting the discharge coefficient to 0.5 at certain manholes impacted results by allowing the model to run to completion and not failing at the associated conduits.

5.4. Model Evaluation

After completing the above adjustments, the model was re-simulated and re-evaluated against the validation criteria. In all cases, the model meets the validation criteria as shown in Table 5-2. Note that there are no FEMA or City claims for the Tax Day event, however simulation results are compared against MAAPNext results in Appendix H. No structural flooding for Tax Day is reported based on model results since there are no claims for that event.

Table 5-2: Model Validation Results

Storm Event	Flood Claims	Model Flooded Structures	Model Flooded Parcels	Structure Percent Difference	Parcels Percent Difference
Harvey	188	146	188	78%	100%
Imelda	6	4	5	67%	83%
Tax Day	0	-	-	-	-
Total	194	150	193	77%	99%

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: IAH System Capacity

Storm Event	Storm Sewers Meeting Capacity	Roadside Ditches Meeting Capacity
2-year	55%	75%
5-year	73%	64%
10-year	67%	55%
25-year	54%	45%
50-year	47%	37%
100-year	43%	31%
500-year	29%	17%

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	188
5-year	281
10-year	377
25-year	554
50-year	732
100-year	923
500-year	1,423

As the storm event rainfall increases, the lower the capacity is for the storm sewer system and roadside ditch system. More structures flood with the increase of rainfall as well. The results show that about half of the storm sewers in the watershed meet the 2-year event level of service, while the roadside ditches meet 75% capacity. For the rest of the storm events, the storm sewer system generally provides more capacity than the roadside ditches. It is noticed that the 2-year event percentage of storm sewer meeting capacity is lower than the 5-year and 10-year events. This is likely due to the difference in definition of "meeting capacity" for the 2-year event. 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.

6.1.3. Major Channels

The channels in the IAH watershed start to influence flooding in the watershed during the 2-year event. Capacity is limited to the 2-year event in Reinhardt Bayou and Garners Bayou. The floodwaters from these bayous contribute to flooding in the surrounding neighborhoods and streets. This is evident through the hydraulic grade lines of the outfall pipes into the Ship Channel, as they can be higher than 1.5 feet above ground for events greater than the 2-year event. This is also evident through the roadside ditch level of capacity, as it is affected by the channels. Inflow from outside the model boundaries contributes to the issue as well.

6.1.4. Capacity Issues in Neighborhoods Serviced by Roadside Ditches

The roadside ditch capacity seems to be similar in every section of the watershed that is predominantly drained by roadside ditches. This tends to affect the residential areas on the east side of the watershed the most. Due to this, most flooded structures are in residential areas, in which many structures are flooded starting at the 2-year event. One of the neighborhoods sits west of US-59, north of Sam Houston Tollway, and south of Reinhardt Bayou. This neighborhood is affected by Reinhardt Bayou.

The other neighborhood with roadside ditch capacity issues sits southeast of the intersection of US-59 and Sam Houston Tollway. This neighborhood shows structural flooding starting at the 2-year event.

6.1.5. Capacity Issues in Neighborhoods Serviced by Storm Sewers

One neighborhood in the IAH watershed that is serviced by storm sewers is located south of Sam Houston Tollway and north of Aldine Bender Road. Significant ponding is seen due to the low capacity of the channel (P135-00-00) that runs through the neighborhood starting at the 2-year event and the undersized conduits. Other areas in the watershed that generally have less storm sewer system capacity are around the airport in the north and northeast sections of the watershed.

6.1.6. Watershed Summary

Beyond the areas discussed, much of the IAH watershed experiences significant flooding with increasing rainfall. There are very few locations that do not show ponding during the 500-year event. This is evident through the system capacity results tables. Many residential areas throughout the watershed are serviced by relatively low-capacity roadside ditches, which impacts several homes.

7 Future Considerations

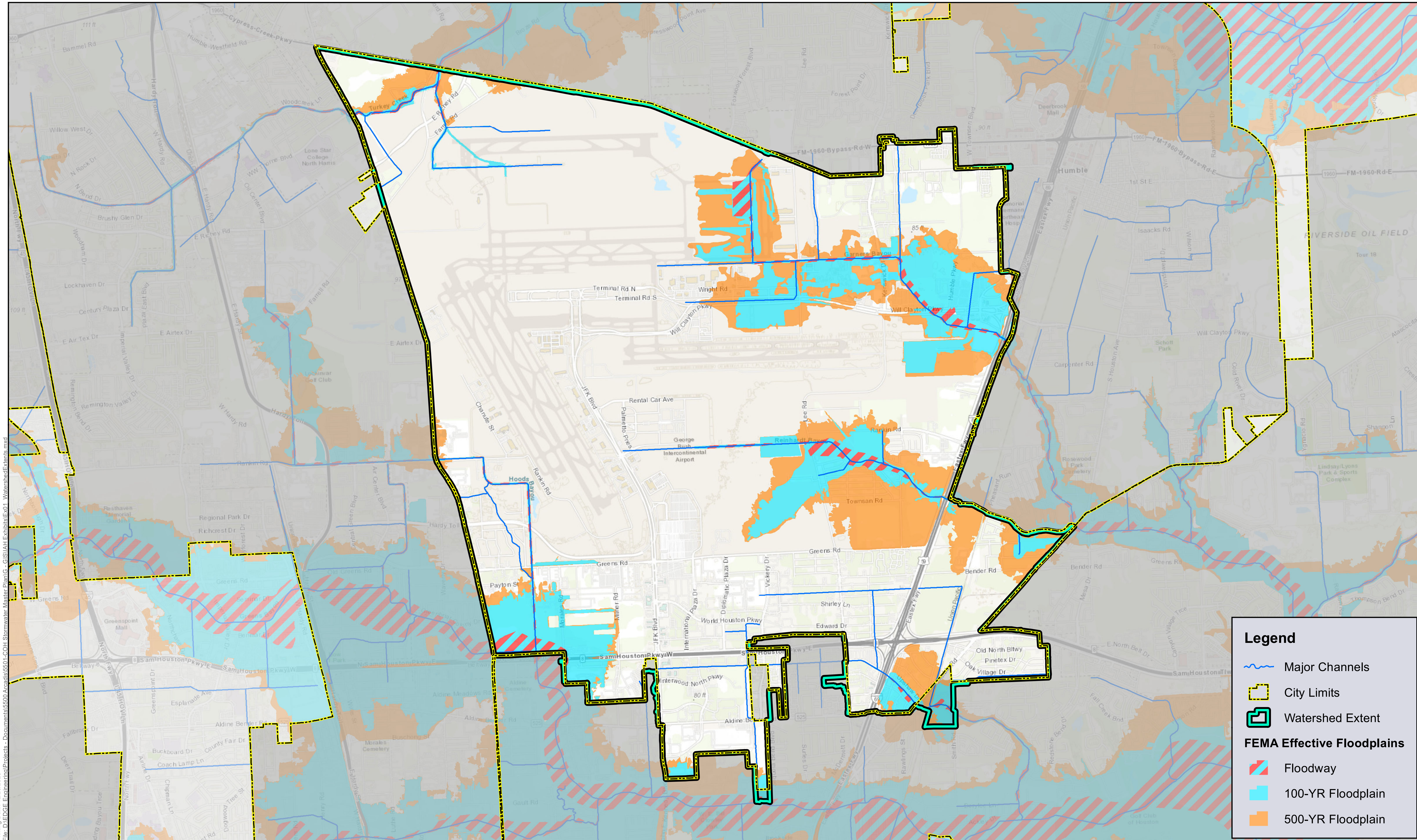
The development of the model for the IAH watershed provides a comprehensive stormwater model that includes the storm sewers, roadside ditches, open channels, and bayous within the City limits. This modeling effort provides extensive information in ponding elevations, overflow patterns, and discharge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

The system capacity should be considered for future modeling purposes because it outlines the problem areas that need more attention. Further investigations into these areas would be beneficial if proposed modifications are modeled to improve the level of service of the whole 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 be considered for future updates to the IAH model. Any ongoing updates and projects should be coordinated with the airport system and HCFCD to make updates in the drainage system.

- Coordination with the Houston Airport System to continue to obtain details regarding the airports drainage network. This relates to both the current infrastructure and as the airport continues to expand and modify its drainage infrastructure. Due to the importance of security at the airport, performing field reconnaissance at the airport is not trivial and therefore coordination with the Houston Airport System is key to continuously obtain the most up to date and accurate information on the airport's infrastructure.
- 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. As was noted in the report, the number of historical storms with claims in the watershed is limited, partially because the airport encompasses a majority of the watershed and there are no residential claims connected to the airport.
- Updates to the terrain used in the model should be considered as the terrain used for this modeling effort is 2018 LiDAR. Small developments and drainage improvements to the airport over the years include the recent airport terminal D expansion project, which was mitigated by building a 60-acre pond downstream along Garners bayou. The terrain in the unstudied channels can be lacking in bathymetry and can be beneficial to collect bathymetry for further, detailed modeling purposes.
- Many neighborhoods are service by collection systems smaller than 36-inches. To fully verify the cause of flooding in those areas, the model should be expanded and validated.

EXHIBITS



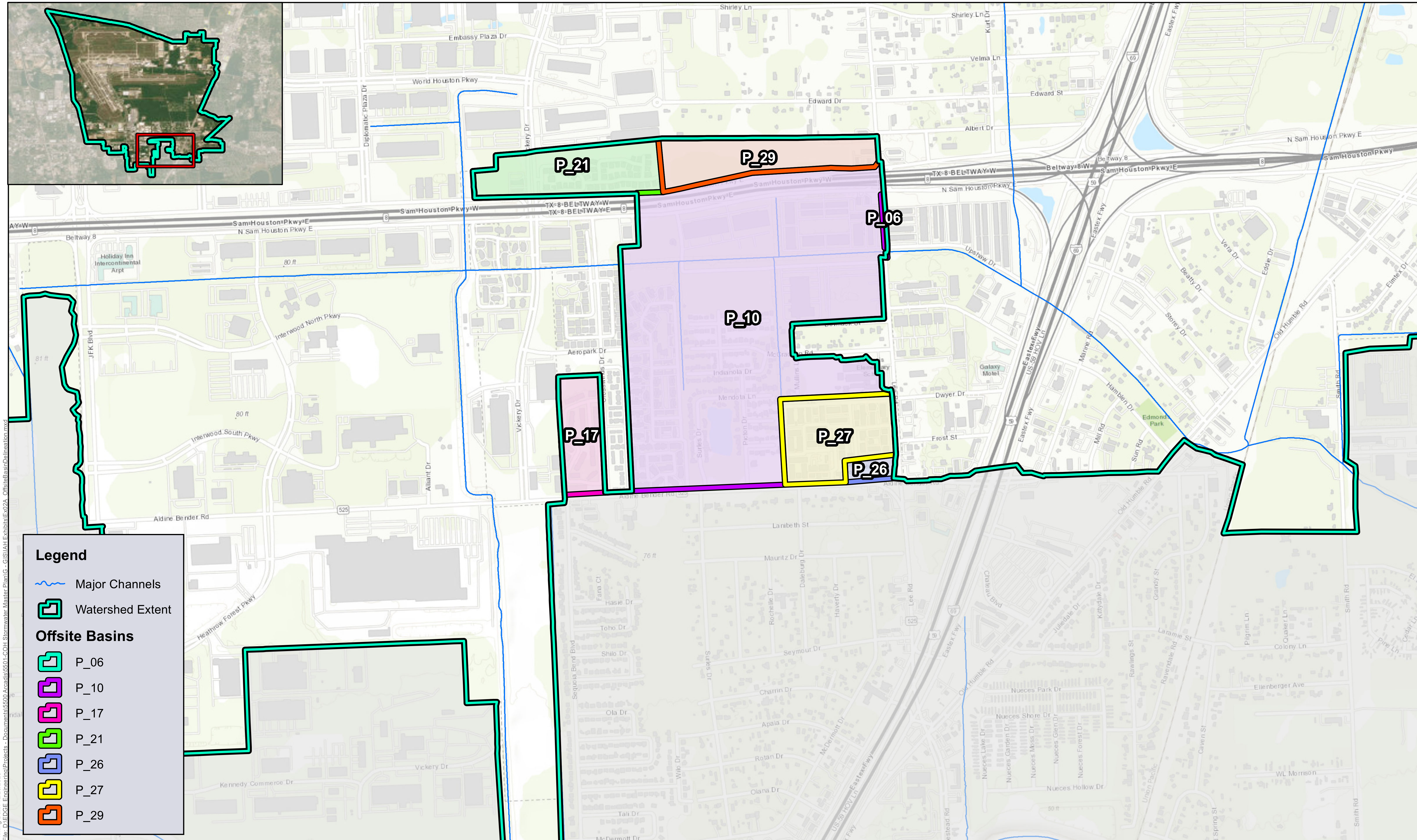
EDGE ENGINEERING

HOUSTON PUBLIC WORKS

IAH WATERSHED
WATERSHED EXTENTS

Stormwater Infrastructure Model

Exhibit 1



Printing Date: 12/20/2023

EDGE ENGINEERING

HOUSTON PUBLIC WORKS

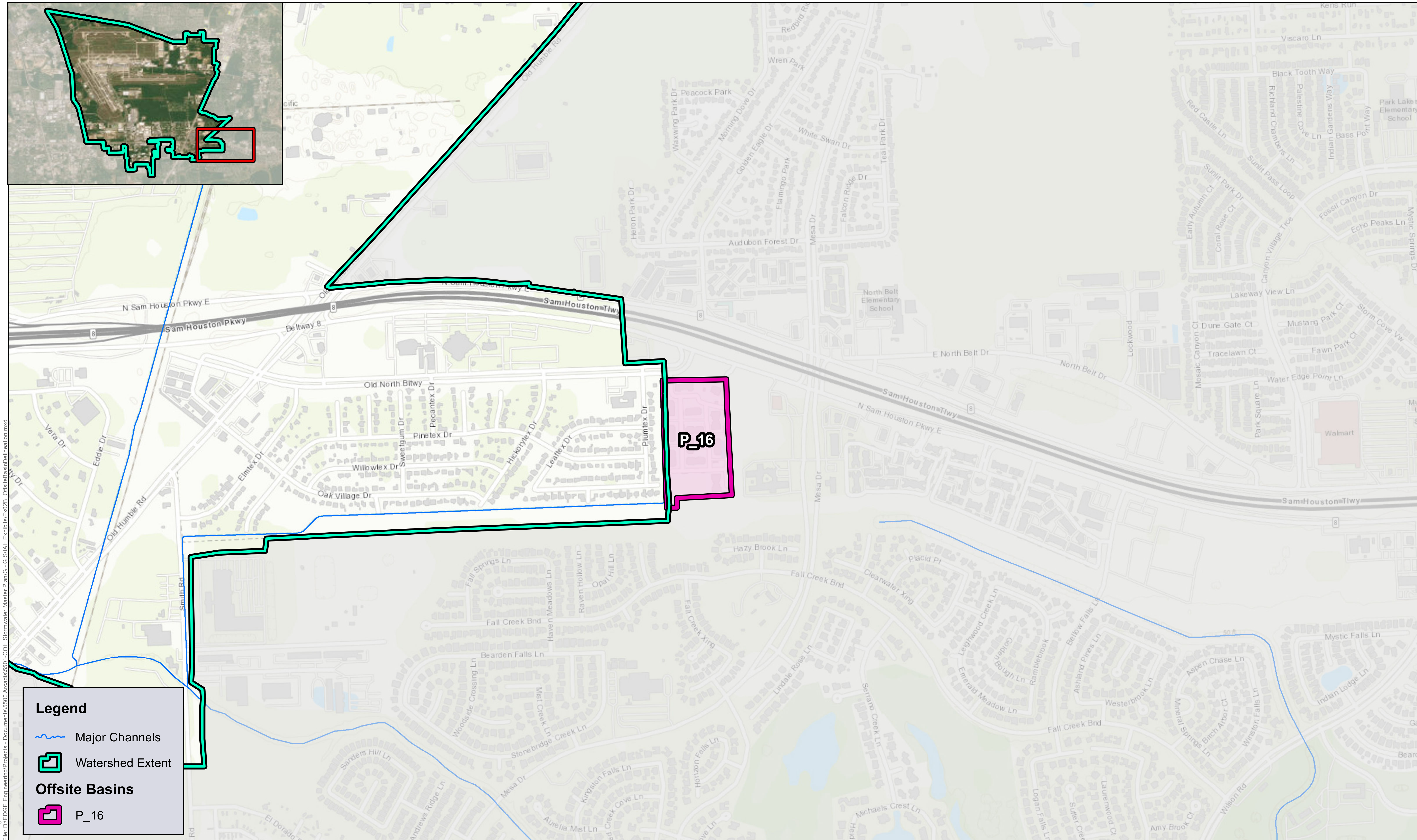
N W E S

IAH WATERSHED OFFSITE DRAINAGE AREAS

0 0.1 0.2 Miles

Stormwater Infrastructure Model

Exhibit 2A



Printing Date: 12/20/2023

EDGE ENGINEERING

HOUSTON PUBLIC WORKS

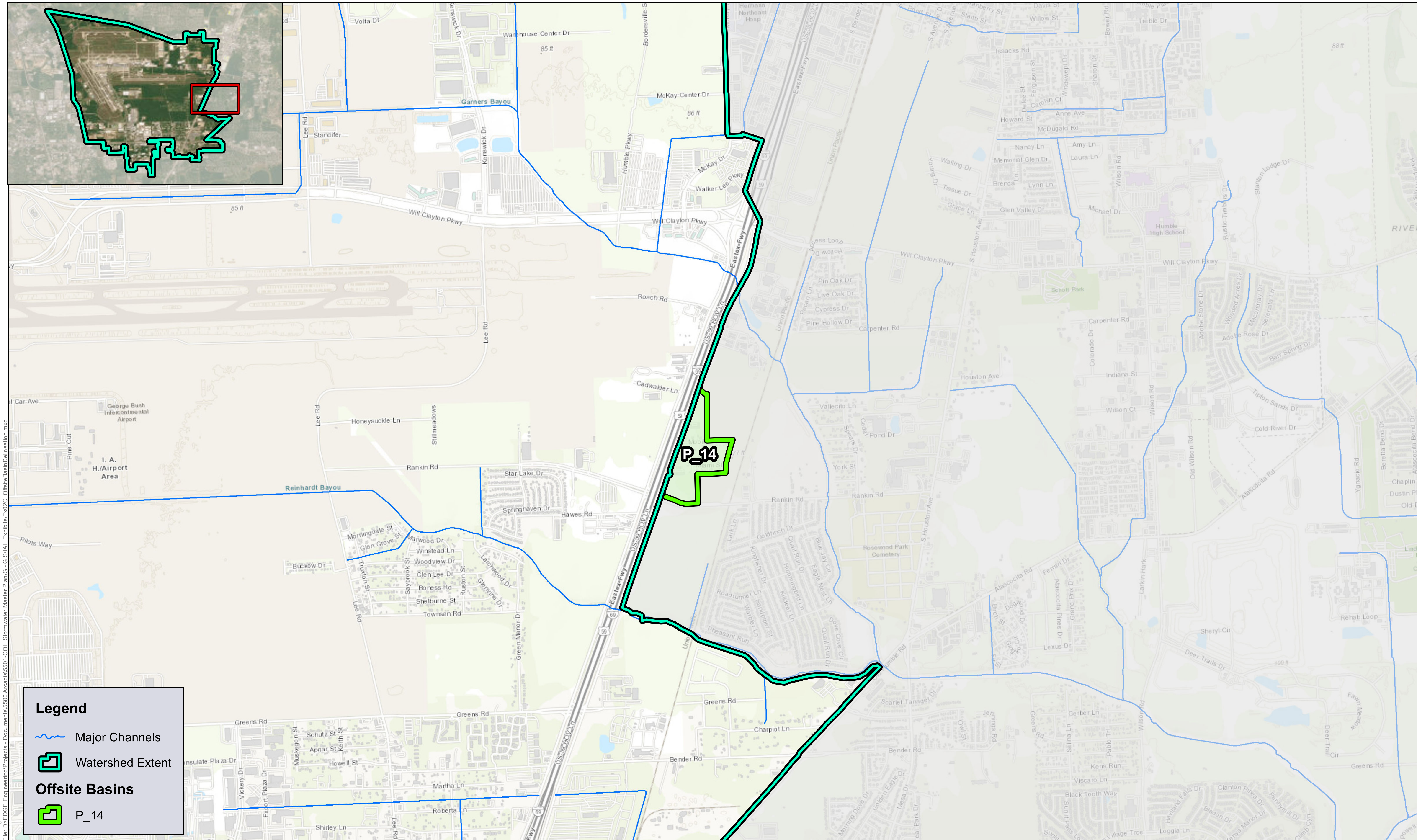
N W E S

IAH WATERSHED OFFSITE DRAINAGE AREAS

0 0.1 0.2
Miles

Stormwater Infrastructure Model

Exhibit 2B



Printing Date: 12/20/2023

EDGE ENGINEERING

HOUSTON PUBLIC WORKS

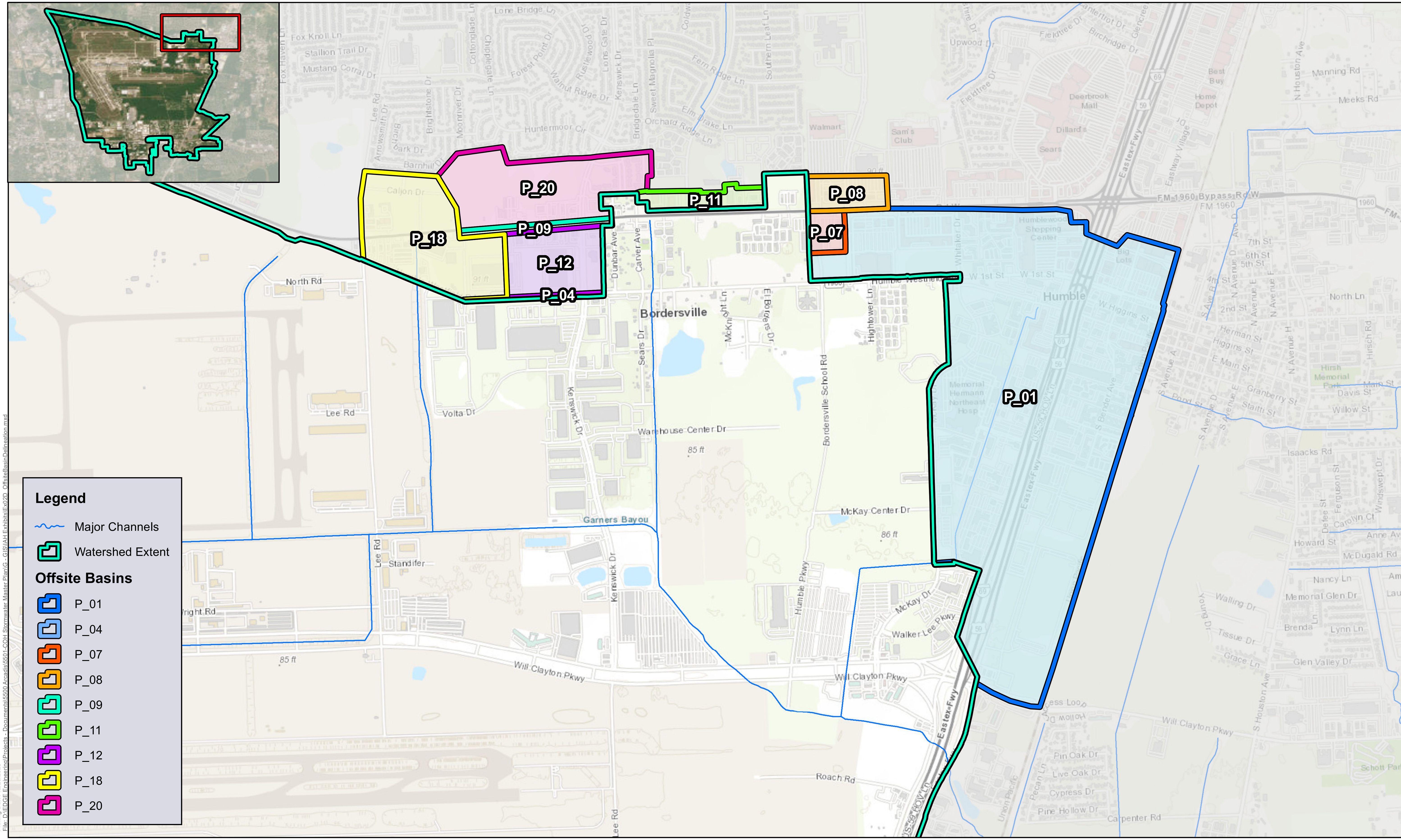
N
W E
S

IAH WATERSHED OFFSITE DRAINAGE AREAS

0 0.2 0.4
Miles

Stormwater Infrastructure Model

Exhibit 2C



EDGE ENGINEERING

HOUSTON PUBLIC WORKS

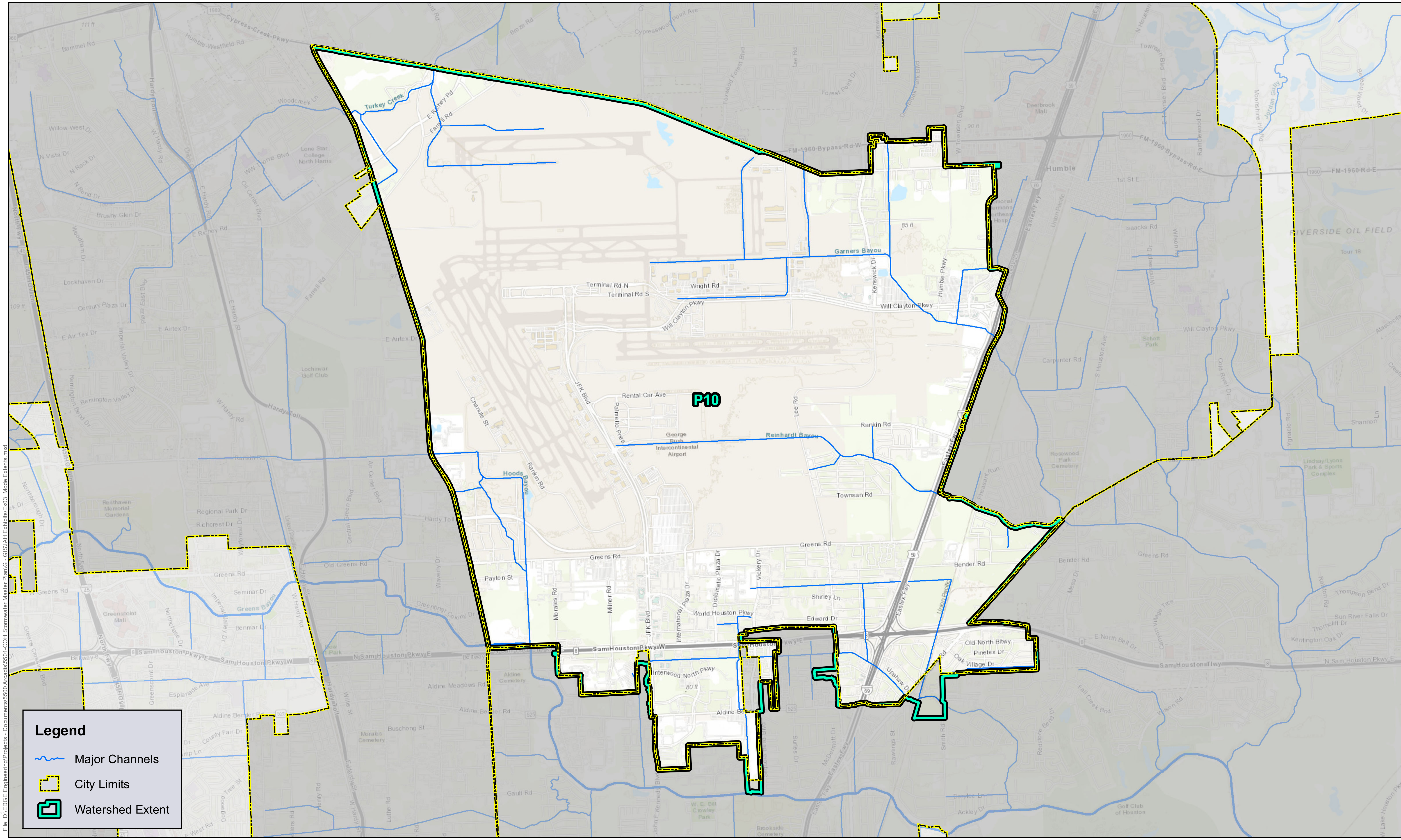
N W E S

IAH WATERSHED OFFSITE DRAINAGE AREAS

0 0.2 0.4 Miles

Stormwater Infrastructure Model

Exhibit 2D



EDGE ENGINEERING

HOUSTON PUBLIC WORKS

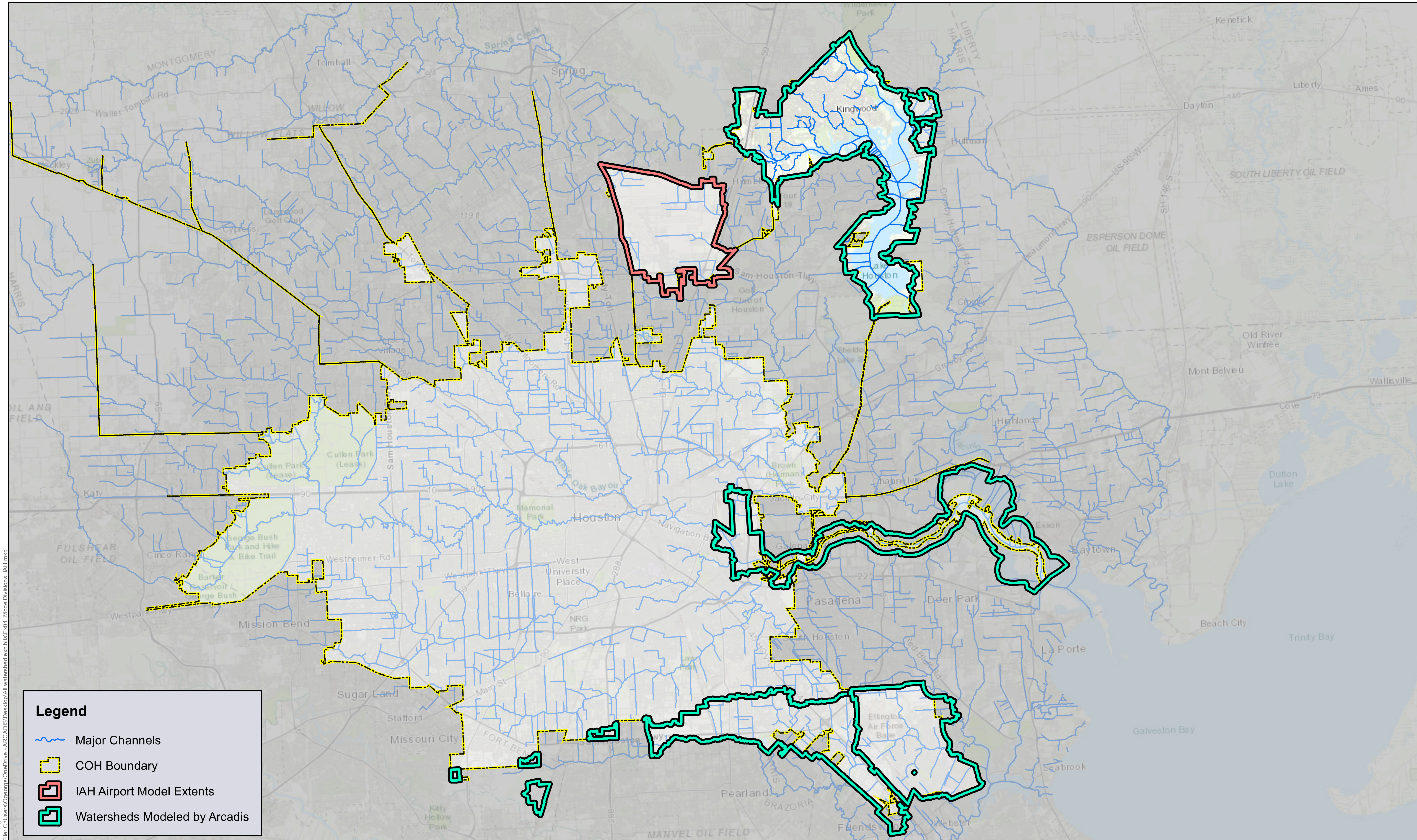
N W E S

IAH WATERSHED MODEL EXTENTS

0 0.5 1 Miles

Stormwater Infrastructure Model

Exhibit 3



Printing Date: 2/6/2024

ARCADIS

HOUSTON PUBLIC WORKS

N W E S

IAH AIRPORT MODEL EXTENTS

0 1.5 3 Miles

Stormwater Infrastructure Model

Exhibit 4