East Fork San Jacinto Watershed, TX Base Level Engineering (BLE) Results

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Executive Summary

FEMA Region VI contracted Compass to complete a Base Level Engineering (BLE) analysis for the East Fork San Jacinto (EFSJ) HUC-8 Watershed in Southeast Texas, to support FEMA's Discovery process and validation of effective Zone A Special Flood Hazard Areas (SFHAs). The BLE process involves using best available data and incorporating automated techniques with traditional model development procedures to produce regulatory-quality flood hazard boundaries for the 1-percent annual chance event as well as estimates of flood hazard boundaries for multiple recurrence intervals.

The source digital terrain data used for surface model development in support of hydrologic and hydraulic analysis as well as mapping activities were leveraged from various local, State, and Federal partners. Details regarding the different datasets used are provided below in Section 1.1.

Flood discharges for this study were calculated using the United States Geological Survey (USGS) regression equations and were modified to account for the Hurricane Harvey-adjusted flood frequency analyses (explained in further detail below). Regression equations were obtained from the USGS Scientific Investigations Report (SIR) 2009-5087, *Regression Equations for Estimation of Annual Peak-Streamflow Frequency for Undeveloped Watersheds in Texas Using an L-moment Based, PRESS-Minimized, Residual-Adjusted Approach* (2009).

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) program version 4.1 was used to compute water surface elevations on a stream by stream basis. All hydraulic models were computed using 1-D steady state analysis.

In August 2017, the East Fork San Jacinto Watershed experienced record rainfall and flooding from Hurricane Harvey. The historic scale of the storm and the anticipated level of reconstruction in its aftermath precipitated a need to provide advisory data to the communities most impacted. Per FEMA Task Order HSFE60-17-J-0003, FEMA contracted Compass to calibrate the BLE models for the watershed to account for observed Hurricane Harvey data. Flood frequency analyses[1] that incorporated peak Hurricane Harvey discharges on six USGS gages in the East and West Fork San Jacinto Watersheds were utilized to determine appropriate factors to apply to the USGS regression equations. The BLE models were calibrated using the Harvey-adjusted peak discharges. These peak discharges are provided in the spatial files delivered in the East Fork San Jacinto BLE database. In addition, roughness coefficients were revised to calibrate the BLE models to observed Hurricane Harvey stream flow. The streamflow and n-value adjustments were applied throughout the watershed. A memorandum detailing the methodology behind the adjustments is provided in Appendix B.

The stream mile network that was validated for these watersheds was compiled using FEMA's Community Needs Management Strategy (CNMS) inventory. CNMS is an inventory of flood hazard studies and flood hazard mapping needs for areas where a study is needed. This data is helpful for community officials in analyzing and depicting flood hazards to enhance the understanding of flood risks. Communities may use this information to make informed decisions on their planning and flood mitigation efforts. Table ES-1 lists the Zone A stream miles associated with this validation analysis.

[1] FEMA (Federal Emergency Management Agency) 2017, *Hurricane Harvey: Precipitation and Streamflow Analysis*.

Table ES-1: Summary of Stream Miles

Source	East Fork San Jacinto Stream Miles
CNMS	381.5

The full inventory of Zone A studies in the watershed were classified in CNMS. Total miles validated in CNMS are summarized in Table ES-2 and illustrated in Figure ES-1 below.

Table ES-2: Zone A Validation Results

Validation Status	Status Type	Total Miles
VALID	BEING STUDIED	73.8
UNVERIFIED	BEING STUDIED	307.7

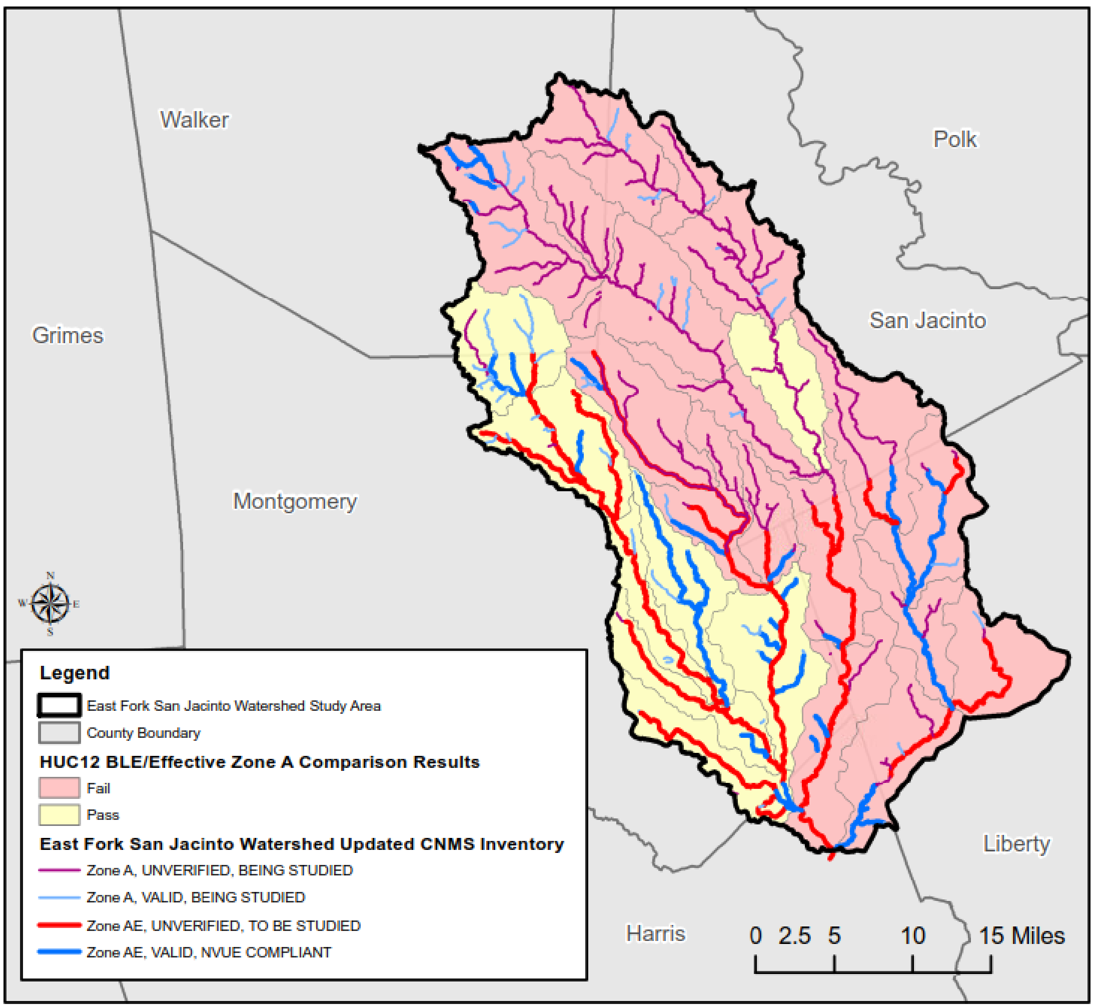

Figure ES-1: East Fork San Jacinto River Watershed CNMS Validation Results

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 ES-2 below shows the range of the East Fork San Jacinto HUC-8 priority scores which can be used to initiate discussions during the Discovery phase.

Lower Tarkington Bayou HUC-12 was determined to have the highest priority score and the most need while Cagle Branch-Caney Creek HUC-12 had the lowest score.

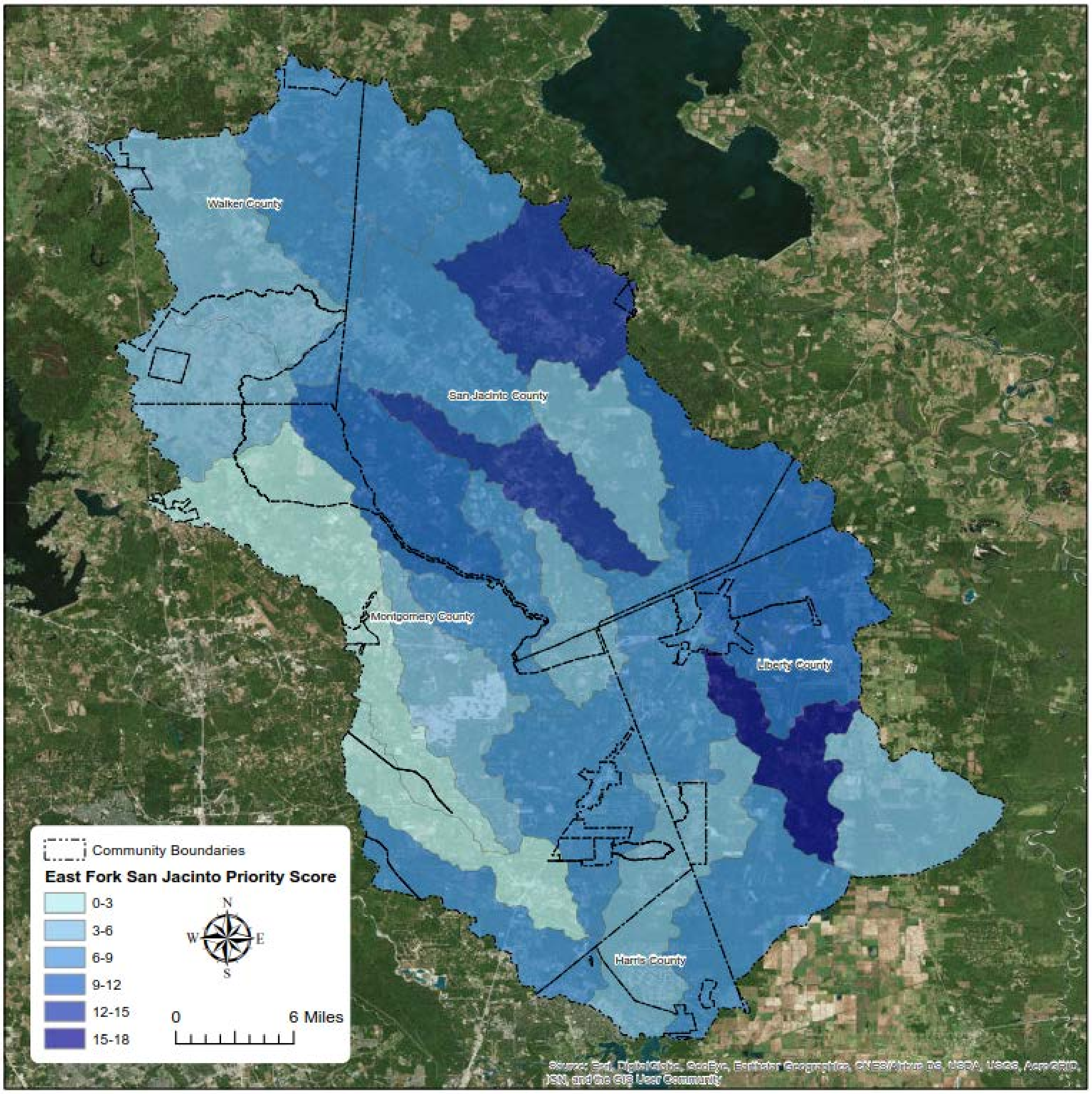

Figure ES-2: Ranking of East Fork San Jacinto River Watershed HUC-12s

Base Level Engineering (BLE) Methodology

Recent innovations and efficiencies in floodplain mapping have allowed the U.S. Department of Homeland Security's Federal Emergency Management Agency (FEMA) to develop a process called Base Level Engineering (BLE), which can be used to address current program challenges, including the validation of Zone A studies and the availability of flood risk data in the early stages of a Flood Risk Project. The BLE process involves using best available data and incorporating automated techniques with traditional model development procedures to produce regulatory quality flood hazard boundaries for the 1-percent annual chance event as well as estimates of flood hazard boundaries for multiple recurrence intervals. The cost for developing the data and estimates resulting from the BLE process are lower than standard flood production costs. The BLE results may be used for eventual production of regulatory and non-regulatory products.

As described in Title 42 of the Code of Federal Regulations, Chapter III, Section 4101(e), once every five years, FEMA must evaluate whether the information on Flood Insurance Rate Maps (FIRMs) reflects the current risks in flood-prone areas. 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 provide a comprehensive method of evaluating the validity of Zone AE studies, a cost-effective approach for evaluating Zone A studies has been lacking.

In addition to the need for Zone A validation guidance, FEMA standards require flood risk data to be provided in the early stages of a Flood Risk Project. FEMA Program Standard SID #29 requires that during Discovery, data must be identified that illustrates potential changes in flood elevation and mapping that may result from the proposed project scope. If available data does not clearly illustrate the likely changes, an analysis is required that estimates the likely changes. This data and any associated analyses should be shared and results should be discussed with stakeholders.

An important goal of the BLE process is the scalability of the results. Scalability means that the results of a BLE analysis can not only be used for CNMS evaluations of Zone A studies, but can also be leveraged throughout the Risk MAP program. The data resulting from a BLE analysis can be updated as needed and used for the eventual production of regulatory and non-regulatory products, outreach and risk communication, and MT-1 processing. Leveraging this data outside the Risk MAP program may also be valuable to external stakeholders.

FEMA Region VI contracted Compass to complete a BLE analysis for the East Fork San Jacinto Watershed in Southeast Texas to support FEMA's Discovery process and validation of effective Zone A Special Flood Hazard Areas (SFHA). The study extents include portions of Harris, Liberty, Montgomery, San Jacinto, and Walker Counties, and include the following communities: the Cities of Cleveland, Coldspring, Conroe, Cut and Shoot, Houston, Huntsville, New Waverly, North Cleveland, Patton Village, Plum Grove, Roman Forest, Splendora, Willis, and Woodbranch. The study area consists of four HUC-10 basins: Peach Creek-Caney Creek, East Fork San Jacinto River – Frontal Lake Houston, Tarkington Bayou-Luce Bayou, and Winters Bayou-East Fork San Jacinto River. Figure 1 shows the orientation of the EFSJ HUC-10 basins with respect to the counties.

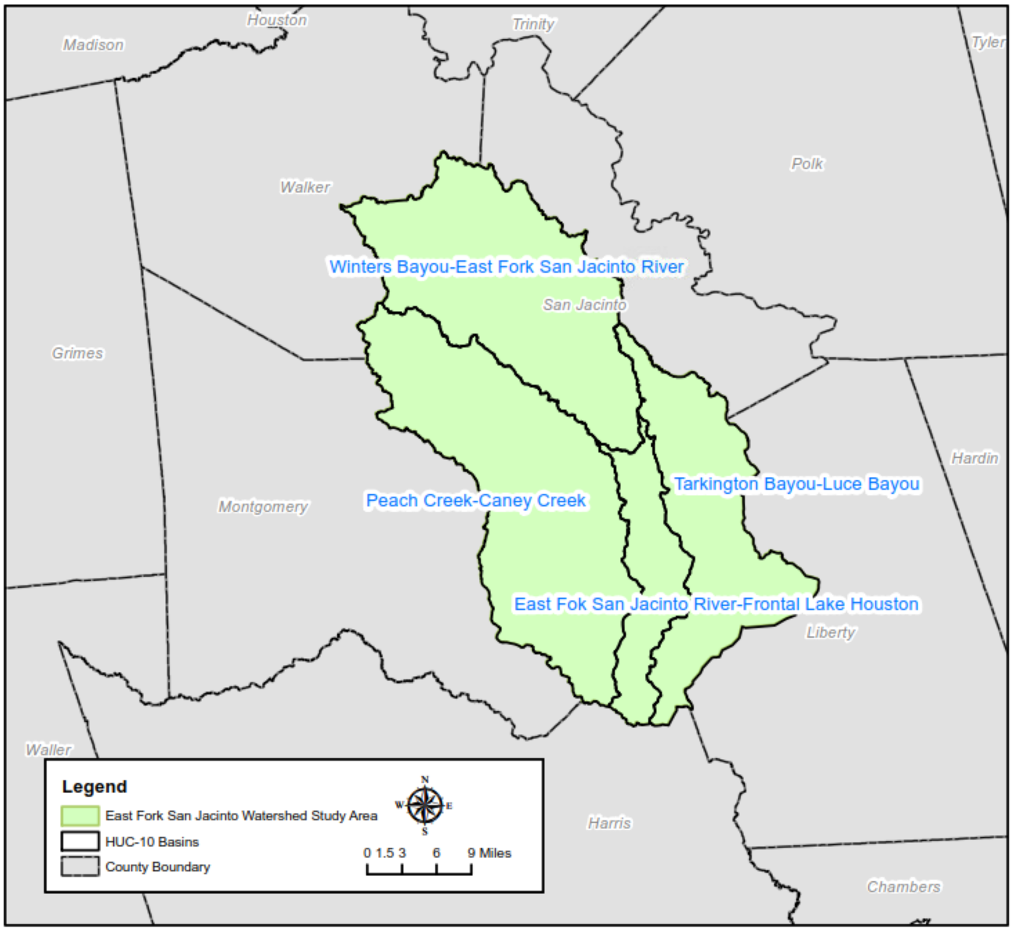

Figure 1: East Fork San Jacinto Watershed HUC-10 Basins

Compass studied approximately 1,474 miles of stream reaches within the East Fork San Jacinto Watershed with a minimum drainage area tolerance of one square mile outside of population centers and half a square mile inside population centers). The selection and extent of stream reaches studied were based upon the number of stream miles with a minimum drainage area of one square mile and not the number of effective Zone A stream miles. Study reaches were extended above this threshold as appropriate to ensure all effective Zone A flood areas received an updated analysis. Topographic data from multiple sources were used to determine the hydrologic and hydraulic characteristics of the watershed. The following sections summarize the BLE process and discuss the results along with their recommended use.

1.1 Topographic Data

Topographic data from multiple sources were used to determine the hydrologic and hydraulic characteristics of the watershed. Topographic data was obtained from the Houston-Galveston Area Council (H-GAC), Texas Natural Resources Information System (TNRIS), and the United States Geological Survey (USGS).

All available metadata, survey reports, and other leverage documentation are available with the source dataset. Figure 2 shows the extents of the source Digital Terrain Model (DTM) data used for the East Fork San Jacinto Watershed.

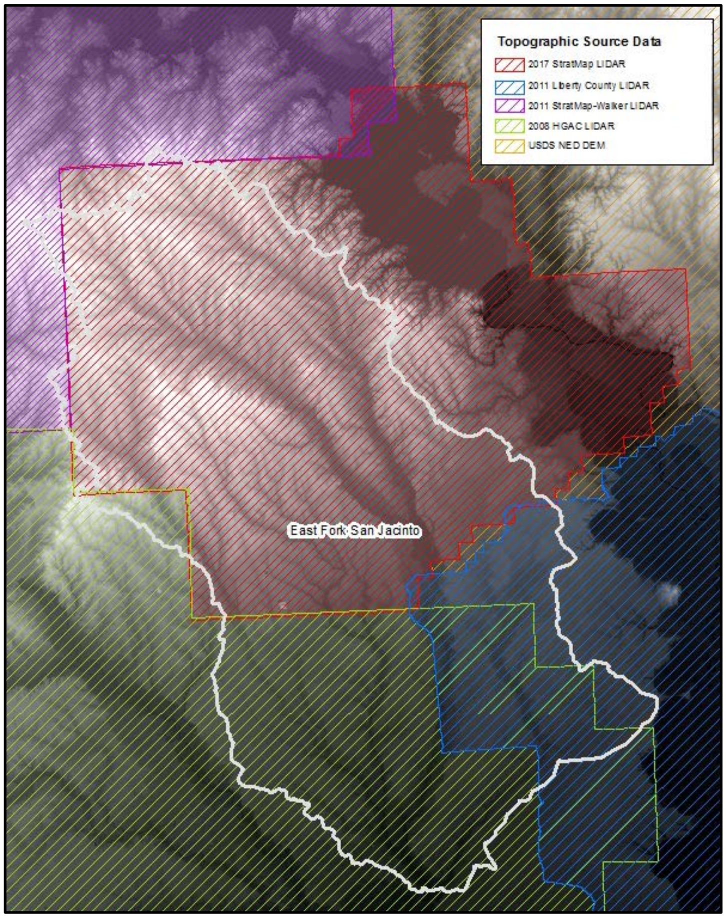

Figure 2: Extent of LiDAR Data for East Fork San Jacinto Watershed

1.1.1 Source Terrain Data

Five topographic datasets were used in the development of the BLE hydraulic models. Details on each dataset are outlined below.

1.1.1.1 2017 StratMap LiDAR

The 2017 StratMap LiDAR was acquired by Fugro Geospatial Inc. for the Texas Water Development Board from February 1, 2017 through March 21, 2017. The project design of the LiDAR data acquisition was developed to support a nominal post spacing of 0.5 meter. The RMSEz reported for the dataset was 4.927 centimeters at the 95% confidence level which meets project accuracy specifications of the National Standard for Spatial Data Accuracy (NSSDA).

1.1.1.2 2011 TNRIS LiDAR

The 2011 TNRIS LiDAR (50cm) for Austin, Grimes, and Walker Counties is 840 tiles covering approximately 3,300 square miles. The project design of the LiDAR data acquisition was developed to support a nominal post spacing of 0.5 meter. The AeroMetric, Inc. acquisition covered 440 flights lines in 51 lifts from January 8, 2011 through February 3, 2011. LiDAR data was processed to achieve a bare ground surface. The RMSEz reported for the dataset was 0.11 meters at the 95% confidence level which meets project accuracy specifications of the NSSDA.

1.1.1.3 2011 Liberty County TNRIS LiDAR

The 2011 Liberty County LiDAR, in the format of LAS, was acquired by Fugro EarthData in January 2011. The project area consists of one Area of Interest (AOI) in Liberty County, Texas and covers an area of approximately 1,055 square miles, which includes a 100 meter perimeter buffer around the original extent. The bore sighted unclassified LAS data for the AOI was delivered in a full swath LAS format, and a subset of 641 square miles was processed to a Level 2, which is a fully calibrated, classified point cloud in LAS format using the following classification scheme: Class 1 – Processed, but unclassified, Class 2 – Bare-earth ground, Class 7 – Low points and noise, Class 9 – Water, Class 11 – Withheld. The RMSEz reported for the dataset was 0.06 meters at the 95% confidence level which meets project accuracy specifications of the NSSDA.

1.1.1.4 H-GAC 2008 LiDAR

The H-GAC 2008 LiDAR was acquired between February 1, 2008 and March 4, 2008 with a publication date of November 3, 2008. Merrick & Company (Merrick) performed the LiDAR survey for the H-GAC. In order to post process the LiDAR data to meet task order specifications, Merrick established a total of 296 QA control points that were used to calibrate the LiDAR to known ground locations established throughout the project area. The Non-vegetated Vertical Accuracy (NVA) reported for the 2012 East Central Texas LiDAR was 0.22 feet at the 95% confidence level, which meets project accuracy specifications of the NSSDA.

1.1.1.5 USGS NED DEM

The National Elevation Dataset (NED), a product of the USGS, is a seamless gridded dataset representing the best available raster elevation data available to the USGS for the conterminous United States, Alaska, Hawaii, and territorial islands. The NED is derived from diverse source data that are processed to a common coordinate system and unit of vertical measure. The NED serves the East Fork San Jacinto Watershed topographic data development by filling in as best available data where there are gaps in the data sets listed above. This dataset was only used for a very small area in comparison to the overall HUC-8 watershed.

1.1.1.6 Terrain Data Processing

The LiDAR data were processed in Environmental System Research Institute (ESRI) ArcGIS software to create a composite Digital Terrain Model (DTM) dataset for the project area. The outputs from the processing described below were used during the hydrology, hydraulics, floodplain mapping and CNMS processes and validations.

The Watershed Information System (WISE) software platform was utilized in order to create a digital surface model for each watershed's project area. This module allows source data from a variety of sources to be prioritized based on level of accuracy or preference of the user.

For the East Fork San Jacinto Watershed, the 2017 StratMap LiDAR was prioritized as the highest data source for the East Fork San Jacinto Watershed. The 2011 TNRIS LiDAR was the second highest priority, 2011 Liberty County TNRIS LiDAR was third highest priority, and the 2008 H-GAC

LiDAR was fourth highest priority. USGS NED data supplemented the datasets to fill in remaining gaps in LiDAR data.

The DEMs created from the LiDAR datasets mentioned above were compiled in order of vertical accuracy into a mosaic dataset using ArcMap. From this mosaic, a tile index was created for the project area and the mosaic was clipped into 50,000-foot tiles, converted to asciis and imported into WISE Terrain Analyst (WTA). Visual inspection of the 10-foot DEMs was performed to ensure no voids and/or artifacts were present in the DEM. The DEM surface model was affirmed to be suitable for hydraulic takeoffs and supporting other hydraulic analyses.

Stream centerlines were manually digitized using the 10-foot DEMs as a source for horizontal alignment and vertical elevation. These stream centerlines are created for use in the hydraulic analysis, hydro-enforcement of the 50-foot DEMs, and visual reference on the FIRM products. Several routines were then used to take localized elevations from the source topographic data and apply them to the streams. This gave the stream vertices elevation information along the Z axis. The resulting elevations ensure that the streams are lower in elevation than any overbank sumps. A separate routine was then used to ensure that the elevations of these vertices descend in height down to an outfall. The final streams file is then "burned" into the 50-foot DEMs to force flow through structures while preventing it from jumping out of the channel banks.

After the DEM was imported, an additional 50-foot DEM was created from the same mosaic and tile index used for the 10-foot DEM. This 50-foot DEM was used for hydro enforcement of the project areas. Proprietary software was used to identify natural sinks, peaks and flat areas in the 50-foot DEM surface. Elevations of the cells in the DEM were algorithmically calculated and the best path to route flow was determined without filling sinks in the DEM. Once all calculations were completed, the flow was checked confirming that all drainage flows downstream correctly and is routed to outside of the HUC-8 basin.

In addition to the quantitative assessment of the source digital terrain, a qualitative visual inspection of the composite DEM was performed using a hillshade derived from the 10-foot DEM. The visual inspection indicated that no unusual or non-terrestrial features were observed in the composite DEM, assuring the surface files used for hydrologic and hydraulic analyses and floodplain mapping activities are sufficient for BLE analysis.

1.2 Hydrology

Flood discharges for this study were calculated using the United States Geological Survey (USGS) regression equations that were adjusted to account for Harvey-adjusted flood frequency analyses (see Section 1.2.1). Regression equations were obtained from the USGS Scientific Investigations Report (SIR) 2009-5087, *Regression Equations for Estimation of Annual Peak-Streamflow Frequency for Undeveloped Watersheds in Texas Using an L-moment Based, PRESS-Minimized, Residual-Adjusted Approach* (2009).

The Watershed Information System (WISE) software was used to delineate drainage basins in shapefile format using the 50-foot DEM. WISE was also used to calculate the main-channel slope for each basin. The basin shapefile attribution was automated by WISE with drainage area, main-channel slope, and precipitation.

Table 1 shows the published equations used in this study. In these equations, Q_i represents peak streamflow for i-recurrence interval (annual chance exceedance (a.c.e.)) in cubic feet per second (cfs), P represents mean annual precipitation in inches, S represents dimensionless main-channel slope, Ω represents the OmegaEM parameter, and A represents cumulative drainage area in square miles.

Table 1: Summary of Regression Equations in Texas (SIR 2009-5087)

Recurrence Interval	Equation
$Q_{10\%}$	$P^{1.203} \times S^{0.403} \times 10^{[0.918\Omega + 13.62 - 11.97A^{\wedge}(-0.0289)]}$
$Q_{4\%}$	$P^{1.140} \times S^{0.446} \times 10^{[0.945\Omega + 11.79 - 9.819A^{\wedge}(-0.0374)]}$
$Q_{2\%}$	$P^{1.105} \times S^{0.476} \times 10^{[0.961\Omega + 11.17 - 8.997A^{\wedge}(-0.0424)]}$
$Q_{1\%}$	$P^{1.071} \times S^{0.507} \times 10^{[0.969\Omega + 10.82 - 8.448A^{\wedge}(-0.0467)]}$
$Q_{0.2\%}$	$P^{0.988} \times S^{0.569} \times 10^{[0.976\Omega + 10.40 - 7.605A^{\wedge}(-0.0554)]}$

Variables:
- Q_i, peak flow for i recurrence interval (a.c.e.), in cubic feet per second;
- P, mean annual precipitation, in inches;
- S, Main-channel slope (dimensionless);
- Ω, OmegaEM parameter;
- A, cumulative drainage area, in square miles

Discharges for the 1-percent plus and 1-percent minus a.c.e. were calculated as $Q_{1\%+/-} = Q_{1\%} \pm 10^{1.6*0.30}$, where 0.30 is the mean residual standard error for the $Q_{1\%}$ equation.

The mean annual precipitation values were determined based on a shapefile coverage obtained from the Texas Water Development Board (TWDB) and available for download at the following location: http://www.twdb.texas.gov/mapping/gisdata/doc/Precipitation_Shapefile.zip

The annual precipitation values reflect data for the climatological period 1981-2010 as recorded by the Natural Resources Conservation Service (NRCS).

Main-channel slope was calculated in WISE. An automated routine determined the longest flowpath from upstream of a reach to the outlet of the sub-basin of interest. Two points along the channel, one at 10 percent and the other at 85 percent of the channel length, determined the endpoints of the segment used in the main-channel slope calculation. The elevations for those endpoints were based on the 10-foot DEM developed from the LiDAR.

From USGS SIR 2009-5087, the OmegaEM parameter is a generalized terrain and climate index that expresses relative differences in peak-streamflow potential. A shapefile was developed and populated with OmegaEM values based on Figure 2 in SIR 2009-5087. This shapefile was used, along with a python script in ArcCatalog, to determine OmegaEM values on a sub-basin basis. For sub-basins spanning more than one OmegaEM grid, the sub-basin's centroid determined its OmegaEM parameter.

Automated basin delineations were performed in WISE. Basin break points were set by the user with a sub-basin target size of one square mile. This criterion was adjusted for the main stem of the East Fork San Jacinto River to avoid excessive and unnecessary discharge breaks. Break points were also set immediately upstream of stream confluences. Cumulative drainage area was determined based on these automated delineations performed by WISE in combination with a stream connectivity routine that defined the stream reach segments with upstream and downstream neighbors.

The sub-basin shapefile was attributed with the computed discharges, and those discharges were incorporated into the HEC-RAS models using an automated routine in WISE. Discharges, as well as water surface elevation results, were associated with the hydraulic cross sections prior to generation of floodplain boundaries and grid mapping. Those results are available in GIS format as part of this BLE submittal package.

1.2.1 Special Considerations: Harvey Advisory Data

In August 2017, the East Fork San Jacinto River watershed experienced record rainfall and flooding from Hurricane Harvey. Per Task Order HSFE60-17-J-0003, FEMA contracted Compass to analyze the EFSJR BLE models to account for observed Hurricane Harvey data.

FEMA performed pre- and post-Harvey flood frequency analyses (FFAs)[2] on 46 USGS stream gages in the Harvey-affected counties. Of the analyzed gages, six were in the East and West Fork San Jacinto River watersheds (see Figure 3). The results of the FFAs for these six gages are shown on Table 2. The analysis indicates substantial increases in peak discharge for all storm events of interest (i.e., 10%, 4%, 2%, 1%, and 0.2% annual exceedance probabilities), and the percent increases are greater in the larger storm events.

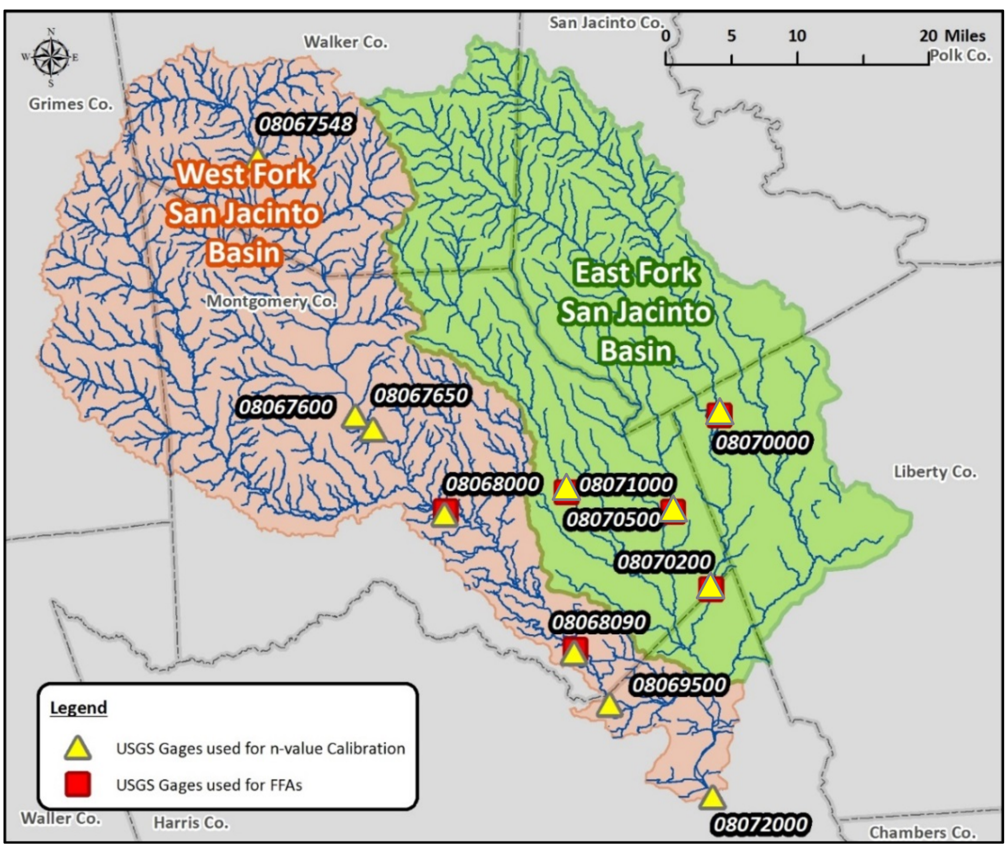

Figure 3: Locations of USGS Gages Utilized in n-value Calibration and Flood Frequency Analyses

[2] FEMA (Federal Emergency Management Agency) 2017, *Hurricane Harvey: Precipitation and Streamflow Analysis*.

Table 2: Post-Harvey Flood Frequency Analyses on Gages in the East and West Fork San Jacinto River Watersheds[3]

Station ID	Station Name	Drainage Area (mi^2)	Post-Harvey Peak Discharge (cfs) for Selected AEPs *(Percent Change from Pre-Harvey)*				
			10%	4%	2%	1%	0.2%
08068000	W Fork San Jacinto River near Conroe	828	31,400 *(6.7%)*	53,800 *(9.3%)*	78,100 *(12.3%)*	111,000 *(14.6%)*	238,000 *(19.7%)*
08068090	W Fork San Jacinto River above Lake Houston near Porter	962	39,900 *(6.3%)*	64,800 *(9.3%)*	89,400 *(11.4%)*	120,000 *(13.3%)*	224,000 *(18.8%)*
08070000	E Fork San Jacinto River near Cleveland	325	22,900 *(5.7%)*	40,200 *(8.7%)*	58,300 *(10.5%)*	82,000 *(12.3%)*	166,000 *(16.3%)*
08070200	E Fork San Jacinto River near New Caney	388	21,000 *(6.7%)*	38,000 *(11.1%)*	57,000 *(14.6%)*	83,100 *(17.8%)*	186,000 *(25.3%)*
08070500	Caney Creek near Splendora	105	10,100 *(5.7%)*	17,100 *(6.4%)*	24,500 *(7.3%)*	34,300 *(8.2%)*	70,400 *(9.7%)*
08071000	Peach Creek at Splendora	117	9,300 *(8.4%)*	17,000 *(11.2%)*	25,200 *(13.5%)*	36,100 *(15.5%)*	75,500 *(19.7%)*

The discharges obtained in the gage analyses (pre- and post-Harvey) were compared to those calculated from the 2009 regression equations. Discharge versus cumulative drainage area data points were plotted on a log-log scale for the six gages and all EFSJR sub-basins (see Figure 4). Power trendlines were fitted to the gage data and the 2009 regression model data points. The resulting trendline equations and R^2 values for the 1% AEP are displayed on Figure 4. When compared to the gage analyses, the 2009 regression models under-predict streamflow.

[3] FEMA 2017, *Hurricane Harvey: Precipitation and Streamflow Analysis*.

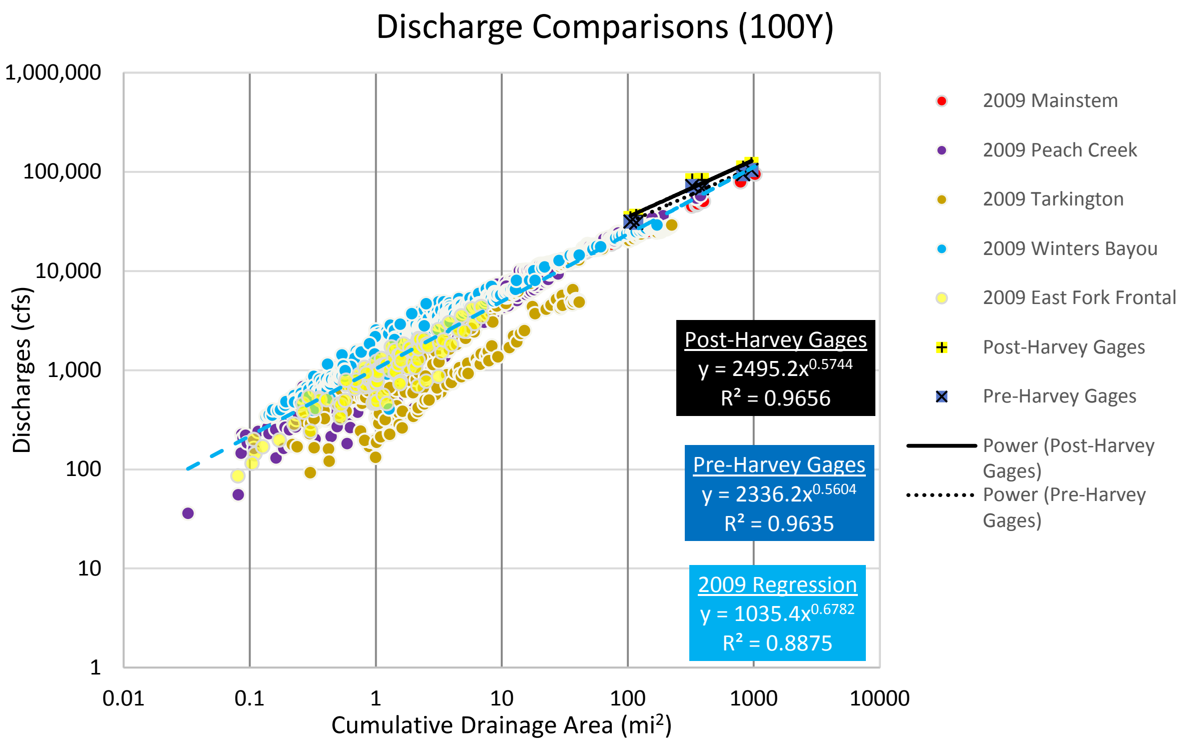

Figure 4: Comparison of Q_{100} values calculated from the regression models and the gage analyses

For each storm recurrence interval, a constant "α" was computed from the trendline equations to adjust the 2009 regression model streamflow predictions to the post-Harvey flood frequency analyses. α was computed as $\alpha = y_{\text{Post-Harvey FFA}} / y_{\text{2009 Regression}}$, where y represents the respective power trendline equations. The α-factors were applied as a constant multiplier to the 2009 regression equations (Table 1) to obtain the adjusted flows. The computed α-factors are presented in Table 3. The α-factor for the 10-year storm event is less than one, so no adjustment was used for the 10-year. The BLE models were updated with the modified discharges. The hydrologic adjustments described here are discussed further in the attached memorandum (Appendix B).

Table 3: Computed α-factors for BLE on the East and West Fork San Jacinto Watersheds

10%	4%	2%	1%	0.2%
0.87 (no adjustment)	1.04	1.17	1.33	1.76

1.3 Hydraulics

The hydraulic approach for this BLE analysis of the East Fork San Jacinto Watershed consisted of using the terrain model described in Section 1.1 in combination with the hydrologic outputs from Section 1.2 to establish water surface elevations using 1-D steady state analysis. The Hydrologic Engineering Center's River Analysis System (HEC-RAS) program version 4.1 was chosen as the computer model to compute water surface elevations on a stream by stream basis. The WISE software was used to establish model stream orientation, generate initial hydraulic cross section layout and stationing, assign n-values to cross sections, and develop all input files for the HEC-RAS program. ESRI's ArcMap program was used to review and refine cross-section layout orientation.

First pass cross-section layout was performed using an automated routine in WISE based on the cumulative drainage area at the cross section location. A first draft model was created based on this initial cross-section layout, and draft boundaries were developed. At this stage, a second pass inspection for cross-section placement occurred. Significant refinement occurred during this step. To improve the hydraulic models, additional cross-sections were added as needed to better define the BLE floodplain boundary. Cross-sections were extended in locations where overtopping occurred. Orientation of cross-sections was refined to improve on the perpendicular orientation to flow. Additional cross-sections were added at floodplain constrictions and at downstream portions of tributaries to ensure a proper tie-in with receiving streams. Cross-sections were adjusted to remove sections that intersected hydraulic crossings in the floodplain. For some of the largest studied streams, cross-sections were laid out manually in order to have more reasonable spacing and better capture the constrictions in the floodplain.

Cross-sections were not drawn on top of roadways or railroads but were placed at the upstream and downstream face of major roads and railroads. Ineffective flow stations were placed in the hydraulic models as appropriate to account for flow constrictions and other locations deemed by the engineer to be ineffective at conveying flow downstream.

Cross-sections were drawn on dam tops for significant dams with well-defined spillways in order to better represent ponded water upstream of the structures. In so doing, it was assumed that the vast majority of the flow during a flood event would pass the spillway and that the hydraulic model would reasonably estimate flow across the spillway as represented in the hydraulic cross-section. The elevations used in the modeling were checked against effective Zone A boundaries, and the results were deemed reasonable.

The relationship between cumulative drainage area and assigned channel geometry is shown in Table 4. These default values for dimensions and spacing were subject to change based on engineering judgment.

Table 4: Cross-Section Default Parameters

Drainage area (upper limit)	XS Spacing	Channel Top Width	Channel Bottom Width	Channel Depth
1.0	500	4	3.5	0.5
2.0	500	6	5	0.5
4.0	500	11	10	0.5
8.0	500	18	17	0.5
10.0	500	20	19	0.5
15.0	600	26	25	0.5
20.0	600	32	31	0.5
25.0	600	38	36	0.5
30.0	600	43	41	0.5
40.0	600	52	50	0.5
50.0	600	60	57	1
75.0	750	68	65	1
100.0	750	76	73	1
150.0	1000	91	88	1
250.0	1000	122	119	2

Drainage area (upper limit)	XS Spacing	Channel Top Width	Channel Bottom Width	Channel Depth
500.0	1500	198	195	2
1000.0	2500	351	346	3
2000.0	4000	657	652	3
5000.0	4000	1575	1565	3

In typical BLE projects, Manning's roughness coefficients (n-values) are determined using the 2011 National Land Cover Data (NLCD) dataset in combination with n-values from Chow (1959) and Calenda et al. (2005). The association between the n-values and the NLCD Classification is shown in Table 5. Manning's n-value takeoffs are performed by WISE (default values taken from the "Normal" column). N-values within channel banks are constrained by the automated routine to a range of 0.030 to 0.070. Then, overbank and channel n-values are manually adjusted in certain locations based on engineering judgment. Under the current BLE task order, the n-value assignments were modified in a calibration process detailed in Section 1.3.1.

Table 5: Manning's "n" Roughness Based on 2011 NLCD Classification (Moore, 2011)

NLCD Classification	Minimum	Normal	Maximum	Source
Open Water	0.025	0.03	0.033	Chow 1959
Developed, Open Space	0.01	0.013	0.016	Calenda et al. 2005
Developed, Low Intensity	0.038	0.05	0.063	Calenda et al. 2005
Developed, Medium Intensity	0.056	0.075	0.094	Calenda et al. 2005
Developed, High Intensity	0.075	0.1	0.125	Calenda et al. 2005
Barren Land	0.025	0.03	0.035	Chow 1959
Deciduous Forest	0.1	0.12	0.16	Chow 1959
Evergreen Forest	0.1	0.12	0.16	Chow 1959
Mixed Forest	0.1	0.12	0.16	Chow 1959
Scrub/Shrub	0.035	0.05	0.07	Chow 1959
Grassland/Herbaceous	0.025	0.03	0.035	Chow 1959
Pasture/Hay	0.03	0.04	0.05	Chow 1959
Cultivated Crops	0.025	0.035	0.045	Chow 1959
Woody Wetlands	0.08	0.1	0.12	Chow 1959
Emergent Herbaceous Wetland	0.075	0.1	0.15	Chow 1959

The boundary condition used for the majority of the study streams was normal depth with a default value of 0.005 ft/ft. For streams with large drainage areas (generally greater than 8 square miles), the normal depth slope was calculated based on the channel inverts of the downstream cross sections.

In cases where streams tie in to a lake, a normal depth slope was calculated based on the channel inverts of the downstream cross sections (typically between 0.0001 and 0.001 ft/ft). Several HUC-10s within this watershed are located in urban areas with storm drain systems, which are unaccounted for in the BLE models. Simplifications of these systems may considerably affect perceived risk.

1.3.1 Special Considerations: Harvey Advisory Data

Per Task Order HSFE60-17-J-0003, FEMA contracted Compass to analyze the EFSJR BLE models to account for observed Hurricane Harvey data. A limited number of gages operate within the EFSJR watershed, with two located on the mainstem of the East Fork San Jacinto River.

To verify the hydraulic methodology of the BLE process in the EFSJR watershed, the peak recorded USGS gage flows on the East Fork San Jacinto River during Harvey were input into the existing hydraulic model. There are two USGS gages (08070200 and 08070000) on the East Fork San Jacinto River that record stream flow. Additionally, there are two USGS gages (08070500 and 08071000) on Caney Creek and Peach Creek. All four of these gages were utilized in the hydraulic calibration (see Figure 3).

Using the initial model created for the East Fork San Jacinto River and the Harvey flows, the computed water surface elevation was an average of 2.9 feet below the recorded water surface elevations.

Manning's roughness coefficients (n-values) assigned by the GIS tool, which utilizes the 2011 National Land Cover Database (NLCD) data, appear to be low when the recorded Harvey USGS gage flows are input into the models and the water surface elevations are compared to the recorded Harvey USGS gage elevations.

An overbank n-value adjustment of +0.05 with a minimum final value of 0.11 is recommended for the East Fork San Jacinto River. This alters the range of Manning's n-values from 0.05 – 0.12 to 0.11 – 0.17. The channel adjustment of +0.02 with a minimum final value of 0.06 is recommended. This will alter the range of Manning's n-values from 0.03 – 0.07 to 0.06 – 0.09. The exception to the adjustment of roughness coefficients within the channel is through large reservoirs or lakes. The Manning's n-value was set to 0.03 through Lake Houston. Increasing the n-values results in water surface elevation profiles more representative of the gage elevations recorded during Harvey.

The n-value calibration process is detailed further in the attached memorandum (Appendix B).

1.4 Quality Control

Following the initial BLE analysis in each watershed, the flood hazard area delineations created by the BLE process were reviewed for areas where the results were not ideal.

QC results indicated that some of the models should be extended to cover the scope of effective flood hazard data. Those streams were extended farther upstream to match the extents of the SFHA data.

Typical manual editing resulting from reasonability checks included adding cross-sections, adjusting orientation of cross-sections, trimming cross-sections and reduction of the default "V" angle of cross-sections. Examples of default "V" angled cross-sections are shown in Figure 5. It is estimated that 75 percent of cross-sections were adjusted in some work areas while other areas did not require as much editing. Other examples of manual editing included the addition of cross-sections at confluence areas (see Figure 6 below), modifications to improve perpendicular orientation at the channel, adjustment of discharge breaks to better represent flow addition points, revisions to dam spillways and dam tops, additional cross-sections bounding major hydraulic structures, and revisions to n-values.

A major component of the QC process was an automated check that identified locations where the 1-percent a.c.e profile was crossed by any other frequency profile. Significant effort was made to reasonably resolve all of these instances. Another automated check identified locations where there was a drawdown of greater than 0.5 foot on the 1-percent a.c.e. water surface profile. This check is particularly useful for identifying errors in the model such as a channel that is too wide, a poorly placed cross-section, or a need for additional cross-sections. Again, significant effort was made to reasonably resolve these drawdown situations.

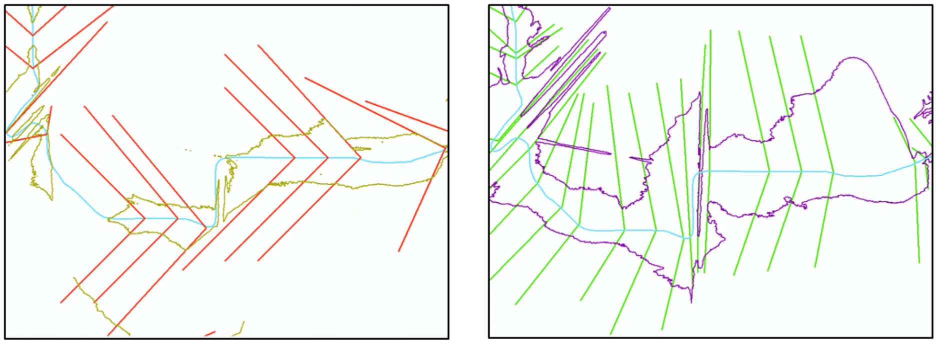

Figure 5: Default "V" angle cross-sections automated by WISE (left). Manually edited cross-sections to more accurately capture terrain (right). Resulting flood boundaries shown in gold (left) or purple (right) for clarity.

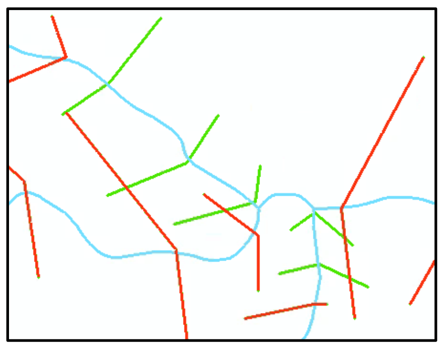

Figure 6: Manually added cross-sections (green) to improve accuracy of tie-ins at confluences.

1.5 One-percent Special Flood Hazard Area Delineation

The 1-percent and 0.2-percent boundaries were mapped using a routine that develops water surface elevation grids based on the 10-foot cell size DEM developed from the LiDAR dataset used for this project (see Section 1.1). This product was converted to a polygon for cleaning. The cleaning routine involved manual inspection of the polygons to identify and remove areas of disconnected flooding. In general, areas with a size of less than 5,000 square feet were removed and all others were investigated to determine whether they should be considered as potentially part of the SFHA. This investigation was aided by the ground DEM and aerial imagery. Manual adjustments to the polygons were made to account for spillways on dams which could not be accurately modeled using HEC-RAS as well as disconnected areas along the flooding source that should reasonably be connected.

Following the removal of disconnected flooding areas and other boundary adjustments, the small islands in the floodplain were filled. Islands with a size between roughly 5,000 and 30,000 square feet were inspected and, in general, islands that were less than 10,000 square feet were filled.

Once the island filling process was complete, the water surface raster mapping routine was run and set to conform to the polygon boundary. This ensures that the water surface raster and the floodplain boundary are consistent with each other. The depth raster product was created at the end of the process by performing a raster subtraction with the water surface elevation raster and the ground DEM.

Challenges

Challenges encountered during BLE analyses vary based on available data on which to run the analysis. The East Fork San Jacinto Watershed presented challenges as summarized in the following paragraphs.

The East Fork San Jacinto Watershed is located in Southeast Texas, an area known for flat terrain. In some of the wide and flat floodplains, small tributaries run parallel to large streams. Parallel streams with shared floodplains were modeled by moving the combined discharge upstream to the cross-section that begins the shared floodplain.

A significant effort was made to improve water surface elevation tie-ins at stream confluences. Cross-sections were manually added on the downstream end of nearly every stream, some of which traverse the receiving stream, so that the water surface elevation of the tributary would be lower than that of the receiving stream.

There are a significant number of small-sized dams on the tributaries throughout the watershed. Discharges calculated with the regression equations do not take into account the impact of these structures. There may be need for further investigation when upgrading these models for detailed studies.

There is a noticeable inconsistency in the mapping of Tarkington Bayou-Luce Bayou HUC-10 in the area where the studied reach moves in and out of the different topography sources.

As noted in Section 1.4 above, multiple streamlines did not extend far enough to fully capture effective flood hazard data. The streamlines generated in the development of the one-square mile basins were extended in order to more closely match the effective areas and CNMS streams.

There are a few containment issues in the Peach-Caney HUC-10 basins. Peach CR 017 was not able to contain the 500-year flooding event due to being a man made channel and perpendicular to the natural hydraulic gradient.

Finally, there are a few containment issues in the Crystal Creek and Frontal Lake Houston HUC-10 basins. Significant effort was made to contain the flooding events, but this was not always achieved due to particularly wide, flat floodplains.

Results and Recommendations

The BLE results for this study produced a SFHA that compares reasonably well with the effective SFHA. These boundaries provide an additional estimated SFHA in areas that 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.

3.1 CNMS Validation of Effective Zone A SFHA

The inventory of Zone A studies (381.5 miles) in the East Fork San Jacinto watershed were classified in CNMS with validation status of "UNVERIFIED" (307.7 miles) or "VALID" (73.8 miles), and with status type of "BEING STUDIED" (381.5 miles). 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.

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 Fork San Jacinto Watershed, the effective Zone A topographic data leveraged a variety of sources, but was primarily based upon United States Interagency Elevation Inventory. Three LiDAR sources are available (2008 H-GAC, 2011 TNRIS, 2011 FEMA LiDAR and 2017 StratMap LiDAR) that are a significant improvement from the effective Zone A topographic source for a small percentage of reaches (38 miles). These 38 miles fail this assessment. The remainder of the mileage passes this check.

INITIAL ASSESSMENT A2 – CHECK FOR SIGNIFICANT HYDROLOGY CHANGES

This check involves first determining 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.

The hydrology methods for all effective Zone A study areas located in the East Fork San Jacinto Watershed are unknown and, therefore, pass this assessment check.

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. Approximately 70% of the effective Zone A studies in this watershed are still considered rural and pass this check. The remainder are classified as urban and have had a >50% increase in urbanization since the effective study and, therefore, fail this check.

All of the initial assessment results are shown in Table 6.

Table 6: Zone A Initial Assessment Results

Assessment Check	Pass / Fail	Notes
A1 – Topography	Pass/Fail	Three LiDAR sources available that are a significant improvement from effective topography affecting a portion of studies.
A2 – Hydrology	Pass	Effective hydrology methods used are unknown.
A3 – Development	Pass/Fail	~30% of streams fall inside HUC-12 watersheds classified as urban and have had a >50% increase in urban area.

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. All Zone A studies, except one small 0.4 mile reach that was restudied as part of a 2016 LOMR, do not have the effective methodology documented. Therefore, all reaches other than the one LOMR segment failed this check.

VALIDATION CHECK A5 – COMPARISON OF BLE AND EFFECTIVE ZONE A

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: +/- 10 feet (one-half contour interval of assumed 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 7 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 7: BLE Comparison Results

HUC-12 Watershed		Total FBS points	Fail	Pass	%Pass	BLE Comparison Pass? (>85%)	Priority Score
Watershed Name	Watershed Number						
East Fork San Jacinto	All Streams	20,998	5,014	15,984	76%	Fail	
Boggy Creek-Peach Creek	120401030106	1,394	484	910	65%	Fail	10.1
Boswell Creek	120401030301	909	197	712	78%	Fail	6.9
Cagle Branch-Caney Creek	120401030104	154	3	151	98%	Pass	1.1
Cobb Creek-East Fork San Jacinto River	120401030305	2,132	438	1694	79%	Fail	8.6
Dry Creek-Caney Creek	120401030105	64	8	56	88%	Pass	1.4
Gourd Creek-Winters Bayou	120401030302	2,252	390	1862	83%	Fail	4.6
Gully Branch-Peach Creek	120401030109	154	6	148	96%	Pass	7.2
Hegar Branch-Caney Creek	120401030101	1670	244	1426	85%	Pass	5.7
Hopkins Branch-Winters Bayou	120401030303	1,997	590	1,407	70%	Fail	7.9
Indian Gulley-Luce Bayou	120401030204	142	29	113	80%	Fail	6.0
Jayhawker Creek	120401030108	600	172	428	71%	Fail	5.1
Lawrence Creek-Peach Creek	120401030107	938	324	614	65%	Fail	6.4
Lower Tarkington Bayou	120401030203	182	46	136	75%	Fail	16.5
Luce Bayou-Frontal Lake Houston	120401030205	416	104	312	75%	Fail	6.8
Marsh Branch-Tarkington Bayou	120401030202	187	30	157	84%	Fail	10.5
McCombs Creek-East Fork San Jacinto River	120401030306	732	180	552	75%	Fail	7.4
McRae Creek-Caney Creek	120401030102	173	10	163	94%	Pass	2.8
Miller Creek-East Fork San Jacinto River	120401030307	2176	500	1676	77%	Fail	12.1
Nebletts Creek-Winters Bayou	120401030304	1,034	567	467	45%	Fail	13.7
Oil Creek-East Fork San Jacinto	120401030308	1,227	159	1068	87%	Pass	3.2
Orange Branch-East Fork San Jacinto River	120401030402	121	51	70	58%	Fail	5.9
Upper Tarkington Bayou	120401030201	1,549	413	1,136	73%	Fail	9.1
West Fork Spring Branch-Spring Branch	120401030103	439	8	431	98%	Pass	3.5
Whiskey Branch-East Fork San Jacinto River	120401030401	332	61	271	82%	Fail	7.6
White Oak Creek-Frontal Lake Houston	120401030110	24	0	24	100%	Pass	6.5

VALIDATION RESULTS

Based on the validation assessments and BLE comparison results described above, the CNMS inventory of Zone A studies in the East Fork San Jacinto Watershed has been updated as summarized in Table 8 and illustrated in Figure 7 below.

Table 8: Zone A Validation Results

Validation Status	Status Type	Total Miles
VALID	BEING STUDIED	73.8
UNVERIFIED	BEING STUDIED	307.7

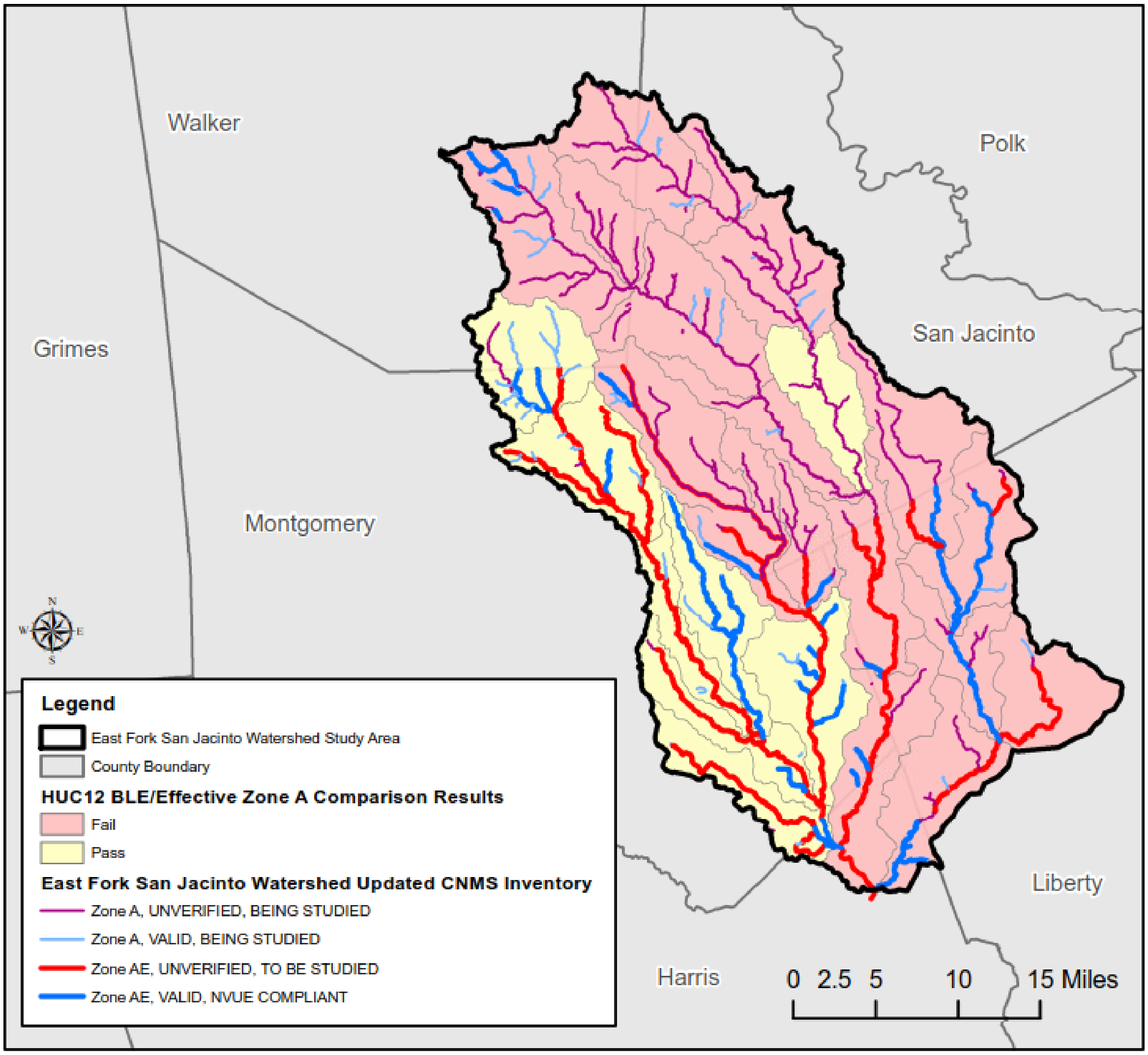

Figure 7: East Fork San Jacinto River Watershed CNMS Validation Results

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 8 below shows the range of the HUC-12 priority scores which can be used to initiate discussions during the Discovery phase.

Lower Tarkington Bayou HUC-12 was determined to have the highest priority score and the most need while Cagle Branch-Caney Creek HUC-12 had the lowest score.

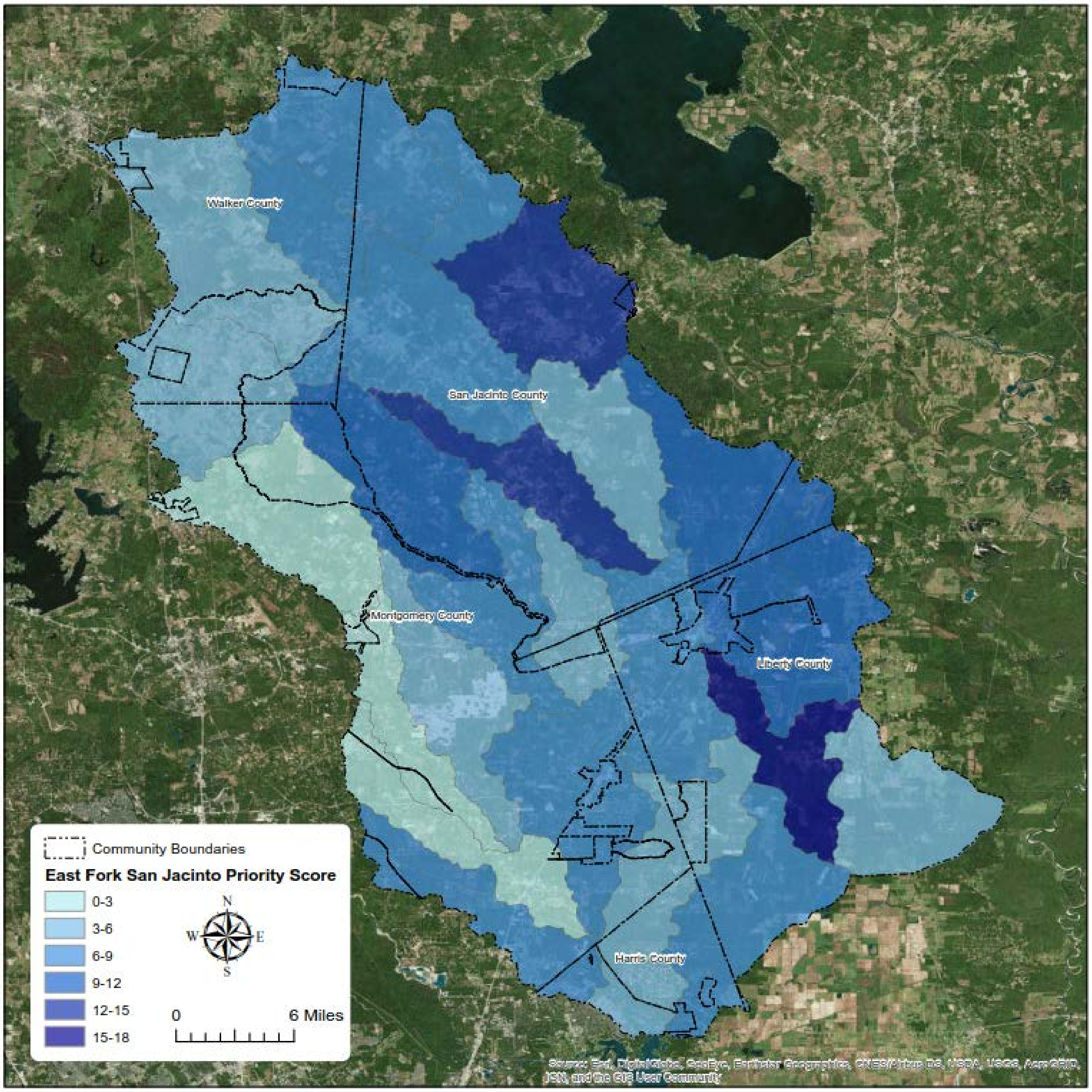

Figure 8: Ranking of East Fork San Jacinto River Watershed HUC-12s

3.2 Flood Risk Analysis

An advanced flood risk analysis was performed using the updated 1-percent-annual-chance grid (known as 'refined' grid) created for this project. The loss analysis uses 2010 census data and the subsequent results are stored in the L_RA_Results table.

Hazus version 4.0 was used for the loss analysis.

The losses are reported via census blocks. It is important to note that Hazus version 4.0 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.

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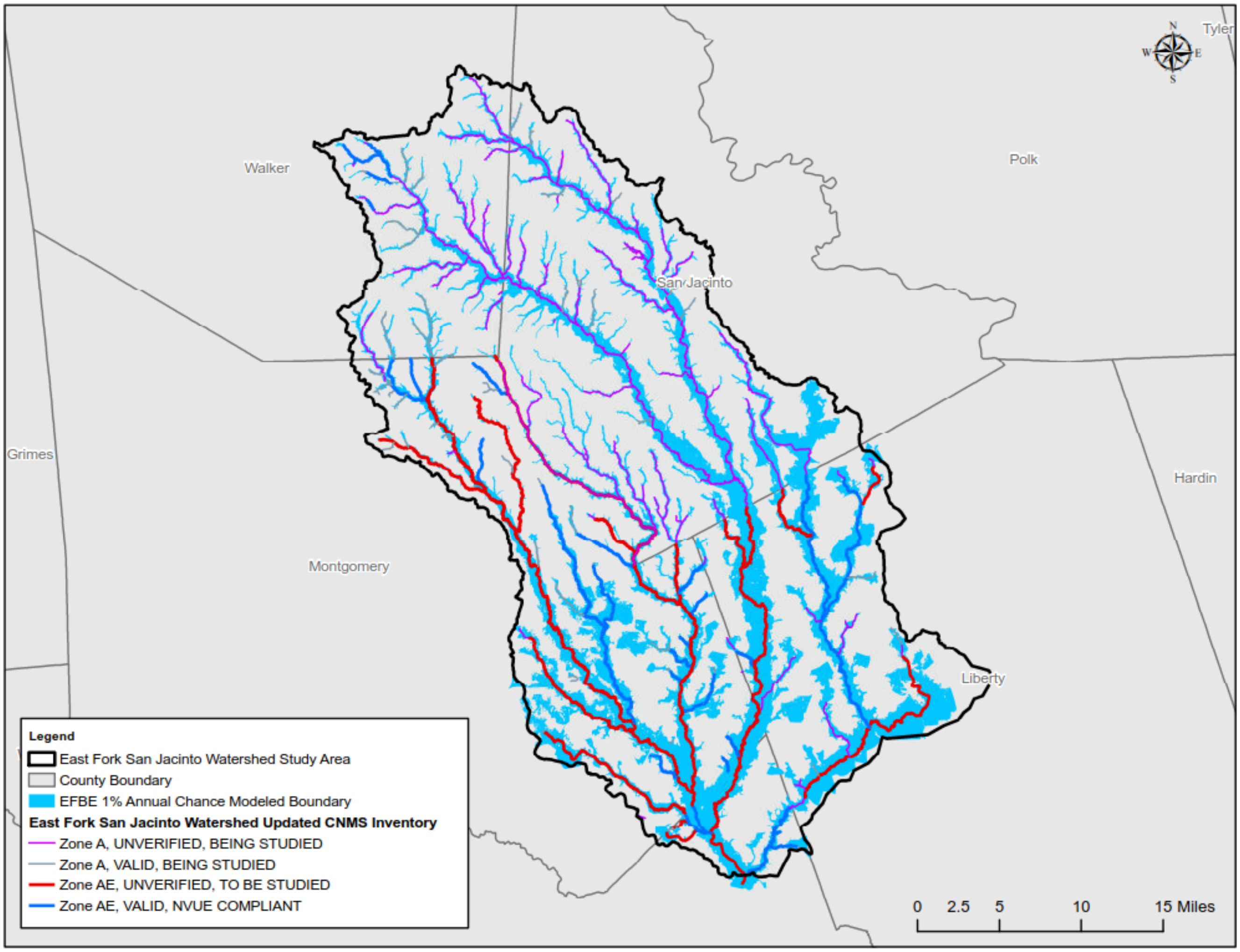
Appendix A BLE Map



Appendix B BLE EFSJR Harvey Hydrology & Hydraulics Memo

Date: May 7, 2018

To: Alan Johnson

Larry Voice

From: April Smith, PE, CFM

Subject: BLE East Fork San Jacinto River Watershed Harvey Hydrology & Hydraulics Update

Summary

The intent of this memo is to summarize the findings and updates incorporated into the Base Level Engineering (BLE) hydrology and hydraulics for the East Fork San Jacinto River (EFSJR) watershed as a result of the recent major storm event Hurricane Harvey. The proposed updates to the EFSJR basin have already been implemented for the West Fork San Jacinto River (WFSJR) watershed. A separate analysis was conducted for the WFSJR watershed with results and recommendations presented in the *BLE West Fork San Jacinto River Watershed Harvey Hydrology & Hydraulics Update* technical memorandum dated December 27, 2017. Due to the schedule of this study, the pre-Harvey hydrology was not used in the EFSJR models and hydraulic results are presented herein.

Major findings related to the incorporation of post-Harvey flood frequency analyses include:

- The 1996 regression model predicts lower 100-year streamflow values than those of the 2009 regression model for 93% of the basins studied (**Figure 1**).
- The 2009 regression equations are recommended for use because they provide streamflow estimates closer to the Flood Insurance Study (FIS) discharges for the EFSJR (**Figure 2**).
- Both the 1996 and 2009 regression models predict lower 100-year streamflow values than the post-Harvey flood frequency analyses on gages located in the East Fork San Jacinto River watersheds (**Figure 2**). Therefore, a frequency adjustment factor is recommended for the 2009 regression equations.
- For each storm recurrence interval and regression model, a constant, "α", was computed from the trendline equations to adjust the 1996 and 2009 regression model streamflow predictions to the post-Harvey flood frequency analyses. The α-factors were applied as a constant multiplier to the regression equations to obtain the adjusted flows (**Figure 3**). The computed α-factors are given in **Table 1**. The factors for the 10-year storm event are less than one, so no adjustment is recommended for the 10-year (**Table 4**).

Table 9. Computed α-factors for the EFSJR Watershed

	10-year	25-year	50-year	100-year	500-year
α_{1996}	1.70	1.82	2.07	2.33	2.50
α_{2009}	0.87	1.04	1.17	1.33	1.76

- The adjusted 2009 model Q_{100} flows were applied to six representative streams—the main stem of the EFSJR, one from Winters Bayou HUC 10, and two each from Tarkington Bayou/Luce Bayou HUC 10 and Peach Creek/Caney Creek HUC 10. The water surface elevations increase is shown in **Figure 4**. There is a positive correlation between the magnitude of the increase and the flow in the stream.

Major findings of BLE model calibration to recorded flows and stages from Harvey:

- Manning's roughness coefficients (n-values) assigned by the GIS tool, which utilizes the 2011 National Land Cover Database (NLCD) data, appear to be low when the recorded Harvey USGS gage flows are input into the models and the water surface elevations are compared to the recorded Harvey USGS gage elevations (**Figures 5** and **6**).

- An overbank n-value adjustment of +0.05 with a minimum final value of 0.11 is recommended for the East Fork San Jacinto River. This alters the range of Manning's n-values from 0.05 – 0.12 to 0.11 – 0.17. The channel adjustment of +0.02 with a minimum final value of 0.06 is recommended. This will alter the range of Manning's n-values from 0.03 – 0.07 to 0.06 – 0.09. The exception to the adjustment of roughness coefficients within the channel is through large reservoirs or lakes. The Manning's n-value was set to 0.03 through Lake Houston. Increasing the n-values results in water surface elevation profiles more representative of the gage elevations recorded during Harvey (**Figure 5**).

- In a review of the East Fork San Jacinto n-values assigned, it was found that the NLCD dataset may assign inaccurate land use values in various locations, which leads to low Manning's n-values reported using the GIS tool and subsequently used in the hydraulic models (**Figure 6**). During the model building process, the n-values assigned using the GIS tool should be reviewed.

Suggested Adjustments Based On Findings

1. The Manning's roughness coefficients for the East Fork San Jacinto River should be increased by 0.02 in the channel and 0.05 in the overbanks, with minimum values of 0.06 and 0.11, respectively. The following table details the adjustments that are suggested while **Figure 7** shows the increase in water surface elevations when using these proposed coefficients.

Table 10. Roughness Value Adjustments

Channel		Overbank		Large Lake/Reservoir	
Original Assigned Value	Suggested Value	Original Assigned Value	Suggested Value	Original Assigned Value	Suggested Value
0.03	0.06	0.05	0.11	0.03	0.015
0.04	0.06	0.075	0.125		
0.05	0.07	0.1	0.15		
0.06	0.08	0.12	0.17		
0.07	0.09				

2. Polygons created by the Manning's roughness assignment tool should be viewed in conjunction with aerial imagery during model building to verify appropriate land use values are present in the NLCD dataset.

3. **Table 3** shows the published 2009 equations for Texas. In these equations, Q_i represents peak stream flow for i-recurrence interval (annual chance exceedance (a.c.e.)) in cubic feet per second (cfs), P represents mean annual precipitation in inches, S represents dimensionless main-channel slope, Ω represents the OmegaEM parameter (**Figure 8**), and A represents cumulative drainage area in square miles. The flows calculated from the 2009 regression equations should be adjusted by the factors in **Table 4**.

Table 11. Summary of Regression Equations in Texas (SIR 2009-5087)

Recurrence Interval	Equation
$Q_{10\%}$	$P^{1.203} \times S^{0.403} \times 10^{[0.918\Omega + 13.62 - 11.97A\text{^}(-0.0289)]}$
$Q_{4\%}$	$P^{1.140} \times S^{0.446} \times 10^{[0.945\Omega + 11.79 - 9.819A\text{^}(-0.0374)]}$
$Q_{2\%}$	$P^{1.105} \times S^{0.476} \times 10^{[0.961\Omega + 11.17 - 8.997A\text{^}(-0.0424)]}$
$Q_{1\%}$	$P^{1.071} \times S^{0.507} \times 10^{[0.969\Omega + 10.82 - 8.448A\text{^}(-0.0467)]}$
$Q_{0.2\%}$	$P^{0.988} \times S^{0.569} \times 10^{[0.976\Omega + 10.40 - 7.605A\text{^}(-0.0554)]}$
Variables: Q_i, peak flow for i recurrence interval (a.c.e.), in cubic feet per second; P, mean annual precipitation, in inches; S, Main-channel slope (dimensionless); Ω, OmegaEM parameter; A, cumulative drainage area, in square miles	

Table 12. Recommended Flow Adjustments for BLE on the EFSJR Watersheds

	10-year	25-year	50-year	100-year	500-year
α_{2009}	None	1.04	1.17	1.33	1.76

Supporting Figures

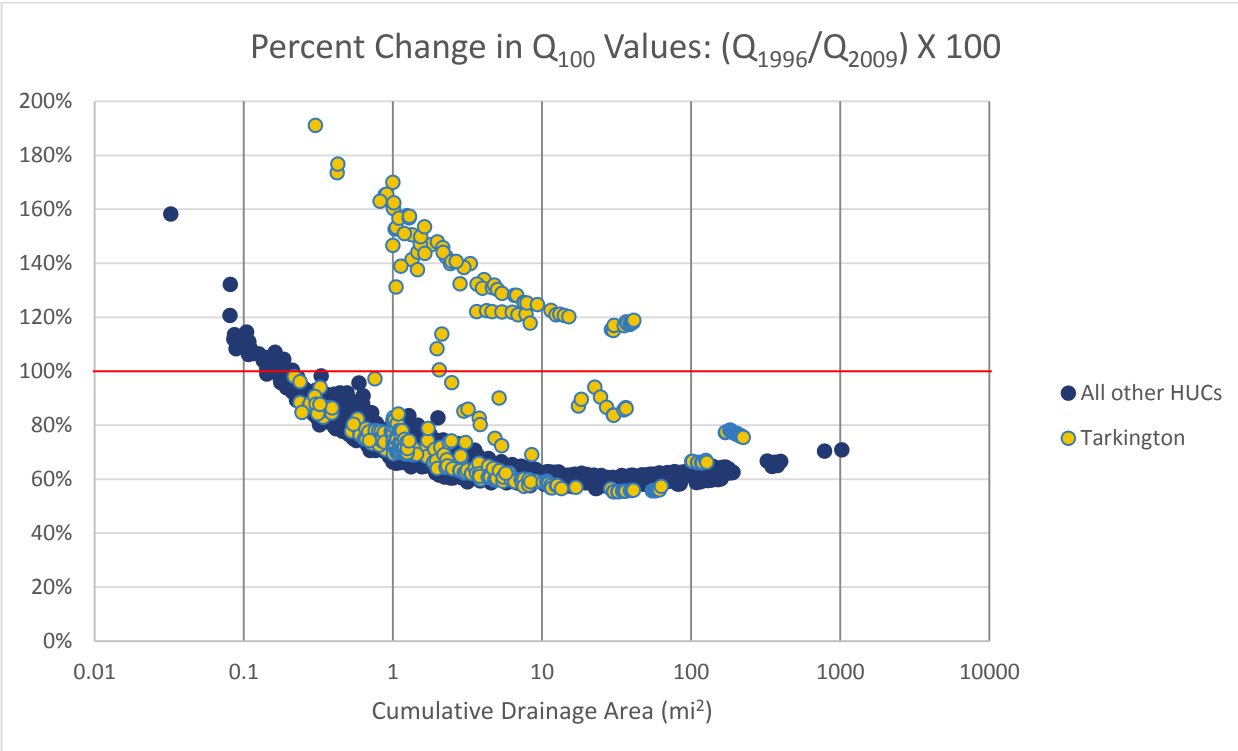


Figure 9. A comparison of Q_{100} values calculated with the 1996 and 2009 regression models for the EFSJR watershed. Tarkington basins are plotted in yellow; all other HUCs within the watershed are blue. 2009 regression flows are higher than 1996 regression flows for 93% of the basins. However, 1996 regression flows are higher in basins with small cumulative drainage area (< 0.1 square miles) or those with a negative Ω value (i.e., Tarkington).

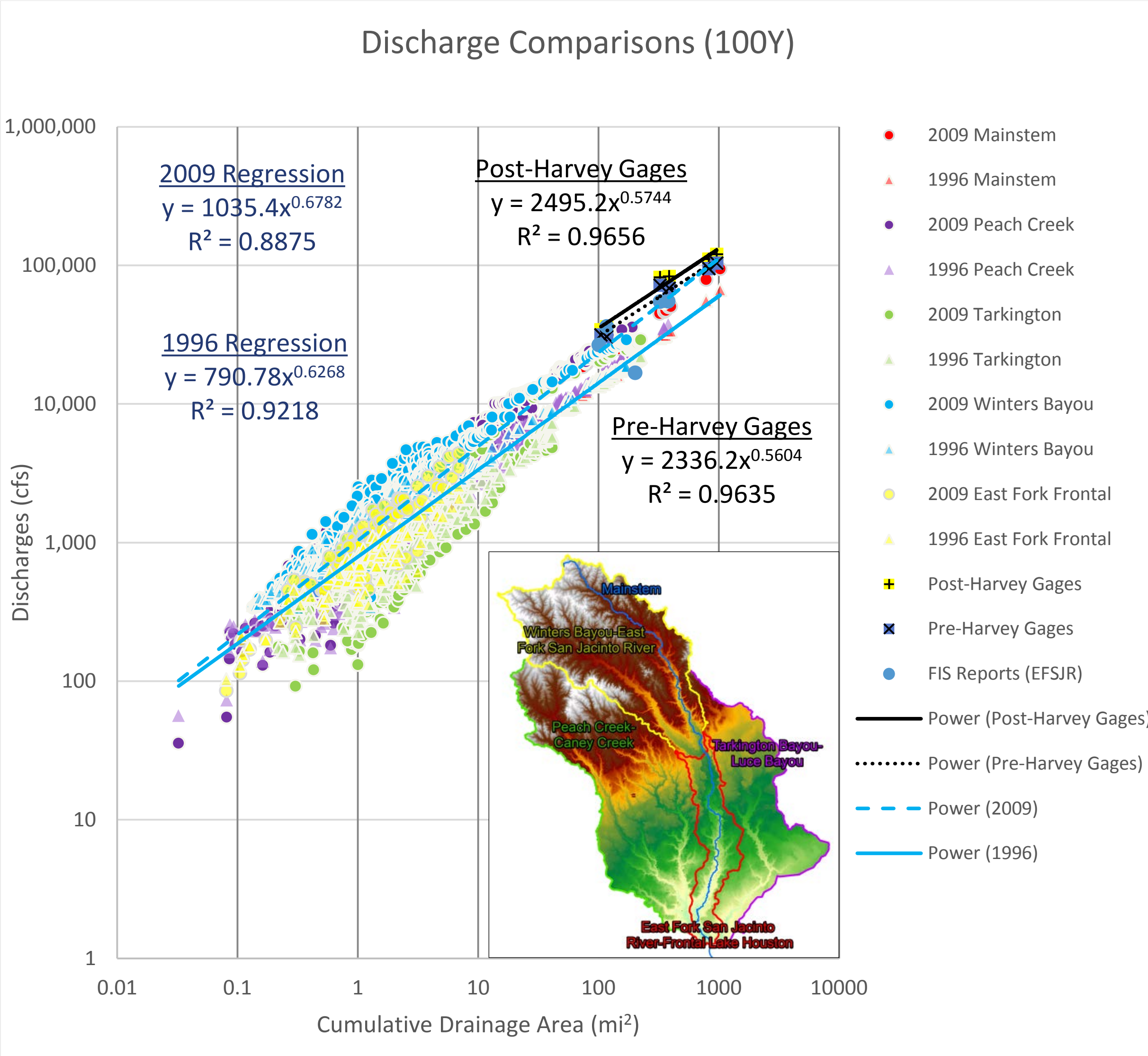


Figure 10. A comparison of Q_{100} values calculated from the regression models and the gage analyses. The HUCs are differentiated by color, as shown on the legend. The circles and triangles represent the 2009 and 1996 regression model discharges, respectively. The solid blue power trendline is fitted to all 2009 data points, and the dashed blue power trendline is fitted to all 1996 data points. In general, both 2009 and 1996 regression models under-predict streamflow when compared to the gage analyses. The 2009 model discharges are closer to the FIS discharges than those of the 1996 model.

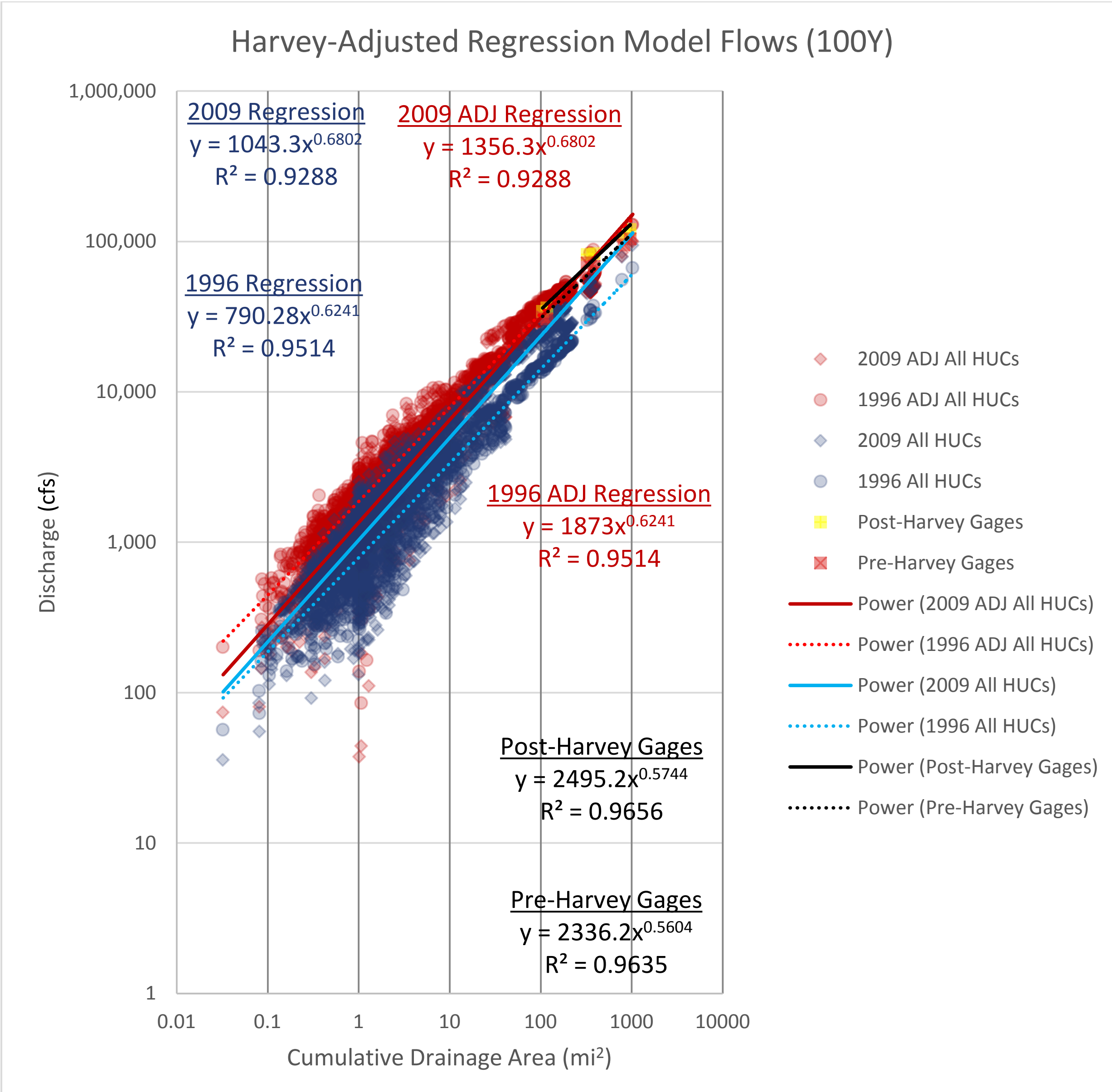


Figure 11. A comparison of Harvey-adjusted and non-adjusted regression model Q_{100} values. The solid black trendline is fitted to the post-Harvey gage analyses, representing the "target" trendline. The dotted blue trendline is fitted to the 1996 non-adjusted model. When flows are multiplied by the α-factor ($\alpha_{1996,\ 100Y}$ = 2.33), the trendline translates upward (represented by the dotted red line). The solid blue trendline represents the 2009 non-adjusted model. When multiplied by its α-factor ($\alpha_{2009,\ 100Y}$ = 1.33), the solid red trendline is the result.

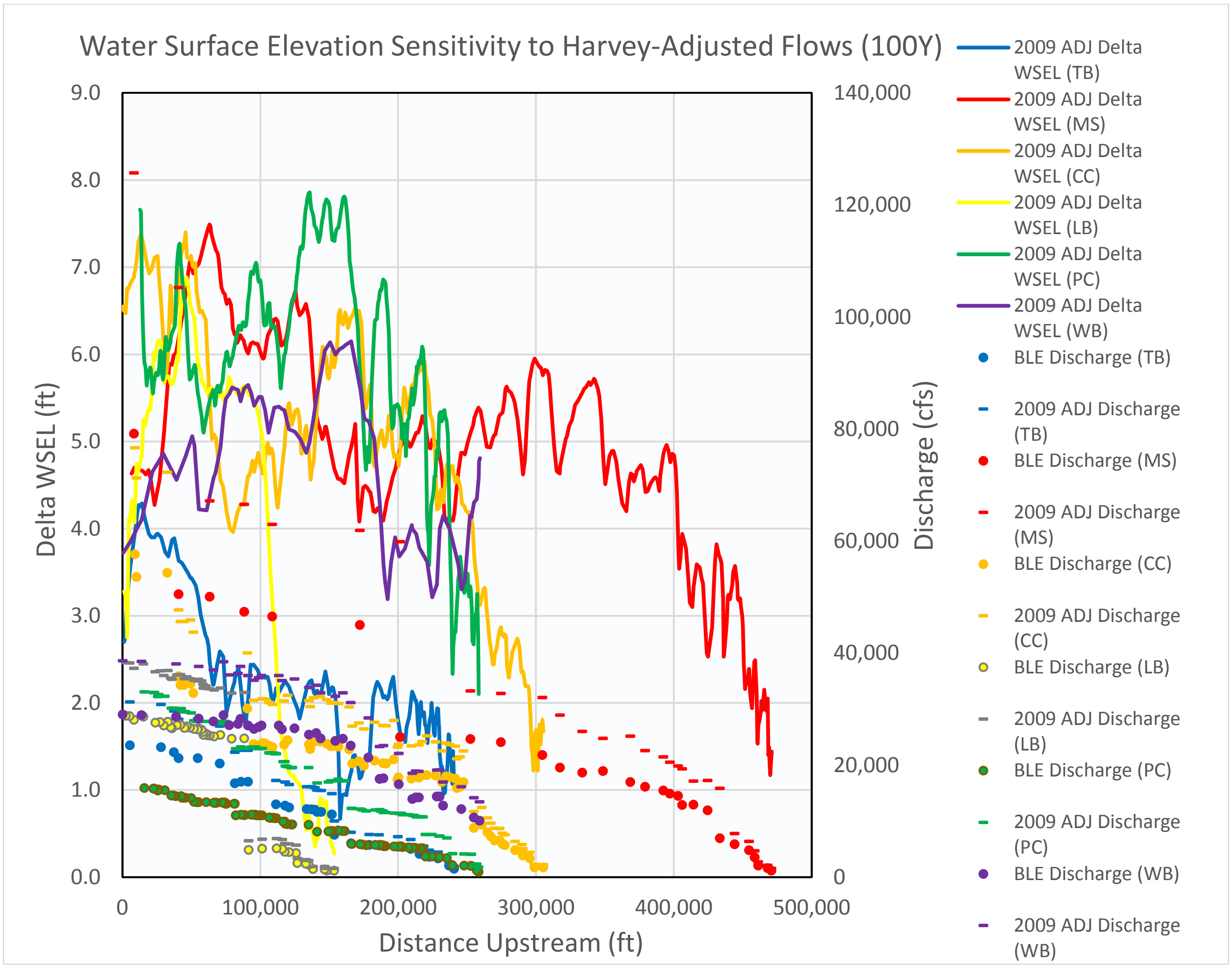


Figure 12. The sensitivity of water surface elevation to changes in Q_{100} for six streams in the EFSJR watershed. The streams studied were: the main stem of the EFSJR (MS), Winters Bayou (WB), Peach Creek (PC), Tarkington Bayou (TB), Caney Creek (CC), and Luce Bayou (LB). The solid lines (color-differentiated by stream) represent the increase in water surface elevation from the original BLE model due to the adjusted 2009 discharges. There is a positive correlation between the magnitude of the increase and the amount of flow in the stream.

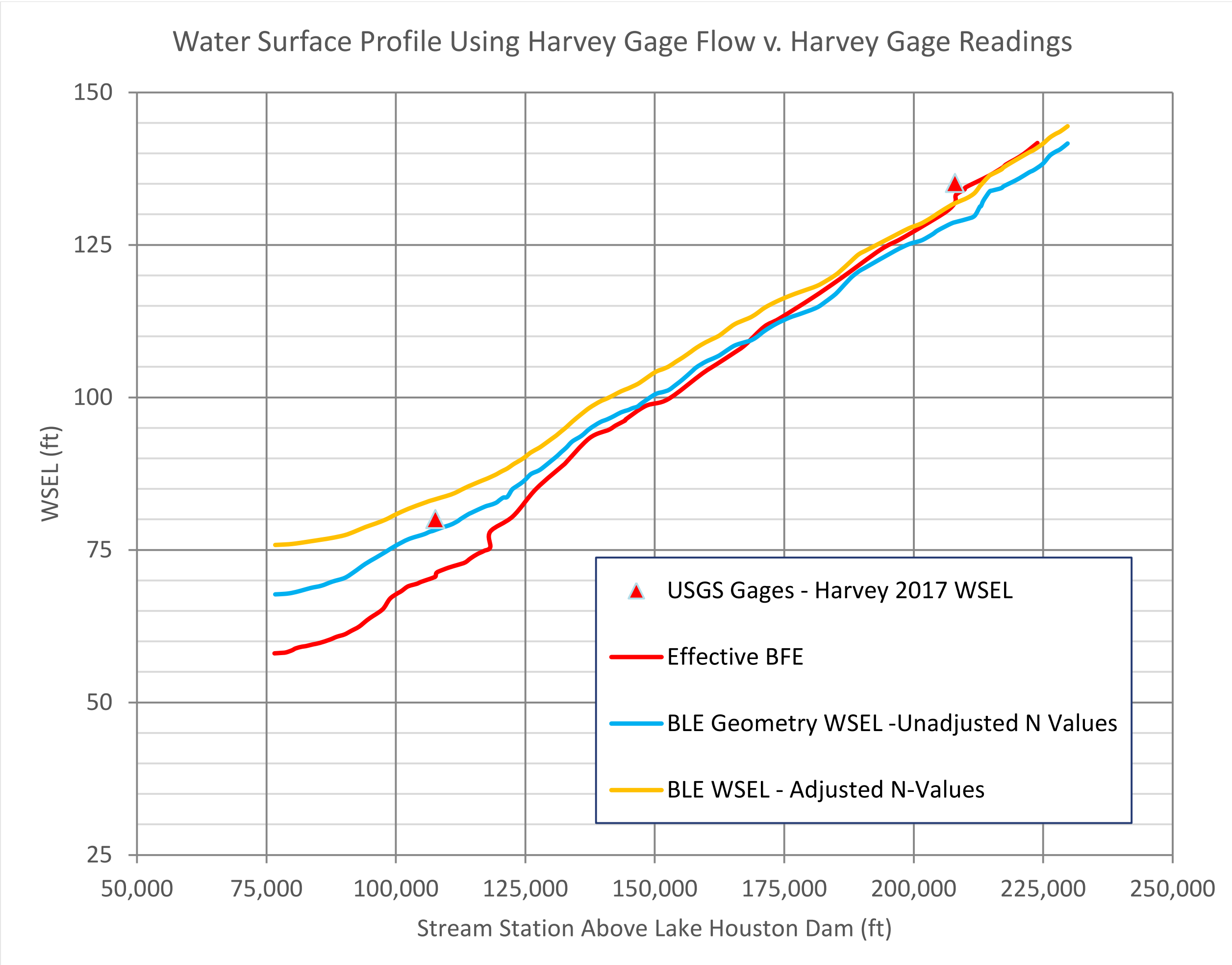


Figure 13. A hydraulic model utilizing the geometry resulting from the standard BLE process and peak flows recorded by USGS gages during Hurricane Harvey resulted in lower water surfaces than those recorded by the gages. A hydraulic model utilizing the BLE geometry with adjusted Manning's roughness coefficients and peak flows recorded by USGS gages during Hurricane Harvey resulted in similar water surfaces to those recorded by the gages.

Table 13. A tabular comparison of the modeled conditions as described in Figure 5. The larger discrepancy in water surface elevations along the East Fork San Jacinto mainstem between the modeled elevation and gage near Cleveland is due to erroneous values in the NLCD dataset. Correcting these values then adjusting according to the recommendations provided in the executive summary raises the water surface elevation to within 0.5 foot of the Cleveland reading during Harvey.

USGS Gage	Gage Location	Gage Peak Water Surface	Original Geometry Peak WS	Adjusted Geometry Peak WS	Orig. Geom WS - Gage WS	Adjusted Geom WS - Gage WS
08070000	E Fork San Jacinto River near Cleveland	135.13	131.27	134.63	-3.86	-0.50
08070200	E Fork San Jacinto River near New Caney	80.05*	78.06	83.12	-1.99	3.07
08070500	Caney Creek near Splendora	145.01	140.48	142.77	-4.53	-2.24
08071000	Peach Creek at Splendora	107.16	103.89	107.14	-3.27	-0.02

*Datum of gage changed from 43.98-ft above NGVD29 to NAVD88, 2001 adjustment, on October 1, 2016. New datum is 43.0-ft below previous datum. In summary, datum of gage is 0 feet above NAVD88.

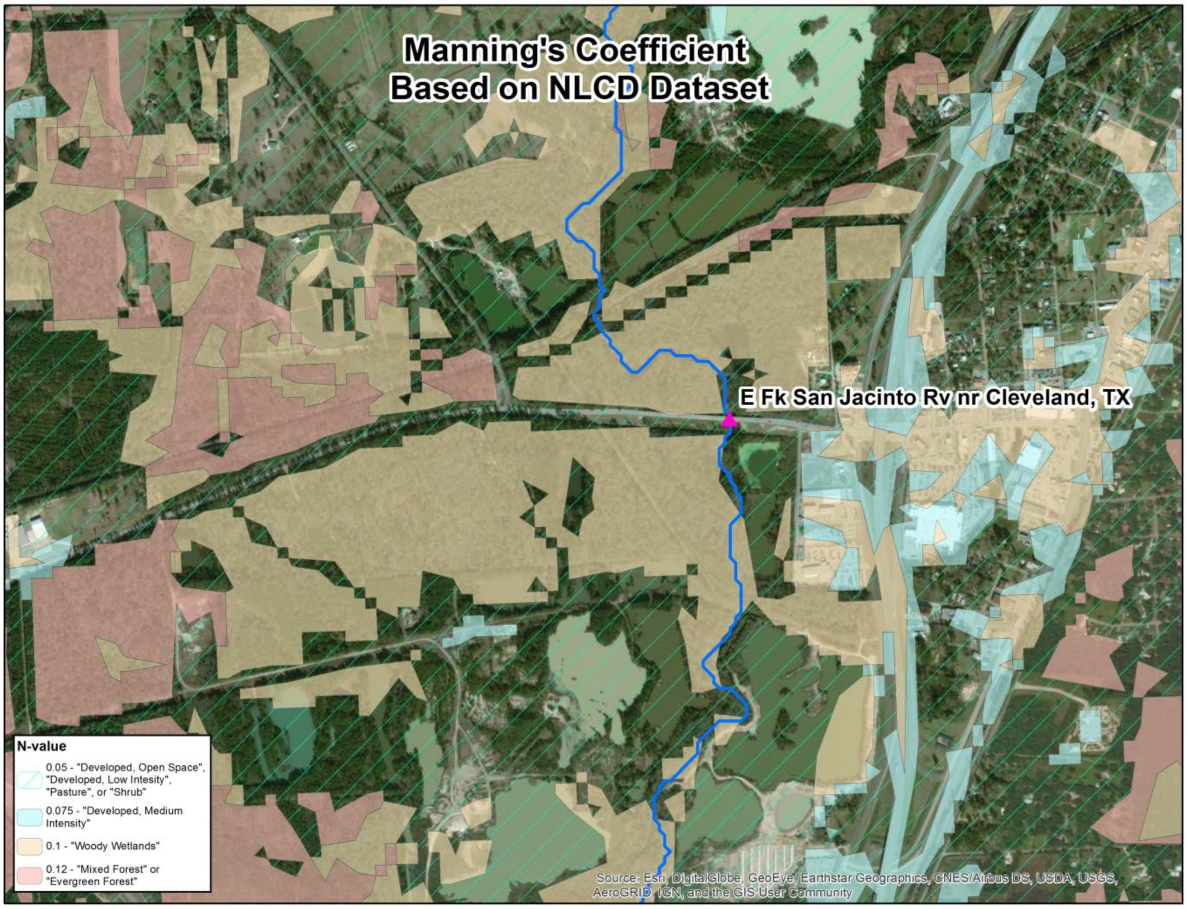


Figure 14. The graphic shows land use type which is erroneously reported in the NLCD. At this location, the NLCD raster shows 'Developed – Open Space/Low Intensity' in the majority of the area. The GIS tool initially assigns a Manning's n-value of 0.013 to this, assumed to represent paving, which is then constrained to a minimum value of 0.05. As seen in the imagery, most of the area is either dense woods, which should be written as 0.12 according to the tool, or woody wetlands with dense tree cover, which should be written as 0.1 according to the tool. Correcting these values then adjusting according to the recommendations provided in the executive summary raises the water surface elevation to within 0.5 foot of the Cleveland gage reading during Harvey.

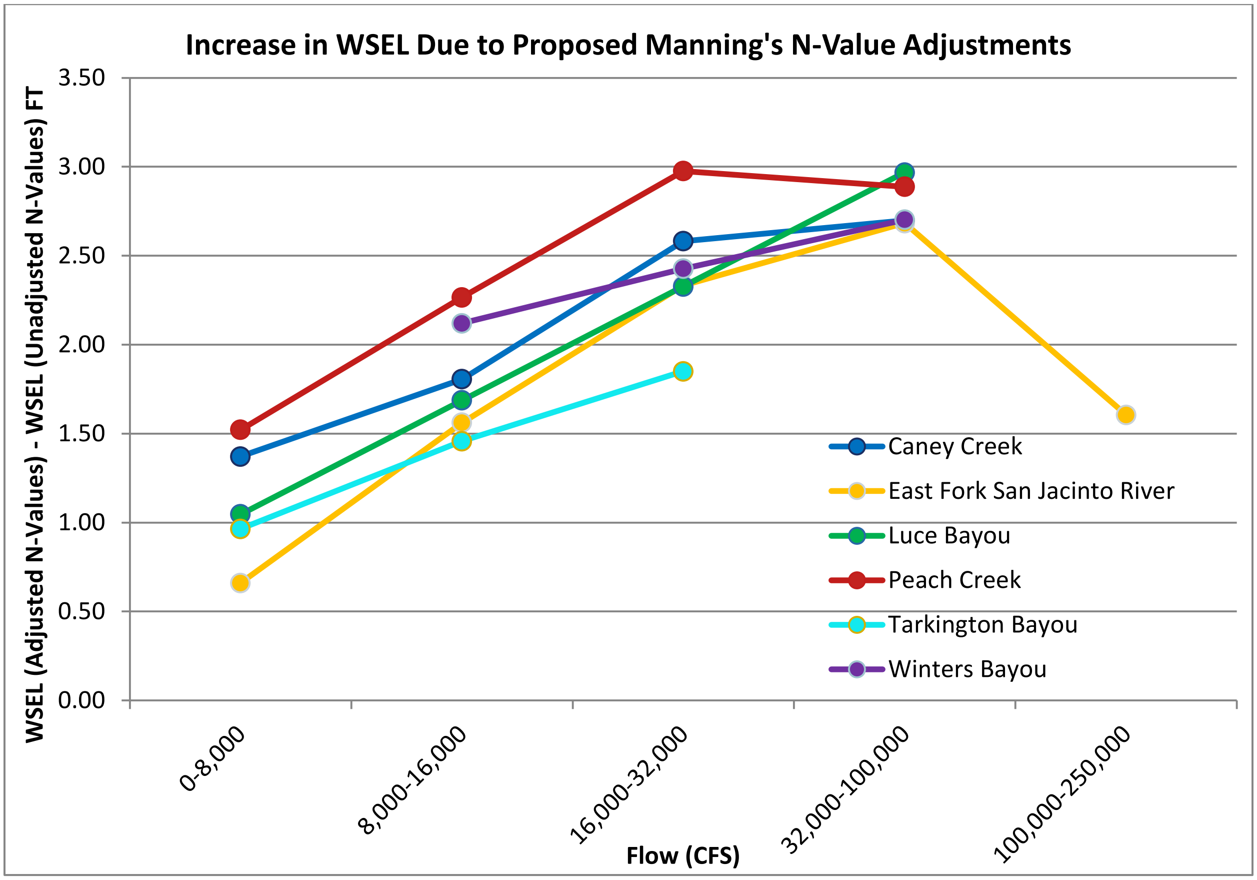


Figure 15. The change in water surface elevation based on the proposed Manning's roughness coefficient adjustments was plotted for several streams. As the flow in the stream increases the effects of the proposed adjustments are increased. There is a fluctuation in the plotting of the EFSJ mainstem because n-values were lowered through Lake Houston.

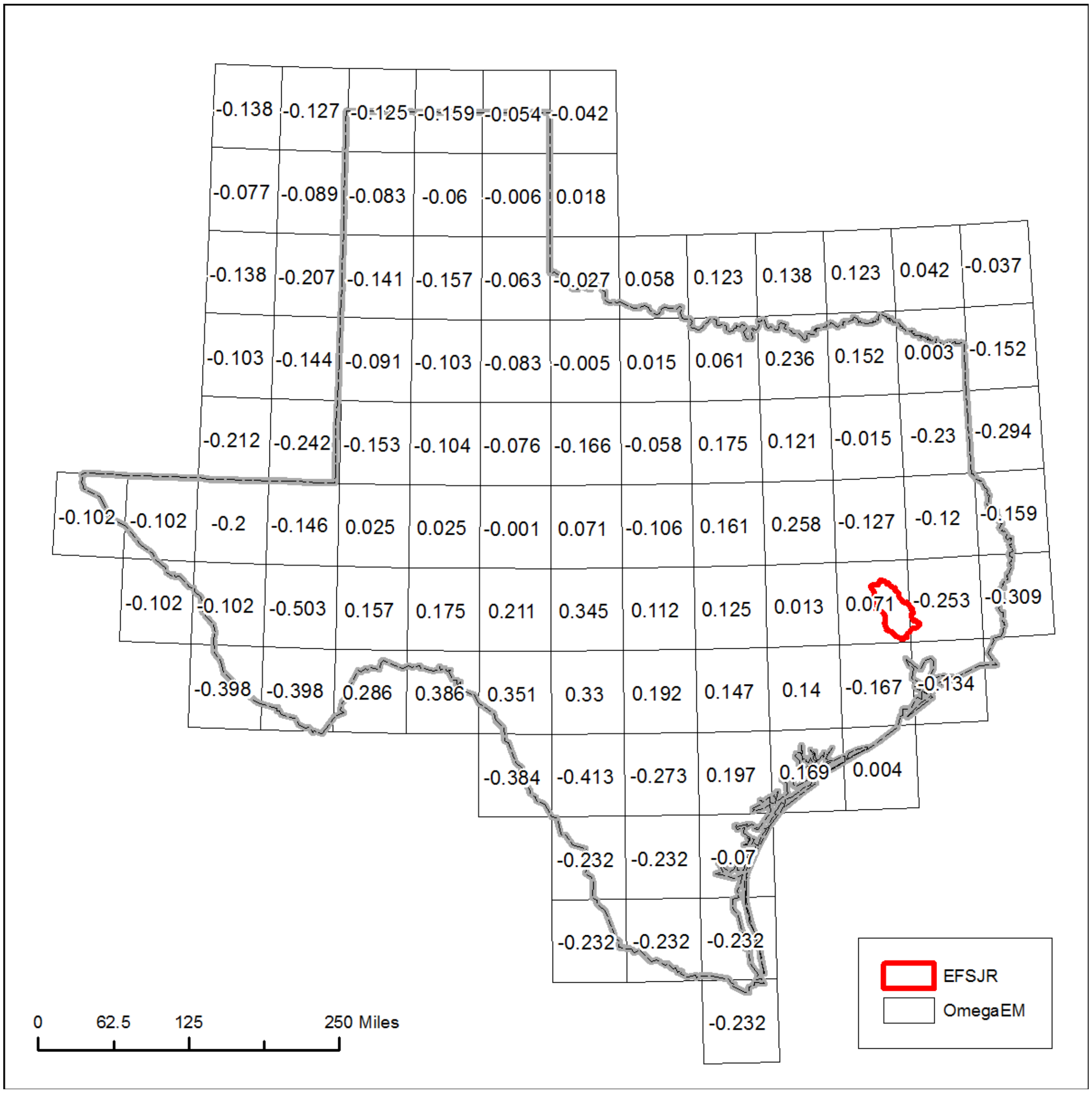


Figure 16. Study area for EFSJR superimposed on statewide map of Omega EM values. Omega EM parameter represents a generalized terrain and climate index for regionalization of peak-streamflow frequency. For full discussion of the development of the Omega EM parameter please consult the 2009 Texas regression report by William Asquith and Meghan Roussel (https://pubs.usgs.gov/sir/2009/5087/).