Compass
Identify, Interpret, Integrate

Middle Brazos Lake Whitney Watershed, TX Base Level Engineering (BLE) Results

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Table of Contents

Executive Summary

FEMA Region VI contracted Compass to complete a Base Level Engineering (BLE) analysis for the Middle Brazos Lake Whitney (MBLW) HUC-8 in Central Texas, to support FEMA's Discovery process and validation of effective Zone A Special Flood Hazard Areas (SFHAs). A portion of the MBLW watershed was recently studied as part of the MBLW Long Term Strategic Plan Phase 2A. The areas studied by Compass do not overlap or replace any of the reaches studied in Phase 2A. To fulfill the project scope, the results of the Phase 2A study have been combined with the results of the study performed by Compass to provide seamless floodplain boundaries, water surface elevation grids, and depth grids.

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 both the United States Geological Survey (USGS) regression equations and gage analysis, where stream gages with sufficient record exist. 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.

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.

Table ES-1: Summary of Stream Miles

Source	Middle Brazos Lake Whitney Stream Miles
CNMS	1,486.3

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	113.3
UNVERIFIED	BEING STUDIED	1,373

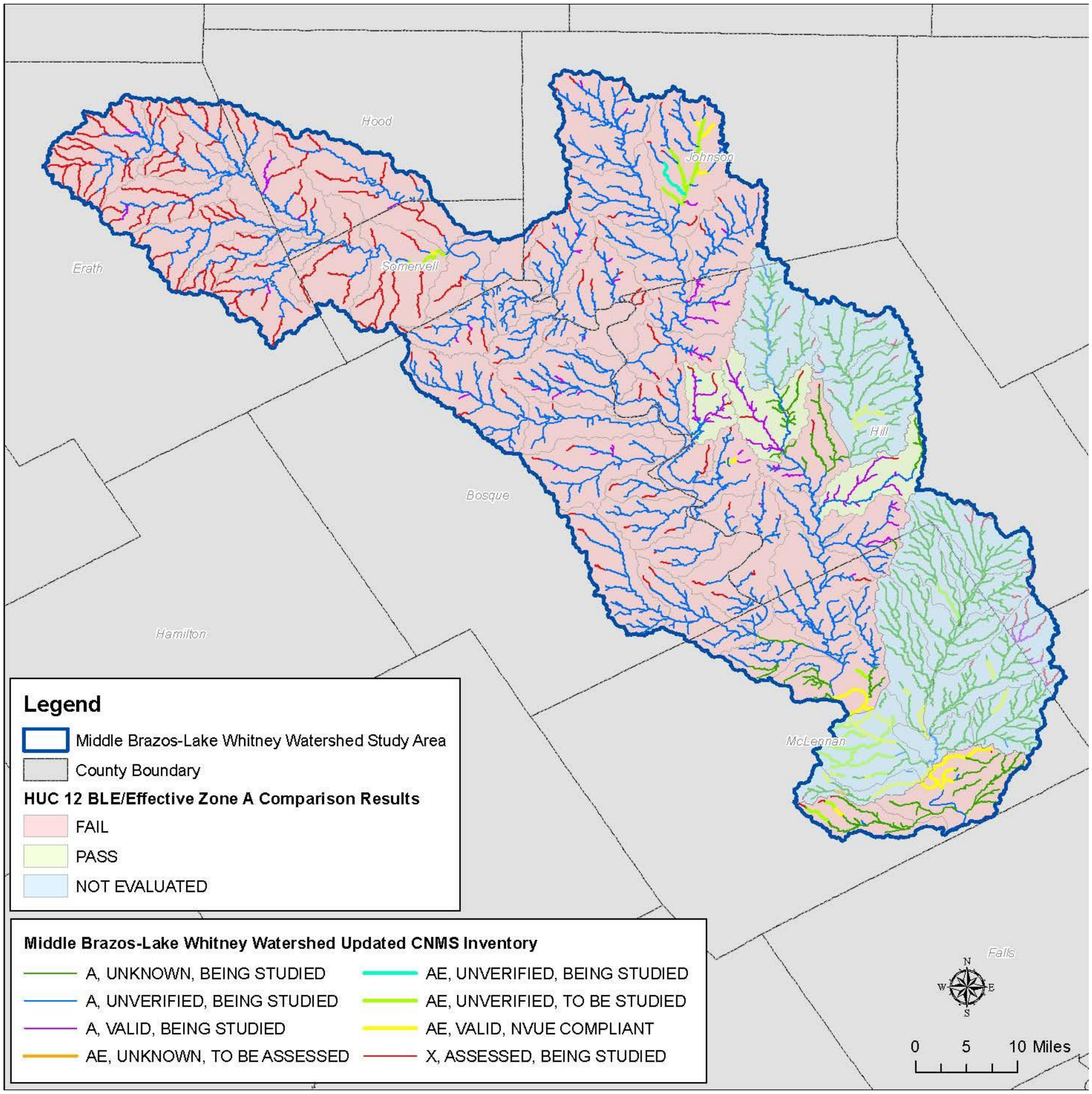

Figure ES-1: Middle Brazos Lake Whitney Watershed CNMS Validation Results

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 Middle Brazos Lake Whitney HUC-8 priority scores which can be used to initiate discussions during the Discovery phase.

Castleman Creek HUC-12 was determined to have the highest priority score and the most need while Cobb Creek and Little Aquilla Creek – Aquilla Creek HUC-12s had the lowest scores.

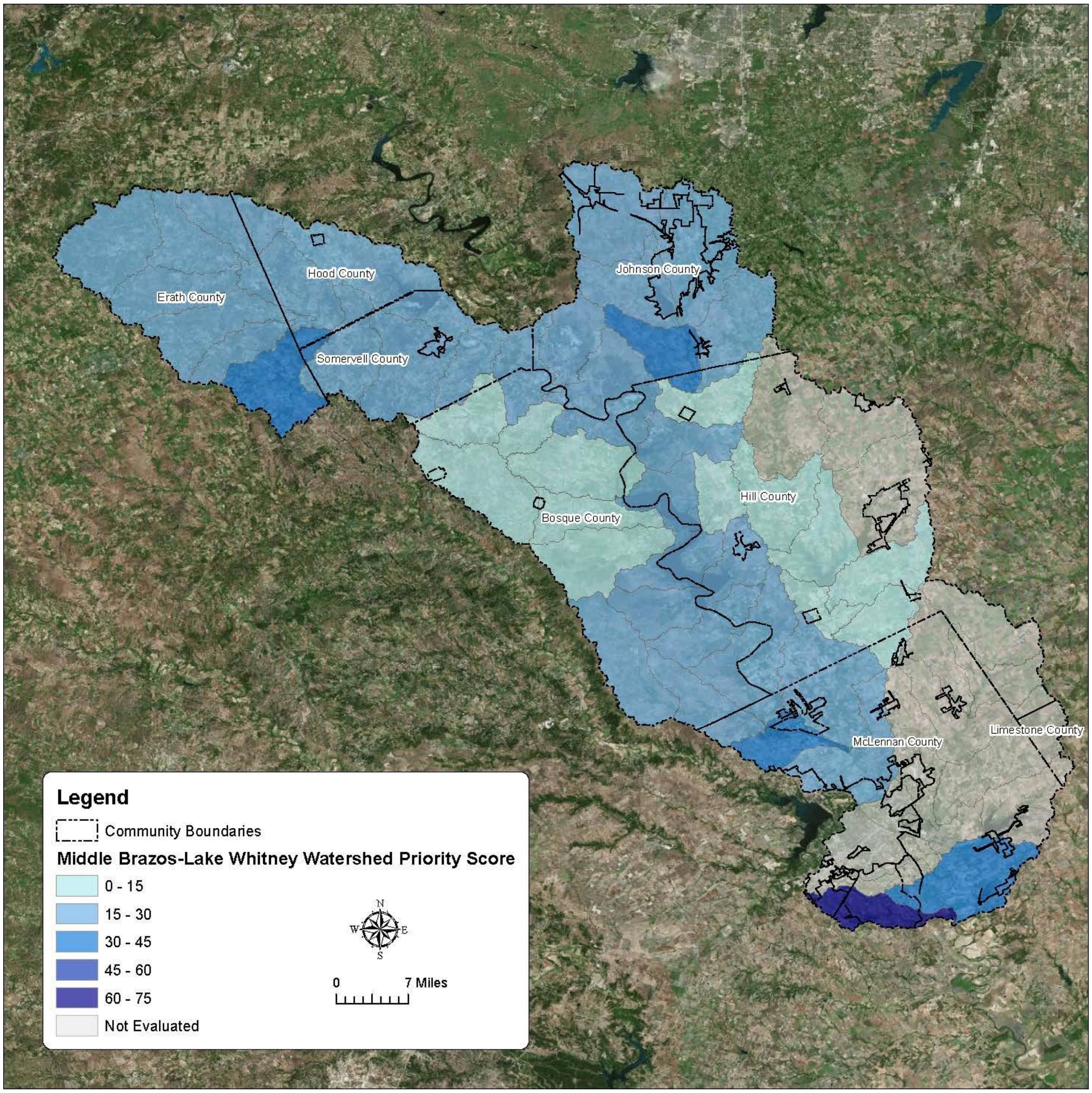

Figure ES-2: Ranking of Middle Brazos Lake Whitney Watershed HUC-12s

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 Middle Brazos Lake Whitney 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 Bosque, Erath, Hill, Hood, Johnson, Limestone, McLennan, and Somervell Counties, and include the following communities: the Cities of Abbott, Aquilla, Bellmead, Beverly Hills, Carl's Corner, Cleburne, Covington, Gholson, Glen Rose, Godley, Hallsburg, Hewitt, Hillsboro, Itasca, Joshua, Keene, Lacy Lakeview, Leroy, Morgan, Rio Vista, Robinson, Ross, Tolar, Waco, Walnut Springs, West, and Woodway. The study area consists of eight HUC-10 basins: Aquilla Creek, Camp Creek-Brazos River, Castleman Creek-Brazos River, Childress Creek-Brazos River, Lake Whitney, Nolan River, Paluxy River, and Tehuacana Creek. Figure 1 shows the orientation of the MBLW HUC-10 basins with respect to the counties.

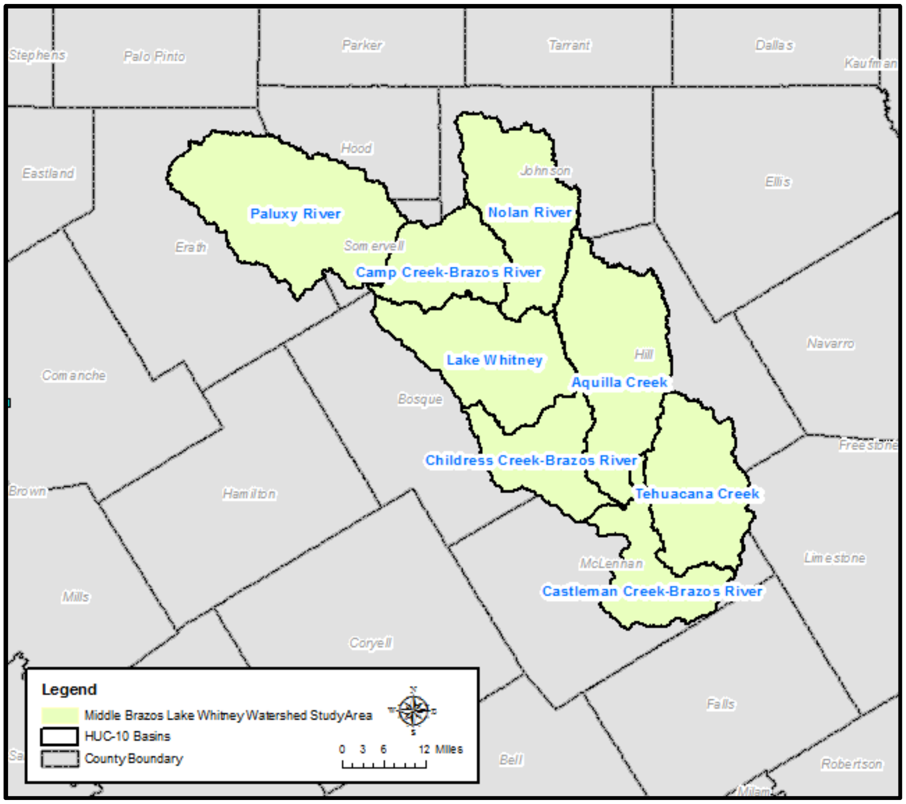

Figure 1: Middle Brazos Lake Whitney Watershed HUC-10 Basins

Compass studied approximately 2,400 miles of stream reaches within the Middle Brazos Lake Whitney 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 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 Middle Brazos Lake Whitney Watershed.

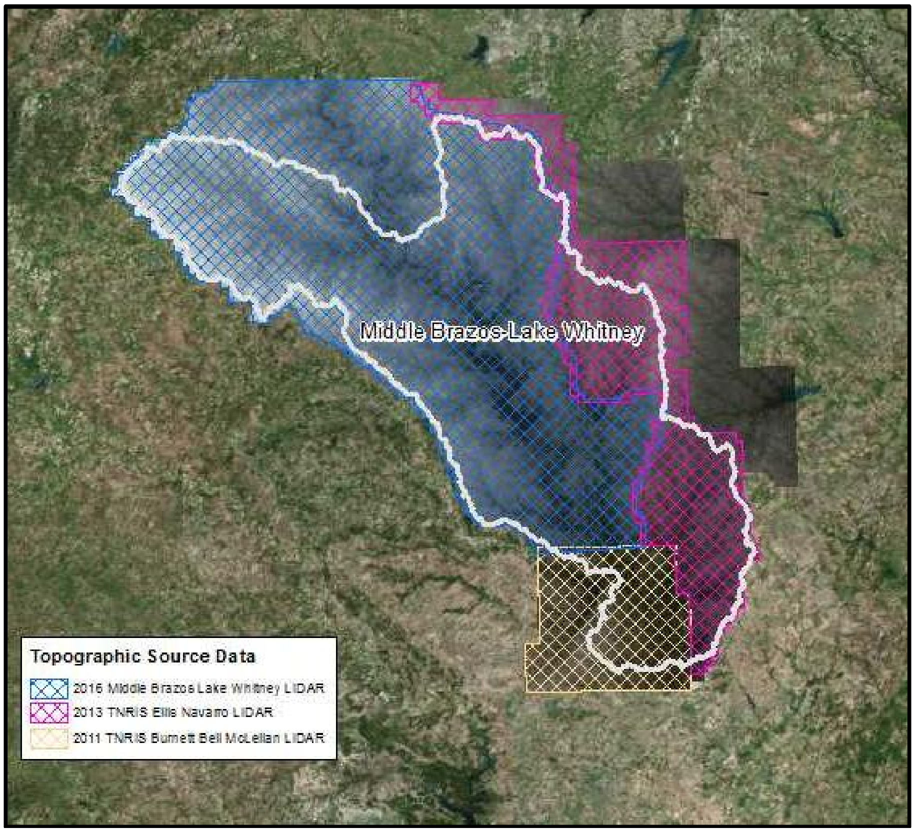

Figure 2: Extent of LiDAR Data for Middle Brazos Lake Whitney Watershed

1.1.1 Source Terrain Data

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

1.1.1.1 2016 USGS Middle Brazos Lake Whitney LiDAR

The 2016 USGS Middle Brazos Lake Whitney LiDAR was acquired by Digital Aerial Solutions, LLC (DAS) for the G16PD00019, Middle Brazos Lake Whitney, TX QL2 LiDAR. The area encompasses approximately 2,370 square miles. LiDAR data collected for the G16PD00019, Middle Brazos Lake Whitney, TX LiDAR survey has a nominal pulse spacing of 0.7-meters, and includes up to 8 discrete returns per pulse, along with intensity values for each return. The RMSEz reported for the dataset was 18.28-cm at the 95% confidence level which meets project accuracy specifications of the National Standard for Spatial Data Accuracy (NSSDA).

1.1.1.2 2013 TNRIS Ellis Navarro LiDAR

The 2013 TNRIS Ellis Navarro LiDAR was acquired February 2013 with a publication year of 2013. These AOIs were designated as the Northern and Central Areas of Interest (AOIs). The Northern AOI covered portions of the following counties in Texas: Parker, Hood, Johnson, Ellis, Hill, Navarro, Henderson, McLennan, Limestone, Kaufmann, and Falls. The Central AOI covered portions of the following counties in Texas: Guadalupe, Atascosa, Wilson, Gonzales, Karnes, DeWitt, Live Oak, and

Bee. The RMSEz reported for the dataset was 0.06-meters at the 95% confidence level which meets project accuracy specifications of the NSSDA.

1.1.1.3 2011 TNRIS Burnett Bell McLennan LiDAR

The 2011 TNRIS Burnett Bell McLennan LiDAR was collected between March 11, 2011 and July 31, 2011, with leaf off and significant snow cover on the ground. The AOI includes Bell, Burnett, Coryell, Falls, Lampasas, and McLennan Counties covering approximately 2,349 square miles in the state of Texas. In order to post process the LiDAR data to meet task order specifications, Photo Science established a total of 64 QA control points that were used to calibrate the LiDAR to known ground locations established throughout the project area. The RMSEz reported for the dataset was 9.45 cm at the 95% confidence level which meets project accuracy specifications of the NSSDA.

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 the 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 Middle Brazos Lake Whitney Watershed, the 2016 USGS Middle Brazos Lake Whitney LiDAR was the highest priority, with the 2013 TNRIS Ellis Navarro LiDAR prioritized second, and the 2011 TNRIS Burnett Bell McLennan LiDAR prioritized third. These datasets were used as the data sources for creating the 10-ft and 50-ft DEMs.

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 flowed downstream correctly and routed to outside of the project area.

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 both the United States Geological Survey (USGS) regression equations and gage analysis, where stream gages with sufficient record exist. Regression equations 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) contain the most recent regression equations for Texas. Weighted discharges for streams with gages were calculated using the weighting procedure described in WRI 98-4015 (see Section 1.2.1).

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, precipitation, and OmegaEM.

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;	

Recurrence Interval	Equation
	A, cumulative drainage area, in square miles

Discharges for the 1-percent plus and 1-percent minus a.c.e. were calculated as well. These values were computed 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: https://tnris.org/data-catalog/entry/precipitation/.

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 0 percent and the other at 100 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 to determine Omega EM values on a sub-basin basis. For sub-basins spanning more than one OmegaEM grid, the sub-basin's centroid determined its OmegaEM parameter.

Drainage area for each sub-basin was determined based on automated basin delineations performed by 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 Brazos 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 Stream Gage Analysis

Figure 3 shows the location of the 9 active or discontinued USGS stream gages on 6 streams in the Middle Brazos Lake Whitney watershed used to develop weighted discharges for the study (Table 2). Flood frequency analyses (FFA) were performed for all 9 gages, according to Bulletin 17B guidelines. The flood flow frequency data from these gages were weighted with the regression developed discharges using the procedure described in USGS WRI 98-4178.

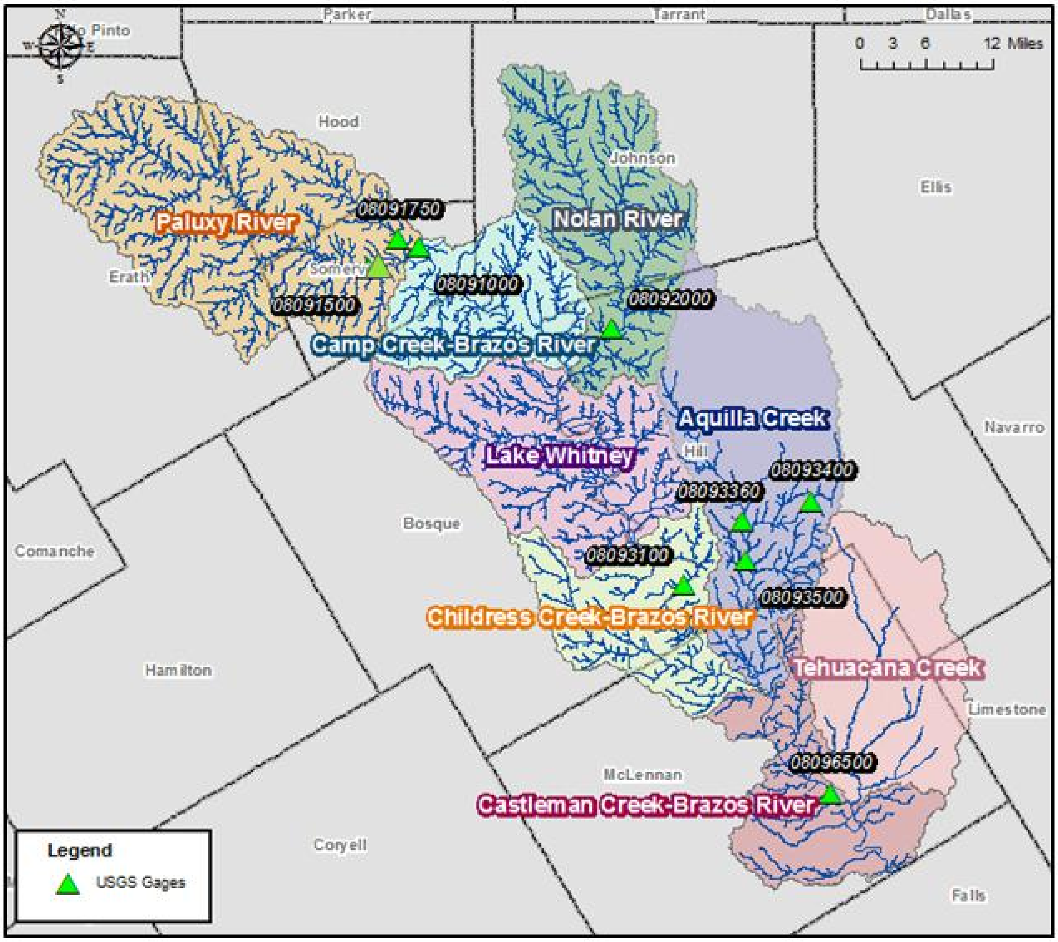

Figure 3: Locations of USGS Gages Utilized in Flood Frequency Analyses

Stream gage analyses were performed with the following working assumptions: (1) All USGS stream gage along the Brazos River were considered, (2) USGS stream gages containing only old records (older than 1941) and fewer records were removed from the analysis, (3) only records starting in year 1941 and recent are considered from each USGS stream gage data in the analysis due to the completion of the Possum Kingdom Dam in 1941, (4) Lake Granbury was completed in 1969, (5) Lake Whitney was completed in 1951, and (6) all results that show a significant decrease in peak flow, while contributing areas are increasing are also discarded from the analysis.

Table 2: USGS Stream Gages in Middle Brazos Lake Whitney Watershed

Gage ID	Flooding Source and Location	Computed Drainage Area (mi.^{2})	Published Drainage Area (mi.^{2})	Period of Record
08091000	Brazos River near Glen Rose, TX	16,252	16,252	1923-present
08093100	Brazos River near Aquilla, TX	17,678	17,678	1939-present
08096500	Brazos River at Waco, TX	20,007	19,993	1885, 1899-present
08091500	Paluxy River at Glen Rose, TX	410	410	1908-1922, 1948-present

Gage ID	Flooding Source and Location	Computed Drainage Area (mi.^{2})	Published Drainage Area (mi.^{2})	Period of Record
08091750	Squaw Creek near Glen Rose, TX	69	70.3	1973-2006
08092000	Nolan River at Blum, TX	281	282	1925, 1947-present
08093400	Cobb Creek near Abbott, TX	13	12.4	1967-1979
08093360	Aquilla Creek above Aquilla, TX	257	255	1980-1984, 1991, 2001-present
08093500	Aquilla Creek near Aquilla, TX	307	308	1936-2001

Table 3 shows the published discharge weighting equations used in this study. In these equations, SE_{TS} represents standard error of the LPIII distribution in log-cubic feet per second (log-cfs), SE_{TR} represents standard error of prediction of the regression at recurrence interval T (a.c.e) in log-cfs, Q_{TW} represents weighted peak discharge at recurrence interval T (a.c.e.) in cfs, Q_{TS} represents log-Pearson Type III peak discharge at recurrence interval T (a.c.e.) in cfs, Q_{TR} represents regression peak discharge at recurrence interval T (a.c.e.) in cfs, $Q_{T-HIGH}^{67\ percent}$ represents the higher prediction interval of the 67-percent in cfs, and $Q_{T-LOW}^{67\ percent}$ represents the lower prediction interval of the 67-percent in cfs.

Table 3: Weighted Discharge Equations (WRI 98-4178)

Variable	Equation
SE_{TS}	$\frac{1}{2}[\log(Q_{TR} - Q_{T-HIGH}^{67\ percent}) - \log(Q_{TR} - Q_{T-LOW}^{67\ percent})]$
Q_{TW}	$(SE_{TR}^2 Q_{TS} + SE_{TS}^2 Q_{TR}) / (SE_{TR}^2 + SE_{TS}^2)$

Variables:

SE_{TS}, standard error of the log-Pearson Type III distribution, in log-cubic feet per second;

SE_{TR}, standard error of prediction of the regression at recurrence interval T, in log-cubic feet per second;

Q_{TW}, weighted peak discharge at recurrence interval T, in cubic feet per second;

Q_{TS}, log-Pearson Type III peak discharge at recurrence interval T, in cubic feet per second

Q_{TR}, regression peak discharge at recurrence interval T, in cubic feet per second;

$Q_{T-HIGH}^{67\ percent}$, higher prediction interval of the 67 percent[2], in cubic feet per second;

$Q_{T-LOW}^{67\ percent}$, lower prediction interval of the 67 percent[1], in cubic feet per second;

[1] The 67-percent confidence limits of USGS WRI 98-4178 are the [100 - (100 - 67)/2] = 83.5-percent confidence limits in PEAKFQ.

For each gage and recurrence interval, a constant SE_{TS} was computed using the published equation on pg. 12 of USGS WRI 98-4178 (Table 3). The computed SE_{TS} values were used in the weighted discharge equations and are presented in Table 4.

Table 4: Summary of Computed SE_{TS} values at USGS Stream Gages in Middle Brazos Lake Whitney Watershed

Gage ID	SE_{TS} (log-cfs)				
	10AEP	4AEP	2AEP	1AEP	0.2AEP
08091000	0.226	0.239	0.245	0.254	0.265
08091500	0.292	0.318	0.333	0.345	0.369
08091750	0.348	0.378	0.397	0.412	0.442
08092000	0.253	0.274	0.286	0.295	0.312
08093100	0.231	0.249	0.258	0.267	0.282
08093360	0.426	0.445	0.454	0.461	0.471
08093400	0.326	0.353	0.368	0.380	0.401
08093500	0.314	0.351	0.373	0.391	0.430
08096500	0.220	0.239	0.246	0.254	0.270

The regression equation discharges for Aquilla Creek, Brazos River, Cobb Creek, Nolan River, Paluxy River, and Squaw Creek were weighted with the FFA discharges for the gages on Aquilla Creek, Brazos River, Cobb Creek, Nolan River, Paluxy River, and Squaw Creek, using the methods described on pg. 10-13 of USGS WRI 98-4015. Weighted discharges determined by gage analysis are presented in Table 5.

Table 5: Weighted Discharges at USGS Stream Gages in Middle Brazos Lake Whitney Watershed

Gage ID	10PCT (cfs)	4PCT (cfs)	2PCT (cfs)	1PCT (cfs)	0.2PCT (cfs)
08091000	72,004	101,473	124,575	150,068	217,838
08091500	20,886	33,214	45,324	60,499	108,485
08091750	8,913	15,039	21,004	28,798	56,115
08092000	30,869	46,617	61,035	77,965	126,947
08093100	57,158	85,675	109,498	137,022	219,374
08093360	16,749	25,342	32,158	39,741	61,975
08093400	3,173	4,496	5,580	6,796	10,270
08093500	18,049	28,856	38,667	50,889	93,047
08096500	75,362	109,108	137,341	169,451	261,870

1.3 Hydraulics

The hydraulic approach for this BLE analysis of the Middle Brazos Lake Whitney 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 that varies cross section spacing 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. Next, a second pass inspection for cross-section placement and alignment 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 crests for 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 6. These default values for dimensions and spacing were subject to change based on engineering judgment.

Table 6: Cross-Section Default Parameters

Drainage area (upper limit)	XS Spacing	Channel Top Width	Channel Bottom Width	Channel Depth
1.0	500	9	7.2	0.5
2.0	500	10.2	8.4	0.5
4.0	500	12	10.2	0.5
8.0	500	13.8	12.6	0.5
10.0	500	15	13.2	0.5

Drainage area (upper limit)	XS Spacing	Channel Top Width	Channel Bottom Width	Channel Depth
15.0	500	16.8	15	0.5
20.0	500	19.2	17.4	0.5
25.0	500	22.2	20.4	0.5
30.0	500	25.2	23.4	0.5
40.0	500	30	28.2	0.5
50.0	600	31.2	27.6	1
75.0	600	32.4	28.8	1
100.0	750	42	38.4	1
150.0	750	51	47.4	1
250.0	1000	60	56.4	2
500.0	1500	66	62.4	2
1000.0	2500	66	62.4	3
2000.0	2500	150	140	3
5000.0	2500	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 7. 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.

Table 7: 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. Implications of these systems may considerably affect risk.

1.4 Quality Control

Following the initial hydraulic model analysis in each watershed, the resulting flood hazard area delineations 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 revisions 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 4. 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 5 below), modifications to improve perpendicular orientation at the channel, adjustment of discharge breaks to better represent flow addition points, revisions to cross sections at dams, 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.

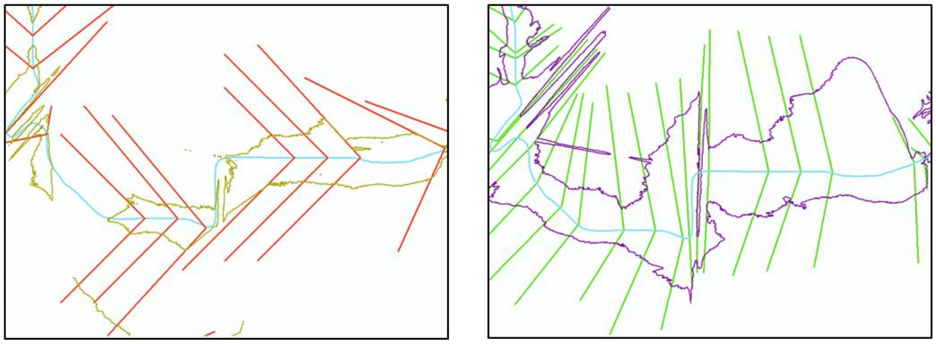

Figure 4: Default "V" angle cross-sections automated by WISE (left). Manually edited cross-sections to more accurately capture terrain (right). Resulting flood boundaries shown in gold (left) or purple (right) for clarity.

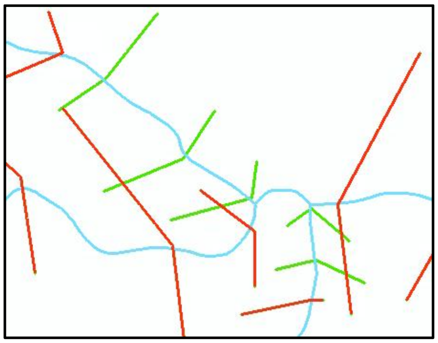

Figure 5: Manually added cross-sections (green) to improve accuracy of tie-ins at confluences.

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 1% flood hazard area. 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

The Middle Brazos Lake Whitney Watershed is located in Central 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 achieve proper 1%-acf 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 dams of varying sizes 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, particularly for those dams designed for flood control, when upgrading these models for detailed studies.

There are a few containment issues across the study area. In some areas the 0.2%-acf flows overtopped cross section. For these situations, additional investigation is recommended when upgrading these models for detailed study.

In the Aquilla Creek HUC-10, UNT 92 in Aquilla Cr Watershed, UNT 106 in Aquilla Cr Watershed, and UNT 16 in Aquilla Cr Watershed were not able to contain 0.2%-acf flooding.

In the Camp Creek-Brazos River HUC-10, UNT 138 in Camp Cr Watershed and Wilson Creek were not able to contain the 0.2%-acf flooding.

In the Castleman Creek-Brazos River HUC-10, Bellmead Ditch, Flat Creek, Meyers Lane Ditch, Primrose Creek, Salem Branch, UNT 052 Castleman Cr Watershed, and Waco Creek were not able to contain the 0.2%-acf flooding.

In the Lake Whitney HUC-10, UNT 011 in Lake Whitney, UNT 083 in Lake Whitney, and UNT 102 in Lake Whitney were not able to contain the 0.2%-acf flooding.

In Nolan River HUC-10, UNT 176 in Nolan River Watershed and West Buffalo Creek were not able to contain the 0.2%-acf flooding.

The LiDAR data used for the MBLW Long Term Strategic Plan Phase 2A was collected at a different time than the LiDAR data used for this study. In this type of situation, differences in the water levels and large streams can vary noticeably. Aquilla Creek is one such case. The LiDAR used in Phase 2A study captured elevations in Aquilla Lake of 533.56-ft. The LiDAR used in this study captured lake elevations of 538.1-ft. Because BLE projects don’t use bathymetric data, this difference in lake elevation occurs. As the result the 1%-acf water surface elevation at the location where the Phase 2A and current study meet has a discontinuity. As the Compass study is more conservative, it is recommended that the Phase 2A study be revised.

Results and Recommendations

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.

3.1 CNMS Validation of Effective Zone A SFHA

The inventory of Zone A studies (1,497.4 miles) in the Middle Brazos-Lake Whitney watershed were classified in CNMS with validation status of "UNVERIFIED" (1,384.1 miles) or "VALID" (113.3 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.

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 Middle Brazos-Lake Whitney Watershed, the effective Zone A topographic data leveraged was based upon United States Interagency Elevation Inventory. The three LiDAR sources discussed in section 1.1 are a significant improvement from the effective Zone A topographic source for the entire study area. Therefore, all reaches failed 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 Middle Brazos-Lake Whitney 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. The entire study area is still classified as rural, so all reaches pass this check.

All of the initial assessment results are shown in Table 8.

Table 8: 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	Effective hydrology methods used are unknown
A3 – Development	Pass	HUC12 watershed is still rural

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 do not have the effective methodology documented. Therefore, all reaches 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 9 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 9: BLE Comparison Results

HUC-12 Watershed		Total FBS points	Fail	Pass	%Pass	BLE Comparison Pass? (>85%)	Priority Score
Watershed Name	Watershed Number						
Middle Brazos-Lake Whitney	All Streams	82,695	27,849	54,846	65%	FAIL	
Alligator Creek	120602020507	1,474	462	1,012	69%	FAIL	10
Bear Creek-Lake Whitney	120602020405	1,659	636	1,023	62%	FAIL	18
Berrys Creek	120602020104	1,192	382	810	68%	FAIL	22
Bowden Branch-Paluxy River	120602020111	372	129	243	65%	FAIL	17
Buck Creek-Brazos River	120602020304	1,933	718	1,215	63%	FAIL	18
Camp Creek	120602020303	1,939	517	1,422	73%	FAIL	21
Castleman Creek	120602020804	63	63	0	0%	FAIL	63
Cedar Creek	120602020404	1,329	159	1,170	88%	PASS	4
Cedron Creek	120602020406	2,687	802	1,885	70%	FAIL	7
Cobb Creek	120602020506	1,484	197	1,287	87%	PASS	4
Coon Creek-Brazos River	120602020601	1,559	567	992	64%	FAIL	18
Dead Horse Creek-Aquilla Creek	120602020508	896	391	505	56%	FAIL	11
Dry Branch-Paluxy River	120602020108	1,556	400	1,156	74%	FAIL	21
Dry Creek-Aquilla Creek	120602020509	3,681	1,557	2,124	58%	FAIL	21
Eagle Creek-Brazos River	120602020605	1,910	916	994	52%	FAIL	38
Eddy Branch-Brazos River	120602020302	856	428	428	50%	FAIL	25
Frazier Creek-Lake Whitney	120602020407	982	419	563	57%	FAIL	19
Gourd Neck Branch-Nolan River	120602020206	1,566	357	1,209	77%	FAIL	9
Haley Branch	120602020205	1,951	783	1,168	60%	FAIL	32
Ham Creek-Brazos River	120602020306	3,660	1,512	2,148	59%	FAIL	25
Hill Creek	120602020301	1,737	428	1,309	75%	FAIL	7
Jacks Branch-Aquilla Creek	120602020505	714	227	487	68%	FAIL	8
Little Aquilla Creek-Aquilla Creek	120602020504	1,056	129	927	88%	PASS	4
Lower Childress Creek	120602020603	2,128	757	1,371	64%	FAIL	17
Lower North Paluxy River	120602020102	1,140	369	771	68%	FAIL	26
Lower Steele Creek	120602020403	2,032	635	1,397	69%	FAIL	9
Manos Creek-Brazos River	120602020805	227	114	113	50%	FAIL	32
Mesquite Creek-Brazos River	120602020401	3,569	1,079	2,490	70%	FAIL	13
Mustang Creek	120602020204	2,759	953	1,806	65%	FAIL	19

Pony Creek	120602020107	1,566	609	957	61%	FAIL	31
Richardson Creek	120602020106	1,783	504	1,279	72%	FAIL	23
Robinson Branch-Nolan River	120602020203	2,483	647	1,836	74%	FAIL	18
Rock Creek-Nolan River	120602020207	1,348	569	779	58%	FAIL	21
Rough Creek-Paluxy River	120602020109	762	207	555	73%	FAIL	17
South Paluxy River	120602020103	1,117	287	830	74%	FAIL	21
Squaw Creek	120602020110	1,275	370	905	71%	FAIL	21
Sycamore Creek	120602020105	823	221	602	73%	FAIL	21
Tuggle Branch-Spring Creek	120602020305	1,041	320	721	69%	FAIL	8
Upper Childress Creek	120602020602	2,386	900	1,486	62%	FAIL	17
Upper North Paluxy River	120602020101	1,624	481	1,143	70%	FAIL	24
Upper Steele Creek	120602020402	4,698	1,394	3,304	70%	FAIL	8
West Buffalo Creek-Buffalo Creek	120602020202	2,133	687	1,446	68%	FAIL	25
West Fork Nolan River-Nolan River	120602020201	3,780	1,276	2,504	66%	FAIL	22
White Rock Creek-Brazos River	120602020801	2,322	983	1,339	58%	FAIL	28
Whiterock Creek-Brazos River	120602020604	2,964	1,371	1,593	54%	FAIL	21
Whitney Creek-Lake Whitney	120602020408	2,479	937	1,542	62%	FAIL	15

VALIDATION RESULTS

Based on the validation assessments and BLE comparison results described above, the CNMS inventory of Zone A studies in the Middle Brazos Lake Whitney Watershed has been updated as summarized in Table 10 and illustrated in Figure 6 below.

Table 10: Zone A Validation Results

Validation Status	Status Type	Total Miles
VALID	BEING STUDIED	113.3
UNVERIFIED	BEING STUDIED	1373.0

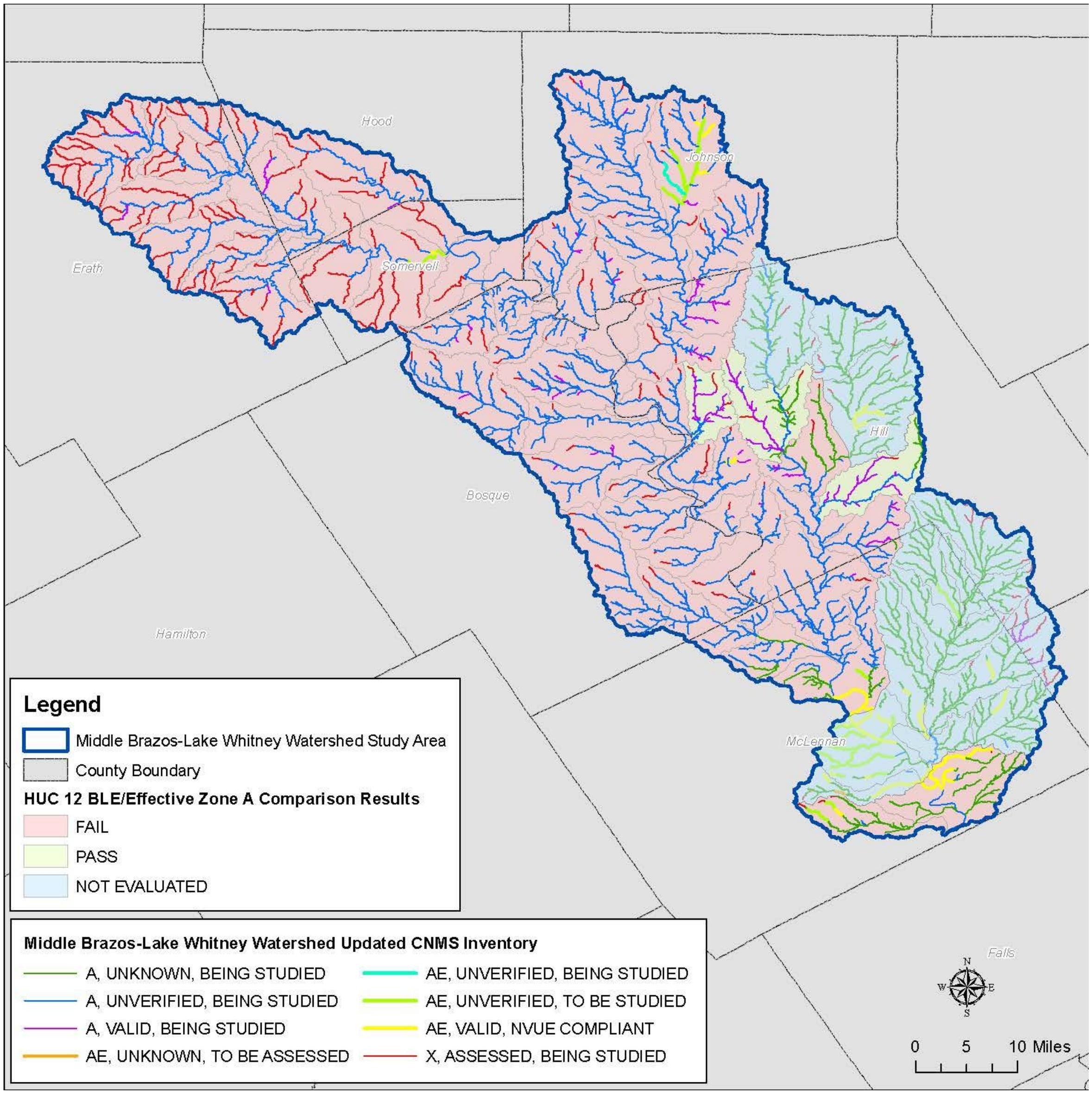

Figure 6: Middle Brazos Lake Whitney Watershed CNMS Validation Results

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

Castleman Creek HUC-12 was determined to have the highest priority score and the most need while Cobb Creek and Little Aquilla Creek – Aquilla Creek HUC-12s had the lowest scores.

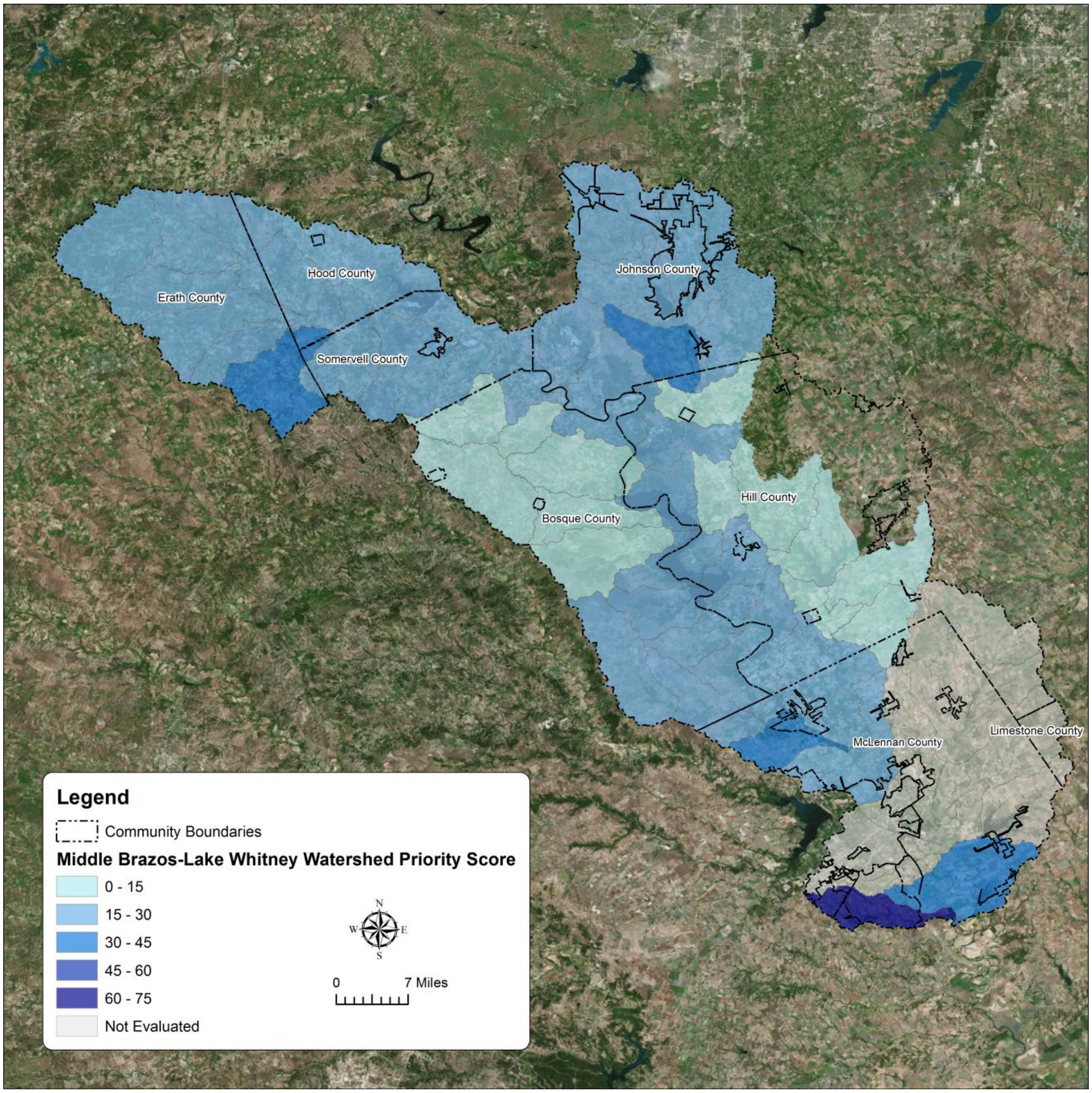

Figure 7: Ranking of Middle Brazos Lake Whitney Watershed HUC-12s

3.2 Flood Risk Analysis

An advanced flood risk analysis was performed using the updated 1-percent-annual-chance grid (known as 'refined base level engineering 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 4.2 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