City of Houston Stormwater Master Plan

Armand Bayou Final Report

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Executive Summary

This report describes the development of a 59 square mile, two-dimensional (2D) rain-on-mesh InfoWorks ICM model of the Armand Bayou watershed within the City of Houston. The model integrates the storm sewer network, roadside ditches, channels, and bayous that form the 75.4 mile-long conveyance system within the watershed. The Armand Bayou watershed is dominantly storm sewer, which makes up almost 50% of the conveyance system.

The Armand watershed is located in the southeast region of the City and is surrounded by the San Jacinto River watershed to the north, the Clear Creek watershed to the east and south, and the Vince Bayou watershed to the west. The headwaters are near the junction of Beltway 8 and Spencer Highway, and the watershed generally drains southeast. Armand Bayou drains into Clear Creek. Major roadways include SH 3 and Red Bluff Road. The watershed was modeled following 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). Further details can be found in the data collection memo, Appendix E.

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 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.

The development of the one-dimensional (1D) and 2D components represented the storm sewer network, roadside ditches, unstudied channels, culverts, bridges, major channels, and bayous that form the 75.4-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.

Three historical rainfall events were selected for model validation: Hurricane Harvey (2017), Memorial Day (2015), and May 14, 2015. These events were selected due to their recent occurrence and wide spread flooding, which allows for greater alignment of physical conditions during the storm with the topography and landcover characteristics assigned to the model. The availability of flood claims within the watershed during the event was also a criterion for event selection, allowing model performance to be compared at the locations where flood claims were reported. The model met the City's validation criteria of 50% model flooding match to historic flooding claims at structures for all three storm events. 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 Armand Bayou 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 for each storm event. The capacity for storm sewers is maximum during the 5-year, at 84%, and decreases to 23% meeting capacity during the 500-year event. For roadside ditches, the capacity criteria are met at 85% of roadside ditches for the 2-year and decreases to 46% during the 500-year event.

Based on these simulation results, the areas in the watershed that have noticeably less storm sewer capacity are the Lyndon B. Johnson Space Center, University of Houston Clear Lake, and residential areas in the southern portion of the watershed. In the northern part of the watershed, areas such as the Bay Oaks Country club and neighborhoods such as Bay Knoll and Clear Lake are also subject to impact from the storm sewers not providing a level of service. The areas in the watershed that generally have less roadside ditch capacity are the Lyndon B. Johnson Space Center, Bay Oaks Country Club, and residential/commercial areas on the west side of the watershed approximately 1 mile east from I-45.

The model results also show the number of structures that have more than 1 inch of ponding for each storm event. Based on the model results, 400 structures would flood for the 2-year event increasing up to over 3,900 structures during the 500-year event.

Overall, the report highlights the complexities involved in modeling urban flooding while also highlighting the significant potential of advanced simulation techniques for better flood risk management and urban planning. The essential objective of these models is to enable the City of Houston to effectively communicate flood risks to its residents and to improve the planning for capital projects. The insights and recommendations provided from this study are crucial for directing future initiatives aimed at strengthening Houston's resilience to flooding, ensuring the city is prepared for a range of flood scenarios.

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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.

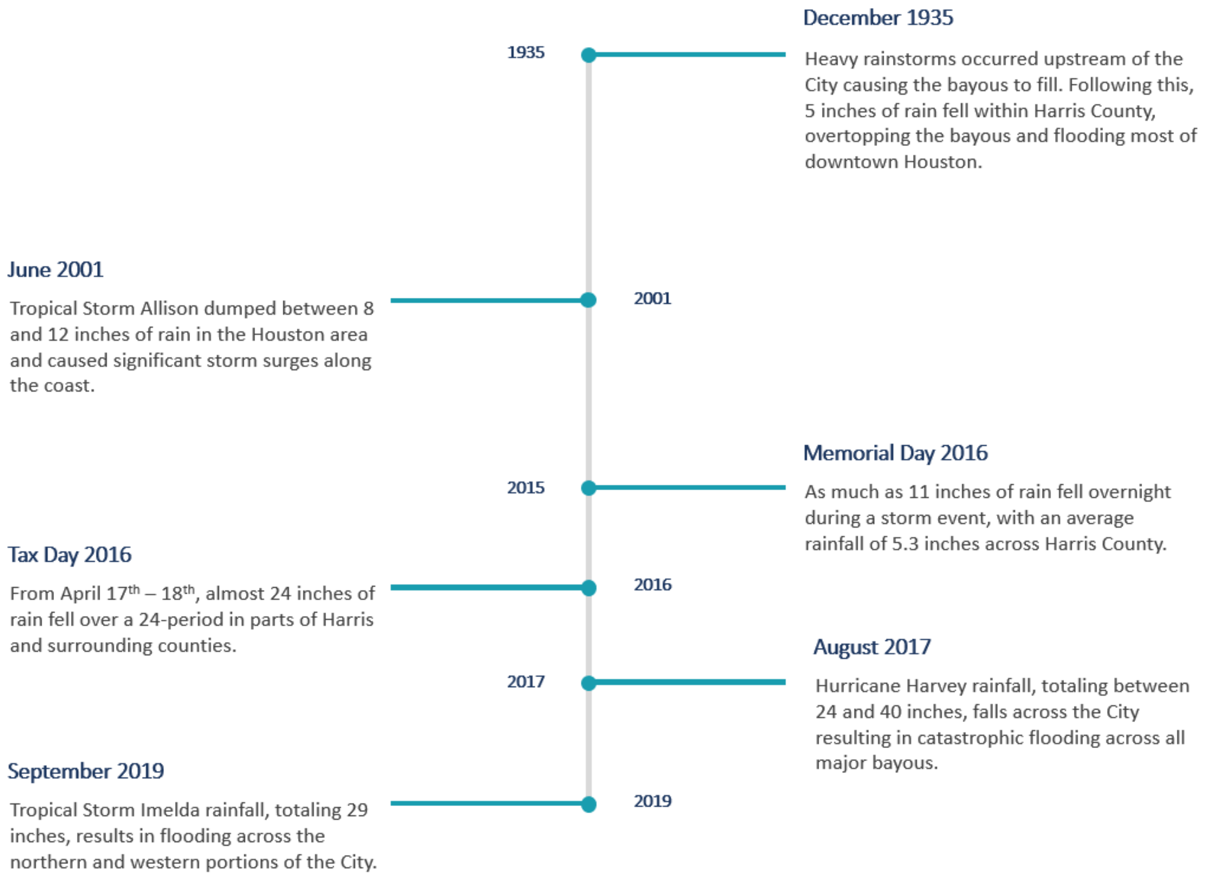


Figure 1-1: Major Historical Storm Timeline

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 surveyed 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 to identity additional 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 Master Plan 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 the storm sewers 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 Armand Bayou watershed is 59.0 square miles located in the southeast region of the City and is surrounded by the San Jacinto River watershed to the north, the Clear Creek watershed to the east and south, and the Vince Bayou watershed to the west. About one-third of the watershed (22.0 square miles) is located within City limits, which was the focus of this modeling effort. The remaining portions are in the cities of Pasadena, La Porte, and Deer Park, and unincorporated Harris County. Exhibit 1 includes the extents of the watershed.

The terrain is generally flat throughout the watershed. The headwaters are located near the junction of Beltway 8 and Spencer Highway, and the watershed generally drains in a southeasterly direction. Armand Bayou drains into Clear Creek. Armand Bayou is subject to tidal influence from Galveston Bay.

The watershed is mostly developed, consisting primarily of small-lot, single-family residential developments. The land is undeveloped along Armand Bayou and in the Armand Bayou Nature Center. Notable features of the watershed include Ellington Air Force Base, La Porte Municipal Airport, University of Houston-Clear Lake, Lyndon B. Johnson Space Center, and an oil field south of Genoa Red Bluff Road and west of Red Bluff Road. These features contain a variety of land use types. A summary of the land uses throughout the Armand Bayou Watershed within City of Houston limits (22 square miles.) is provided in Table 1-1.

Table 1-1: Armand Bayou Watershed Land Use Summary

Land Use[1]	Area (sq. mi.)	Percentage (%)
Undeveloped	5.0	23%
Developed Open Space	5.4	25%
Residential	10.3	47%
Commercial	1.3	6%

[1]Source: Houston Galveston Area Council

The watershed is home to multiple small-lot, residential developments. These developments utilize storm sewer systems for drainage; however, significant areas of these developments do not have any drainage infrastructure cataloged in the City of Houston GIMS. Table 1-2 shows the storm sewer mileage and size distribution of the conveyance systems in the watershed within City limits according to GIMS. However, as previously noted, these numbers are low due to missing storm sewer data for the large residential developments in the southeast region of the watershed. The Armand Bayou watershed contains only 11 miles of roadside ditches.

Table 1-2: Conveyance Infrastructure Distribution in Armand Bayou Watershed

Description	Length (mi.)	Percent of Total Conveyance System
Pipe Diameter ≤24”	0.0	0%
Pipe Diameter ≥ 36”	30.7	37%
Pipe Diameter ≥ 60”	10.5	13%
Roadside Ditch	11.0	13%
Studied Channel	9.0	11%
Unstudied Channel	21.6	26%

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 Armand Bayou are provided per SFHA zone type for the 1% and 0.2% annual chance of exceedance (ACE).

Table 1-3: Armand Bayou Watershed Floodplain Summary

Floodplain Classification	Area (sq. mi.)	Structures[1]
Within 1% ACE Floodplain (Zone AE)	1.6	400
Additional within 0.2% ACE Floodplain	5.6	5,100
Outside the 0.2% ACE Floodplain	16.4	12,900

[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 Armand Bayou watershed since 2015.

Table 1-4: Armand Bayou Watershed Flood Claims

Source	Claims	Percent of Total[1]
FEMA Flood Claims (since 2015)	700	4%
Other Flood Claims (since 2015)	3,200	18%

[1]Total number of structures within City limits in the Armand Bayou watershed is approximately 18,000 structures.

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.

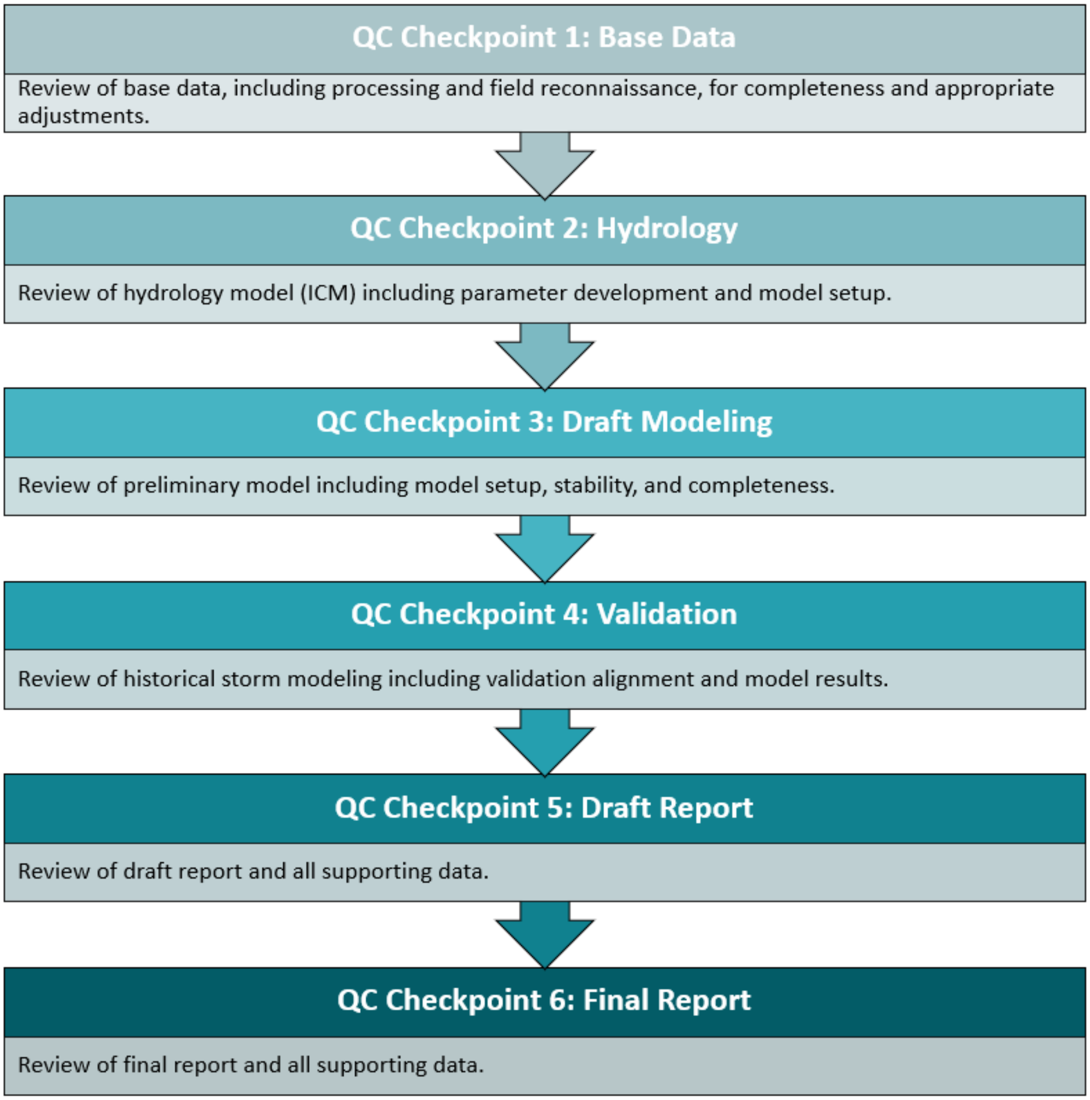


Figure 1-3: QC Checkpoints

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 a realistic 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 were needed especially along channels. Structure data were reviewed, and missing data was determined from 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 effort 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. Fixing model instabilities, especially along 1D river reaches, used most of the additional time. Submittal dates for each milestone are shown in Table 1-5.

Table 1-5: Armand Bayou Submittal Dates

Armand Bayou Deliverables	Submittal Date
Data Collection	4/7/2023
Hydrology	5/26/2023
Base Hydraulics Model	9/10/2023
Validation Model	11/10/2023
Final Model and Draft Report	1/10/2024
Final Report	2/28/2024

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 as originally planned, 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 Armand Bayou watershed in three phases. Phases 1 and 2 focused on field reconnaissance at bridges and culverts on unstudied channels to enhance the 1D river reach hydraulic structure modeling. Information collected at these structures is summarized in Appendix E. Arcadis developed a mobile application for 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.

At storm sewer manhole gaps, traditional survey was performed as part of Phase 3. The survey methods and procedures were followed as prescribed in the Data Collection White Paper. The survey deliverables, which include the initial survey request exhibits, field survey base files, and field survey notebooks are provided in Appendix E.

Table 2-2 below summarizes the survey type performed in Armand Bayou during the phases of the field reconnaissance tasks.

Table 2-2: Structures Collected in Armand Bayou Watershed

Phase	Type	Number of Structures Collected
Phase 1	Bridge	7
	Culvert	4
Phase 2	Bridge	7
	Culvert	1
Phase 3A	Culvert	1
	Manholes	39
Total		59

2.3. Watershed Adjustments

Most of the storm sewers in the Armand Bayou watershed fall within the jurisdiction of the Clear Lake City Water Authority (CLCWA) and therefore was not included in the City's GeoLink database. The team requested as built and GIS data from the CLCWA and these data sources provided most of the storm sewer network in the model. Additionally, the CLCWA provided as-built drawings for detention pond and channel improvements from the Exploration Green project. This allowed for the assignment of topography and inlet / outlet information to the model for these improvement areas, many of which were constructed following the collection of the region's most recent LiDAR in 2018.

The data for the remaining part of the watershed storm system that fell within the City of Houston was available in the GeoLink storm sewer data which 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.

There was also a location in the Armand Bayou watershed that was served by a curb-and-gutter system where the GeoLink storm sewer network was missing data due to recent development. The topography of this area was newer than the 2018 LiDAR. Plans were not available to determine the geometry and elevations for these assets so connections were added to the model to convey runoff from this area. This area should be prioritized for survey when future updates of the stormwater infrastructure model are developed.

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 five breaklines to define the centerline, toe, 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.

Roadside ditches were reviewed against aerial imagery and updates were made where the layer was found to be outdated by adding or removing roadside ditches. 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 collected final data that was used to create the ICM model.

Table 2-3: ICM Model Components

Model Component	Value
Storm Sewer	53.4 miles
Roadside Ditch	15.1 miles
Unstudied Channels	20.8 miles
Manholes	1,685
Breaklines	644.6 miles
Building Footprints	16,857
Roughness Zones	6,716

3 Hydrology

The hydrologic analysis provided the rainfall and discharge rates that were used within the ICM model. An approach to the analysis was provided 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 based on drainage area. Areas smaller than and up to 100 acres used the rational method, and areas greater than 100 acres used 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 Armand Watershed, the impervious percentage was calculated to be 18.36%. 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.

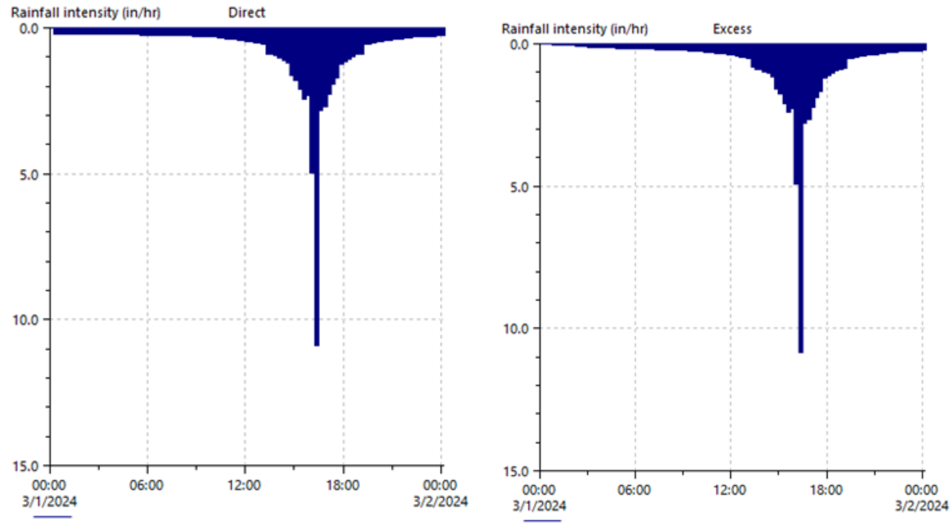


Figure 3-1: Rainfall Hyetographs for Armand Bayou (Left – Total Rainfall; Right – Excess Rainfall)

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 Rational Method or 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 Armand Bayou watershed.

3.6. Results

The Armand Bayou watershed had 3 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 Armand Bayou watershed consists of a series of two small models (subbasins) covering the entire 59-square mile watershed. The watershed was divided into two models to be more manageable regarding model development, runtimes, and future use. Table 4-1 summarizes the drainage infrastructure included within each model for the Armand Bayou Watershed and the model divisions 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.)	(#)
B_10	19.10	1,634	38.7	13.7	13.6	7.9	0	12,812
B_20	6.33	449	14.7	2.7	7.2	1.1	3	4,045

The hydraulic model includes approximately 35% of the storm sewer infrastructure within the Armand Bayou watershed. The breakdown of the infrastructure included in the model is shown in Table 4-2.

Table 4-2: Modeled Storm Sewer

Watershed Storm Sewer (miles)	Modeled Storm Sewer (miles)	Modeled Storm Sewer (%)
153.6	53.4	35%

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 for the watershed were derived from the provided HCFCD MAAPnext hydraulic model of Armand Bayou. The location of these boundary conditions is included in Appendix G.

Flows between models but outside the mapped floodplain were included as boundary conditions as well. Discharge hydrographs were used at the upstream end of each model to simulate flows coming from the upstream models.

4.4. Watershed Considerations

For the Armand Bayou hydraulic model, there were several deviations from the guidance issued in the white papers. The variations were made on a case-by-case basis and were centered around improving hydraulic model stability in the longer validation storm simulations. The following changes were made to the hydraulic model:

4.4.1. Unstudied Channels/River Reaches

There are many unstudied channels throughout Armand Bayou. As per white paper guidance, these are represented in the hydraulic model by river reach objects. A few of the river reaches have their downstream end close to the boundary of the model boundary. These particular river reaches were found to cause stability issues during the initial minutes of model simulations. As the hydraulic model attempted to backfill water from the downstream level boundary condition, this would cause the nearby river reaches to become unstable. This instability led to the model not running. The issue was resolved using the following process:

1. The unstable river reaches nearest the downstream level boundary were removed from the model and replaced with breaklines to define the channel as shown in Figure 4-1 and Figure 4-2.
2. The downstream level boundary condition was modified to provide a linear "ramp-up" in level from zero to the actual recorded value over the first few hours of the model simulation. This allowed the main bayou channel to fill up slower and increased model stability. An example is shown on Figure 4-3.

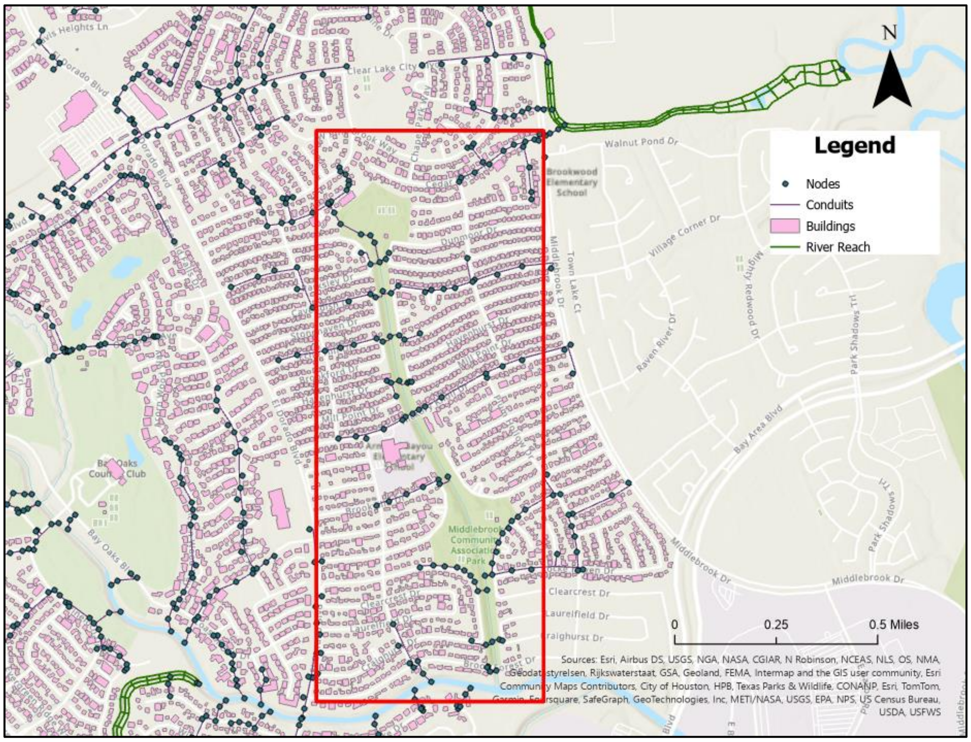


Figure 4-1: Removal of Downstream River Reach

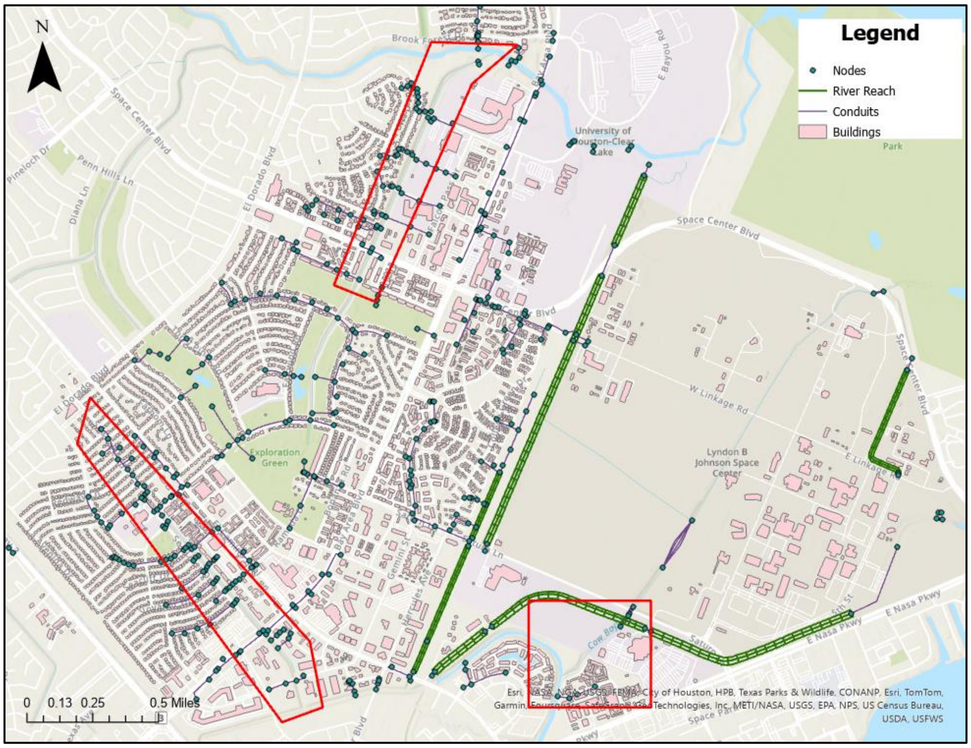


Figure 4-2: Removal of Downstream River Reach

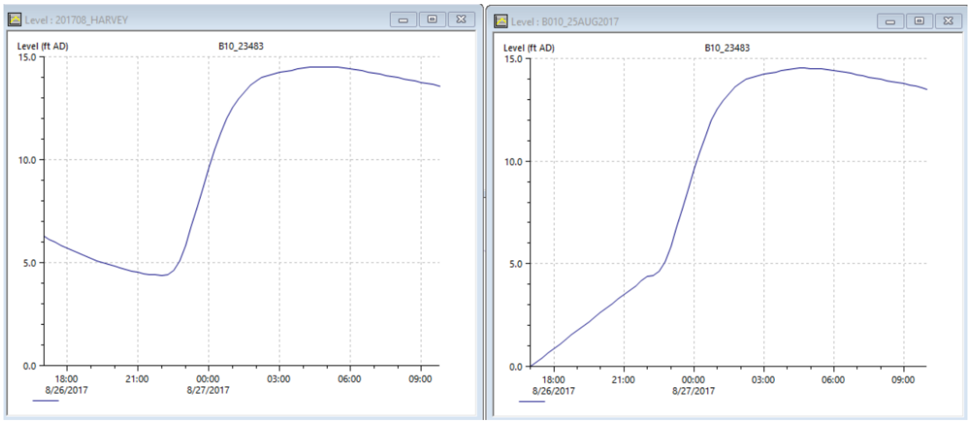


Figure 4-3: Level Boundary Ramp-up Adjustment

4.4.2. Node Types

Throughout the model there are outfalls from the 1D storm sewer network onto the 2D mesh. Conversely, there are also inlet pipes above grade that allow flow from roadside ditches on the 2D mesh into the 1D storm sewer network. At these locations, the node type was changed from Manhole to Connect 2D. Connect 2D nodes improve the accuracy of the hydraulic model by including the outfall calculations from the pipe network as part of the 2D mesh calculations, therefore allowing a more realistic representation of modeled structures. For all Connect 2D nodes, the Connection Type was set to 2D. The associated 1D storm sewer Conduit Type was also modified to work with the new node type and was changed from Conduit to Conduit (2D).

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 Armand Bayou 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 above or 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 Armand Bayou watershed has been subject to frequent storms over the past few decades. These events were used to select three storms 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. Table 5-1 provides a summary of the maximum total rainfall and the number of flood claims for each historical event. It is noted that the Memorial Day event has a limited number of claims, however, there were no other recent storms with more claims to replace it. The limited number of Memorial Day claims made it difficult to meet the criteria but the model in general did not show widespread flooding in areas without claims, confirming the lack of flooding for this validation storm event.

Table 5-1: Summary of Historical Storm Events

Historical Storm Event	Maximum Total Rainfall (in)	Number of Flood Claims
8/25/2017 (Harvey)	38.56	1,711
5/14/2015	7.49	26
5/25/2015 (Memorial Day)	7.39	2

5.3. Model Adjustments

Upon initial simulation of the historical events, the hydraulic models were found to meet or exceed the validation criteria. Therefore, no changes were required in the model network beyond those necessary to improve the model stability. The validation criteria for Armand Bayou is shown in Table 5-2. The validation criteria for parcels for the May 14 event was not met, but due to the very limited claims this was deemed acceptable.

Table 5-2: Model Validation Results

Storm Event	Flood Claims	Model Flooded Structures	Model Flooded Parcels	Structure Percent Difference	Parcels Percent Difference
Harvey	1,711	1,676	1,189	100%	70%
May 14,2015	26	25	5	96%	19%
Memorial Day	2	2	1	100%	50%
Total	1,739	1,704	1,195	98%	69%

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.

As shown in Table 6-1, the percentage of storm sewers meeting capacity is maximum during the 5-year, at 84%, and decreases to 23% during the 500-year event. For roadside ditches, the capacity criteria are met at 85% of roadside ditches for the 2-year and decreases to 46% during the 500-year event.

Table 6-1: Armand Bayou System Capacity

Storm Event	Storm Sewers Meeting Capacity	Roadside Ditches Meeting Capacity
2-year	54.2%	85.4%
5-year	84.6%	79.1%
10-year	75.3%	75.2%
25-year	62.0%	71.1%
50-year	51.6%	67.2%
100-year	39.9%	60.8%
500-year	23.0%	46.8%

6.1.2. Flooded Structures

Flooded structures for the frequency storms 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	440
5-year	558
10-year	644
25-year	810
50-year	971
100-year	1,377
500-year	3,935

As shown in Table 6-2, Structure flooding is over expected to be over 400 structures for the 2-year event and increases up to over 3,900 structures during the 500-year event.

6.1.3. Major Channels

All the major channels within the model boundary contain the flow during the 2- and 5-year. During the 10-year event, Channel A107-00-00, also known as Cow Bayou, begins to overtop and contribute to flooding in the Lyndon B. Johnson Space Center.

6.1.4. Area east of Bay Area Blvd, bounded by Middlebrook Dr. from the north and Saturn Ln from the south

The areas in the watershed that have less roadside ditch capacity are the Lyndon B. Johnson Space Center and residential areas in the watershed's southern portion. Localized flooding is seen throughout these areas starting in the 10-year event from. This flooding is caused by overtopping of the Cow Bayou which runs through the Lyndon B. Johnson Space Center. Depths within the area reach 3 feet in the 100-year event and contribute to structural flooding. Flooding is largely attributed to the insufficient capacity of roadside ditches which were designed prior to updated Atlas 14 rainfall statistics.

The University of Houston Clear Lake and residential areas in the Clear Lake City subdivision, are made up of storm sewers. Flooding is largely contained to the ditches through the 50-year event. In the 100-year event, the storm sewers have inadequate capacity and overflow into the university and residential homes. Flooding in the university is also caused by overtopping of Horsepen Bayou. This channel runs through the university from west to east. As this channel overtops, flow is captured in the neighboring ponds north and south of the channel. The area has ample topographic relief and ponding does not reach the buildings within the area.

6.1.5. Area east of I-45, bounded by Clear Lake City Blvd from the north and Pineloch Dr. from the south

In the western part of the watershed, an area consisting of many residential and commercial buildings, are mainly serviced by roadside ditches approximately 1 mile east from I-45. Flooding from the overtopping of the insufficient capacity of the roadside ditches is seen in the 500-year event. Depths within the area reach 2 feet in the 500-year event and contribute to structural flooding.

6.1.6. Clear Lake and Bay Knoll Neighborhood

In the watershed's northern part, areas such as the Bay Oaks Country club and neighborhoods such as Bay Knoll and Clear Lake are mainly serviced by storm sewers. These areas are under capacity starting at the 100-year event, when these neighborhoods begin to show significant flooding.

6.1.7. Watershed Summary

Beyond the areas discussed, much of the Armand Bayou 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 and commercial areas throughout the watershed are serviced by high-capacity roadside ditches and storm sewers until the 100- and 500-year storm events.

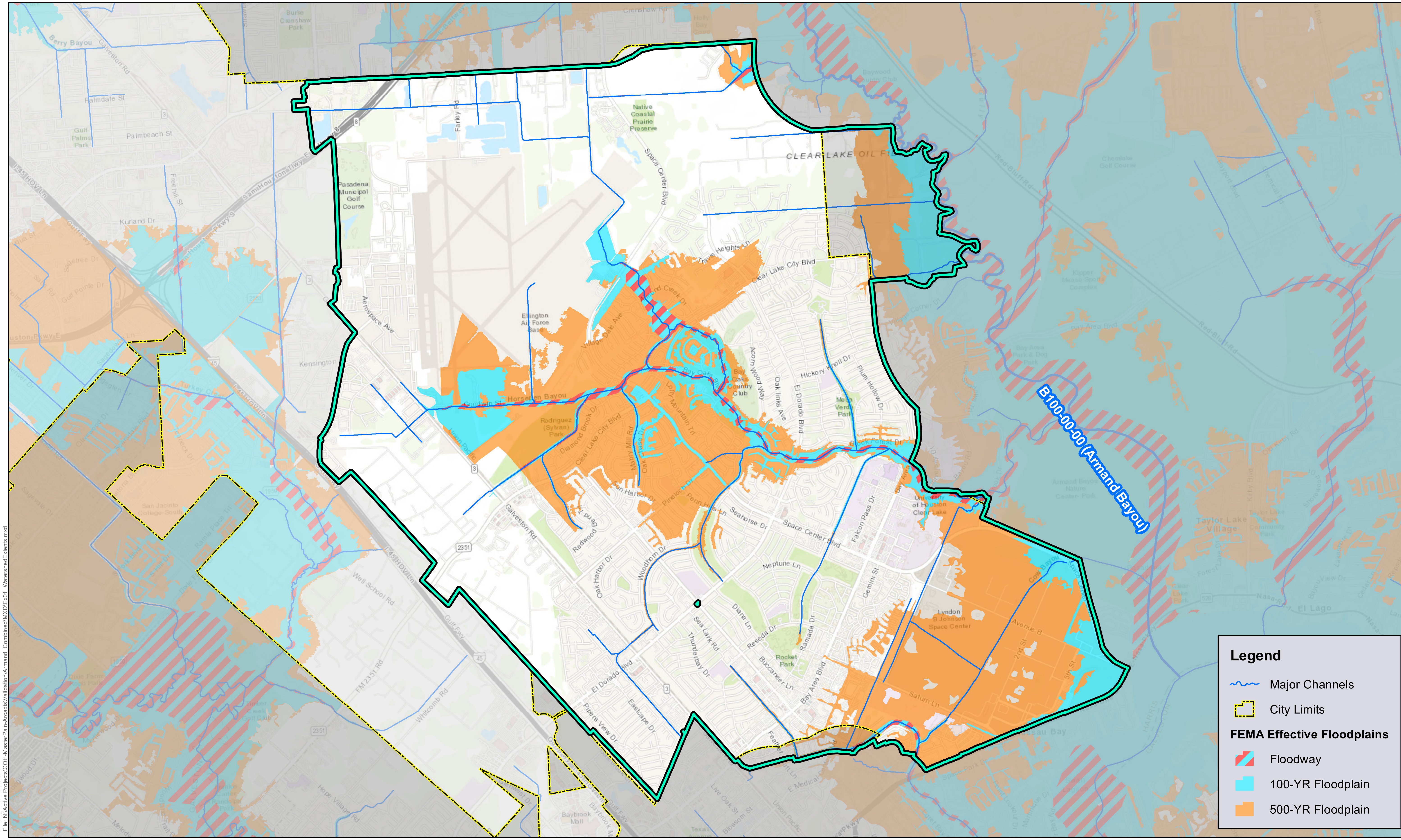
7 Future Considerations

The development of the model for the Armand Bayou watershed provides a 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 for future updates to the Armand Bayou models.

- Collection of high-water marks and other drainage observations during rainfall events should be prioritized to make available more information to improve model performance. With the newly acquired data, the watershed should then be resimulated and parameter adjustments made (if necessary) to align with the new data.
- Revaluation of claims data should be prioritized for the May 14, 2015 event to better reflect no evident flooding near most of the claims and them being located sporadically. This may provide a more accurate validation of the model.
- Coordination with the Houston Airport System and NASA for structure information at Ellington Airport and the Johnson Space Center. Limited information was available for stormwater assets in these areas and field reconnaissance for missing stormwater infrastructure in these areas could not be performed due to the enhanced security coordination and clearance that would be required.
- Continued coordination with the CLCWA for as-builts and infrastructure updates made to the storm water network in the CLCWA's jurisdiction. This also includes further improvements associated with the expansion and construction of the Exploration Green project.

EXHIBITS



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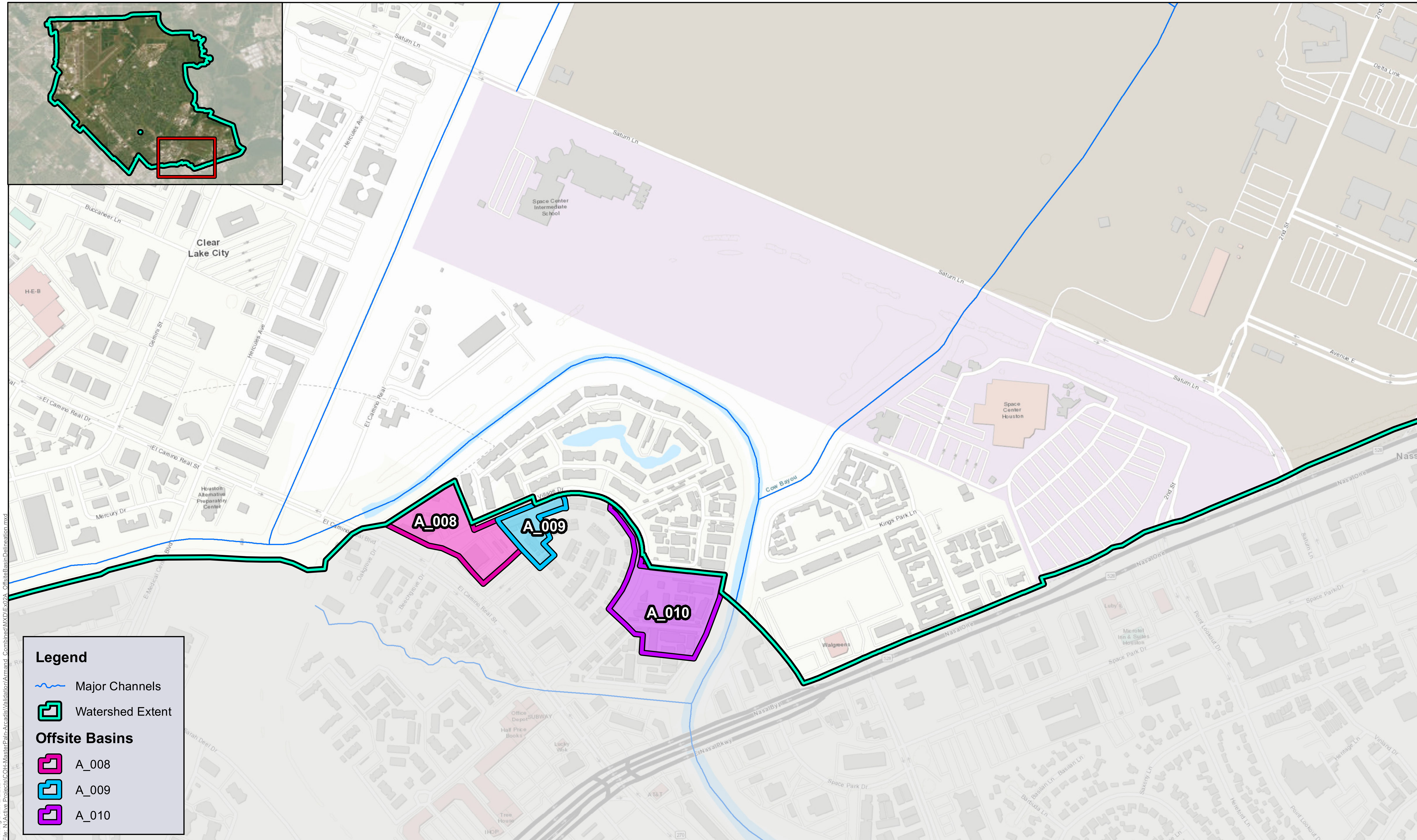
ARMAND BAYOU WATERSHED EXTENTS

0 0.3 0.6 Miles

Stormwater Infrastructure Model

Exhibit 1



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HOUSTON PUBLIC WORKS

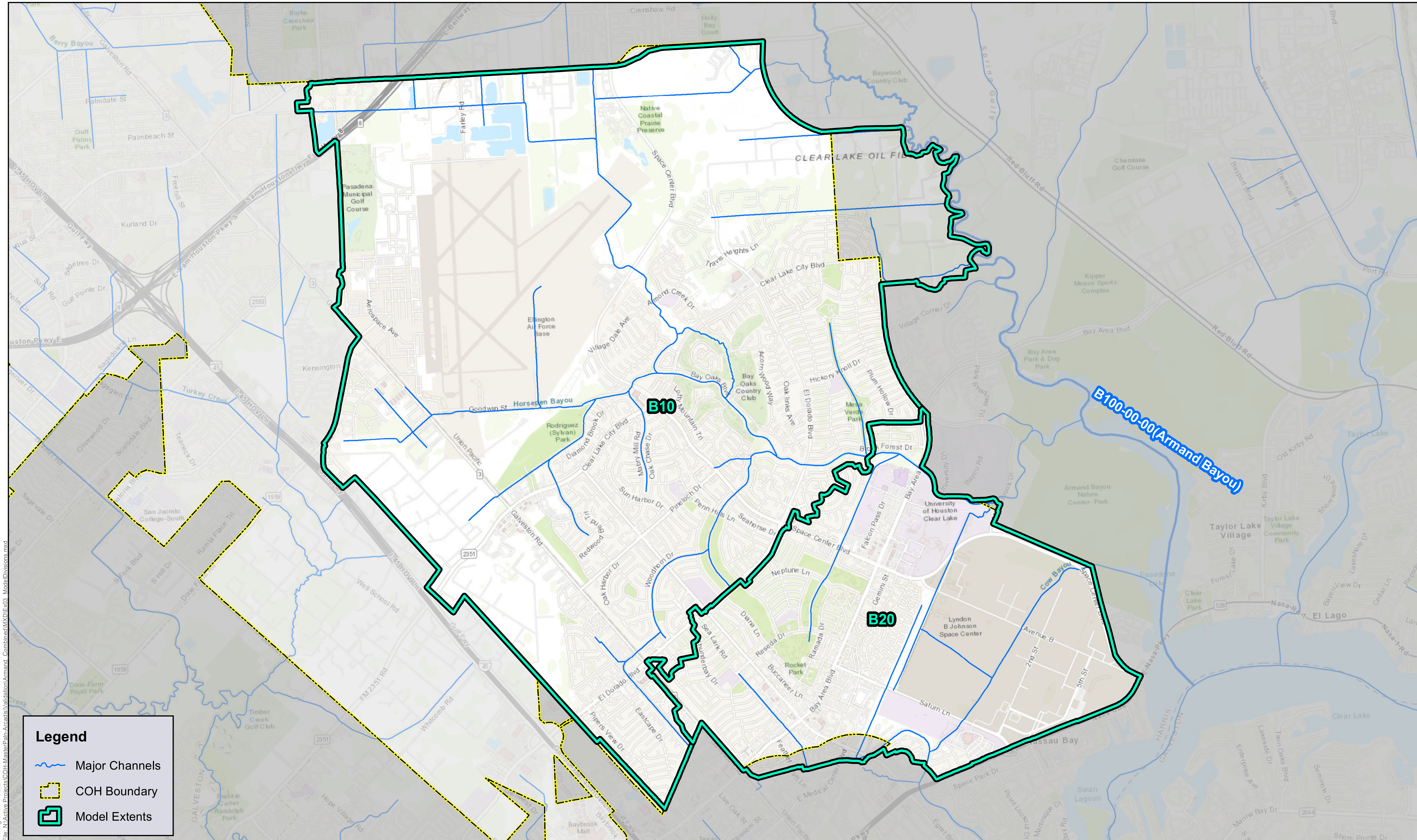
N W E S

ARMAND BAYOU OFFSITE DRAINAGE AREAS

0 140 280 560 840
Feet

Stormwater Infrastructure Model

Exhibit 2



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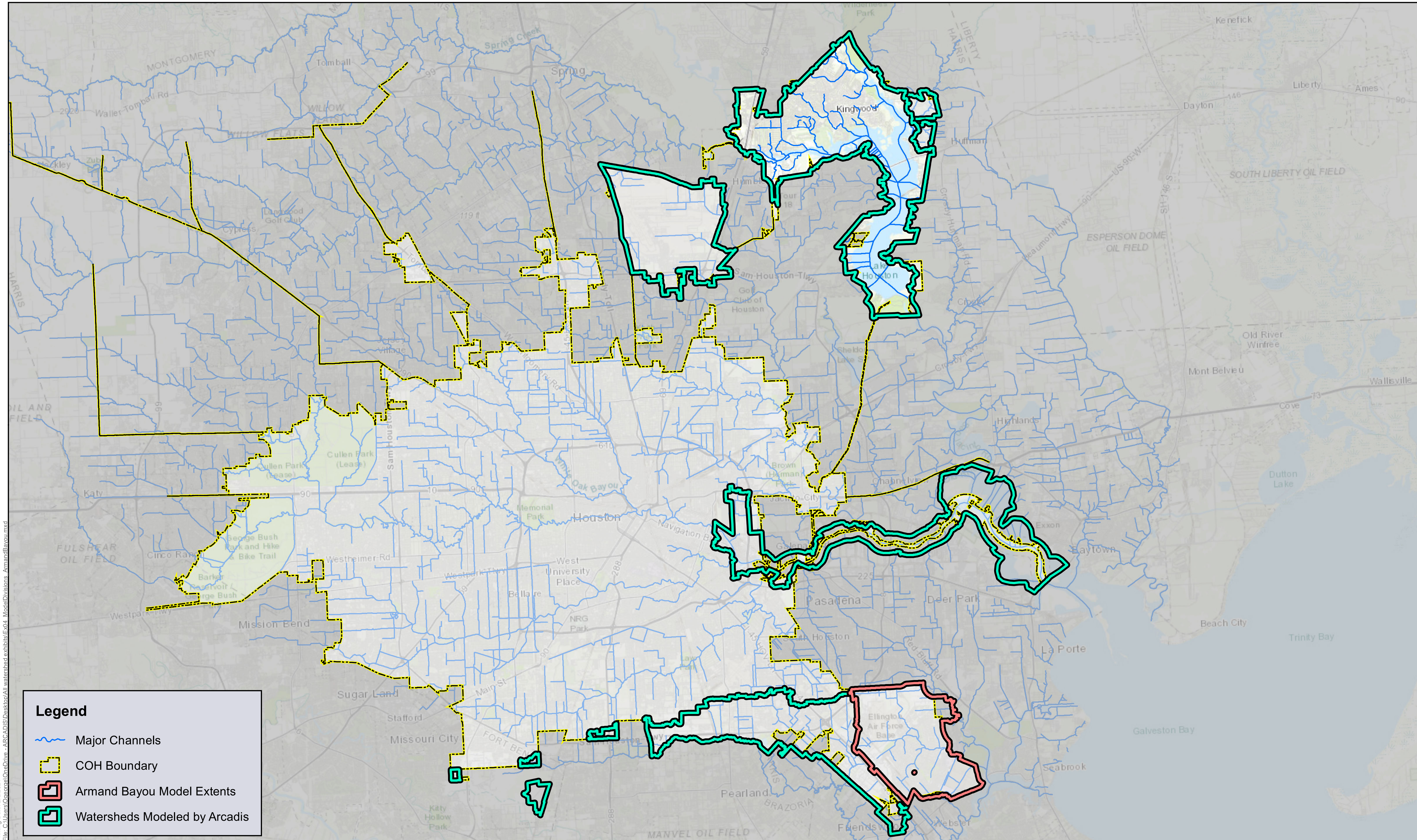
ARMAND BAYOU MODEL EXTENTS

0 0.275 0.55 Miles

Stormwater Infrastructure Model

Exhibit 3



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N W E S

ARMAND BAYOU MODEL EXTENTS

0 1.5 3
Miles

Stormwater Infrastructure Model

Exhibit 4