

East Galveston Bay Watershed, Texas 2D Base Level Engineering and Mapping Methods and Results

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1. Introduction

Base Level Engineering (BLE) provides technically credible flood data for various geographies - community, county, watershed and/or state level. BLE data can be shared with Federal, State, local and tribal governments, this data sharing provides stakeholders at all levels the necessary data to make informed decisions to reduce future flood losses. Without the mapping of flood prone areas, there can be a lack of information to effectively communicate flood risk to community officials, citizens, and businesses.

BLE is a riverine hydrologic and hydraulic modeling approach that builds on lessons learned to produce a baseline understanding of flood risk to communities, produced to support the assessment and maintenance of the national flood hazard inventory. Engineering models are created during a BLE assessment, producing information that meets the mapping Standards for Flood Risk Projects (FEMA Policy Memo FP 204-078-1) to produce Zone A (1-percent-annual-chance flood) information. BLE data is intended to represent the base level of investment needed for all flood study efforts FEMA will undertake. The East Galveston Bay Watershed BLE documented here was designed to use two-dimensional (2D) modeling techniques with enhancements and calibration to develop products that can be communicated and shared with stakeholders, and transitioned into FEMA regulatory data development workflows.

The intent of BLE is to provide communities technically credible flood hazard information in a cost efficient and timely manner. Additionally, BLE provides communities a chance to review draft modeling information, reflecting the potential changes in risk within their community. Providing additional flood risk datasets, like water surface elevation grids and flood depth grids, delivers alternative information that reinforces the variability of flood risk within a designated floodplain and supports historic community requests for a source to determine a Base Flood Elevation in Zone A areas.

For floodplain management purposes, BLE data may be used as best available information in areas that are designated as Zone A floodplain. It may also be used to regulate development in areas where no Special Flood Hazard Area (SFHA) has been mapped before. Communities may adopt BLE data to support local regulations, which facilitates use of the data in local floodplain management activities, including in the post disaster environment where a need for updated and/or enhanced flood hazard information may be necessary.

BLE provides information to communities who are currently unmapped and provides a digital entry to communities that are currently un-modernized. BLE acts as a measuring tool to allow FEMA to assess the current Zone A inventory identified as unknown or unverified in FEMA's Coordinated Needs Management Strategy (CNMS), which FEMA is required to evaluate once every five years, as described in Title 42 of the Code of Federal Regulations, Chapter III, Section 4101(e). FEMA makes this determination of flood hazard data validity by examining flood study attributes and change characteristics, as specified in the Validation Checklist of the Coordinated Needs Management Strategy (CNMS) Technical Reference. The CNMS Validation Checklist provides a series of critical and secondary checks to determine the validity of flood hazard areas studied by detailed methods (e.g., Zone AE, AH, or AO). While the critical and secondary elements in CNMS provides a comprehensive method of evaluating the validity of Zone AE studies, a cost-effective approach for evaluating Zone A studies has been lacking. Another important goal of the BLE process is scalability of the results, meaning that the model produced during the BLE assessment may be refined to produce a more enhanced model with additional manual correction and on the ground survey. If BLE modeling exists, FEMA will recommend that it be used as the base model for any detailed studies performed in those areas.

BLE practices leverage high-resolution topography that meets or exceeds the United States Geological Survey (USGS) 3-D Elevation Program standards and often applies flood engineering at a large scale as opposed to targeting stream reaches within a watershed. BLE can be conducted at any scale, commonly for larger areas (HUC-8 watershed) but may be produced at the county or local level too. It is encouraged to do BLE for wider areas in order to build on efficiencies in modeling and ensure cost efficiency. Using current technologies, multiple watersheds or watersheds with large land areas can be analyzed at a more efficient rate to produce water-surface elevations and site-specific hazard data replacing outdated flood studies shown in existing Flood Insurance Rate Maps (FIRMs). All flood prone areas within a watershed will have an engineering model calculating multiple flood recurrence intervals and defining floodplains with elevation grids using high-resolution topography.

Per standards #84 and #133, BLE will include all recurrence intervals (0.2-percent, 1-percent, 1-percent plus, 1-percent minus, 2-percent, 4-percent, and 10-percent-annual-chance floods). As such, hydrologic and hydraulic

analysis should be performed to determine the expected water surface elevations for each of the seven recurrence intervals previously identified.

The East Galveston Bay Watershed 2D BLE project was scoped as described in the FEMA Region 6 FY19 Mapping Activity Statement No. 20. In an effort to increase and enhance the flood risk products in Texas, the study was contracted through the Texas Water Development Board's (TWDB's) Cooperative Technical Partner (CTP) program to AECOM Technical Services, Inc. This report documents the BLE process, products, and results for this watershed. Figure 1 depicts the East Galveston Bay Watershed footprint.

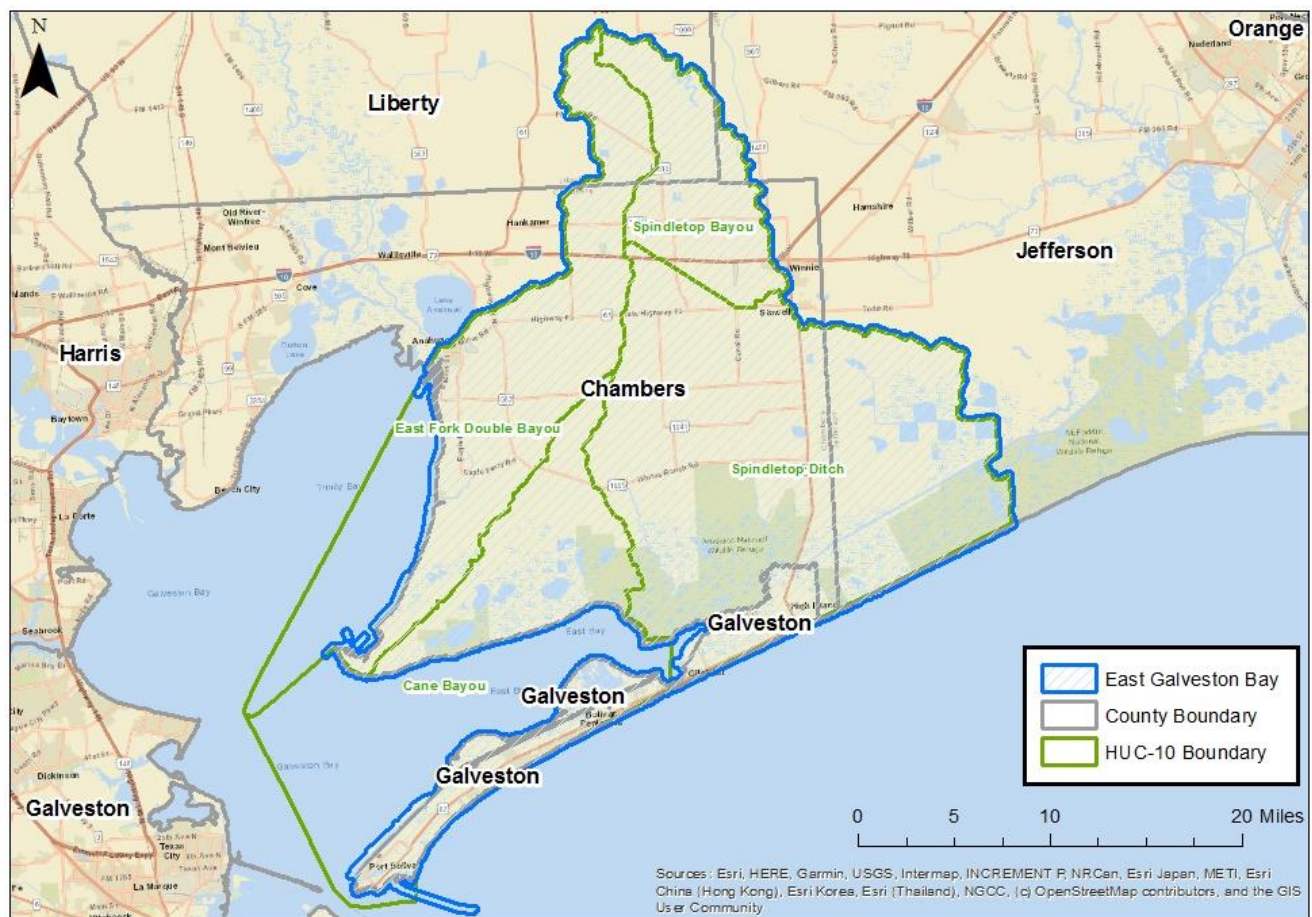


Figure 1: East Galveston Bay Watershed

2. 2D BLE Modeling Inputs and Controls

Section 2 presents fundamental components required to execute a two-dimensional (2D) hydraulic engineering analysis for the East Galveston Bay Watershed. Inputs such as elevation data, hydrology from rain-on-grid, and hydraulic analyses and variables are defined herein. HEC-RAS 5.0.7 rain-on-grid utility was applied in the production of the 2D BLE products produced for this watershed.

2.1 Topographic Data

A high resolution Digital Elevation Model (DEM) is a fundamental component for two-dimensional engineering analyses by providing a detailed representation of the surface for hydraulic routing through the model area. As such, DEMs were developed for the East Galveston Bay BLE project by leveraging available high resolution gridded elevation data derived from Light Detection and Ranging (LiDAR) collections throughout the States of Texas. The 10-

foot DEM developed to support the 2D BLE modeling and analysis, within the East Galveston Bay Watershed, was executed using the following steps:

1. Available elevation data for the project area were inventoried and collected.
2. Leveraged elevation data were evaluated and prioritized based on source vertical accuracy, year of collection, and resolution.
3. Seamless DEMs were processed using GIS.
4. Quality was assured using quantitative and qualitative assessment.

Documentation regarding leveraged data including coverage, accuracy, acquisition dates, and source contact/agency are presented in the figures, tables and text within Section 2.1.2. All vertical accuracy specifications were obtained from the metadata or survey reports provided with the leverage datasets. All available metadata, survey reports, and other leverage documentation are included in the FEMA Data Capture Technical Reference compliant submittal content for the East Galveston Bay Watershed.

2.1.1 Inventory

An inventory of existing topographic data was conducted for the East Galveston Bay BLE watershed footprint. Figure 2 depicts the datasets identified and leveraged across the project area. FEMA, National Oceanic and Atmospheric Administration (NOAA), United States Geological Survey (USGS), and other State and Federal agencies were queried to build the inventory with the most current and available data sources.

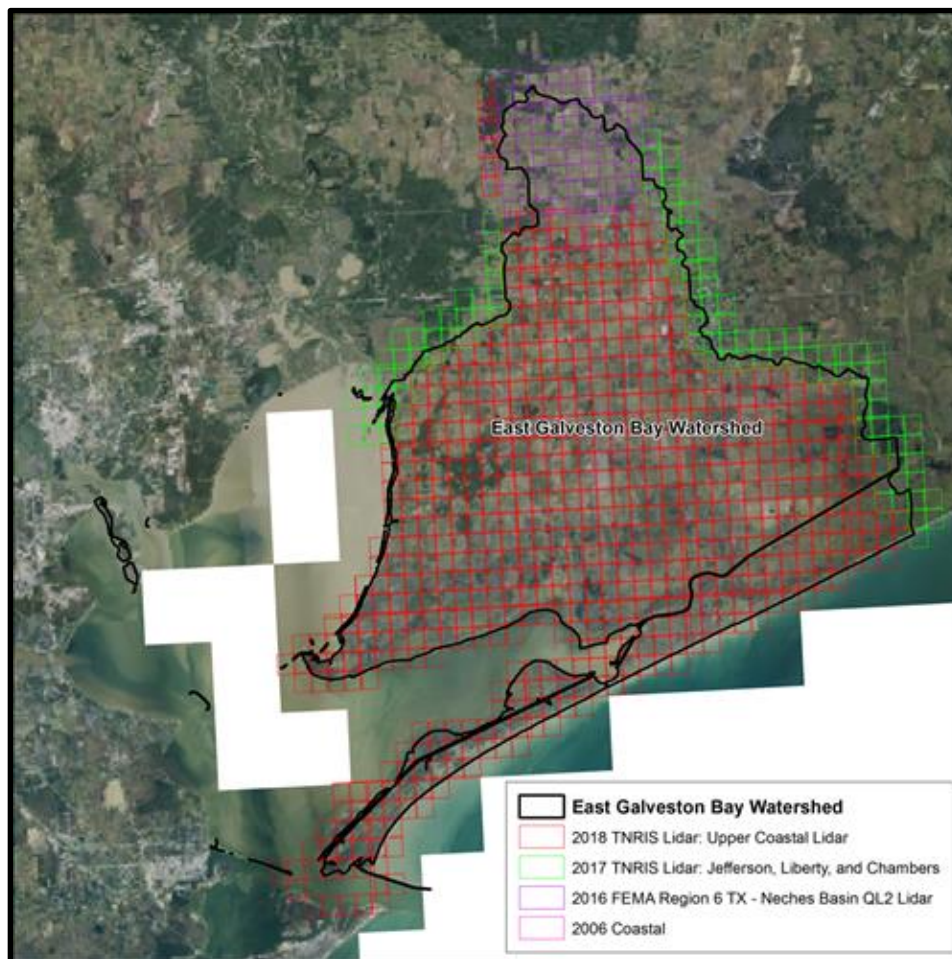


Figure 2: East Galveston Bay Watershed BLE Source Terrain Data

2.1.2 Evaluation

A data coverage assessment was conducted to check for data gaps, extent, accuracy, and completeness. A review of related documentation, reports, indexes, and metadata associated with the leveraged datasets ensured each dataset meets FEMA accuracy requirements for topographic data. Decisions to leverage or exclude a dataset (or portion of it), were based generally on the following criteria coupled with engineering judgment:

- Data meet FEMA vertical accuracy standards (Table 1)
- Date of origination
- Data density and coverage

Table 1 depicts the Risk MAP SID #43 vertical accuracy requirements based on flood risk and terrain slope within the floodplain being mapped.

Table 1: FEMA Vertical Accuracy Requirements for Leveraged Data

Level of Flood Risk	Typical Slopes	Specification Level	Vertical Accuracy*	LiDAR Nominal Pulse Spacing (NPS)
High (Deciles 1,2,3)	Flattest	Highest	24.5 cm / 36.3 cm	≤ 2 meters
High (Deciles 1,2,3)	Rolling or Hilly	High	49.0 cm / 72.6 cm	≤ 2 meters
High (Deciles 2,3,4,5)	Hilly	Medium	98.0 cm / 145 cm	≤ 3.5 meters
Medium (Deciles 3,4,5,6,7)	Flattest	High	49.0 cm / 72.6 cm	≤ 2 meters
Medium (Deciles 3,4,5,6,7)	Rolling	Medium	98.0 cm / 145 cm	≤ 3.5 meters
Medium (Deciles 3,4,5,6,7)	Hilly	Low	147 cm / 218 cm	≤ 5 meters
Low (Deciles 7,8,9,10)	All	Low	147 cm / 218 cm	≤ 5 meters

*Vertical Accuracy at 95% Confidence Level (FVA or NVA)/(CVA or VVA)

Table 2 depicts the complete list of source elevation data and attributes leveraged for the East Galveston Bay Watershed. All datasets used for hydraulic analyses and mapping meet the highest specification level defined in Table 1. The following datasets were evaluated and prioritized as best available:

Table 2: LiDAR Topographic Data Available for the East Galveston Bay Watershed

Year	Description	Source/Owner	Accuracy ¹	Approximate Footprint (Sq. Mi.) ²
2018	2018 TNRIS LiDAR: Upper Coastal LiDAR	TNRIS/TWDB	9.4 cm	653.9
2017	2017 TNRIS LiDAR: Jefferson, Liberty, and Chambers	TNRIS/TWDB	19.6 cm & 16.2 cm	109.7
2016	2016 FEMA Region 6 TX – Neches Basin QL2 LiDAR	FEMA/USGS	15.6 cm	66.1
2006	2006 Texas Water Development Board (TWDB) Coastal LiDAR	FEMA/TWDB	14.03 cm	2.3

¹RMSEz reported at the 95% confidence level

²Size of LiDAR DEM footprint utilized for BLE study

2.1.2.1 East Galveston Bay Watershed Source Terrain Data

The source elevation data for the East Galveston Bay Watershed are DEMs derived from the 2018 TNRIS Upper Coastal LiDAR; the 2017 TNRIS Jefferson, Liberty, and Chambers LiDAR; the 2016 FEMA Region 6 Neches Basin QL2 LiDAR; and the 2006 TWDB Coastal LiDAR. Only points classified as “ground” points (i.e., bare earth) were imported from the LiDAR and used for development of the project DEMs. Bare-earth LiDAR data are typically made by filtering non-ground returns (e.g. buildings, vegetation, etc.) from the raw laser returns. Figure 2 depicts the extent of the data defined in Table 2.

2018 TNRIS LiDAR: Upper Coastal LiDAR

TWDB in cooperation with their project partners tasked Fugro Geospatial, Inc. (Fugro) under the Department of Information Resources (DIR) Geographic Information Systems (GIS) Hardware, Software and Services contract also known as the Texas Strategic Mapping (StratMap) Contract to acquire high resolution elevation data and associated products from airborne LiDAR systems during the 2017-2018 leaf-off season. The StratMap Program promotes inter-governmental collaboration and partnerships to purchase geospatial data products that provide cost savings and project efficiencies. Both the StratMap Program and the StratMap Contract are administered by TNRIS, a division of TWDB. Project partners include: H-GAC, Harris County Flood Control District (HCFCD), and the United States Geological Survey (USGS). This Coastal Texas project consists of approximately 9,758 DO4Q tiles and is located on the Texas Coast covering much of Orange to Matagorda County along with Harris County and the surrounding area. The project includes large metropolitan areas as well as coastal areas. The Urban and Coastal AOIs consist of approximately 4.045 square miles and were acquired between January 12 and March 22, 2018 utilizing both Riegl LMS-Q680i and Riegl LMS-Q780 sensors; collecting multiple return x, y, and z as well as intensity data. Specialized in-house and commercial software processes the native LiDAR data into 3-dimensional positions that can be imported into GIS software for visualization and further analysis. The horizontal datum for the data is the North American Datum of 1983 (NAD83, 2011) in meters and the vertical datum is the North American Vertical Datum of 1988 (NAVD88) in meters realized with GEOID12B. The RMSEz reported for the dataset was 9.4 cm at the 95% confidence level which meets project accuracy specifications of the NSSDA.

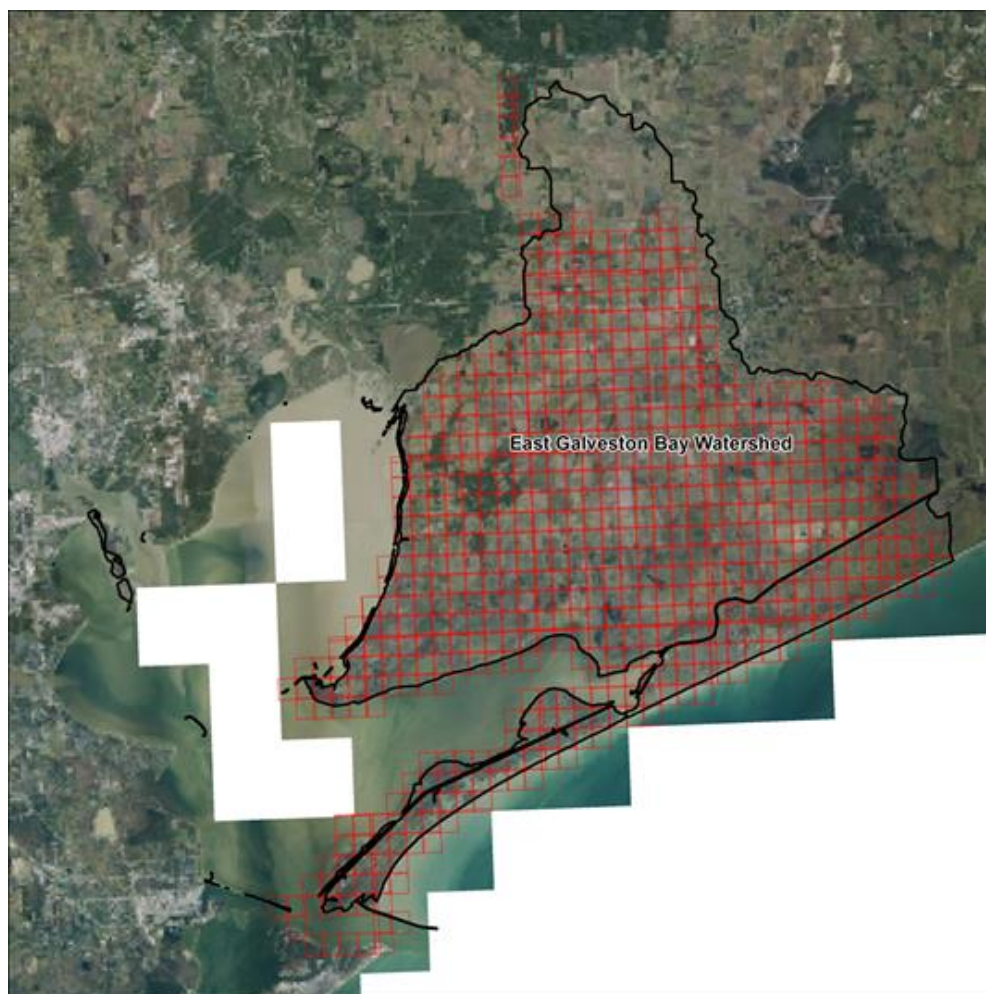


Figure 3: 2018 TNRIS LiDAR: Upper Coastal LiDAR

2017 TNRIS LiDAR: Jefferson, Liberty and Chambers

This StratMap LiDAR project covers portions of the north east Texas coast. Sanborn Map Company was contracted by Texas Water Development Board (TWDB) in cooperation with the Trinity River Authority (TRA) to perform LiDAR aerial surveys of Texas coastal areas of about 1140 square miles. Collection was completed utilizing multi-return systems LiDAR data in the form of 3-dimensional positions of a dense set of mass points between February 22nd and March 23rd, 2017. LiDAR acquired from this project will be used for floodplain management and planning, feature extraction, water quality modeling, stream restoration potential analysis, change detection, 9-1-1, wildfire mitigation, habitat identification/modeling for endangered species, and dam safety. The project area of interest covers areas where previous LiDAR acquisition did not meet USGS Quality level 2 data specifications. The project covers two AOI's, Eastern and Western. The RMSEz reported for the Eastern AOI dataset was 19.584 cm which meets project accuracy specifications of the NSSDA. The RMSEz reported for the Western AOI data was 16.16 cm at the 95% confidence level which meets project accuracy specification of the NSSDA.

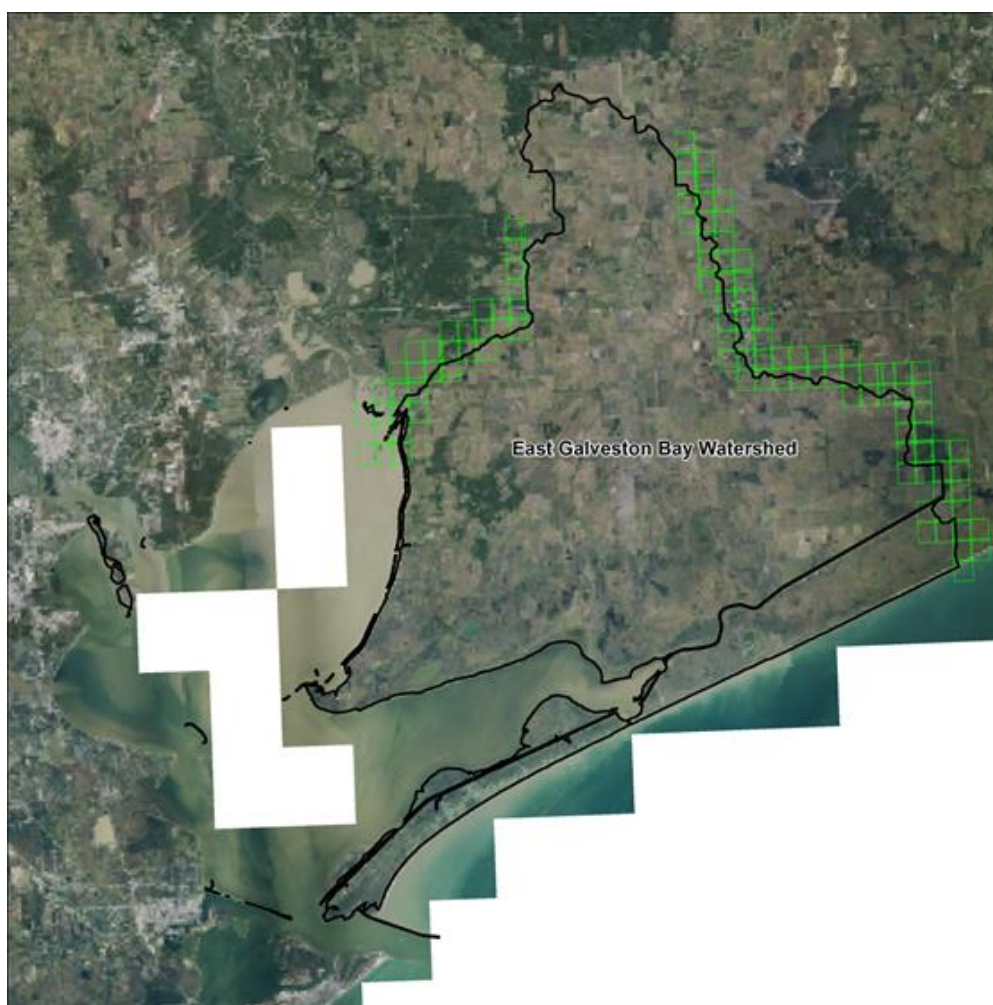


Figure 4: TNRIS LiDAR: Jefferson, Liberty and Chambers

2016 FEMA Region 6 TX – Neches Basin QL2 LiDAR

This USGS LiDAR project was conducted to capture the Neches river basin in East Texas. The project area falls within the Texas counties of Kaufman, Navarro, Freestone, Leon, Madison, Van Zandt, Henderson, Smith, Anderson, Cherokee, Rusk, Shelby, Nacogdoches, Houston, Trinity, Angelina, San Augustine, Sabine, Newton, Jasper, Tyler, Hardin, Polk, Liberty, Jefferson and Orange. Dewberry served as the prime contractor for the project. In addition to

project management, Dewberry was responsible for LAS classification, all LiDAR products, breakline production, DEM production, and quality assurance. Quantum Spatial, Inc (Quantum Spatial) and Precision Aerial Reconnaissance (PAR) completed LiDAR data acquisition and data calibration for the project area.

The date of the acquisition spanned two years. Collection in 2016 was flown March 3, 2016 through March 5, 2016. Collection in 2017 was flown January 25, 2017 through February 22, 2017. A reflight occurred on October 9, 2017. The purpose of this project was to produce high accuracy 3D elevation products for the region which previously did not have any LiDAR data.

The LiDAR data were processed and classified according to project specifications. Detailed breaklines and bare-earth DEMs were produced for the project area. Data was formatted according to tiles with each tile covering an area of 1500m by 1500m. The Texas Neches area of interest covers approximately 14,148 square miles and an additional 89 square miles of Texas Red River was added to the Texas Neches LiDAR project. A total of 16,796 tiles were produced for the project encompassing an area of approximately 14,237 sq. miles. The RMSEz reported for the dataset was 15.6 cm at the 95% confidence level which meets project accuracy specifications of the NSSDA.

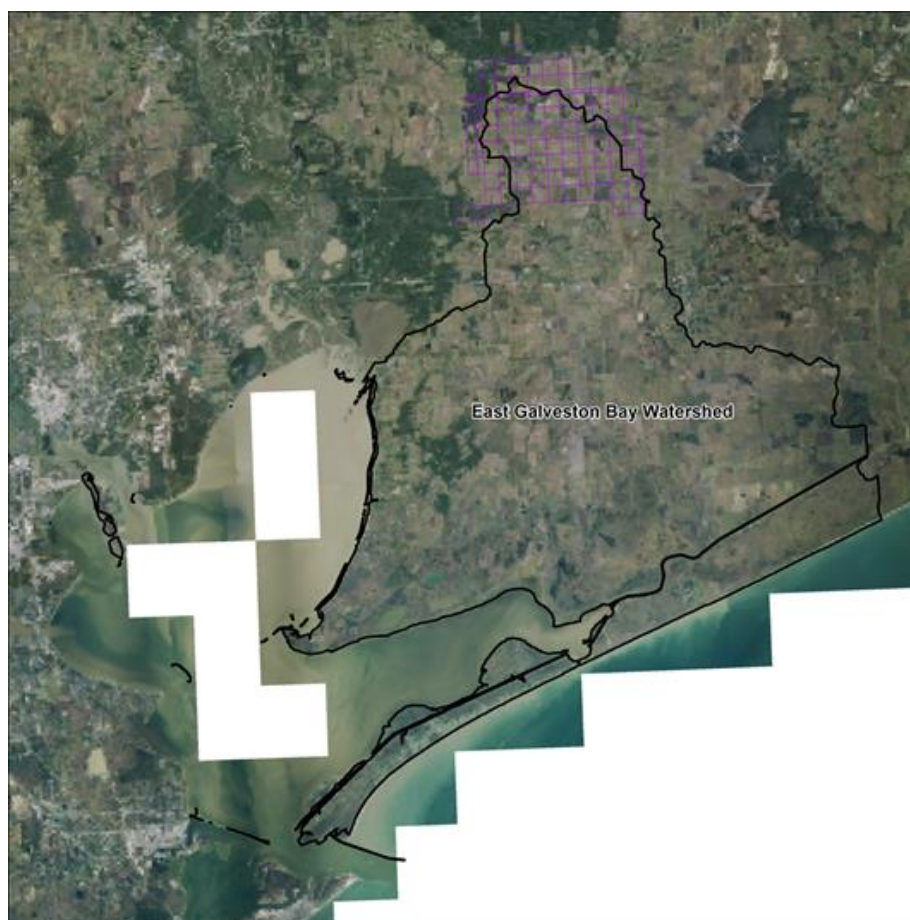


Figure 5: FEMA Region 6 TX - Neches Basin QL2 LiDAR

2006 Texas Water Development Board (TWDB) Coastal LiDAR

This LiDAR project is intended to provide high density elevation information of 13 coastal counties of Texas. It includes Bare Earth DEM (vegetation removal) and a high density set of mass points within the defined areas. The data sets are suitable for the development of contours for use in hydraulic/hydrologic model development and for assessing environmental impacts. Typical uses include FEMA Digital Flood Rate Insurance Map (DFIRM) updates, watershed boundary delineations, and other hydro studies per FEMA specifications. County mapping projects include several uses such as flood mitigation assessment and mapping projects that include accuracy verification, reporting,

and metadata. The RMSEz reported for the dataset was 14.03 cm at the 95% confidence level which meets project accuracy specifications of the NSSDA.

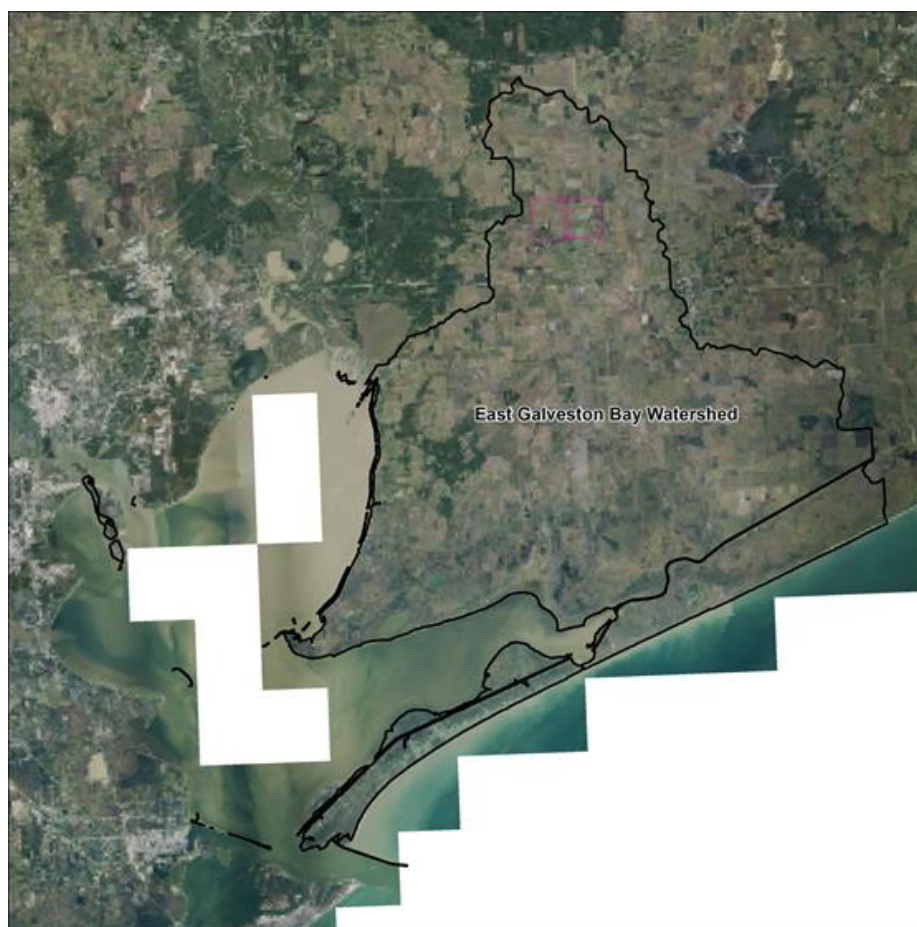


Figure 6: 2006 Texas Water Development Board (TWDB) Coastal LiDAR

2.1.3 Data Processing

ArcGIS software was utilized in order to create a digital surface model for the East Galveston HUC-8 Watershed project area. The LiDAR datasets were added to a mosaic dataset and prioritized by date with the most recent dataset taking the first priority. If two datasets are from the same year or flown at similar dates, the accuracy was reviewed to determine the priority. The mosaic dataset was exported to make a seamless bare earth DEM.

The exported DEM was reviewed through automated QC to check for anomalies and outlier locations based on slope and cells that exceed z value differences from surrounding cells. Visual review was also performed to check for ground differences at the extents of the datasets for differences in ground values. Where necessary, minor adjustments were made to represent a more accurate bare earth surface using aerial imagery. A shapefile with specific notes has been included for reference for modified locations.

2.1.4 DEM QA/QC

DEMs developed for use in the East Galveston Bay Watershed BLE analysis were developed and independently assured to meet quality standards of the project. The data were developed using a controlled process, were evaluated and assured by a topographic data development team, and were evaluated and assured by the engineering team. Quality assurance during the data development process includes, but is not limited to the following QC checks:

- Horizontal Projection Check
- Vertical Datum Check
- Resolution Check
- Format Check
- Seamless Data Check to ensure the DEM files are consistent and seamless along source data edges

The quality control after the development process by the DEM development team included visual observations using hillshade, contouring, color rendering, and/or other visual aids to review and identify potential impactful anomalies within the DEM surface. This QC step included, but were not limited to the following QC checks:

- Seamless Data Check to ensure no voids along the edges and between the prioritized datasets
- NoData Value Check to ensure no null values
- Manual Elevation Check using hillshade rasters to find erroneous elevation issues
- Unit Consistency Check
- Legacy Cell Value Anomalies

Quality assurance conducted after the seamless DEM development conducted by the engineering team included visual or automated assessments to identify potentially impactful anomalies or slope changes that may adversely impact hydraulic analysis.

The final DEM data developed for the East Galveston Bay Watershed is assured to meet FEMA standards and present a representative surface developed from leveraged elevation data for the purposes of this BLE project.

2.2 2D BLE Methods

HEC-RAS 5.0.7 (RAS5) rain-on-grid utility was applied in the Texas 2D Base Level Engineering (BLE) products workflow. The following sections describe the engineering methods and model inputs used.

2.2.1 2D Computational Mesh and Settings

The RAS5 2D computational mesh was created for the East Galveston Bay model area using ArcGIS toolsets, which reduce the need for manual edits to mesh cells within RAS5 that result in error generation. The model's 2D mesh contains 1,133,288 cells consisting of 200 foot cells, with the exception of 100 foot along the 1 square mile streams and 50 foot cells within community boundaries using refinement regions. Internal connections were used to extract flow readings for gage locations throughout the model, while profile lines were used for all other flow extractions. An adaptive 30-second time step was used to allow the model to lower the time step, as necessary, to keep the maximum courant number under 1 for the duration of the simulation. The time step was allowed to reach 60 seconds for a maximum and 0.94 seconds for the minimum. A theta value of 0.6 was used due to the models alignment with the coast. The RAS5 model was ran with Diffusion Wave (simplified Full Momentum) equations.

2.2.2 Model and Boundary Condition Setup

Using RAS5 rain-on-grid modeling requires a 2D computational mesh boundary and excess precipitation was applied to the 2D mesh as a precipitation boundary condition. The process to determine the excess precipitation to be applied is outlined in the hydrology section. The figure below depicts the East Galveston model boundaries.

Outflow boundary conditions (from the computational 2D mesh) were used along model boundaries without an inflow boundary condition. Unique outflow boundaries were established for obvious riverine outflows, while the remaining boundaries were defined as continuous boundaries to allow drainage to adjacent basins to leave the model area freely. Normal depth was used for all non-unique outflow boundary conditions using approximate energy grade-line slopes estimated from the LiDAR terrain data.

A stage hydrograph was used for boundary conditions along the coast. The water elevation was determined by the Mean Higher High Water (MHHW) of the nearby tide station. The tide stations referenced for these boundary conditions are Highland (8770808) and Rollover Pass (8770971). On the day it was accessed, the MHHW was 0.65 and 0.61, respectively. An average MHHW value of 0.63 was applied as a constant stage hydrograph in the RAS model.

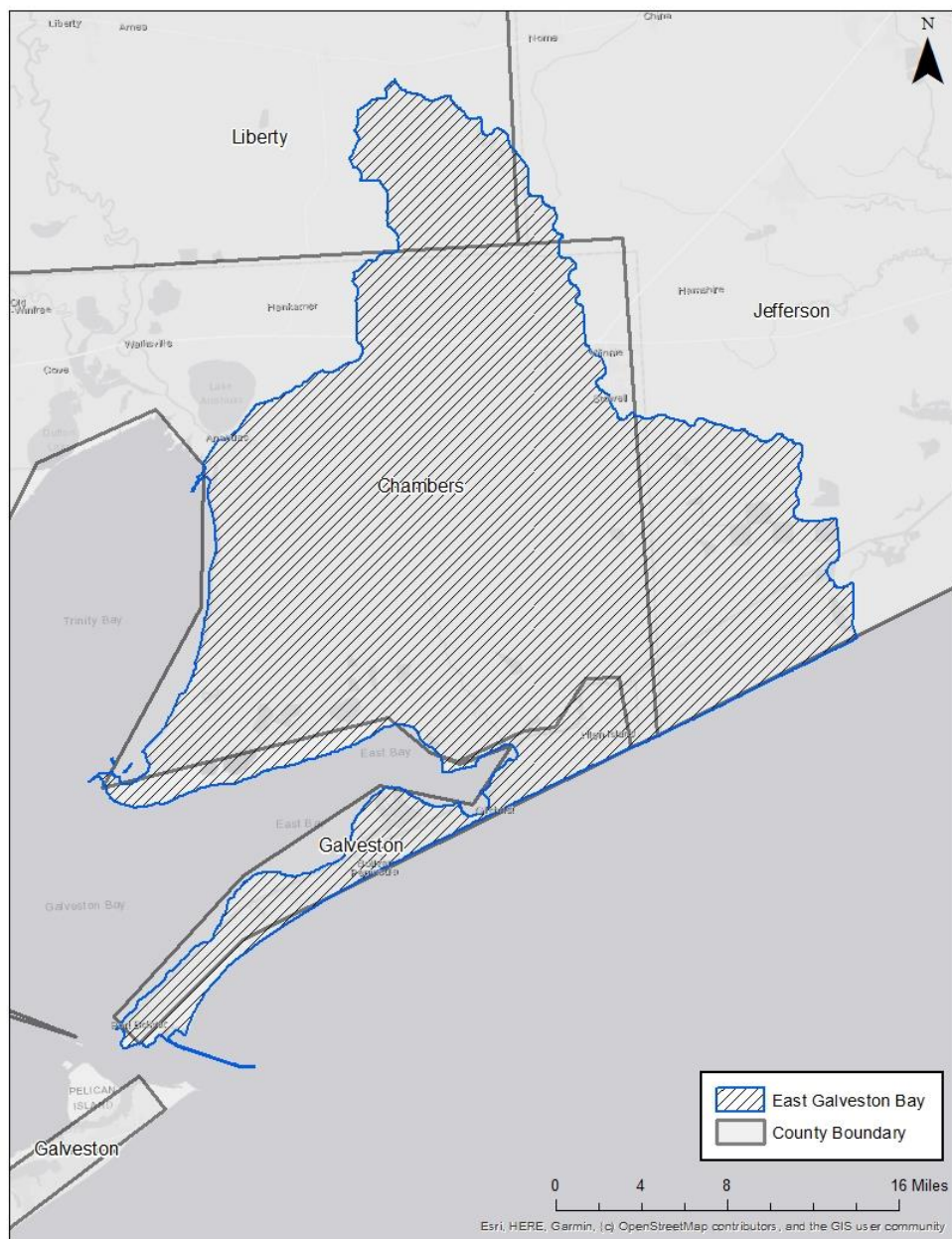


Figure 7: RAS5 2D Computational Mesh and Boundary Conditions

2.2.3 Hydrology

Precipitation frequency data (NOAA Atlas 14, 2018) was used for this study. These data were obtained from NOAA's Precipitation Frequency Data Server (PFDS) (<http://hdsc.nws.noaa.gov/hdsc/pfds/index.html>), and appropriate values for all sub-basin elements were determined considering spatial variation and a representative total for East Galveston Bay. Excess precipitation for the 2D mesh was developed as described in Section 2.2.3.1. Since USGS streamflow gage data were not available for East Galveston Bay HUC-8, effective data and regression analysis were used to calibrate the hydraulic results, as discussed in Section 3.1. The 10-, 4-, 2-, 1-, and 0.2-percent annual chance 24-hour precipitation depths for all sub-basin elements were determined by area-weighted intersection of gridded PFDS data with sub-basins.

2.2.3.1 Excess Precipitation for 2D Computational Mesh

HEC-HMS version 4.6 was used to apply the Soil Conservation Service (SCS) Curve Number method to calculate losses and define excess precipitation for this watershed. Temporal distributions of point rainfall totals were defined using 24-hour, frequency-based storm distributions. The plus and minus standard error for the 1% annual chance precipitation depths were determined as the upper and lower 84% confidence limits on the nominal 1% depth, assuming a normal distribution of the logarithms for the precipitation depths. A default areal reduction as per Technical Paper 40 (TP-40) was used in HEC-HMS on all recurrence interval total precipitation depths in order to determine the effective precipitation for the sub-basin representing 2D mesh.

In addition to recurrence interval precipitation estimates, NOAA Atlas 14 provides 90% confidence intervals of reported precipitation values. On a normal distribution curve, 90% confidence intervals (i.e. the upper and lower 95% confidence limits) correspond to ± 1.645 standard deviations. The 1% plus and minus events are defined to be one standard deviation above and below the 1% event.

Curve numbers were computed by intersecting the National Land Cover Dataset (NLCD) 2016 coverage and NRCS soils data based on the matrix presented in Table 3.

Table 3: Land Use-Soils-CN Matrix for Defining Initial Curve Number

LU_GridCode	NLCD LU Description	Hydrologic Soil Group			
		A	B	C	D
11	Open Water	99	99	99	99
21	Developed Open Space	49	69	79	84
22	Developed Low Intensity	61	75	83	87
23	Developed Medium Intensity	81	88	91	93
24	Developed High Intensity	89	92	94	95
31	Barren Land	39	61	74	80
41	Deciduous Forest	30	55	70	77
42	Evergreen Forest	30	55	70	77
43	Mixed Forest	30	55	70	77
52	Shrub Scrub	30	48	65	73
71	Herbaceous	49	62	74	85
81	Hay Pasture	39	61	74	84
82	Cultivated Crops	51	67	76	80
90	Woody Wetlands	72	80	87	93
95	Emergent Herbaceous Wetlands	72	80	87	93

A Curve Number (CN) can be considered a parameter, exhibiting variability that follows some frequency distribution. While Antecedent Runoff Condition (ARC) II CNs were used for a 1% event, the range between ARC I and ARC III for the ARC II CN was assumed to correspond to an 80% confidence interval of the ARC II CN. The CN loss method assumes a maximum potential retention parameter, S , is inversely related to a CN by $S = 1000 / CN - 10$; this relationship is based on a median value of S determined from plotting a large number of observations.

Chapter 5 of the NRCS National Engineering Handbook (NEH) Part 630 provides an example of computing a CN for a watershed based on annual peak gage observations. The example involves computing a CN and corresponding S value for each event, then taking the logarithms of the S values. Further, the logarithm of S is assumed to vary normally, and the mean of the logarithms corresponds to the arithmetic median. Therefore, 10% (S_{10}) and 90% (S_{90}) extremes of lognormally distributed S values can be assumed to correspond to ARC III and ARC I condition CN values, respectively. This range represents an 80% confidence interval, corresponding to ± 1.282 standard deviations from the mean. The following procedure was used to estimate one standard deviation of a given CN (in fact, one standard deviation of the logarithm of S) for the purposes of modeling 1% plus and minus events. First, ARC III (corresponding to S_{10}) and ARC I (corresponding to S_{90}) CN values can be estimated from a 1% CN (ARC II) by:

$$CNI = 4.2 * CNII / (10 - 0.058 * CNII)$$

$$CNIII = 23 * CNII / (10 + 0.13 * CNII)$$

Next, S_{90} and S_{10} can be computed by:

$$S_{10} = 1000 / CNIII - 10$$

$$S_{90} = 1000 / CNI - 10$$

The following relationship can then be used to compute one standard deviation of the logarithm of S :

$$\log(S_{10}) = \text{mean}(\log(S)) + 1.282 \text{ std. dev.}(\log(S))$$

$$\log(S_{90}) = \text{mean}(\log(S)) - 1.282 \text{ std. dev.}(\log(S))$$

$$1 \text{ std. dev.}(\log(S)) = (\log S_{10} - \log S_{90}) / 1.282$$

Therefore, 1% plus and minus S values can be estimated by:

$$\log S_{\text{Plus}} = \log S + [1 \text{ std. dev.}(\log S)]$$

$$\log S_{\text{Minus}} = \log S - [1 \text{ std. dev.}(\log S)]$$

Finally, 1% plus and minus CNs can be computed by:

$$CN_{\text{Plus}} = 1000 / (S_{\text{Plus}} + 10)$$

$$CN_{\text{Minus}} = 1000 / (S_{\text{Minus}} + 10)$$

Since the 1% plus and minus events represent plus and minus one standard deviation of a 1% event, CNs used in a rainfall-runoff simulation for modeling 1% plus and minus events were developed, as described above. A single basin was used in HEC-HMS for simulation to estimate excess precipitation.

The table below shows the curve numbers both initially computed and revised values based on reasonability check revisions.

Table 4: Rainfall-Runoff Curve Numbers

Sub-basin Description	Base CN	Calibrated CN	CN 1% Minus	CN 1% Plus
East Galveston Bay	87.0	87.0	78.08	92.70

NRCS rainfall-runoff methods were used to define excess precipitation applied to the 2D mesh, including curve numbers for defining rainfall losses for transforming the runoff temporally. No routing was considered in the rainfall-runoff modeling. Frequency-based storm with 50% storm centering were used for defining temporal distributions of point rainfall totals. Table 5 provides the precipitation totals applied to the model including areal reduction.

Table 5: Precipitation Totals estimated in HEC-HMS (post ARF)

Percent Annual Chance Precipitation Depths (in.)							
Sub-Basin Description	1%	0.2%	2%	4%	10%	1% Plus	1% Minus
Austin Oyster	16.47	25.03	13.56	11.19	8.44	20.04	12.90

Table 6 shows the excess precipitation totals determined from the HMS model. These values are a factor of the average curve number and precipitation depths for each model area. The CNs were modified during the calibration process and the excess precipitation depths were recalculated to install confidence in the final model results.

Table 6: Total Excess Precipitation Applied to 2D Mesh

Percent Annual Chance Excess Precipitation Depths (in.)							
Sub-Basin Description	1%	0.2%	2%	4%	10%	1% Plus	1% Minus
East Galveston Bay	14.80	23.32	11.92	9.58	6.88	19.12	10.06

Figure 8 shows the excess precipitation hyetograph used for East Galveston Bay. Curve Number and precipitation depth are the two factors used by the HMS model to determine the magnitude of the excess precipitation event. The excess precipitation hyetograph is calculated in 6-minute increments. All models in this study have excess hyetograph shapes that closely resemble, but with varying maximum excess precipitation values.

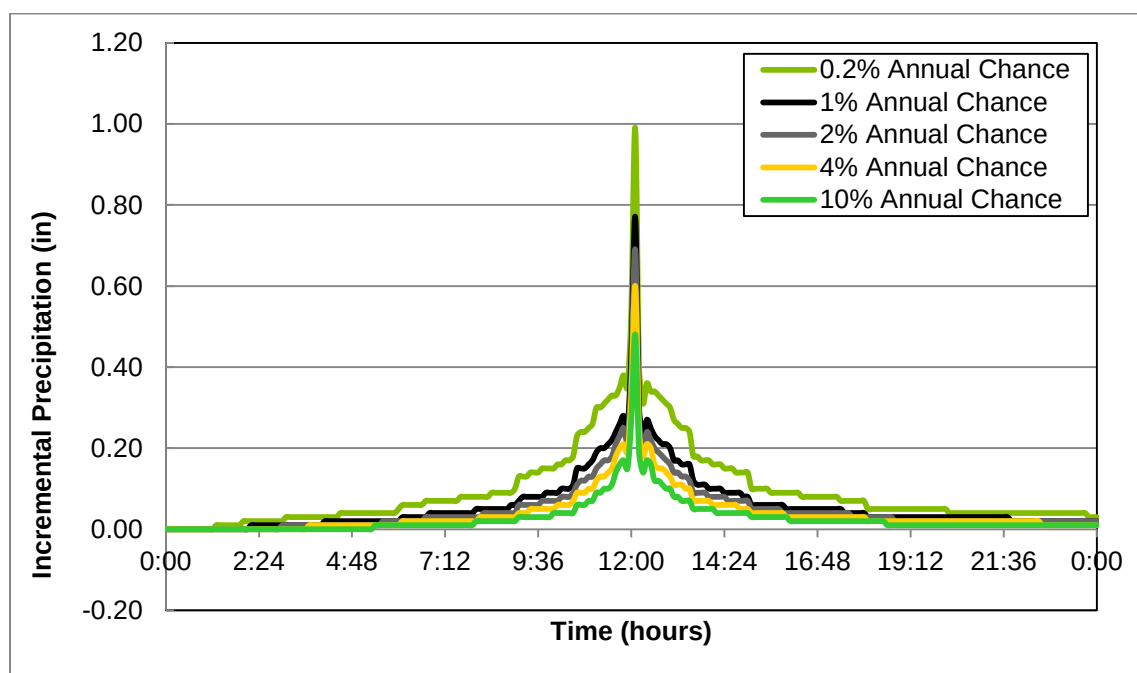


Figure 8: Excess Precipitation Hyetograph

2.2.4 Hydraulics

This section describes the remaining hydraulic modeling considerations, including implementation of Manning's roughness, breaklines, refinement regions, and hydraulic structures within the 2D computational mesh.

2.2.4.1 Roughness Coefficients

Manning's (n) roughness coverage was developed for the 2D computational mesh using typical roughness values for given NLCD land classifications. Two different sets of Manning's N values were used for areas within the channel and all other areas outside of the channels of the stream network. The channel layers were created using a 100-ft buffer. This allows for the model to accurately represent deep, swift flow within the channel and shallow overland flow outside of the channel areas. The table below shows a typical landuse-roughness matrix used in defining the roughness coverage for the study area for areas both inside and outside of the channel.

Table 7: NLCD 2016 Manning's N Roughness Matrix

NLCD Classification	Channel		Overbank	
	N Value	Source	N Value	Source
Open Water	0.03	Chow, 1959	0.03	Chow 1959
Developed, Open Space	0.035	Chow, 1959	0.04	NRCS KS Dam Breach Analysis, 2016
Developed, Low Intensity	0.035	Chow, 1959	0.08	NRCS KS Dam Breach Analysis, 2016
Developed, Medium Intensity	0.035	Chow, 1959	0.1	NRCS KS Dam Breach Analysis, 2016
Developed, High Intensity	0.035	Chow, 1959	0.15	NRCS KS Dam Breach Analysis, 2016
Barren Land	0.03	Chow, 1959	0.03	NRCS KS Dam Breach Analysis, 2016
Deciduous Forest	0.05	Chow, 1959	0.16	NRCS KS Dam Breach Analysis, 2016
Evergreen Forest	0.05	Chow, 1959	0.16	NRCS KS Dam Breach Analysis, 2016
Mixed Forest	0.05	Chow, 1959	0.15	NRCS KS Dam Breach Analysis, 2016
Scrub/Shrub	0.04	Chow, 1959	0.1	NRCS KS Dam Breach Analysis, 2016
Grassland/Herbaceous	0.04	Chow, 1959	0.15	HCFCF modeling Guidelines, 2018
Pasture/Hay	0.04	Chow, 1959	0.15	HCFCF modeling Guidelines, 2018
Cultivated Crops	0.04	Chow, 1959	0.1	HCFCF modeling Guidelines, 2018
Woody Wetlands	0.04	Chow, 1959	0.12	NRCS KS Dam Breach Analysis, 2016
Emergent Herbaceous Wetland	0.04	Chow, 1959	0.07	NRCS KS Dam Breach Analysis, 2016

2.2.4.2 Breaklines

Breaklines align grid cell faces and were used within the 2D mesh area to define prominent features including road embankments and hydraulic structures. Road embankment features were delineated in GIS and imported into RAS5 as breaklines to contain water where appropriate. Similarly, significant bridge/culvert crossings that were not processed out of the terrain data were modeled by v-notch breaklines adjacent to the road embankment to align grid cells around the embankment and allow water to be routed through the embankment without creating artificial backwater. An example of the v-notch breakline approach is shown in Figure 9.

County, interstate, common name, state recognized, and U.S. roads were incorporated for road breaklines from the U.S. Census Bureau TIGER/Line road layer.

As per 2018 National Inventory of Dams, no public owned dams were present in the HUC-8. Private dams were not modeled as showing protection. This is to lessen the burden on private dam owners to maintain their dams in order to sustain the regulatory products created as a result of this study.

Breaklines were also used along all the stream centerlines of streams draining greater than one square mile of drainage area. Each stream centerline was enforced with 100 foot cell spacing in order to align cells along the stream line and capture more detail along the one square mile stream network.

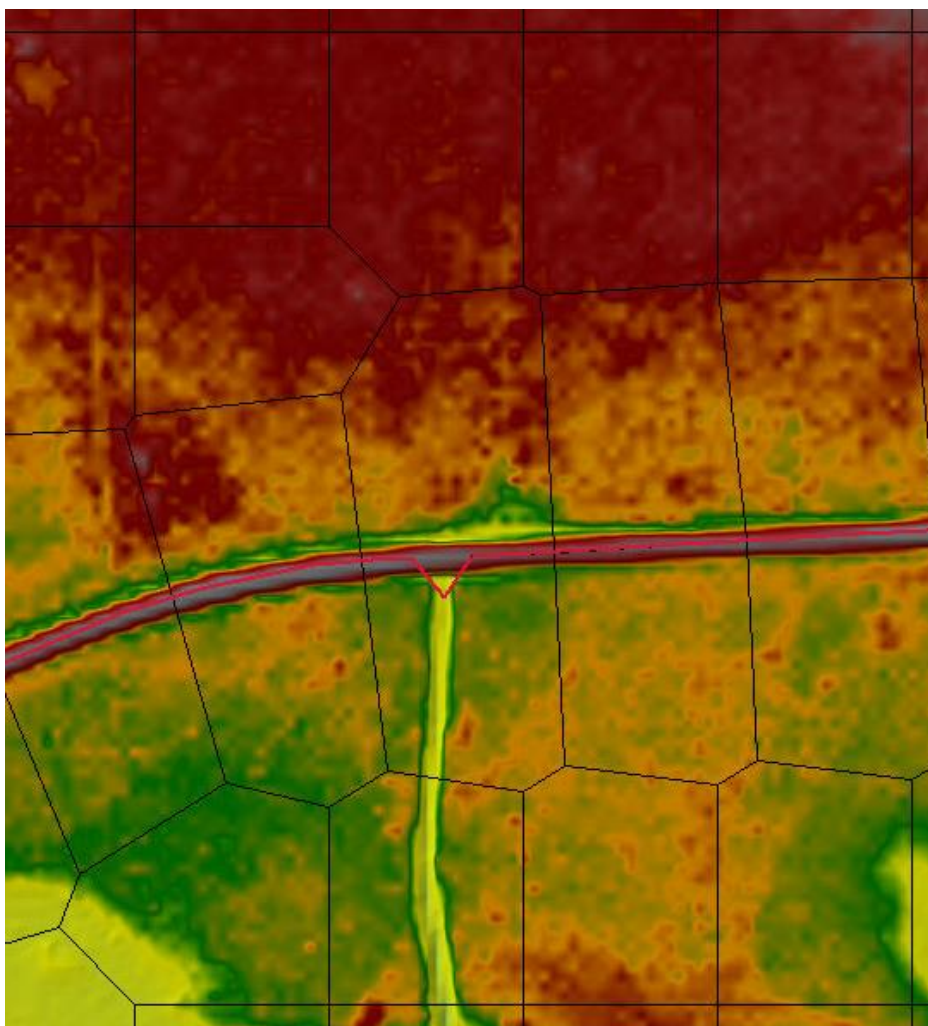


Figure 9: V-notch Breakline Approach at Bridge Crossing

2.2.4.3 Refinement Regions

Refinement regions were created for each community within the model. The political boundary was used to determine the shape of the refinement region. The regions were assigned a cell spacing of 50 feet by 50 feet. This finer cell spacing allows for more hydraulic calculations and mapping detail near areas where there are likely to be more structures. The table below shows the communities contained within East Galveston Bay watershed that were modeled with refinement regions as well as the square mileage of the refinement region.

Table 8: Communities with 2D Mesh Refinement

Community Name	Area (mi ²)
Anahuac city	2.12
Bolivar Peninsula CDP	48.14
Stowell CDP	7.45
Winnie CDP	1.44
Oak Island CDP	1.20

2.2.5 Quality Control

The results of 2D BLE results were independently assured to meet quality standards of the project. Standard checklists complying with FEMA standards were used to review hydrology and hydraulics results, the resulting flood hazard area delineations and CNMS dataset. Quality assurance during the data development process includes, but is not limited to the following QC checks:

- Hydrological QC – included checks for curve number calculation, input precipitation, flood events, areal reduction factor and human error.
- Hydraulic QC – included checks for RAS geometry, breakline placement, v-notch placement to ensure water conveyance at crossings, refinement regions, roughness coefficients, boundary/initial conditions, timestep and mapping outputs
- Mapping – included checks for spot checking flood inundation accuracies based on floodplain mapping criteria described in section 4.1.2, ensuring flood extents from higher frequency events did not exceed lower frequency extents due to GIS smoothing algorithms, and topological overlap and cluster tolerance errors were resolved
- CNMS - Included review of the A1-A5 analysis for all effective approximate reaches in the HUC, geometry updates to newly studied reaches added as Zone X, and removal of scoped areas which lie outside of the final BLE footprint.

3. Results

The 2D BLE results for the study produced flood hazard area that compared reasonably well with effective special flood hazard area (SFHA) in most cases, and provides additional estimated flood hazard risk area where not previously mapped. The HEC-RAS peak (max) results were exported for mapping and the HEC-RAS model was run with a hydrograph output interval of 30 minutes, mapping output interval of 1 hour and the detailed output interval of 1 hour. The East Galveston Bay Watershed is sufficient to facilitate FEMA regulatory processes while also providing the best available information for planning purposes. The 2D BLE results should be verified through community work map meetings as part of the regulatory workflow.

Table 9: Effective and Model BFE Comparison

Location Description	Effective BFE (feet)	Model BFE (feet)	Difference (feet)
East Fork Double Bayou-I-10	62.0	62.7	-0.7
Spindletop at Highway 124	63.5	64.5	-1

Table 9 continued: Effective and Model BFE Comparison

Location Description	Effective BFE (feet)	Model BFE (feet)	Difference (feet)
Oyster Bayou-Lone Star Canal	58.9	58.4	0.5
Confluence of East/West Fork	63.7	62.5	1.2

3.1 Calibration

Effective data was used for calibration of 1% annual chance event as no USGS streamgages were found in the HUC-8. Modeled flows were compared to flows from the summary of discharges table from the Chambers County Flood Insurance Study. Known water surface elevations were used for validation of the model results. Upper and lower limits for the effective flows were estimated manually by:

$$\text{Upper Limit} = 0.501 * 1\%Q$$

$$\text{Lower Limit} = 1.995 * 1\%Q$$

As a second priority, regression discharge estimates were utilized in different locations throughout the county to ensure accurate results. The regression analysis was performed as per regional regression equations using the drainage area, dimensionless main channel slope (S), OmegaEM parameter and mean annual precipitation (P) (USGS- SIR 2009-5087). Regression comparisons were made at three locations with varying contributing drainage area to ensure a reasonable amount of excess precipitation was being applied to the 2D mesh. Adjustments to curve number and hydraulic features within the model were made until the flows in the model matched closely with the peak flows determined from effective data and regression equations. Final results following model calibration at the calibration locations are presented in Table 10.

Table 10: Calibration Results

Calibration Location	Source	Method Used in Original Study	Reference			HEC-RAS 5.0.7 (2D)
			Lower Limit	1%	Upper Limit	
East Fork Double Bayou-I-10	Chambers County FIS	HEC-1	1,904	3,800	7,581	3,008
Spindletop at Highway 124	Chambers County FIS	HEC-1	3,707	7,400	14,763	4,619
Oyster Bayou-Lone Star Canal	Chambers County FIS	HEC-1	847	1,690	3,372	1,972
Confluence East/West Fork	Chambers County FIS	HEC-1	3,607	7,200	14,364	5,833
Spindletop Bayou	Regression	USGS- SIR 2009-5087	2,593	5,173	10,322	2,615
Cane Bayou Trib	Regression	USGS- SIR 2009-5087	410	817	1,631	839
East Fork Double Bayou	Regression	USGS- SIR 2009-5087	2,672	5,332	10,639	3,838

Figure 10 shows the final results of the calibration locations compared to modeled flows throughout the East Galveston Bay watershed along with error bars created using the difference between 1% and 1%+ discharges and 1% and 1%- discharge as minimum and maximum values. Seven comparisons were made with varying drainage areas to ensure the calibration of excess precipitation for different points over the entire watershed area. This calibration points provides confidence in results throughout the entire Watershed.

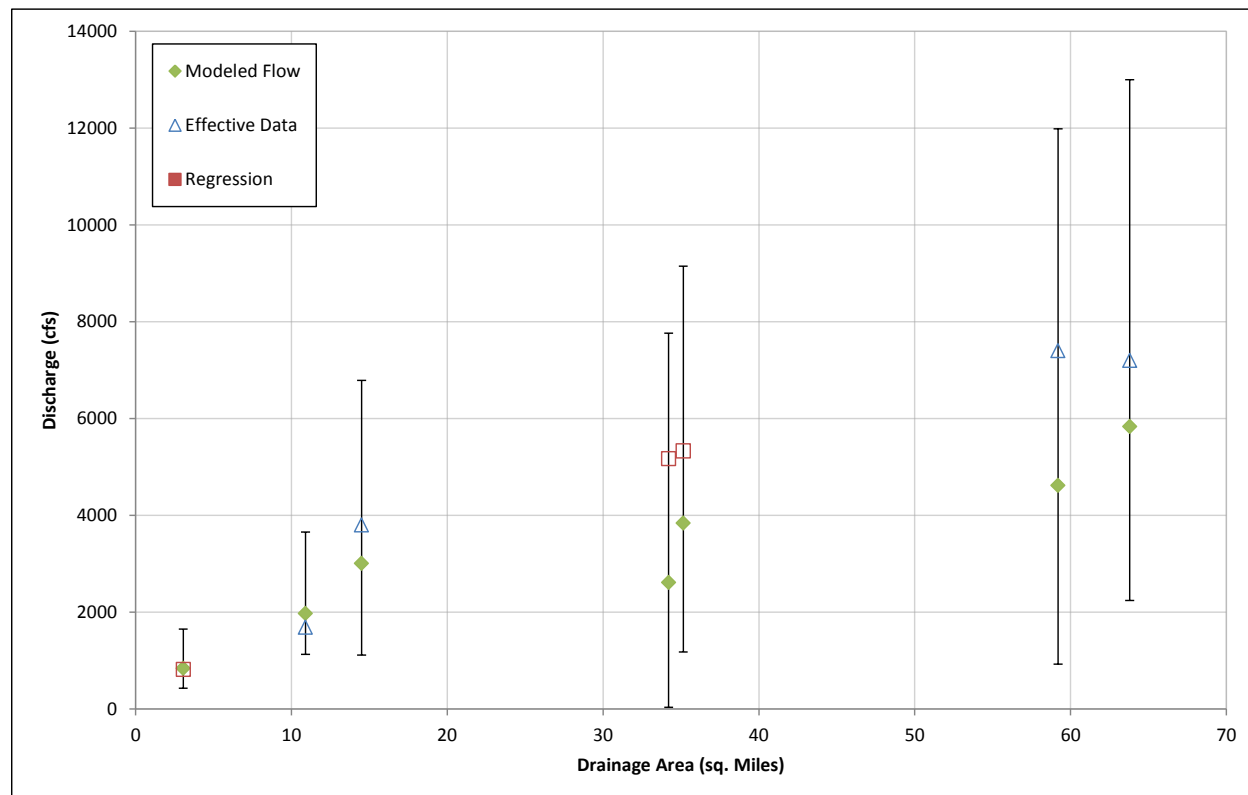


Figure 10: Calibration Comparison

3.2 Challenges

Major challenges included a lack of peak streamflow gage record and the proximity to the coast. However, East Galveston Bay modeling provide full confidence in the results. Within the watershed, there are several populated areas and agricultural fields that appear to be trapping water which prevents runoff from reaching the channel in the model. Various v-notches were applied to represent cross culverts and improve conveyance. Several breaklines and refinement regions increased the total number of cells and thereby increasing the model runtime.

The calibration of this model was also challenging due to the lack available data. There are no usable gages within the model area. However, regression equations were used in addition to the effective data to provide the model results.

3.3 Recommendations

The goal of modeling the 626 square mile area of the East Galveston HUC-8 is to make it as seamless as possible. For better modeling, the HUC-8 can further be divided into smaller modeling areas to act as one large model that encompasses the full watershed. This would eliminate the HEC-RAS limitations with lesser number of cells and optimal runtime. Due to the size of the HEC-RAS model, point source Atlas 14 rainfall data was used. For detailed modeling and further improvements smaller sized model is recommended which will have less rainfall, soils and land use variability. The hydraulic model can further be improved by using a smaller cell size than 200 ft along with adding structural and survey data for each crossing to represent storm water systems.

This study provides significant information useful for flood identification and communication among those affected. The study is highly scalable, and stakeholder input and further analysis would enhance the product and inform implementation of regulatory flood hazard areas. In addition, the validity of the 2D BLE results should be verified through community work map meetings before being applied as a regulatory product.

4. Floodplain Mapping and Effective Zone A Validation

The following sections provide a synopsis of how raw modeled depths were translated into Special Flood Hazard Areas (SFHA). In addition to developing a new SFHA, the BLE model data was leveraged to validate the effective Zone A studies within the project footprint.

4.1 Special Flood Hazard Area

4.1.1 Model Outputs

The HEC acknowledged RAS Mapper may not render water surface elevation values and/or delineate inundation extent appropriately for direct use in FEMA regulatory mapping products. With guidance from TWDB, AECOM created a workflow to export model water surface elevation values for each 2D mesh cell to develop regulatory-ready water surface elevation grids and subsequent flood hazard area mapping features.

4.1.2 Methodology

Maximum water surface elevation values were exported for each model's two-dimensional computational mesh cell centroid. Densified points were added to the cell centroid points along the edges of the floodplain in the water surface elevation rasters (exported from the model in sloping render mode) and areas of zero slope (ponds) from the terrain DEM to help meet FEMA regulatory mapping product requirements. A triangular irregular network (TIN) was created from the points, and water surface elevation and depth grids were created from the TIN to match the resolution of the input terrain DEM.

Discussion with AECOM, Halff Associates and TWDB determined that floodplain outputs in coastal areas should reduce the overall inundation using statistical analysis of flood hazard depths and areas. For the East Galveston watershed, the following parameters were applied to remove or reduce floodplain inundation:

- Removal of all depths below 1/3rd of a foot across the watershed
- Removal of all polygons smaller than 10,890 square feet, regardless of depth
- Removal of polygons between 10,890 and 21,780 square feet, with an average depth between 1/3rd and 1/2 foot.

The final polygons were smoothed and simplified in order to meet FEMA regulatory mapping specifications. Small islands less than 13,068 sq ft in the polygons were filled in.

Minor adjustments were made to the floodplain boundaries along open water rivers, ponds and other waterways to ensure floodplain connectivity in situations where floodplain areas were removed based on the parameters mentioned above. Minor tributaries or roadside ditches that aren't fully inundated were not adjusted. The watershed does contain open water detention ponds that are elevated compared to surrounding areas. These ponds have not been included in the floodplain boundaries in situations that the sloping model raster did not show inundation.

Mapping for the 0.2% annual chance was mapped in a similar manner as mentioned above in regard to removal of depths and areas. Due to methodologies and tolerances applied in the ArcGIS smoothing tool, minor differences between 1% and 0.2% boundaries where the extent of the 1% boundary would exceed the 0.2% have been resolved by copying the 1% boundaries into the 0.2% boundaries and merging the boundaries together.

Mapping for the 10% annual chance was mapped as well in a similar manner in regard to removal of depths and areas. No adjustments were made beyond the removal of very minor differences that could result from the smoothing methodologies and tolerances as mentioned previously. In locations that the 10% boundary exceeded the 1% boundary, those areas have been removed.

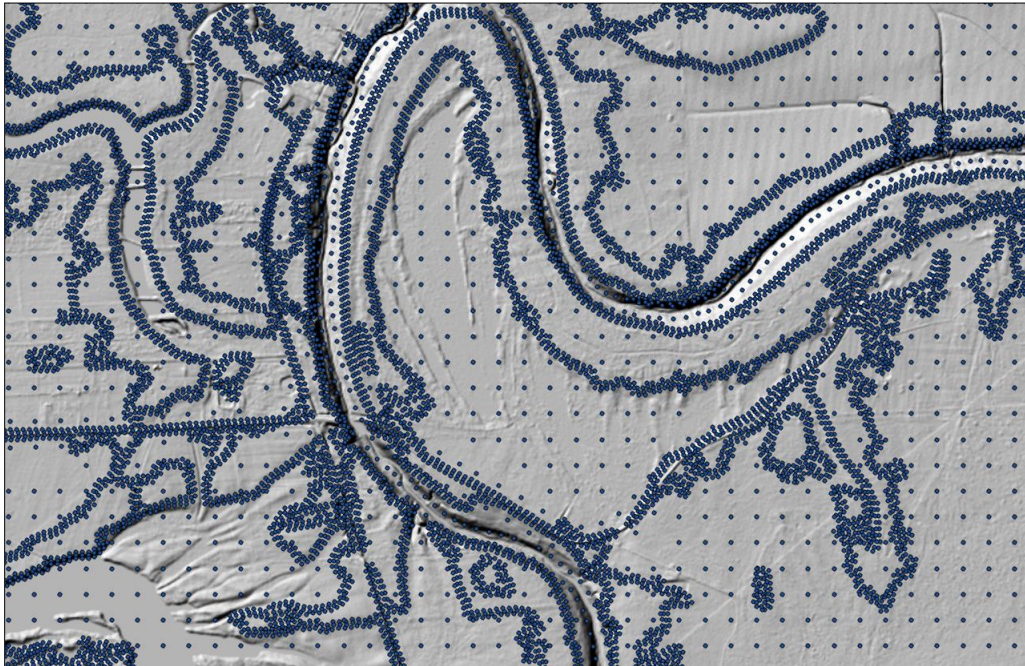


Figure 11: 2D BLE Model Points for Mapping Workflow

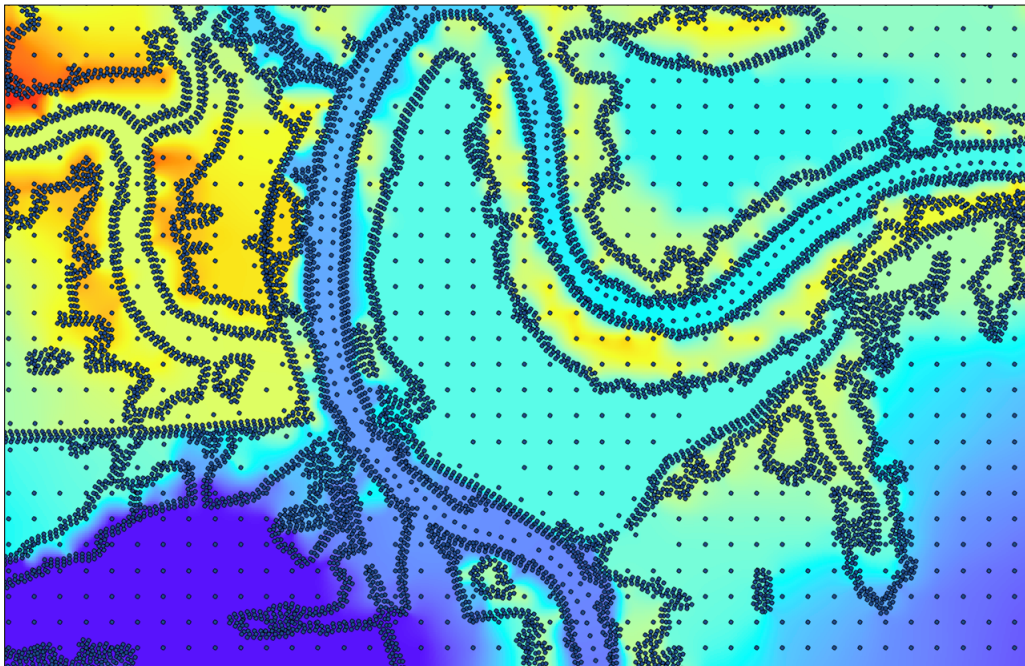


Figure 12: 2D BLE Model Points to Water Surface Elevation TIN

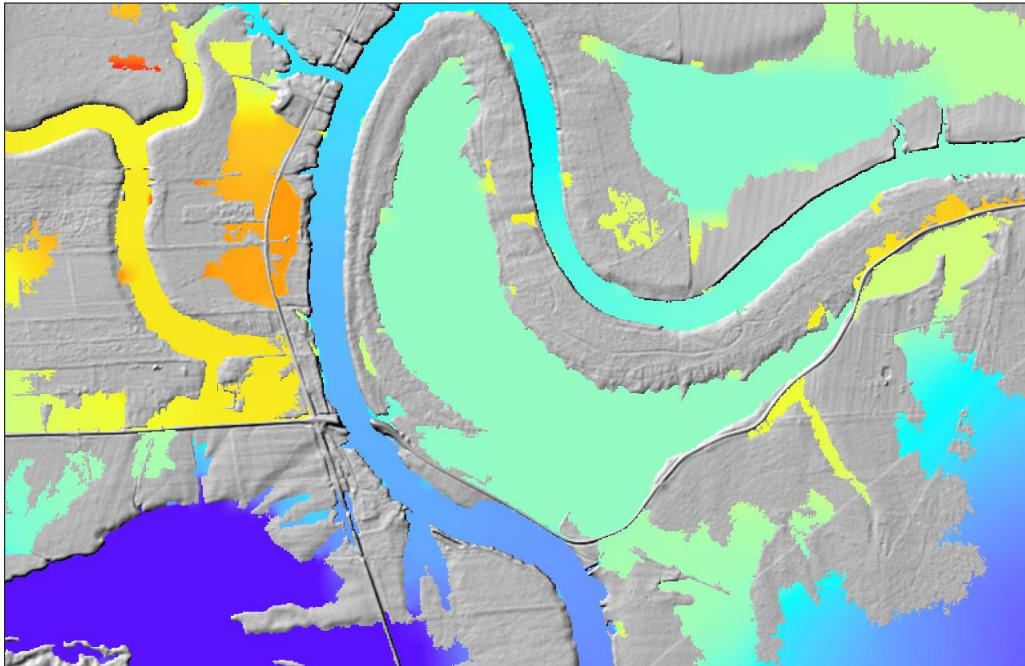


Figure 13: Water Surface Elevation TIN to Grid

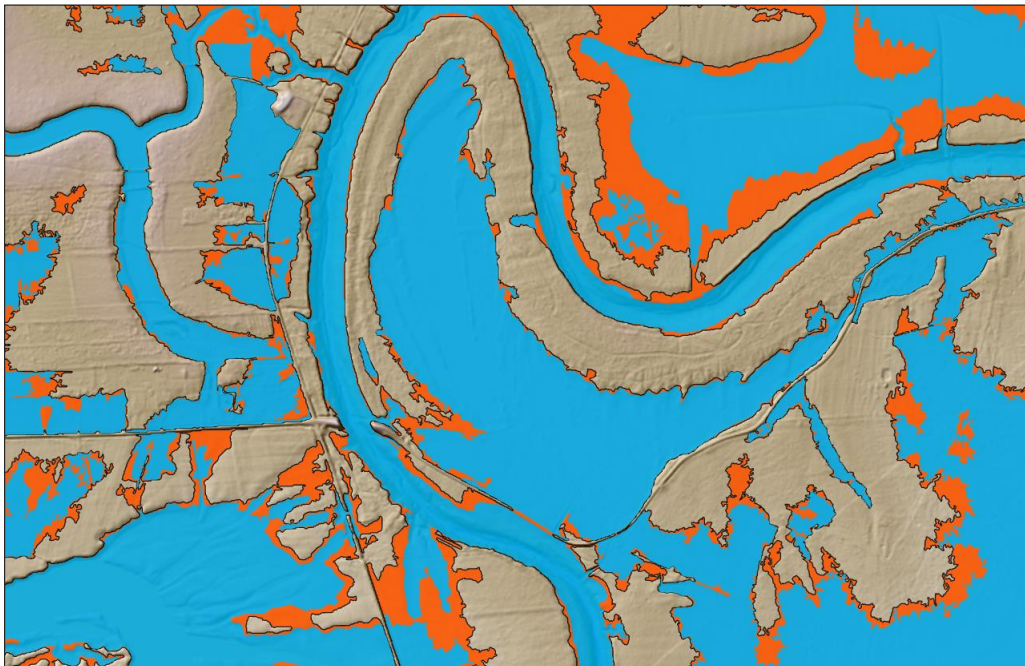


Figure 14: Water Surface Elevation Grid to Mapping Products

4.1.3 BLE Flood Hazard Layer

BLE database format FLD_HAZ_AR feature classes were developed and attributed with Zone A and Shaded Zone X features. The BLE FLD_HAZ_AR feature class was tested for topological errors described in the FIRM Database Technical Reference and all errors were fixed for data integrity and schema agreement. The 10% boundaries have been included in the BLE TENPCT_FP feature class.

4.1.4 Additional 1-Percent Features

The BLE results for this study produced a SFHA that compares favorably with the effective SFHA. These boundaries provide an estimated SFHA in areas that have not been previously studied and therefore do not currently have an SFHA mapped. These results provide context for flood risk communication as part of the Discovery process, and should be verified through community work map meetings before being applied to a regulatory product.

A map showing the BLE results is included as Appendix A BLE Map.

BLE 1% annual chance inundation not mapped as BLE SFHA is retained in an additional 1% feature class that can be used at Discovery to communicate other areas of flood hazard.

4.2 Validation of Effective Zone A SFHA

The inventory of Zone A studies (111.2 miles) in the East Galveston Bay Watershed were classified in CNMS with validation status of “UNVERIFIED” (110.1 miles) or “VALID” (1.1 miles), and with status type of “BEING STUDIED.” The following is a summary of the results of the CNMS validation assessment for the effective Zone A studies in the study area. Initial Assessment checks A1-A3 were evaluated for the CNMS inventory of Zone A studies.

4.2.1 Initial Assessment A1 – Significant Topography Update Check

This check involves determining whether a topographic data source is available that is significantly better than what was used for the effective Zone A modeling and mapping. For the study area in the East Galveston Bay Watershed, all effective zone A studies utilized USGS topographic maps. There is now LiDAR available for the entire watershed. Therefore, all reaches fail this check.

4.2.2 Initial Assessment A2 – Check for Significant Hydrology Changes

This check involves first determining if regression equations were used for the effective study. Next, it must be determined whether new regression equations have become available from the USGS since the date of the effective Zone A study. If newer regression equations exist for the area of interest, then an engineer must determine whether these regression equations would significantly affect the 1-percent annual chance flow.

Methods of the effective hydrological studies are unknown for all effective Zone A studies in this watershed and, therefore, all effective zone A studies in this watershed pass this check.

4.2.3 Initial Assessment A3 – Check for Significant Development

This check involves using the National Urban Change Indicator (NUCI) dataset to assess increased urbanization in the watershed of the Zone A study. If the percentage of urban area within the HUC-12 watershed containing the effective Zone A study is 15% or more, and has increased by 50% or more since the effective analysis, the study would fail this check. Although the NUCI data provide year-to-year changes in urbanization, the NLCD also is needed to establish a baseline of urban land cover for this analysis. The check for significant development in this watershed was completed by evaluating percentage of urban change at the HUC-12 level. The entire study area is still classified as rural. As a result, all reaches pass this check.

All of the initial assessment results are shown in Table 11.

Table 11: Zone A Initial Assessment Results

Assessment Check	Pass / Fail	Notes
A1 – Topography	Fail	LiDAR sources available are a significant improvement from effective topography
A2 – Hydrology	Pass	Regression equations not known to be used in effective study
A3 – Development	Pass	HUC-12 watershed does not meet urban threshold

4.2.4 Validation Check A4 – Check of Studies Backed by Technical Data

Zone A studies that pass all initial assessment checks described above may be categorized as “Valid” in the CNMS Inventory only if the effective Zone A study is supported by modeling or sound engineering judgment and all regulatory products are in agreement. If the effective Zone A study passes all initial assessment checks, but is not supported by modeling, or if the original engineering method used is unsupported or undocumented, a comparison of the BLE results and effective Zone A’s is performed. None of the effective studies are modeled-back within the East Galveston Bay HUC-8 and, therefore, fail this check.

4.2.5 CNMS Zone A Validation Check A5

The BLE /effective Zone A comparison method leverages the existing Floodplain Boundary Standard (FBS) certification procedures described in FEMA SID 113, but with a slight modification. This modified FBS comparison approach uses the 1-percent plus and 1-percent minus flood profiles and horizontal and vertical tolerances described in FEMA’s Automated Engineering guidance document dated May 2016. For the comparison of BLE and effective Zone A in the Texas study area, the following vertical and horizontal tolerances were used to conduct the modified FBS procedure. One point was placed every 200 feet along the floodplain boundaries for comparison.

- Vertical Tolerance: +/- 2.5 - 5 feet (one-half contour interval of effective topographic source).
- Horizontal Tolerance: +/- 75 feet (standard horizontal tolerance for BLE comparison testing).

Comparison results for these streams were grouped at the HUC-12 level and are summarized in Table 12 to better understand the general health of the HUC-12 watershed, but the validation check was performed at the stream level. Streams where the percentage of passing FBS sample points is greater than or equal to 85% are marked as “Pass”, otherwise marked as “Fail”.

Table 12: BLE Comparison Results

HUC-12 Watershed		Total FBS points	Fail	Pass	%Pass	BLE Comparison Pass? (>85%)	Priority Score
Watershed Name	Watershed Number						
East Galveston Watershed	All Streams	5,975	3,093	2,882	48%	FAIL	
Cane Bayou	120402050300	177	87	90	51%	FAIL	46.7
East Fork Double Bayou	120402050400	1,237	542	695	56%	FAIL	24.4
Spindletop Bayou	120402050200	3,287	1,742	1,545	47%	FAIL	34.4
Spindletop Ditch	120402050100	1,274	722	552	43%	FAIL	30.8

4.2.6 Validation Results

Based on the validation assessments and BLE comparison results described above, the CNMS inventory of Zone A studies in the East Galveston Watershed has been updated as summarized in Table 13 and illustrated in Figure 15 below.

Table 13: Zone A Validation Results

Validation Status	Status Type	Total Miles
VALID	BEING STUDIED	1.1
UNVERIFIED	BEING STUDIED	110.1

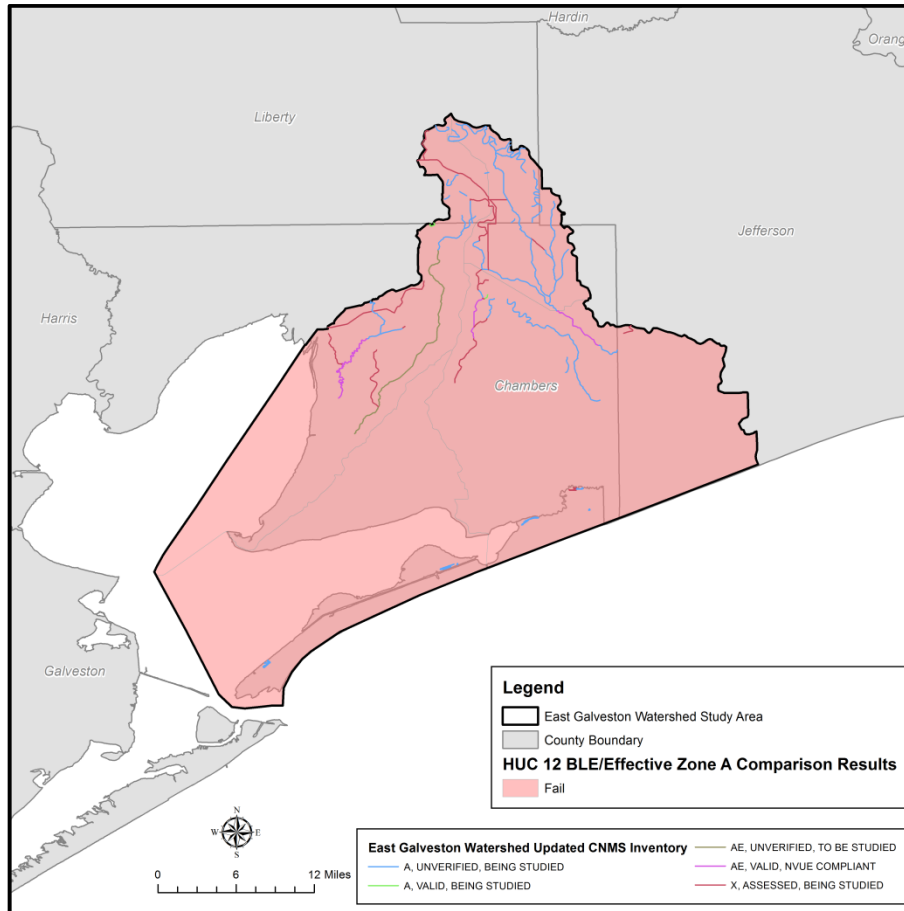


Figure 15: East Galveston Watershed CNMS Validation Results

An overall risk for each HUC-12 watershed was calculated using the National Flood Risk Percentages Dataset and its proportional area. The weighted risk was multiplied by the percentage of points in the watershed that failed the CNMS comparison to effective to determine the priority score. Figure 16 below shows the range of the HUC-12 priority scores which can be used to initiate discussions during the Discovery phase.

Cane Bayou HUC-12 was determined to have the highest priority score and the most need while East Fork Double Bayou HUC-12 had the lowest scores.

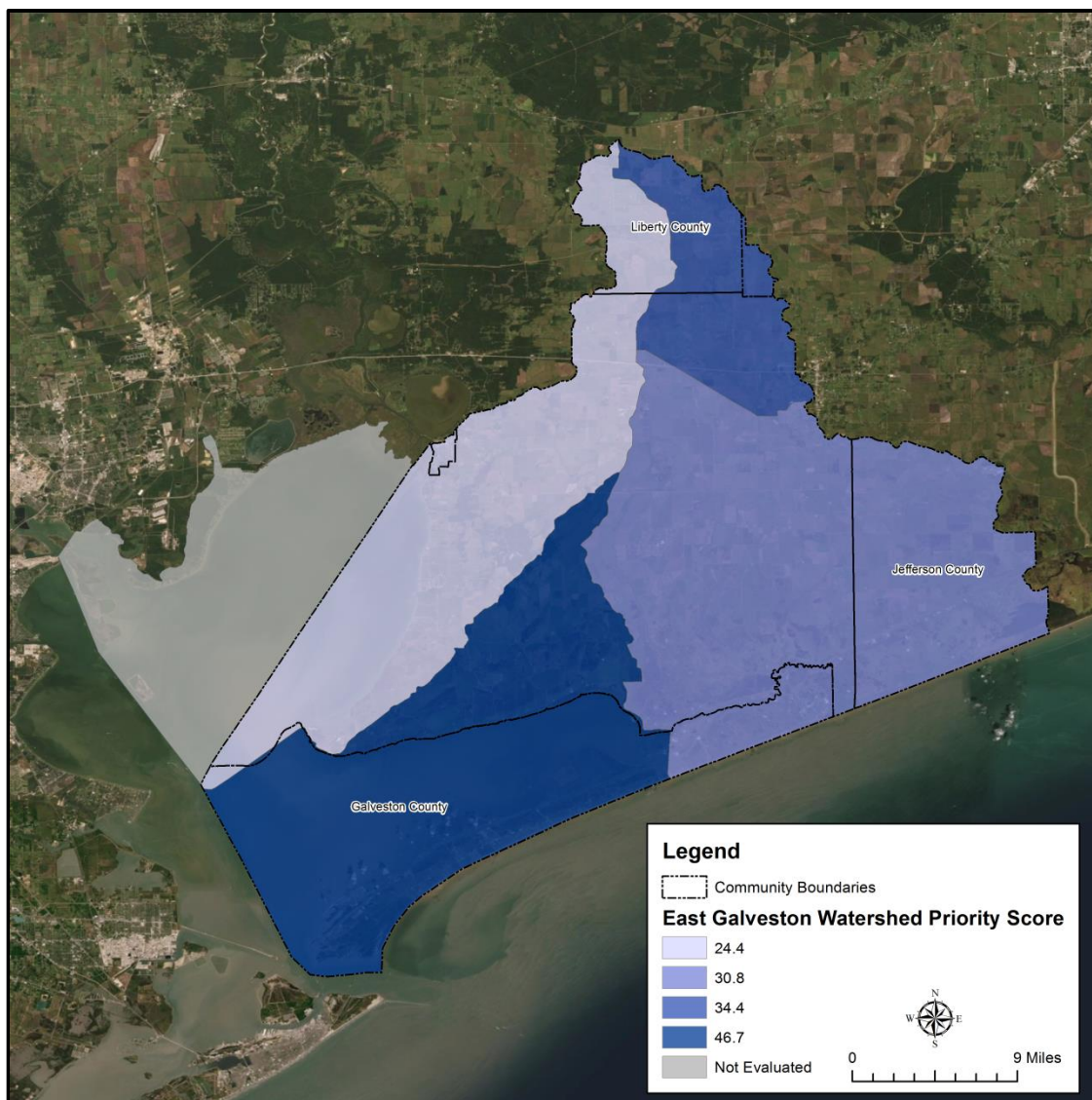


Figure 16: Ranking of East Galveston Watershed HUC-12s

4.3 Flood Risk Analysis

A flood risk analysis was performed for this project. The updated 1% annual chance and 0.2% annual chance depth grids were used to calculate the potential flood losses. The loss results are stored in the S_FRAC_AR spatial file within the FRD geodatabase. All results are reported in whole dollar values.

Hazus version 4.2 (SP03) was used for the basic and refined loss analysis.

The losses are reported via census blocks. It is important to note that Hazus version 4.2 (SP03) uses dasymetric census blocks. Dasymetric mapping removes undeveloped areas (such as areas covered by other bodies of water, wetlands, or forests) from the census blocks, changing their shape and reducing their size in these areas. For more information on dasymetric data visit FEMA's [Media Library](#) for the [Hazus-MH Data Inventories: Dasymetric vs. Homogenous](#), or [Hazus 3.0 Dasymetric Data Overview](#).

Hazus analysis was performed by county within the project watershed extents for each return period to ensure proper model processing. A summary of results for these counties for the 1-percent a.c.e. scenarios are shown in Table 14.

Table 14:: Hazus 4.2 (SP03) Results for 1-Percent-Annual-Chance (100 year) Scenario

County	Full Replacement – Total Loss	Dollar Exposure (Replacement Value) - Buildings	Dollar Exposure (Replacement Value) - Contents
Chambers	113,973,000	732,483,000	469,000,000
Galveston	47,107,000	527,306,000	299,290,000
Jefferson	226,000	9,537,000	5,162,000
Liberty	904,000	7,730,000	4,547,000

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Appendix A BLE Map

