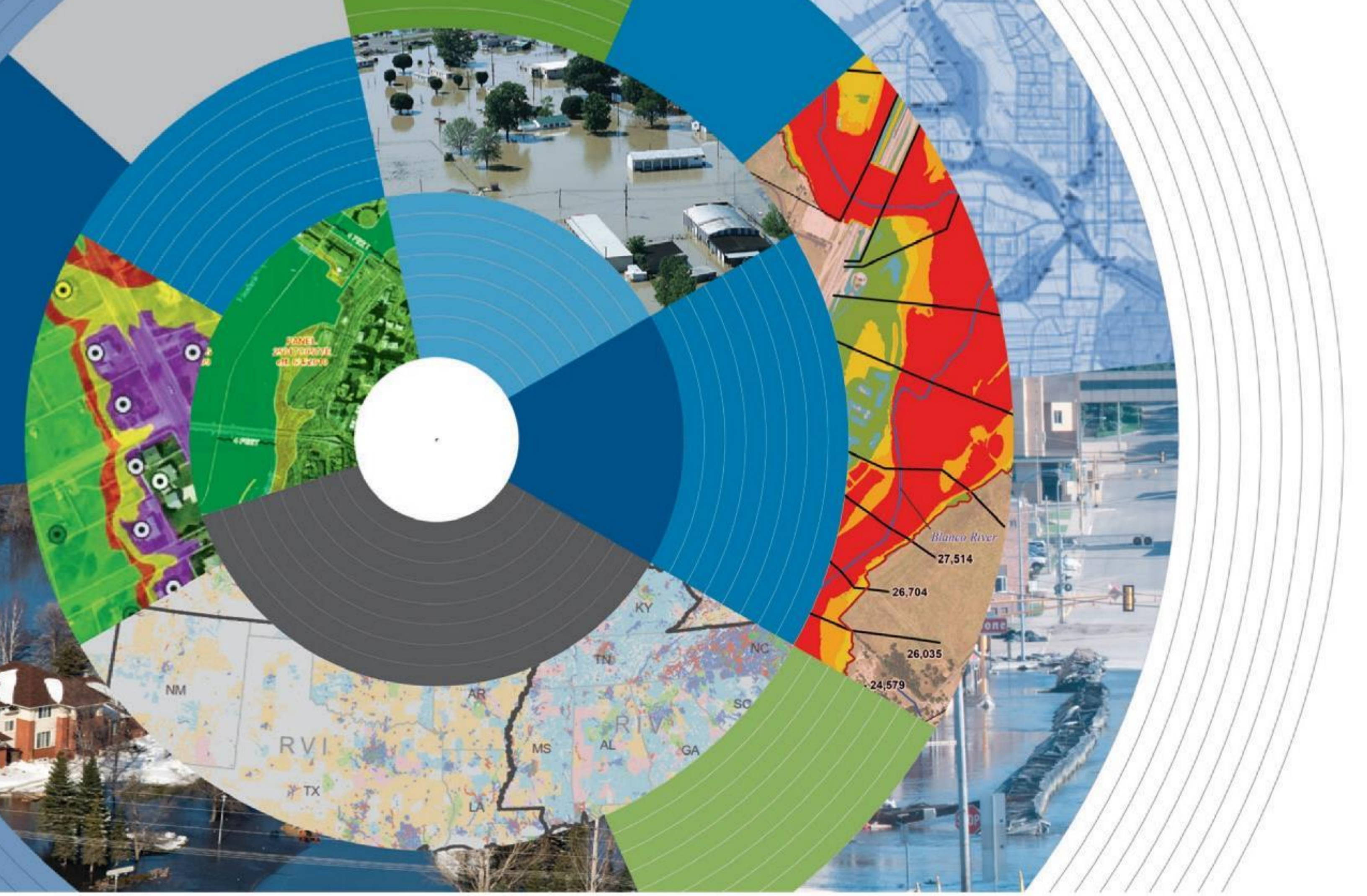

Base Level Engineering Report

South Llano (12090203)

Texas Water
Development Board

January 31, 2025

Version 1.0

Report Prepared for:	**Report Prepared by:**
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Revision History

Version Number	Version Date	Summary of Changes	Author
1.0	January 31, 2025	Initial Report for Estimated Base Flood Elevation Viewer	AtkinsRéalis USA, Inc.

FINAL REPORT FOR SOUTH LLANO (12090203)

PREPARED FOR:

Texas Water Development Board

Prepared By:

AtkinsRéalis USA, Inc.

Texas Registered
Engineering FIRM # 474

06/12/2025

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Executive Summary

The Texas Water Development Board (TWDB) contracted with AtkinsRéalis USA, Inc. (AtkinsRéalis) to complete two-dimensional (2D) Base Level Engineering (BLE) in the South Llano HUC-8 watershed (12090203). This watershed is located in Central Texas, between Rocksprings and Junction, Texas. The watershed area is 933 square miles (mi^2). Approximately 672 miles of stream centerlines were modeled. The information produced during this assessment is available on the U.S. Department of Homeland Security's Federal Emergency Management Agency's (FEMA) Mapping Information Platform (MIP) under case number 22-06-0047S.

The following guidance documents provided the methodologies for this project:

- *Base Level Engineering – Region 6 Submittal Guidance* (FEMA, January 2019)
- *Base Level Engineering – Region 6 Submittal Guidance – Appendix A: 2-D Base Level Engineering Guidance* (FEMA, January 2019)
- *Texas Two-Dimensional Base Level Engineering Guidelines, Version 1.0* (TWDB, May 2022)

Light Detection And Ranging (LiDAR) topographic data available for download from the Texas Natural Resources Information System (TNRIS) were leveraged to build a 3D terrain surface for the watershed.

The hydrologic and hydraulic modeling was completed using the U.S. Army Corps of Engineers' Hydrologic Engineering Center River Analysis System (HEC-RAS), Version 6.2. In accordance with FEMA's Standard Identification Number (SID) 84, the 10%, 4%, 2%, 1%, 0.2%, 1% plus, and 1% minus annual-chance events were simulated. Precipitation data from the National Oceanic and Atmospheric Administration's (NOAA) Atlas 14 were leveraged to develop the 24-hour rainfall distribution for each event. A rain-on-grid methodology was applied to distribute the rainfall across the extents of the 2D hydraulic model area. Infiltration losses were computed using the Natural Resources Conservation Services (NRCS) Curve Number (CN) loss rate method.

The South Llano watershed was divided into seven HEC-RAS model domains—0301_A1, 0301_A2, 0302_A3, 0302_A4, 0303_A5, 0303_A6, and 0304_A7. Per TWDB guidance, a 200-foot by 200-foot nominal cell spacing was used for the 2D area and a finer 100-foot by 100-foot cell spacing was used along the breaklines and within the refinement regions. Breaklines were added to capture roadways, railroads, dam crests, and embankments to force the terrain surface to drain properly. Refinement regions were defined in and near urban areas, major reservoirs, and dam overflow areas to enhance the identification of the flood hazards in these higher-risk areas.

Model results were validated using stream gage data, regression flows, effective FEMA data, and outcomes from other studies in the project area.

Floodplain mapping was developed for the 10%, 1%, and 0.2% annual chance events. Raw mapping output from HEC-RAS was post-processed to delineate floodplains that aligned with the TWDB's 2D BLE mapping standards.

A summary of FEMA's Coordinated Needs Management Strategy (CNMS) data for the South Llano watershed is in Table 1 and Table 2 and shown on Figure 1.

Table 1: Summary of Stream Miles

Source	Stream Miles
Current Inventory -- CNMS	633.7
New Study Streams -- CNMS	37.9
Total (BLE) Stream Miles	**671.6**

Table 2: Zone A Validation Results

Validation Status	CNMS Validation Status	CNMS Project Start	CNMS Post-BLE Assessment
VALID	TO BE STUDIED	0	0
	BEING STUDIED	0	0
UNVERIFIED	TO BE STUDIED	552.1	0
	BEING STUDIED	0	631.5

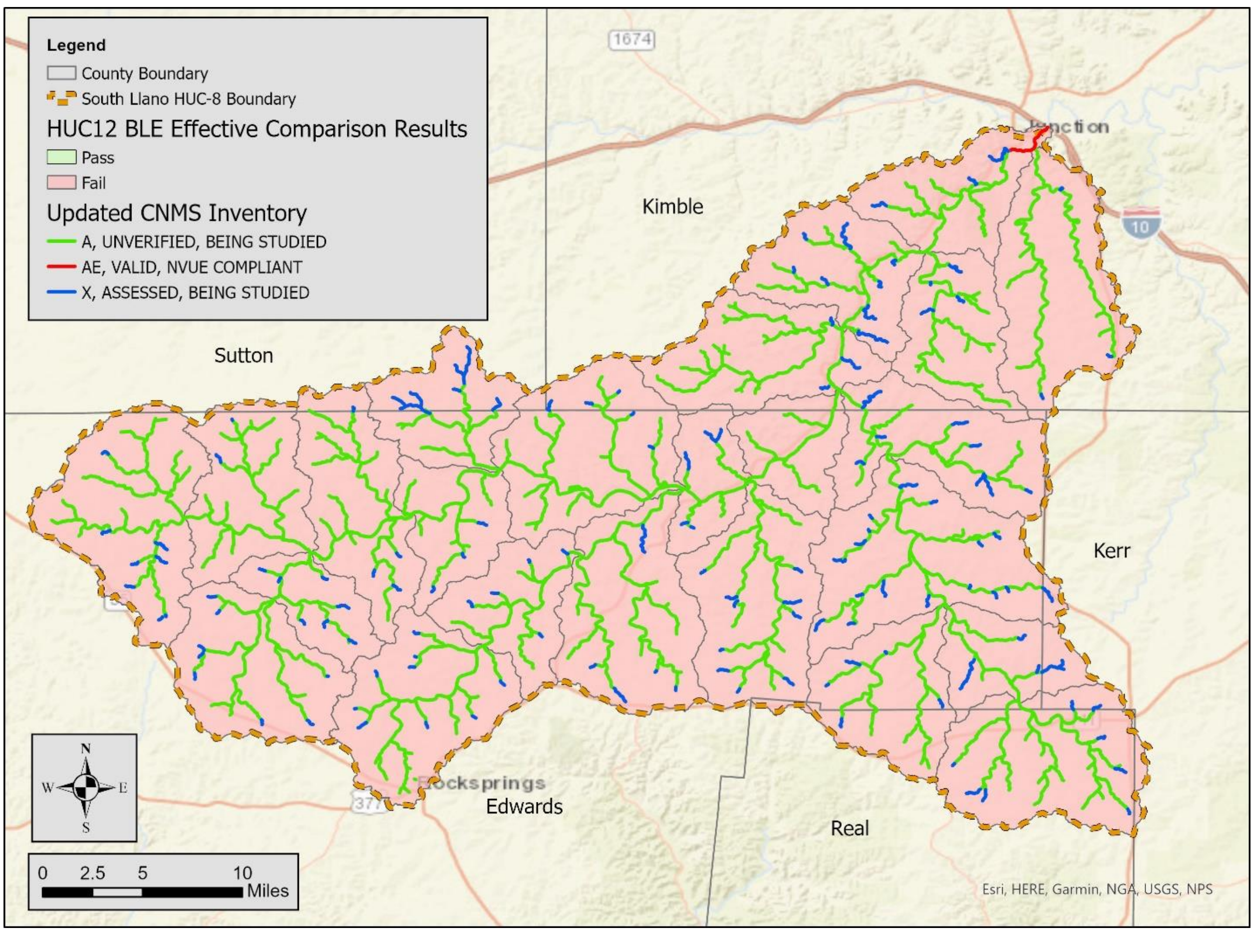


Figure 1: South Llano - 12090203 CNMS Validation Results

Base Level Engineering (BLE) Methodology

Recent innovations and increased efficiency in floodplain mapping have allowed FEMA to develop a process called 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% 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 5 years, FEMA must determine whether the information on its 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 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 SID 29 requires that during the Discovery process, 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, then an analysis is required that estimates the likely changes. This data and any associated analyses should be shared, and the 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 cannot 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 Mapping, Assessment, and Planning (Risk MAP) program may also be valuable to external stakeholders.

The TWDB contracted with AtkinsRéalis to complete a BLE analysis for the South Llano watershed (HUC-8 12090203). The watershed is mostly rural and the land is predominantly used for farming and ranching. Parts of Edwards, Kerr, Kimble, Real, and Sutton counties fall within the watershed. The city of Junction and the town of Rocksprings partially reside within the watershed. See Figure 2 for a map of the South Llano watershed.

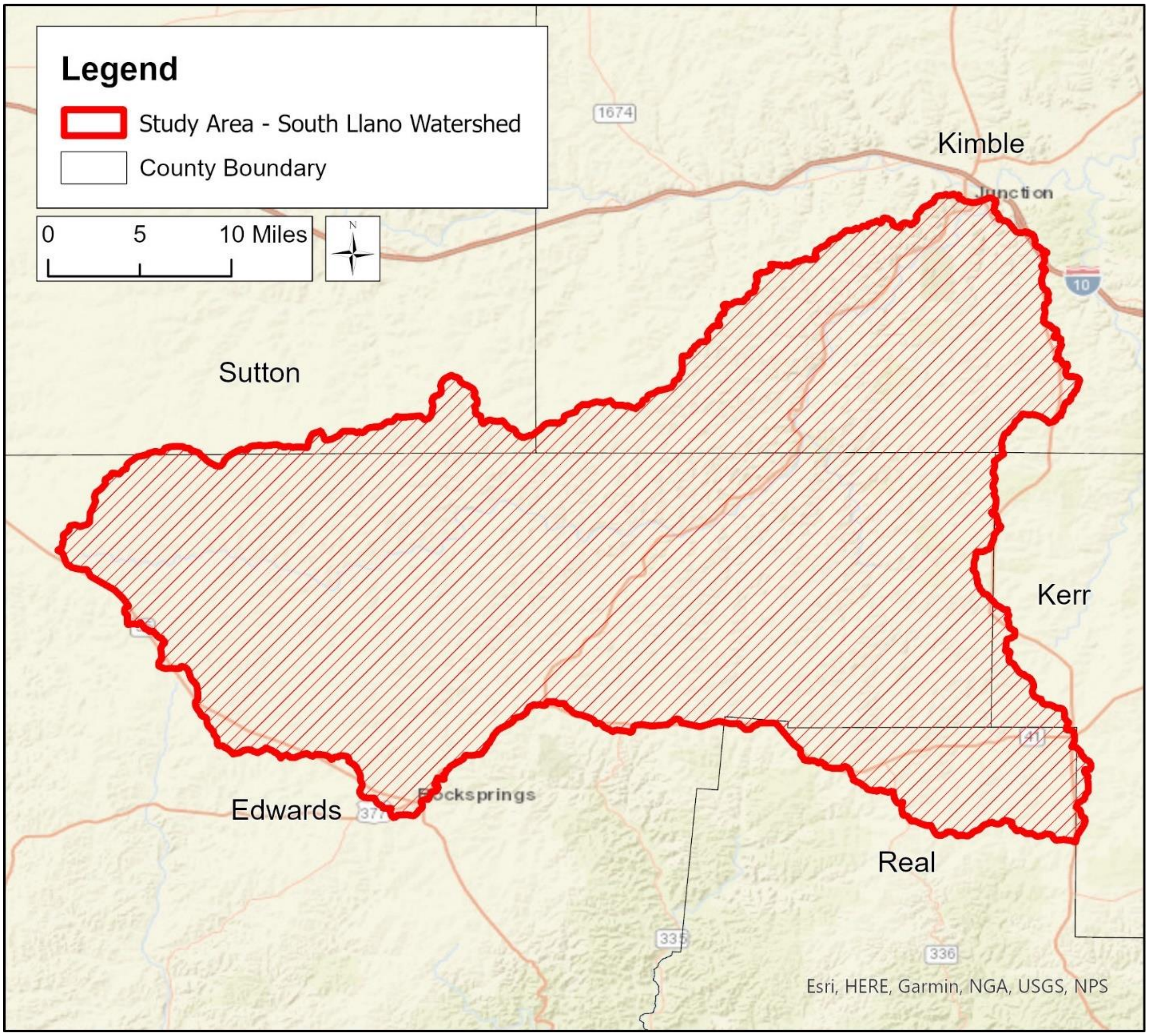


Figure 2: South Llano Watershed – HUC-8 12090203

The BLE assessment prepared a cursory engineering analysis for approximately 672 miles of stream reaches within the South Llano watershed with a minimum drainage area tolerance of 1 mi^2. The selection and extent of the stream reaches studied were based on the number of stream miles meeting the minimum drainage area of 1 mi^2 and not the number of effective Zone A stream miles. Study reaches were extended above this 1-mi^2 threshold as appropriate so the entire effective Zone A floodplain received an updated analysis. The following sections summarize the BLE process and discuss the results, along with their recommended use.

1.1. Topographic Data

1.1.1. Development of the Seamless HUC-8 Digital Elevation Model (DEM)

The topographic data used to develop the terrain surface for the South Llano watershed included two primary data sources in the form of Digital Elevation Models (DEMs). These datasets were provided by the TWDB or downloaded directly from the TNRIS website. A description of all terrain data sources used in the study is in Table 3.

Some of the LiDAR datasets overlapped one another. Therefore, a priority hierarchy was established to determine which LiDAR dataset took precedent over the others in overlap areas. Factors used to establish the hierarchy included the age of the terrain data and its accuracy. This hierarchy is as follows:

- Lower Colorado San Bernard LiDAR
- Hurricane LiDAR

The above-mentioned LiDAR data sets were used to create a seamless set of tiled 5-foot DEMs for the South Llano watershed and a buffered area around the watershed. Each DEM tile measured 6,000 feet by 6,000 feet. This tile size was used because tiles this size can easily be resampled by other users to 1-, 2-, 3-, 5-, 10-, 20-, or 25-foot rasters since 6,000 is evenly divisible by all of these numbers. A 1,000 meter buffer was included since the watershed divide was outside the HUC-8 watershed extents in some areas. A 5-foot cell size was used in accordance with the maximum 10-foot cell size criterion outlined in FEMA's Region 6 BLE guidance from 2021. After projecting the terrain into the Texas State Plane Zone 3 (Central) projection (North American Datum [NAD] 1983 [2011]) with units of U.S. feet, the tiles were mosaicked into one DEM. The sources and extents of the original DEMs used to create the mosaicked DEM are shown on Figure 3.

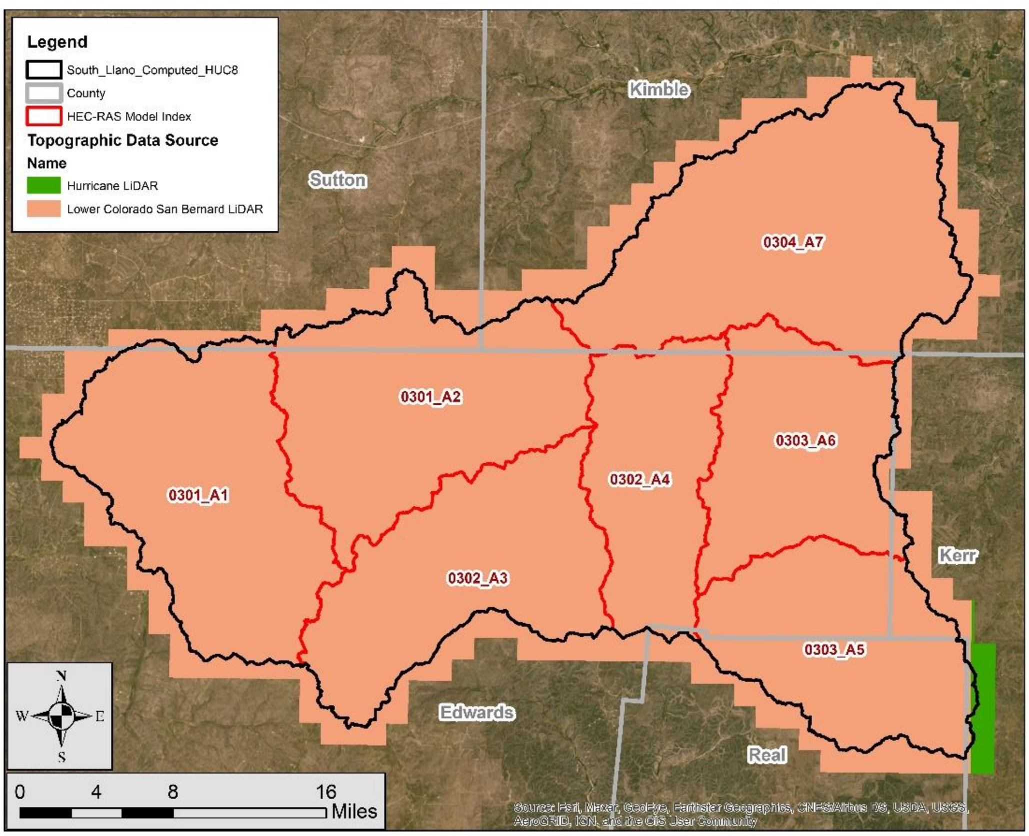


Figure 3: Topographic Data Extents in the South Llano Watershed

Table 3: Topographic Data Sources

County	Year Acquired	Vertical Accuracy	Source	Approximate Footprint (mi^2)
Lower Colorado San Bernard LiDAR (Edwards, Kerr, Kimble, Real, and Sutton Counties)	2018	4.9 cm	USGS	1,116
Hurricane LiDAR (Kerr County)	2019	3.8 cm	USGS	9

An overview of each topographic dataset follows. The vertical datum for all terrain datasets was the North American Vertical Datum of 1988 (NAVD 88).

Data Set One – Lower Colorado San Bernard LiDAR

The United States Geological Survey's (USGS) Lower Colorado San Bernard LiDAR dataset captured in 2018 contains data for 17,942 mi^2 across 26 counties in Texas. In the South Llano watershed, this dataset includes parts of Edwards, Kerr, Kimble, Real, and Kerr counties. The vertical accuracy (RMSEz, or root mean square error in the z direction) of this dataset is 4.9 centimeters (cm). The native cell size of the data is 1 square meter (m^2).

Data Set Two – Hurricane LiDAR

The USGS Hurricane LiDAR dataset captured in 2019 contains data for 14,512 mi^2 across 45 counties in Texas. In the South Llano watershed, this dataset includes a small portion in Kerr County. The vertical accuracy, as defined by the vertical Root Mean Square Error (RMSEz) of this dataset is 3.8 cm. The native cell size of the data is 1 m^2.

No modifications were made to this terrain surface. The goal was to use this terrain 'as is' in the hydraulic modeling, floodplain mapping, and grid development tasks. Maintaining the source terrain data in an unmodified state avoids customized changes to the terrain dataset that future users may not be able to replicate. It also reduces the chance of future users applying an outdated version of the terrain. Any changes that were required in the hydraulic model phase were made in the HEC-RAS terrain, not in the processed tiles.

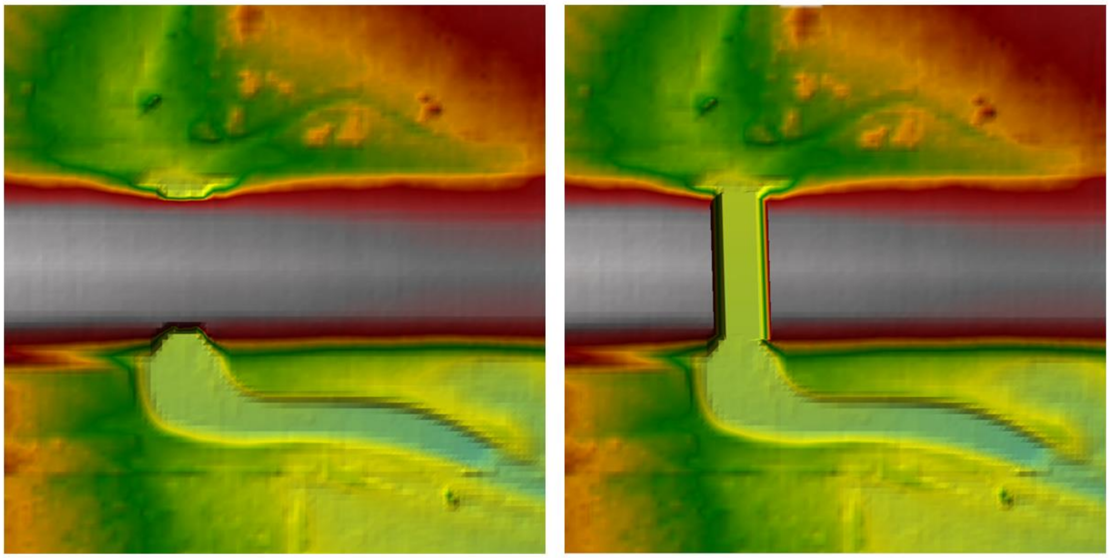
1.1.2. Development of the Stream Networks and Drainage Basins

A hydro-conditioned terrain surface was developed to define the stream networks and drainage basins. A 1,000-meter buffer was applied to the HUC-8 boundary to capture the watershed divide. A 5-meter mosaicked DEM was developed from the source LiDAR data in the same projection as the source data. Using a 5-meter DEM for hydrologic network development maintained sufficient accuracy and produced datasets that were smaller in size and easier to manipulate.

The process for terrain preparation and network and basin delineation is outlined below:

- The flow direction grid, flow accumulation grid, hydrologic stream network, and hydrologic basins were developed.
- Burn lines were defined as needed at roadway/railroad crossings or where reservoirs/ponds artificially diverted the flow path from the natural alignment. The bridge/culvert crossing burn lines developed in this task were subsequently incorporated into the HEC-RAS terrain as terrain

modification features. Terrain modifications, when applied, allowed flow through roadways.



(a) without terrain modifications

(b) with terrain modifications

Figure 4: HEC-RAS Terrain Modification at a Culvert Crossing to Allow Flow through a Roadway

- The streamlines and watershed delineations were reviewed and burn lines were continually added and adjusted until the flow paths, basins, and computed drainage areas were reasonable and justifiable.
- A drainage area grid was computed along the flow paths. There were four USGS gages with drainage areas greater than 1 mi^2 in the watershed. The table below summarizes the difference between the reported and computed values for the drainage area at each gage. The maximum difference is 1.1%, which is acceptable.

Table 4: Reported and Computed Drainage Areas at Each USGS Gage

USGS Gages			Computed Values	
Site No.	Site Name	Drainage Area (mi^2)	Drainage Area (mi^2)	Difference
08149400	S Llano Rv nr Telegraph, TX	508	513.7	1.1%
08149700	S Llano Rv US of Little Pain Ck nr Telegraph, TX	749	749.1	0.01%
08149720	S Llano Rv DS of Little Paint Ck nr Telegraph, TX	786	786.6	0.08%
08149900	S Llano Rv at Flat Rock Ln at Junction, TX	879	878.9	-0.01%

The following information has been placed in the terrain supplemental data folder:

- The computed watershed boundaries at the HUC-8, HUC-10, and HUC-12 levels developed during the terrain processing task.
- The 1-mi^2 stream network developed during the terrain processing task. These lines represent locations where the drainage area is 1 mi^2 or greater.
- Additional supporting layers such as roads, NHD waterbodies, and NHD flow lines.

1.2. Hydrologic and Hydraulic Analysis

A 2D BLE analysis of the South Llano watershed was completed using HEC-RAS, Version 6.2. The analysis applied a rain-on-grid methodology over a 3D terrain. Average basin rainfall was applied to the 2D computational mesh, and losses were computed using the spatially-varied infiltration capabilities of HEC-RAS. In accordance with SID 84, the 10%, 4%, 2%, 1%, 0.2%, 1% plus, and 1% minus annual-chance events were simulated.

Model Layout

The South Llano watershed was split into seven model domains — 0301_A1, 0301_A2, 0302_A3, 0302_A4, 0303_A5, 0303_A6, and 0304_A7, as shown on Figure 5. The first 4 numbers in the model domain name are the final 4 numbers in the name of the HUC-10 watershed number. A1, A2, etc. in the model domain name is just a linear naming convention for the domains. Per recommendation from the TWDB, the model domains (work areas) were no larger than roughly 300 mi^2, which is the size of a typical HUC-10 watershed. The primary reason for having a domain size equal to or smaller than a HUC-10 watershed was to satisfy the assumption that the rainfall across the domain was uniform. The initial model domain boundaries were derived from revised HUC-10 watershed delineations that were established using the LiDAR data. A buffer of 1,000 feet was applied to each HUC-10 watershed boundary to create overlapping domain boundaries. The purpose of the overlap areas was to facilitate clean floodplain and Base Flood Elevation (BFE) transitions between models, to capture the full extent of the floodplain within the watershed, and to minimize the impact of model boundary conditions on model results. At the confluences of model domains, the overlap areas along the main channel were increased in some locations to facilitate tie-ins between model domains.

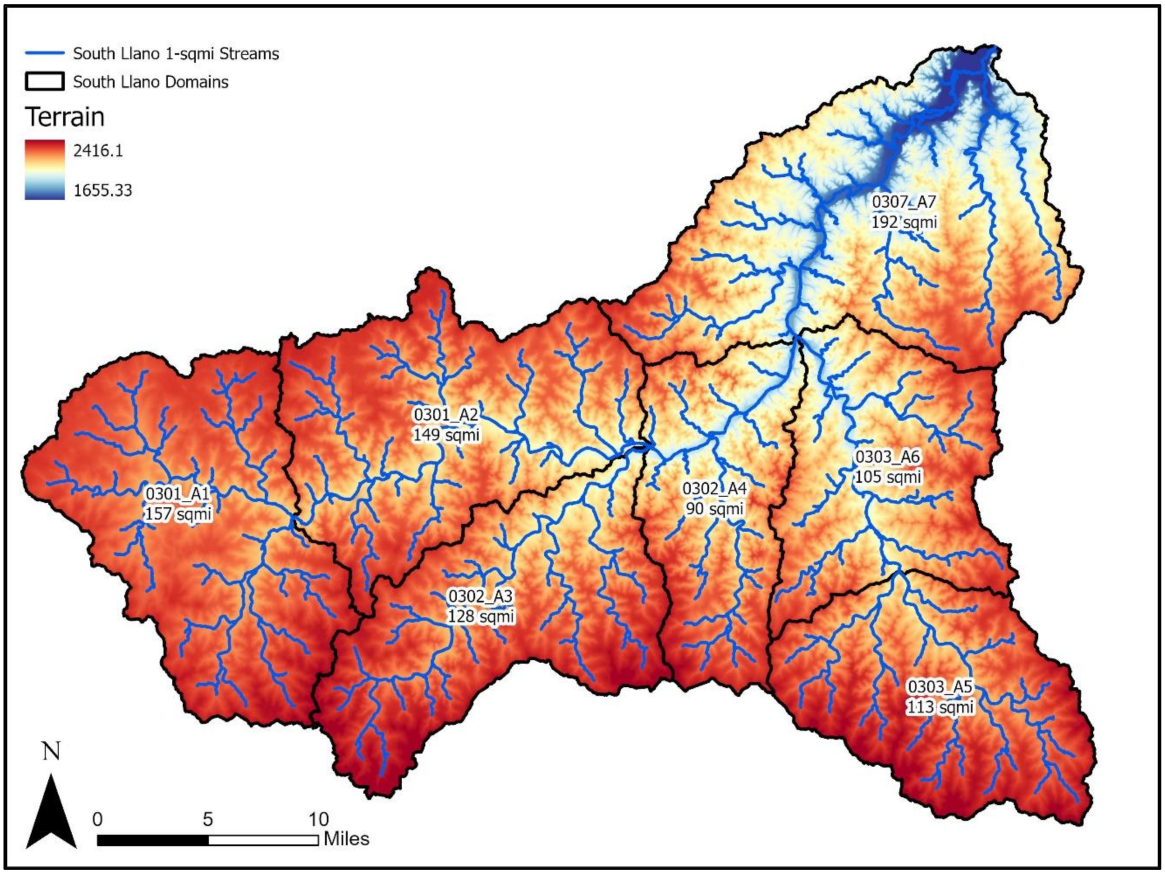


Figure 5: South Llano Model Domains and Linkages

1.2.1. Total Precipitation

Using NOAA's Atlas 14 precipitation statistics, an area-averaged precipitation frequency table was computed for each event in each model domain. For all events, a 24-hour rainfall distribution was calculated using an NRCS nested temporal distribution. The NRCS rainfall distribution development methodology is documented in Title 210, Part 630, Chapter 4, Section 630.0407 of the *National Engineering Handbook*. To create the 24-hour rainfall distribution for an event, the model domain-averaged rainfall totals for the 5-minute, 10-minute, 15-minute, 30-minute, 1-hour, 2-hour, 3-hour, 6-hour, 12-hour, and 24-hour durations were calculated for that event. The ratio of each duration's precipitation total to the 24-hour duration's precipitation total was calculated to produce a preliminary symmetric rainfall distribution. These rain ratios were manipulated as described in Section 630.0407 to obtain the final 24-hour rainfall distribution for the event. This process was repeated for all events in the model domain. The results were exported to DSS (data storage system) files for input into the HEC-RAS models.

The 1% plus and 1% minus annual-chance rainfall totals were computed using the approach provided in subsection 2.2.3 of the TWDB's *2D BLE Guidance Version 1.0* (May 2022). The 1% plus and 1% minus storms were based on the NRCS temporal distribution described in Section 630.0407 of the *National Engineering Handbook*. Additional checks were performed to confirm the 1% plus and 1% minus hyetographs did not cross the hyetographs for other events. The precipitation data used in this study has been included in the supplemental data folder.

1.2.2. Infiltration Losses

The NRCS CN loss rate method was used to account for infiltration losses. A spatially varying infiltration layer for the study area was developed in HEC-RAS by using gridded soils and gridded land cover data sets.

To develop the soils dataset, the 2021 Gridded Soils Survey Geographic (gSSURGO) database was downloaded from NRCS's website (https://data.nal.usda.gov/dataset/gridded-soil-survey-geographic-database-gssurgo). The SSURGO database contained hydrologic soil type information, which was used to develop the gridded soils layer in HEC-RAS.

To develop the land cover dataset, the 2019 National Land Cover Database (NLCD) was downloaded from the Multi-Resolution Land Characteristics Consortium (MRLC) website (https://www.mrlc.gov/data/nlcd-2019-land-cover-conus). The land cover dataset provided land use classification codes and the extent of each land use. This information was used to create the gridded land cover dataset.

The infiltration layer was created in HEC-RAS by combining the soils and land cover gridded datasets. The CN values required for the loss rate computations were obtained from Table 2.4 of the TWDB's *2D Base Level Engineering Guidance Version 1.0* (May 2022) and are shown below in Table 5. The initial abstraction ratio of 0.2 was used to obtain the initial loss.

During the model validation phase, the CN values were adjusted as needed to bring the model results into alignment with the validation data (e.g., stream gage data, effective discharges, etc.). CN values presented in Table 5 were based on average Antecedent Moisture Condition II (AMC II), and during validation, the values were revised by no more than ±10% of their initial values. In some cases, however, a 10% reduction in the AMC II CN values produced flows that continued to be too high to be considered validated. For these model domains, CN values corresponding to AMC I conditions were used to achieve model validation. AMC I CN values are shown in Table 6.

Research completed for this project revealed that antecedent moisture conditions in Texas vary from AMC II in the east to AMC I in the west, and the South Llano watershed resides within the transition from AMC II to AMC I. Therefore, the application of AMC I conditions to support validation was appropriate. Including AMC I CN values in these domains produced flows that were able to be validated while avoiding adjustments to the AMC I CN values. See Section 1.2.9 for more information about the use of AMC I and AMC II CNs in the South Llano watershed.

Table 5: AMC II Curve Number Values

Land Use Grid Code	NLCD Land Use Description	CN for Each Hydrologic Soil Group			
		A	B	C	D
0	No Data	75	75	75	75
11	Open Water	99	99	99	99
21	Developed, Open Space	49	69	79	84
22	Developed, Low Intensity	61	75	83	87
23	Developed, Medium Intensity	81	88	91	93
24	Developed, High Intensity	89	92	94	95
31	Barren Land	39	61	74	80
41	Deciduous Forest	30	55	70	77
42	Evergreen Forest	30	55	70	77
43	Mixed Forest	30	55	70	77
52	Shrub Scrub	30	48	65	73
71	Herbaceous	49	62	74	85
81	Hay Pasture	39	61	74	80
82	Cultivated Crops	51	67	76	80
90	Woody Wetlands	72	80	87	93
95	Emergent Herbaceous Wetlands	72	80	87	93

Table 6: AMC I Curve Number Values

Land Use Grid Code	NLCD Land Use Description	CN for Each Hydrologic Soil Group			
		A	B	C	D
0	No Data	56	56	56	56
11	Open Water	98	98	98	98
21	Developed, Open Space	29	48	61	69
22	Developed, Low Intensity	40	56	67	74
23	Developed, Medium Intensity	64	75	81	85
24	Developed, High Intensity	77	83	87	89
31	Barren Land	21	40	54	63
41	Deciduous Forest	15	34	49	58
42	Evergreen Forest	15	34	49	58
43	Mixed Forest	15	34	49	58
52	Shrub Scrub	15	28	44	53
71	Herbaceous	29	41	54	70
81	Hay Pasture	21	40	54	63
82	Cultivated Crops	30	46	57	63
90	Woody Wetlands	52	63	74	85
95	Emergent Herbaceous Wetlands	52	63	74	85

Manning's n values were defined within the infiltration layer. These values were used to compute the energy losses as the flow was routed through the 2D computational mesh in the HEC-RAS model. For this study, the overbank Manning's roughness coefficients were obtained from Table 2.2 of the TWDB's *2D Base Level Engineering Guidance Version 1.0* (May 2022) and are presented in Table 7. Manning's n values for the main channel areas were refined by adding Manning's n override regions. The extents of the override regions in the channels were established by adding a typical buffer of 100 feet to the streamlines. For larger streams, where the channel polygon widths were wider than 200 feet, the channel polygons were adjusted by reviewing the typical channel widths on the terrain surface and aerial photography. Manning's n values in the main channels ranged from 0.040 to 0.050.

Table 7: Manning's n Values for Overland and Overbank Areas

Land Use Grid Code	NLCD Land Use Description	Typical n Value	n Value Range
0	No Data	0.040	0.040 - 0.040
11	Open Water	0.038	0.025 - 0.050
21	Developed, Open Space	0.040	0.030 - 0.050
22	Developed, Low Intensity	0.090	0.060 - 0.120
23	Developed, Medium Intensity	0.12	0.080 - 0.140
24	Developed, High Intensity	0.16	0.12 - 0.20
31	Barren Land	0.025	0.023 - 0.030
41	Deciduous Forest	0.15	0.10 - 0.20
42	Evergreen Forest	0.12	0.080 - 0.16
43	Mixed Forest	0.14	0.080 - 0.20
52	Shrub Scrub	0.115	0.070 - 0.16
71	Herbaceous	0.038	0.025 - 0.050
81	Hay Pasture	0.038	0.025 - 0.050
82	Cultivated Crops	0.035	0.020 - 0.050
90	Woody Wetlands	0.098	0.045 - 0.15
95	Emergent Herbaceous Wetlands	0.068	0.050 - 0.085

1.2.3. 2D Computational Mesh

The 2D computational mesh is one of the key components of a rain-on-grid 2D model, and it has a significant impact on model outcomes. Per the TWDB's 2D BLE guidelines, a 200-foot by 200-foot nominal cell spacing was used for the 2D area, and a finer 100-foot by 100-foot cell spacing was used along the breaklines and within the refinement regions. Breaklines were included in the model to capture linear features in the topographic data that represented high ground or streamlines. Breaklines were added to capture roadways, railroads, dam crests, and embankments to force the terrain surface to drain properly. For main channel areas where flow depths and velocities are higher and in urban areas, refinement regions were added to enhance the identification of the flood hazards in these higher-risk areas.

The following list provides additional details of the mesh refinement that was performed:

- The stream centerlines defined during the hydro-enforcement task were applied as breaklines to align the mesh cells with the direction of flow. For undeveloped/rural areas, the 1 mi^2 stream centerlines were used to create the breaklines. For urban areas, the 0.5 mi^2 stream centerlines were used.
- Texas Department of Transportation (TxDOT) road lines (https://gis-txdot.opendata.arcgis.com/) were used as breaklines.
- Breaklines were placed on the spillways and crests of significant reservoirs.
- Polygons computed by buffering the streamlines were used to establish channel refinement regions. The buffers were 200 feet wide for small streams and increased for wider streams with larger drainage areas.

- Refinement regions were defined in urban areas, major reservoirs, and dam overflow areas.
- Breaklines were split into multi-parts at all intersections using the planarize tool in ArcGIS Pro.
- Since the model runtime increases as more breaklines and refinement regions are added, all breaklines and refinement regions were reviewed to confirm that improved the quality of the model. Those that did not improve the quality were removed.
- The 2D perimeter, refinement regions, and breaklines were smoothed and cleaned using Geographic Information Systems (GIS) software to minimize mesh generation errors.
- As discussed in Section 1.1.2, the bridge/culvert crossing burn lines developed for this study were incorporated into the HEC-RAS terrain as terrain modification features to allow flow through roadways.

1.2.4. Model Boundary Conditions

The BLE analysis included four types of model boundary conditions—precipitation, flow hydrograph, stage, and normal depth. The following is a summary of where each type of boundary condition was applied.

Precipitation Boundary Conditions

As described previously, basin-averaged NOAA Atlas 14 precipitation depths were calculated for each model domain and were temporally distributed using an NRCS distribution. The precipitation hyetographs were applied to the 2D area using a precipitation boundary condition for the rain-on-grid analysis.

Flow Hydrograph Boundary Conditions

Flow hydrograph boundary conditions were added at major stream inflow locations. In this study, a direct-flow approach was used to transfer flows from upstream watersheds to downstream watersheds. In the direct-inflow method, the precipitation and upstream inflows assume the same annual-chance event is occurring simultaneously. So, for each event, the outflows from the upstream watersheds were directly applied as inflows to the model of interest without adjustments to the timing of the peaks.

Storage Area-2D (SA/2D) connections were added near the main channel outflow location in the upstream HEC-RAS model to compute the outflow from the upstream model. A flow boundary condition line was then added in the downstream model at a location that coincided with the SA/2D line to maintain consistency. The breaklines were enforced at the SA/2D connections and flow boundary condition lines to align the cell faces with the boundary. The purpose of adding SA/2D connections was to limit the impact of the boundary conditions on the inflow applied to the downstream models and to clearly document the flow transfer locations and hydrographs, as this information is stored in the DSS output files. The lengths of the inflow boundary condition lines for the downstream model were shortened to a length between the widths of the 1% and 10% floodplain limits to mimic the distribution of the inflow in the upstream model.

Stage Hydrograph Boundary Conditions

Stage hydrographs were applied at the main stem outflow locations to account for the downstream backwater elevations. This approach served two purposes. First, it facilitated the tie-ins of the water surface elevations at the model domain boundaries, which were required to be within 0.5 foot. Second, the application of the stage hydrograph boundaries accounted for the timing of the tailwater conditions in the downstream model. In short, the stage hydrograph in the upstream model was obtained from the downstream model at the upstream main channel's outflow location.

Figure 6 and Figure 7 show an example of the iterative process used to extract and apply a stage hydrograph at the transition of two model domains (which overlap) in the Jim Ned watershed. These figures show the location used to obtain the stage hydrograph between domains 0801_A2 (upstream domain) and 0802_A3 (downstream domain). A stage hydrograph was iteratively extracted from the downstream model results and applied to the upstream model as a boundary condition. This boundary condition was based upon the hydrograph results calculated from a SA/2D connection in the upstream model applied as a discharge in the downstream model. The iterative process was necessary to balance the upstream model's peak outflow within 10% of the downstream model's peak inflow while also achieving a WSEL tie-in of 0.5 foot or less at the transition location.

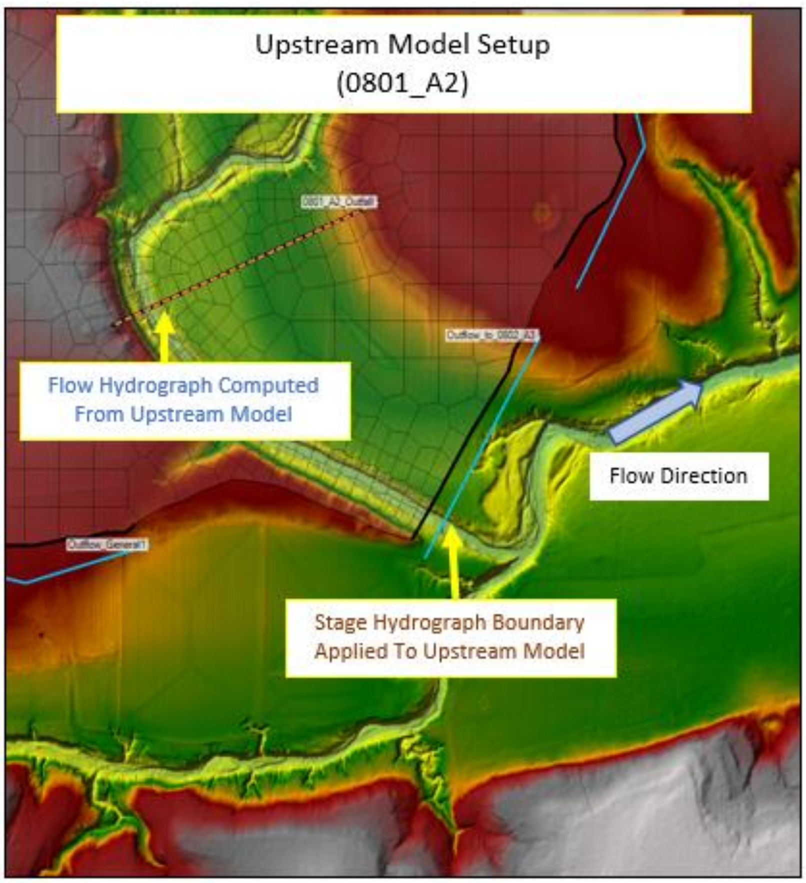


Figure 6: Extraction of Flow Hydrograph from the SA/2D Connection in the Upstream Domain for Use in the Downstream Domain

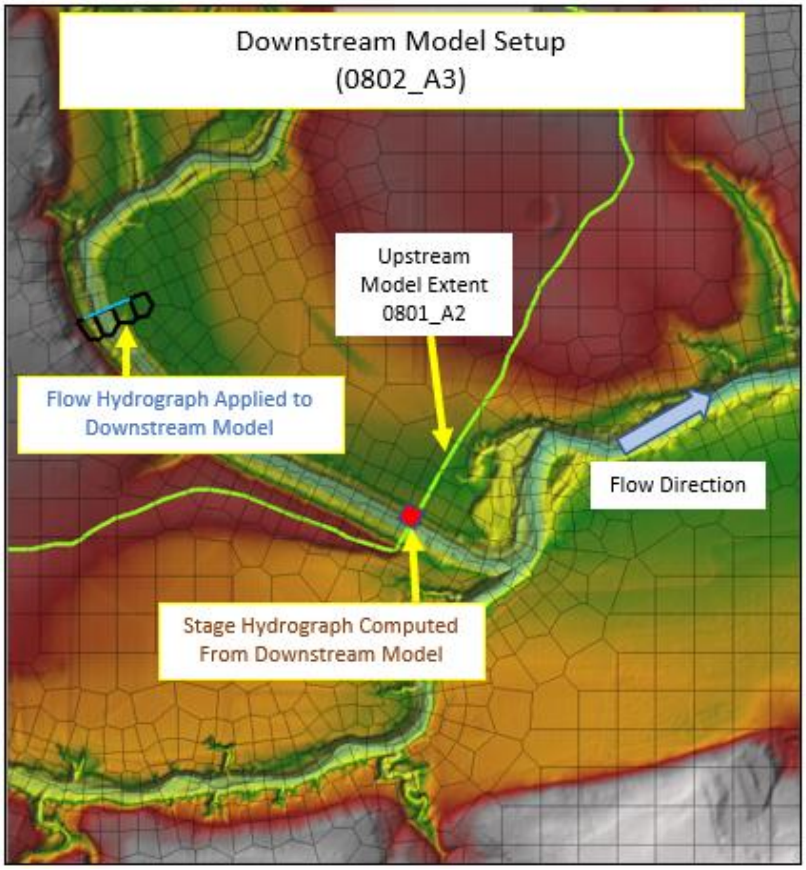


Figure 7: Application of Upstream Flow Hydrograph in the Downstream Domain

Normal Depth Boundary Conditions

Since each 2D model domain extent included a buffer to the watershed boundary, normal depth boundary conditions were applied along each 2D area perimeter to avoid ponding along the perimeter. At main channel outflow or tributary inflow locations where other boundary conditions were already present, a normal depth boundary was not applied.

1.2.5. Reservoir Modeling

There were no major reservoirs in the South Llano watershed.

1.2.6. Computation Settings

The computation settings applied in the HEC-RAS models are listed below:

- The Diffusion Wave equation was used.
- A 96-hour simulation time was generally applied to capture the peaks and tails of the hydrographs.

- An advanced time step control based on the Courant number was applied as shown below in Figure 8. This option was chosen to decrease run times while generally maintaining Courant number values less than 1.

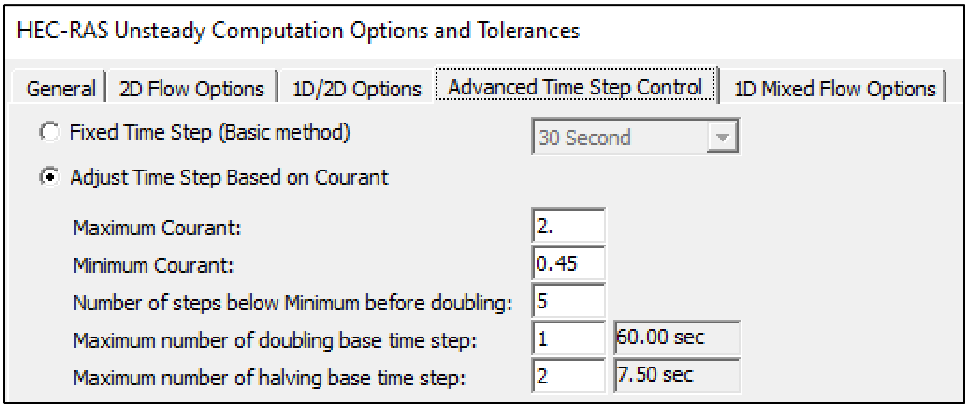


Figure 8: HEC-RAS Unsteady Computation Options and Tolerances

- Typical model run times with this advanced time step control setting were approximately 2 hours per simulation.
- The mapping and hydrograph output intervals were 10 minutes.

1.2.7. Regression Analysis

Regression flows were used for model validation where gage data was not available. The flow direction and flow accumulation grids created during the hydro-enforcement task were used to develop regression input parameter grids and regression peak flow grids for locations with drainage areas of 1 mi^2 or larger. The peak flows were computed using the regression equations documented in *Regression Equations for Estimation of Annual Peak-Streamflow Frequency for Undeveloped Watersheds in Texas Using an L-moment-Based, PRESS-Minimized, Residual-Adjusted Approach* (Asquith and Roussel 2009).

The contributing drainage area (A), mean-annual precipitation (P), dimensionless channel slope (S), and the basin-averaged OmegaEM parameter (Ω) were the input parameters for the regression equations. The regression equations are shown in Table 3 in the regression report (Asquith and Roussel 2009) and below on Figure 9.

Regression equation
$Q_2 = P^{1.398} S^{0.270} \times 10^{[0.776\Omega+50.98-50.30A^{-0.0058}]}$
$Q_5 = P^{1.308} S^{0.372} \times 10^{[0.885\Omega+16.62-15.32A^{-0.0215}]}$
$Q_{10} = P^{1.203} S^{0.403} \times 10^{[0.918\Omega+13.62-11.97A^{-0.0289}]}$
$Q_{25} = P^{1.140} S^{0.446} \times 10^{[0.945\Omega+11.79-9.819A^{-0.0374}]}$
$Q_{50} = P^{1.105} S^{0.476} \times 10^{[0.961\Omega+11.17-8.997A^{-0.0424}]}$
$Q_{100} = P^{1.071} S^{0.507} \times 10^{[0.969\Omega+10.82-8.448A^{-0.0467}]}$
$Q_{200} = P^{1.034} S^{0.531} \times 10^{[0.975\Omega+10.61-8.058A^{-0.0504}]}$
$Q_{250} = P^{1.021} S^{0.541} \times 10^{[0.977\Omega+10.56-7.943A^{-0.0516}]}$
$Q_{500} = P^{0.988} S^{0.569} \times 10^{[0.976\Omega+10.40-7.605A^{-0.0554}]}$

Figure 9: Regression Equations for the South Llano Watershed

The lower and upper limits of the slope in the regression analysis were 0.00023 and 0.0703, respectively. The computed flows are sensitive to the channel slope and unreasonable flows tend to be computed when slopes are outside the range used in the regression analysis. Therefore, when the channel slope was less than 0.00023, 0.00023 foot per mile was used in place of the computed value. Similarly, when the channel slope exceeded 0.0703, 0.0703 was used in place of the computed value.

The average standard error of prediction (SEP) for the 1% annual-chance event was 64.8% according to the PRESS statistic in Table 3 of the regression report (Asquith and Roussel, 2009). The 1% plus and 1% minus gridded flows were computed using the SEP as shown in the equations below. The 1% minus flows were not computed by multiplying the 1% flow by 1 minus SEP to avoid unreasonably low flows when the standard errors were large.

$$Q_{1\%plus} = Q_{100} \cdot (1.648)$$

$$Q_{1\%minus} = \frac{Q_{100}}{1.648}$$

The flows resulting from the regression analysis were not used downstream of flow-regulating reservoirs or for streams with inflows from other HUC-8 watersheds.

1.2.8. Gage Analysis

There were four USGS gages in the watersheds, but none of them had a period of record long enough to support a reliable Bulletin 17C frequency-flow analysis. Therefore, no gage analyses were performed for this BLE study.

Table 8: Summary of USGS Gages in the South Llano Watershed

Site No.	Site Name	Computed Drainage Area (mi^2)	Was Gage Analysis Performed?	Source of Gage Analysis	Reason why gage analysis was not performed to support BLE validation
08149400	S Llano Rv nr Telegraph, TX	513.7	No	N/A	Only 1 year of flow data was available (2000).
08149700	S Llano Rv US of Little Pain Ck nr Telegraph, TX	749.1	No	N/A	Gage was installed in 2021. Not enough flow data were available.
08149720	S Llano Rv DS of Little Paint Ck nr Telegraph, TX	786.6	No	N/A	Gage was installed in 2021. Not enough flow data were available.
08149900	S Llano Rv at Flat Rock Ln at Junction, TX	878.9	No	N/A	Only 9 years of flow data were available (2013-2021).

1.2.9. Model Validation

There were limited data available to support the validation of the South Llano BLE hydraulic analysis. Although there were 4 USGS gages in the watershed, no flow-frequency analyses were able to be completed since the period of record at each gage was too short. There was a single FEMA effective flow rate available at the downstream end of the watershed that was leveraged to support validation. At all other validation locations, the regression analysis previously discussed was applied to validate the HEC-RAS models.

Validation checks were made at 68 locations throughout the South Llano watershed. The locations may be grouped as follows:

- Sixty-eight validation locations compared the 1% BLE flows with the 1% minus, 1%, and 1% plus regression flows.
- One validation location compared the 1% BLE flow with the 1% effective flow.

The validation locations were scattered throughout the watershed in locations that provided a comprehensive coverage of drainage areas and stream characteristics. Validation points were added where effective flow information was available. The drainage areas of the validation points ranged from approximately 1 mi^2 to 932 mi^2. At the 68 locations where 1% plus and 1% minus regression flows were available, the validated BLE 1% flows were within the 1% plus and 1% minus range at 54 locations and outside 1% plus and 1% minus bounds at 14 locations. At the single location where the 1% effective flow was available, the 1% BLE flow was 19% less than the effective flow, which is acceptable. The comparisons of the BLE 1% flows with the regression and effective 1% flows is shown in Table 12.

The first step of the validation effort was to review the initial BLE results. When the initial BLE flows fell outside the 1% plus and 1% minus range of the regression flows, the Manning's n and CN values were adjusted iteratively until the computed flows at as many validation points as possible were within the 1% plus and 1% minus range of the regression flows. The Manning's n values were revised as needed, provided they remained within the ranges specified in Table 7. The AMC II CNs were adjusted by no more than ±10% of their initial values. If the computed flows were within the 1% plus and 1% minus range (i.e., valid), then the adjusted AMC II CNs and Manning's n values were used in the final model.

There were some model domains where these adjustments to the Manning's n and AMC II CN values did not reduce the flows enough to produce valid flows at an acceptable number of validation locations. In these domains, the Manning's n values were reset to their initial values and the baseline antecedent moisture conditions were revised from AMC II to AMC I. According to *Engineering Technical Note No. 210-18-TX5,* published by the Soil Conservation Service (SCS) in October 1990, antecedent moisture conditions in Texas vary from AMC II in the east to AMC I in the west. Since the South Llano watershed resides within the transition zone from AMC II to AMC I, it was reasonable to assume AMC I conditions were present in the watershed for validation purposes. See Figure 10 and Appendix B for a map from the SCS report showing the average antecedent moisture conditions across Texas.

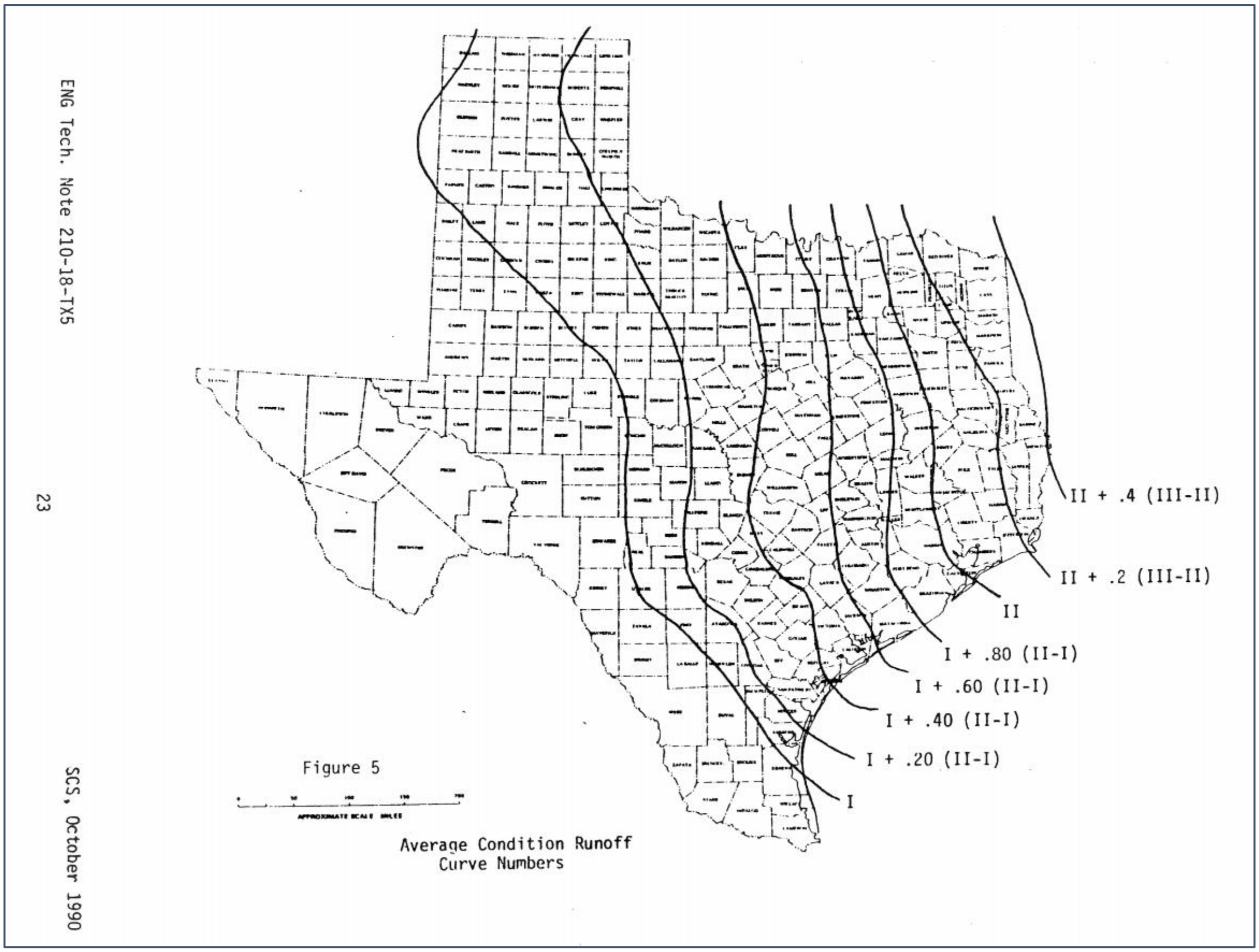


Figure 10: Typical Antecedent Moisture Conditions in Texas

A summary of the parameter adjustments made during the validation task is shown in Table 9.

Table 9: Summary of Parameter Adjustments Made During Validation in the South Llano Watershed

Model Domain	CN Adjustment	Overland n Adjustment	Channel n Adjustment	Number of Validation Locations	Pass	Fail
0301_A1	AMC I	No Change (Baseline n)	No Change (Baseline n)	12	9	3
0301_A2	AMC I	No Change (Baseline n)	No Change (Baseline n)	9	7	2
0302_A3	AMC I	No Change (Baseline n)	No Change (Baseline n)	10	8	2
0302_A4	Reduced by 10% from AMC II	No Change (Baseline n)	No Change (Baseline n)	9	9	0
0303_A5	AMC I	No Change (Baseline n)	No Change (Baseline n)	9	6	3
0303_A6	Reduced by 10% from AMC II	No Change (Baseline n)	No Change (Baseline n)	9	8	1
0303_A7	Reduced by 10% from AMC II	No Change (Baseline n)	No Change (Baseline n)	10	7	3
			Total	**68**	**54**	**14**

During the validation process, domain-wide parameter adjustments were applied to the CNs and the Manning's n values to maximize the number of streams where the 1% BLE flows fell between the 1% minus and 1% plus regressions flows. No particular area or tributary in a domain was considered a priority over the others when these adjustments were made. As a result, in areas where the stream/watershed characteristics were significantly different from the rest of the domain, some of the 1% BLE flows might fall outside of the 1% minus and 1% plus bounds. Other factors that contributed to the 1% BLE flows falling outside of the 1% minus and 1% plus bounds included differences in the regression and 2D BLE analysis methodologies; the use of updated topographic data in the BLE analysis; and the higher NOAA Atlas 14 rainfall totals that were used in the BLE analysis.

The model validation process for domain 0301_A2 is described here. Iterative results from this process are presented in Table 10. This description is representative; a similar process was applied to all domains in the South Llano watershed. In Table 10, the flow values in green are between the 1% plus and 1% minus regression flows, and the values in red are outside this range.

For Iteration 1, the baseline AMC II CNs and Manning's n values were simulated. The Iteration 1 results showed that the majority of the computed 1% BLE flows were higher than the 1% plus regression values. To reduce the computed flows, Iteration 2 lowered the AMC II CN values by 10%, which brought all flows within the 1% plus and 1% minus range. However, they still remained above the 1% regression flows by 13% to 63%.

To bring the computed flows into better alignment with the 1% regression flows, Iteration 3 increased the overland Manning's n values to their maximum values (see Table 7). The CNs remained unrevised from Iteration 2 (90% of baseline). The Iteration 3 flows were lower than those from Iteration 2;

however, they were still generally higher than the 1% regression estimates by 2% to 63%, and one location was outside the regression bounds.

To reduce the flows further, Iteration 4 reset the CNs from 90% AMC II to baseline AMC I and reverted the overland Manning's n values from maximum to baseline. The results of Iteration 4 showed that for the smaller tributaries, the computed BLE flow values were lower than the 1% regression estimate, and for larger streams such as the South Llano River, the computed flows were higher than the 1% regression estimates. In addition, there were two locations where the computed flow was lower than the 1% minus flow. To further refine the validation, Iteration 5 lowered the overland Manning's n values to their minimums (see Table 7). The Iteration 5 flow values were a slight improvement over the results from Iteration 4; only one flow rate was less than the 1% minus regression estimate and none was above the 1% plus regression estimate.

For the final model for domain 0301_A2, AMC I CNs with normal overland Manning's n values (i.e., Iteration 4) were used for the following reasons:

- The flow values that were computed using the 90% AMC II CNs were too high, particularly along the larger streams.
- The AMC I CN values combined with the baseline Manning's n values produced reasonable results for domains 0301_A1 and 0302_A3, which are adjacent to domain 0301_A2. Using the same adjustments in adjacent domains promoted parameter consistency.
- The initial model runs showed that the computed flows along the main stem were increasing significantly in the downstream direction as each domain was added to the river. Adjusting the 0301_A2 model during validation so that it produced flows toward the lower end of the range of acceptable flows contributed to improved validation results toward the downstream end of the watershed.

Table 10: Summary of the Model Validation Process for Domain 0301_A2

Validation Location	Name	Drainage Area (mi^2)	Regression			Iteration 1	Iteration 2	Iteration 3	Iteration 4	Iteration 5
			1%-	1%	1%+	Initial CN and n	90% CN	90% CN + Max N	AMC I	AMC I + Min N
Point 1	Unnamed	28.8	8,744	14,411	23,749	27,918	21,523	18,654	11,109	13,715
Point 2	Unnamed	17.1	6,205	10,225	16,851	16,968	12,977	11,691	6,785	8,056
Point 3	Unnamed	8.7	3,821	6,297	10,378	10,471	7,969	7,068	4,063	5,005
Point 4	Unnamed	1.0	845	1,392	2,295	1,311	948	780	456	600
Point 5	Unnamed	15.0	4,987	8,219	13,544	14,662	10,907	9,268	5,403	6,792
Point 6	Unnamed	7.8	3,024	4,984	8,213	7,699	5,747	5,086	3,008	3,643
Point 7	South Llano River	204.1	16,786	27,664	45,590	45,924	45,291	45,095	43,740	44,182
Point 8	Unnamed	3.6	2,270	3,740	6,264	5,682	4,246	3,595	2,083	2,755
0301_A2 Outfall	South Llano River	305.2	22,843	37,645	62,039	68,054	54,951	55,103	51,301	51,402

The effective 1% flow rate at the mouth of the South Llano River was 231,000 cubic feet per second (cfs). The effective study computed this flow rate from a flow-frequency analysis of a gage along the North Llano River (USGS gage 08148500). Although this analysis was for a gage on the North Llano River, the analysis concluded that the 1% effective flow rate on the North and South Llano Rivers were the same since each river has a similar drainage area (within 1.5%) and watershed characteristics. The BLE model computed a 1% flow rate of 187,810 cfs at the mouth of the South Llano River, which was 19% lower than the effective 1% flow rate. The 1% plus regression flow rate at this location was 179,406 cfs, which means the BLE 1% flow rate fell the between the 1% plus regression flow rate and the 1% effective flow rate. The model overview and results spreadsheet (*South_Llano_Model_Overview_and_Results.xlsx*) has been placed in the task documentation folder of this submittal. The validation locations are included in the HEC-RAS models and may also be found on the validation location maps for each domain in the model overview and results spreadsheet.

A comparison between the 1% BLE WSELs and select effective 1% WSELs for the South Llano River is presented in Table 11. The effective 1% WSELs were estimated using BFEs available in the RMSI digitized floodplain mapping dataset. For the South Llano River, the BLE WSELs were lower than the effective WSELs, which is expected since the 1% BLE flows were 19% lower than the effective flows.

Table 11: Comparison of Effective 1% WSELs with 1% BFE WSELs

Location	Effective 1% WSEL (feet)	BLE 1% WSEL (feet)	Difference (Eff. - BLE) (feet)
South Llano River at Main Street (Junction, TX)	1,701.9	1,700.1	1.8
South Llano River at Flatrock Lane (Junction, TX)	1,709.6	1,708.9	0.7

* A vertical datum conversion of +0.124 feet was used to convert the effective WSELs from NGVD 29 to NAVD 88.

See Figure 11 and Table 12 on the following pages for a summary of the 1% validation results at the validation points in the South Llano watershed.

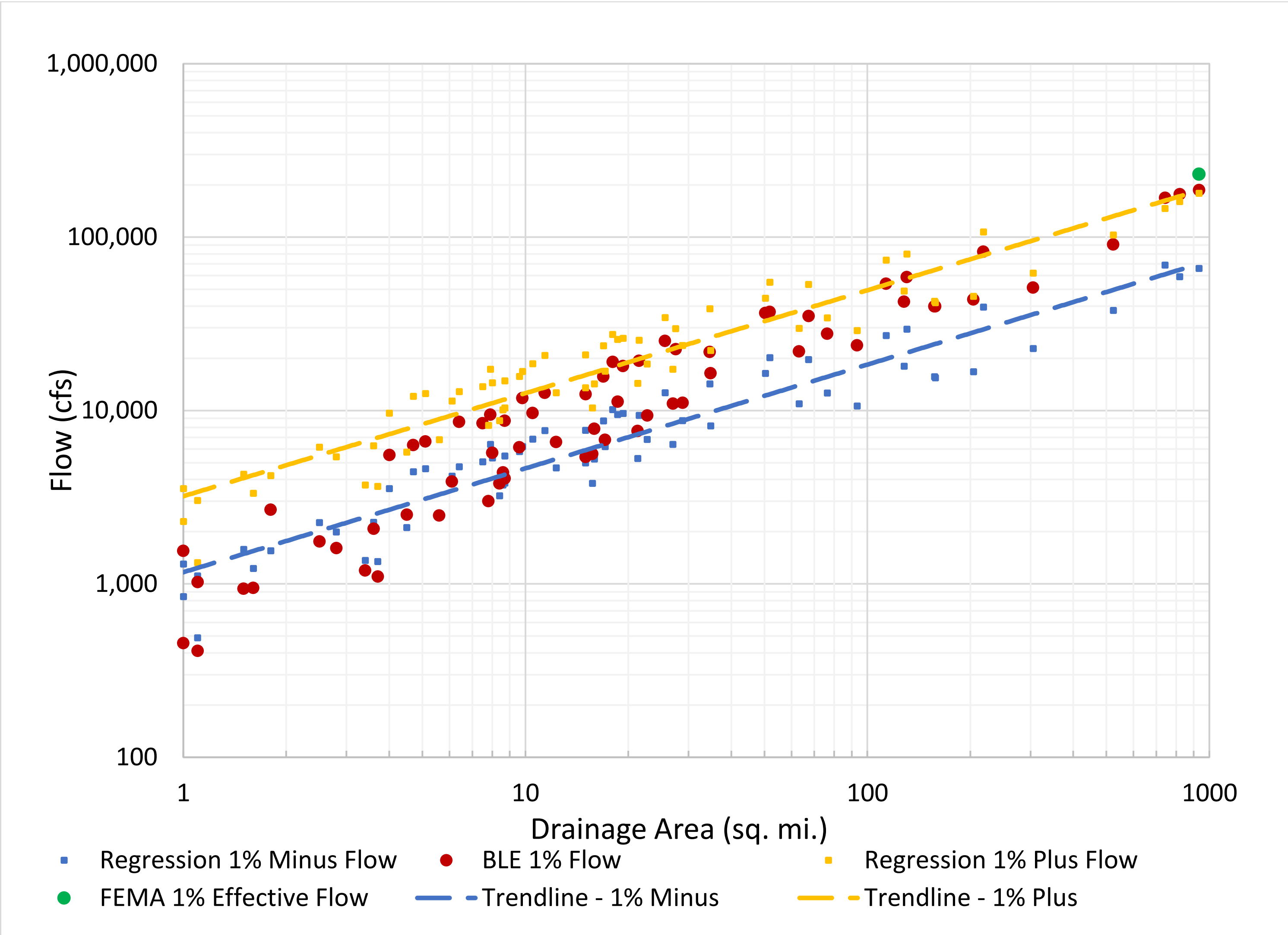


Figure 11: Computed Flow vs Drainage Area for Select 1% BLE Flows and 1% Regression Flows

Table 12: 1% Peak Flow Validation Results for the South Llano Watershed

Point ID	Validation Point Name	Drainage Area (mi^2)	Regression 1%- Flow (cfs)	Regression 1% Flow (cfs)	Regression 1%+ Flow (cfs)	BLE 1% Flow (cfs)	Gage 1%- Flow (cfs)	Gage 1% Flow (cfs)	Gage 1%+ Flow (cfs)	FIS 1% Flow (cfs)
Domain 0301_A1										
Pt1	South Llano River	157.1	15,711	25,892	42,670	39,941	-	-	-	-
Pt2	Unnamed	27.0	6,383	10,520	17,337	10,965	-	-	-	-
Pt3	Unnamed	15.7	3,809	6,278	10,346	5,620	-	-	-	-
Pt4	Unnamed	3.4	1,370	2,258	3,721	1,197	-	-	-	-
Pt5	Unnamed	1.1	489	807	1,329	412	-	-	-	-
Pt6	Unnamed	3.7	1,347	2,219	3,658	1,102	-	-	-	-
Pt7	South Llano River	93.3	10,650	17,551	28,924	23,771	-	-	-	-
Pt8	Unnamed	63.1	10,961	18,064	29,769	21,976	-	-	-	-
Pt9	Unnamed	21.3	5,298	8,731	14,388	7,627	-	-	-	-
Pt10	Unnamed	8.4	3,227	5,318	8,764	3,798	-	-	-	-
Pt11	Unnamed	5.6	2,506	4,130	6,806	2,484	-	-	-	-
Outfall	South Llano River	157.9	15,431	25,430	41,908	39,874	-	-	-	-

Point ID	Validation Point Name	Drainage Area (mi^2)	Regression 1%- Flow (cfs)	Regression 1% Flow (cfs)	Regression 1%+ Flow (cfs)	BLE 1% Flow (cfs)	Gage 1%- Flow (cfs)	Gage 1% Flow (cfs)	Gage 1%+ Flow (cfs)	FIS 1% Flow (cfs)
Domain 0301_A2										
Pt1	Unnamed	28.8	8,744	14,411	23,749	11,109	-	-	-	-
Pt2	Unnamed	17.1	6,205	10,225	16,851	6,785	-	-	-	-
Pt3	Unnamed	8.7	3,821	6,297	10,378	4,063	-	-	-	-
Pt4	Unnamed	1.0	845	1,392	2,295	456	-	-	-	-
Pt5	Unnamed	15.0	4,987	8,219	13,544	5,403	-	-	-	-
Pt6	Unnamed	7.8	3,024	4,984	8,213	3,008	-	-	-	-
Pt7	South Llano River	204.1	16,786	27,664	45,590	43,740	-	-	-	-
Pt8	Unnamed	3.6	2,270	3,740	6,264	2,083	-	-	-	-
Outfall	South Llano River	305.2	22,843	37,645	62,039	51,301	-	-	-	-
Domain 0302_A3										
Pt1	Unnamed	76.3	12,641	20,832	34,332	27,763	-	-	-	-
Pt2	Unnamed	2.8	1,995	3,287	5,418	1,608	-	-	-	-
Pt3	Unnamed	12.3	4,669	7,694	12,680	6,581	-	-	-	-

Point ID	Validation Point Name	Drainage Area (mi²)	Regression 1%- Flow (cfs)	Regression 1% Flow (cfs)	Regression 1%+ Flow (cfs)	BLE 1% Flow (cfs)	Gage 1%- Flow (cfs)	Gage 1% Flow (cfs)	Gage 1%+ Flow (cfs)	FIS 1% Flow (cfs)
Pt4	Unnamed	34.8	8,177	13,476	22,209	16,423	-	-	-	-
Pt5	Unnamed	8.6	3,724	6,137	10,114	4,394	-	-	-	-
Pt6	Unnamed	1.6	1,229	2,025	3,337	951	-	-	-	-
Pt7	Deer Creek	22.7	6,828	11,252	18,543	9,368	-	-	-	-
Pt8	Unnamed	15.9	5,256	8,661	14,274	7,847	-	-	-	-
Pt9	Unnamed	4.5	2,118	3,491	5,753	2,512	-	-	-	-
Outfall	Unnamed	128.0	18,040	29,731	48,996	42,497	-	-	-	-
Domain 0302_A4										
Pt1	Contrary Creek	27.5	10,921	17,998	29,660	22,588	-	-	-	-
Pt2	Unnamed	6.4	4,742	7,814	12,878	8,611	-	-	-	-
Pt3	Contrary Creek	50.3	16,384	27,000	44,496	36,596	-	-	-	-
Pt4	Contrary Creek	16.9	8,706	14,347	23,644	15,737	-	-	-	-
Pt5	Contrary Creek	10.5	6,854	11,295	18,614	9,686	-	-	-	-
Pt6	Unnamed	7.5	5,067	8,350	13,760	8,447	-	-	-	-

Point ID	Validation Point Name	Drainage Area (mi^2)	Regression 1%- Flow (cfs)	Regression 1% Flow (cfs)	Regression 1%+ Flow (cfs)	BLE 1% Flow (cfs)	Gage 1%- Flow (cfs)	Gage 1% Flow (cfs)	Gage 1%+ Flow (cfs)	FIS 1% Flow (cfs)
Pt7	Bluff Creek	4.7	4,447	7,329	12,079	6,319	-	-	-	-
Pt8	Unnamed	1.8	1,556	2,564	4,225	2,677	-	-	-	-
Outfall	South Llano River	523.5	37,892	62,446	102,911	90,838	-	-	-	-
Domain 0303_A5										
Pt1	Unnamed	18.6	9,475	15,614	25,732	11,260	-	-	-	-
Pt2	Hunger Creek	34.6	14,240	23,467	38,674	21,767	-	-	-	-
Pt3	Paint Creek	67.3	19,664	32,406	53,405	35,083	-	-	-	-
Pt4	Earwood Creek	8.0	5,328	8,781	14,470	5,707	-	-	-	-
Pt5	Unnamed	1.5	1,583	2,609	4,299	938	-	-	-	-
Pt6	Unnamed	6.1	4,189	6,904	11,377	3,901	-	-	-	-
Pt7	Paint Creek	2.5	2,264	3,731	6,148	1,761	-	-	-	-
Pt8	Hunger Creek	9.6	5,806	9,569	15,770	6,142	-	-	-	-
Outfall	Paint Creek	113.4	27,127	44,705	73,674	53,881	-	-	-	-
Domain 0303_A6										

Point ID	Validation Point Name	Drainage Area (mi^2)	Regression 1%- Flow (cfs)	Regression 1% Flow (cfs)	Regression 1%+ Flow (cfs)	BLE 1% Flow (cfs)	Gage 1%- Flow (cfs)	Gage 1% Flow (cfs)	Gage 1%+ Flow (cfs)	FIS 1% Flow (cfs)
Pt1	Unnamed	25.6	12,672	20,883	34,415	25,208	-	-	-	-
Pt2	Paint Creek	130.4	29,464	48,557	80,022	58,799	-	-	-	-
Pt3	Unnamed	1.1	1,115	1,838	3,029	1,026	-	-	-	-
Pt4	Unnamed	9.8	6,195	10,210	16,825	11,785	-	-	-	-
Pt5	Unnamed	18.0	10,132	16,698	27,519	19,097	-	-	-	-
Pt6	Unnamed	8.7	5,466	9,007	14,844	8,729	-	-	-	-
Pt7	Unnamed	5.1	4,615	7,606	12,534	6,637	-	-	-	-
Pt8	Unnamed	4.0	3,554	5,857	9,653	5,536	-	-	-	-
Outfall	Paint Creek	218.2	39,545	65,170	107,401	82,556	-	-	-	-
Domain 0304_A7										
Pt1	Cedar Creek	15.0	7,708	12,703	20,935	12,413	-	-	-	-
Pt2	South Llano River	818.4	59,227	97,606	160,855	176,800	-	-	-	-
Pt3	Unnamed	1.0	1,306	2,152	3,547	1,554	-	-	-	-
Pt4	Salina Creek	21.5	9,374	15,448	25,458	19,369	-	-	-	-

Point ID	Validation Point Name	Drainage Area (mi^2)	Regression 1%- Flow (cfs)	Regression 1% Flow (cfs)	Regression 1%+ Flow (cfs)	BLE 1% Flow (cfs)	Gage 1%- Flow (cfs)	Gage 1% Flow (cfs)	Gage 1%+ Flow (cfs)	FIS 1% Flow (cfs)
Pt5	Cedar Creek	51.8	20,223	33,328	54,924	37,144	-	-	-	-
Pt6	Chalk Creek	19.3	9,630	15,870	26,153	18,066	-	-	-	-
Pt7	Joy Creek	7.9	6,385	10,522	17,340	9,474	-	-	-	-
Pt8	Cajac Creek	11.4	7,663	12,629	20,812	12,677	-	-	-	-
Pt9	South Llano River	742.1	69,116	88,806	146,650	168,516	-	-	-	-
Outfall	South Llano River	932.8	66,058	108,863	179,406	187,124	-	-	-	231,000

1.3. Floodplain Delineation (10%, 1%, and 0.2% events)

Floodplains were delineated throughout the entire watershed for the 10%, 1%, and 0.2% annual-chance events. The 1% and 0.2% floodplains may be found in the FLD_HZD_AR feature class in the flood risk database. The 10% floodplain may be found in the TENPCT_FP feature class in the database.

The floodplains were derived from the raw modeled grids using the maximum water surface elevation and depth values in each cell of the mesh. These grids were exported from HEC-RAS as rasters in TIF format with an interpolated rendering that slopes values at the center and along the faces/edges of the computational mesh cells. Using GIS software, the TIF rasters were post-processed into 10%, 1%, and 0.2% annual-chance floodplains.

The following general steps were completed to delineate the floodplains:

- Export the depth rasters and WSEL rasters for the 10%, 1%, and 0.2% ACEs from the HEC-RAS models using a sloping water surface elevation render mode to a GIS environment. When exporting the model results, the “Raster based on terrain” parameter in HEC-RAS was changed from “Terrain.HydroEnforced” to “Terrain.” This change was made so the original terrain surface was used to develop the floodplain mapping, not the hydro-enforced terrain surface. Using the hydro-enforced terrain would have led to mapping that would have incorrectly shown the roadway as being overtopped where the hydro-enforced culverts had been added.

- For each ACE, merge the raw WSEL rasters into a single raster that covers the entire watershed. Do the same for the depth rasters. Where the floodplain mapping needed to tie-in across two model domains, the model domain boundaries overlapped. Tie-in locations were identified in these overlap areas using split line shapefiles. Three split line shapefiles were created, one for each of the mapped events (i.e., 10%, 1%, and 0.2%). Split line alignments for each event were determined by creating difference rasters that subtracted the WSEL rasters from one another in the model domain overlap areas. Split lines were then drawn around the entire perimeter of each model domain through areas where the WSELs in the difference rasters were within 0.5 feet of each other. See the split line shapefiles in the *Supplement Data* folder to understand where the mapping tie-ins are located.

- To understand how a split line is placed, consider Figure 12, which shows two floodplains that overlap along a model domain boundary. The split line must be placed where the WSELs are within 0.5 feet of one another in the overlap area. To determine where the WSELs meet this criterion, a WSEL difference raster was created.

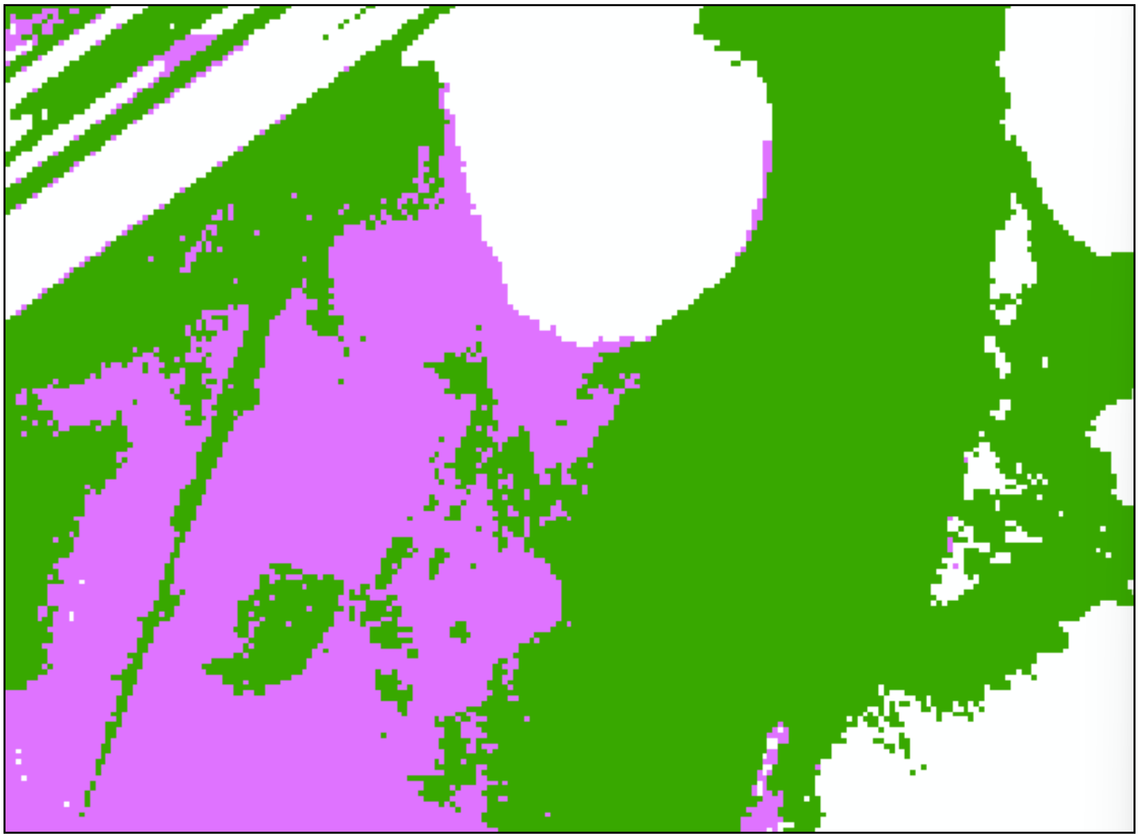


Figure 12: Example of Overlapping Mapping along a Model Domain Boundary

Figure 13 shows what the difference raster looks like for the area in Figure 12. Light green means the WSELs are within 0.5 feet of each other and red means they are not. The blue-black line is the split line. It has been aligned so that it crosses the difference raster where the raster is light green. To the south of this line, the purple raster in Figure 12 is the source of the floodplain mapping. To the north of the split line, the dark green raster is the source of the floodplain mapping. Along the split line is where the source of the mapping transitions from the purple mapping to the dark green mapping.

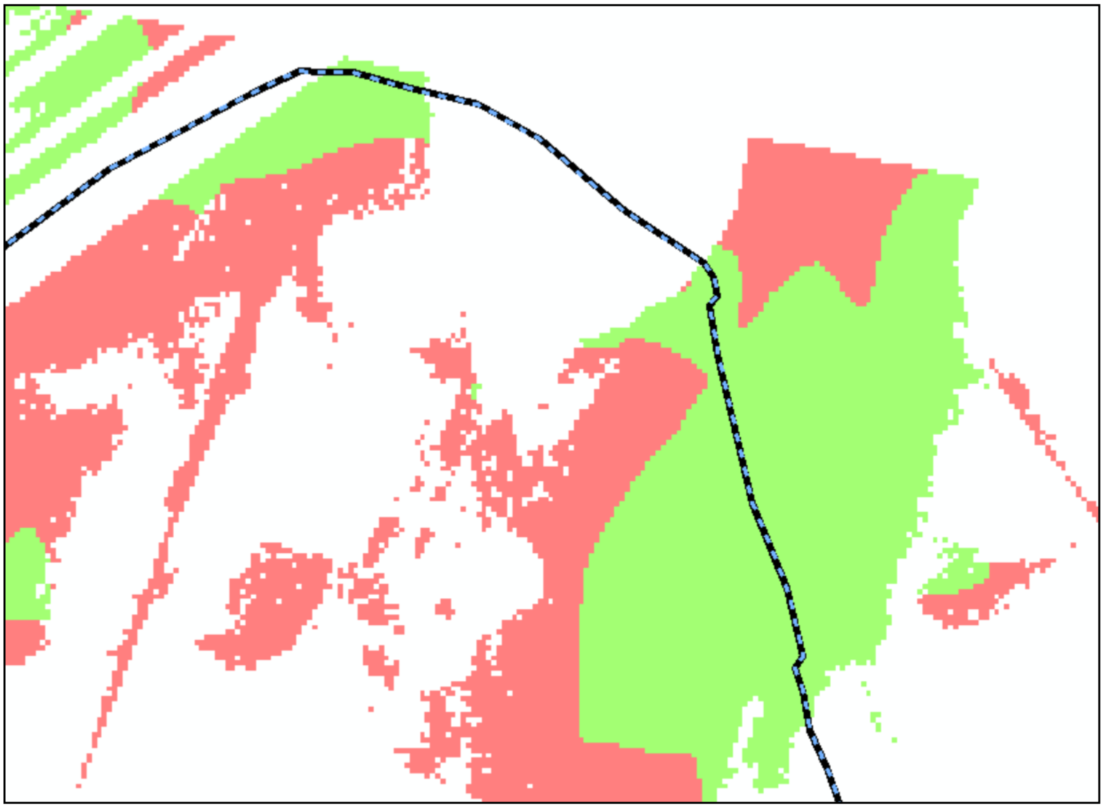


Figure 13: WSEL Difference Raster and Split Line for the Overlap Area

- The merged raw raster grids included connected and disconnected areas of potential flood hazard. To reduce the extent of these disconnected flood areas, process the rasters to filter and remove disconnected small, shallow areas of flooding. To do this, apply the TWDB's mapping threshold matrix to remove shallow depths, small areas of flood risk, and disconnected areas. According to Figure 3.1 in TWDB's 2D BLE guidelines, the watershed falls in the Inland Areas of Texas. Therefore, disconnected areas were removed if they met ***both*** of the criteria in Table 13.

Table 13: Inland Mapping Threshold Matrix

Area (acres)	Depth (feet)
Less than 0.33	Remove all flooding
0.33 to 0.50	Less than 0.33
0.50 to 1.0	Less than 0.25
1.0 to 2.0	Less than 0.10

- Fill the holes (i.e., islands) in the rasters using the Elevation Void Fill routine. For the 1% and 0.2% ACEs, holes in the rasters less than 2 acres were filled. For the 10% ACE, holes in the raster less than 0.5 acres were filled. Application of the Elevation Void Fill routine occasionally produces WSELs that are below the ground elevation. In cases where this phenomenon occurred, the WSELs were not revised from their subterranean values, but the depths at these locations were set to 0.1 feet.

- Convert each WSEL raster to a floodplain polygon.

- Many ponding areas were present throughout the watershed. Due to the large mesh cells used in the 2D modeling, the extent of the smaller ponds was not always mapped properly in the model output. To properly identify the flood hazard in these areas, transfer the ponding extents available in the National Hydrography Dataset into the 1% and 0.2% floodplain polygons. Do not transfer them into the 10% floodplain polygon.

- If any dams are present that have been catalogued by the National Inventory of Dams and include a normal pool storage of 200 acre-feet or more, review the spillway mapping along each dam. If the 1% and/or the 0.2% model output did not include any flooding along the spillway, manually revise the floodplain polygon(s) to flood the spillway.

- Add waterbodies of lake and reservoir inundation areas of 20 acres or greater to the WTR-LN and FLD_HAZ_AR feature classes. The National Inventory of Dams was used to identify dams with inundation areas greater than 20 acres. The areas of inundation were computed by measuring the areas of the normal pools visible on the aerial photography.

- Clean up each polygon by simplifying it and smoothing it. The intent of the simplify and smooth processes is to eliminate unnecessary/erroneous vertices, remove rough edges, and reduce the size and complexity of the raw floodplain polygons. Apply professional judgement to determine the appropriate tolerance for simplifying and smoothing the floodplain polygons. Set initial thresholds to 5 feet for simplifying and 25 feet for smoothing.

- Merge the 1%, and 0.2% ACE polygons into one feature class. Keep the 10% ACE polygon as a separate feature class.

- The extents of the final depth and WSEL grids must match the extents of the flood inundation polygons. Because of the clipping and smoothing procedures applied to the floodplain polygons, they will no longer match the extents of the rasters. Clip the depth and WSEL grids to each respective flood frequency inundation polygon to align the extents of the rasters with the extents of the floodplain polygons.

- Clip the rasters and the floodplain polygons using the HUC-8 watershed boundary.

Challenges

A handful of challenges were encountered during the South Llano BLE analysis. These challenges and their solutions are catalogued in the following subsections.

Balancing Flows between Small and Large Streams

The BLE models developed for the South Llano watershed are watershed-wide models. Each domain is similar in size to a HUC-10 watershed. As a result, streams with both large and small drainage areas are in the same model and cannot be isolated from one another. One of the main challenges of the BLE analysis was adjusting the model input parameters so that valid flows were produced along streams with both large and small drainage areas. For example, when the CNs were increased to increase flows that were too low along the smaller tributaries, this adjustment would occasionally lower the flows along the more-significant streams to a point below the lower end of that which was considered valid and vice versa. To address this challenge, a range of acceptable CNs and Manning’s n values was established for the watershed. The parameters were adjusted only within this set range so that the model results did not skew the too heavily in favor of the larger streams or the smaller streams. Balancing the validation needs between the small and large stream was further enhanced by assigning an equal weight to all validation locations and choosing validation locations such that a representative coverage of drainage areas and stream characteristics was included.

Modeling of Hydraulic Structures

Although detailed modeling of hydraulic structures was outside the scope of this BLE analysis, completing ignoring the structures would have produced invalid model results. Therefore, hydraulic structures were modeled using as simplified approach. This included adding breaklines along dam crests, elevated roadways, and railroads to force the terrain surface to drain properly. Bridge and culvert openings were represented by hydro-enforcing burn lines that were roughly equal in width to the bridge and culvert opening sizes. The addition of breaklines at the dam crests throughout AtkinsRéalis’ BLE study area typically resulted in an overestimation of the 1% BLE floodplain extents and WSELs on the upstream side of the dam. On the downstream side of the dams, the floodplains and flows tended to be underestimated.

Limited Data to Support Validation

There were limited data available to support the validation of the South Llano BLE hydraulic analysis. Although there were 4 USGS gages in the watershed, no flow-frequency analyses were able to be completed since the period of record at each gage was too short. There was a single FEMA effective flow rate available at the downstream end of the watershed that was leveraged to support validation. At all other validation locations, the regression analysis discussed in Subsection 1.2.7 was applied to validate the HEC-RAS models.

Cupping

Within HEC-RAS, the RAS Mapper interface provides three render modes for visualization of floodplains: Horizontal, Sloping, and Hybrid. Currently, the results of only the horizontal and sloping render modes can be exported. While the horizontal render mode produces “bathtubs” of isolated ponding per cell, the sloping render mode produces “cupping.” Cupping is a ramp-up of the depth in the overbanks occurring most often in areas of significant topographic relief. USACE’s HEC is aware of this issue, which is an error caused by the WSEL projecting to the adjacent cell’s average elevation. However, the timeframe for a solution to this error by the HEC is unknown. Since the TWDB mapping process is based on the sloping render mode output, this cupping effect can be identified in the final mapping products produced, as shown by the pink areas in Figure 14. The areas of cupping will not be removed or cleaned beyond the extents of the mapping cleanup process discussed herein. There is significant topographic relief throughout the South Llano watershed. Therefore, cupping is prevalent throughout the BLE mapping.

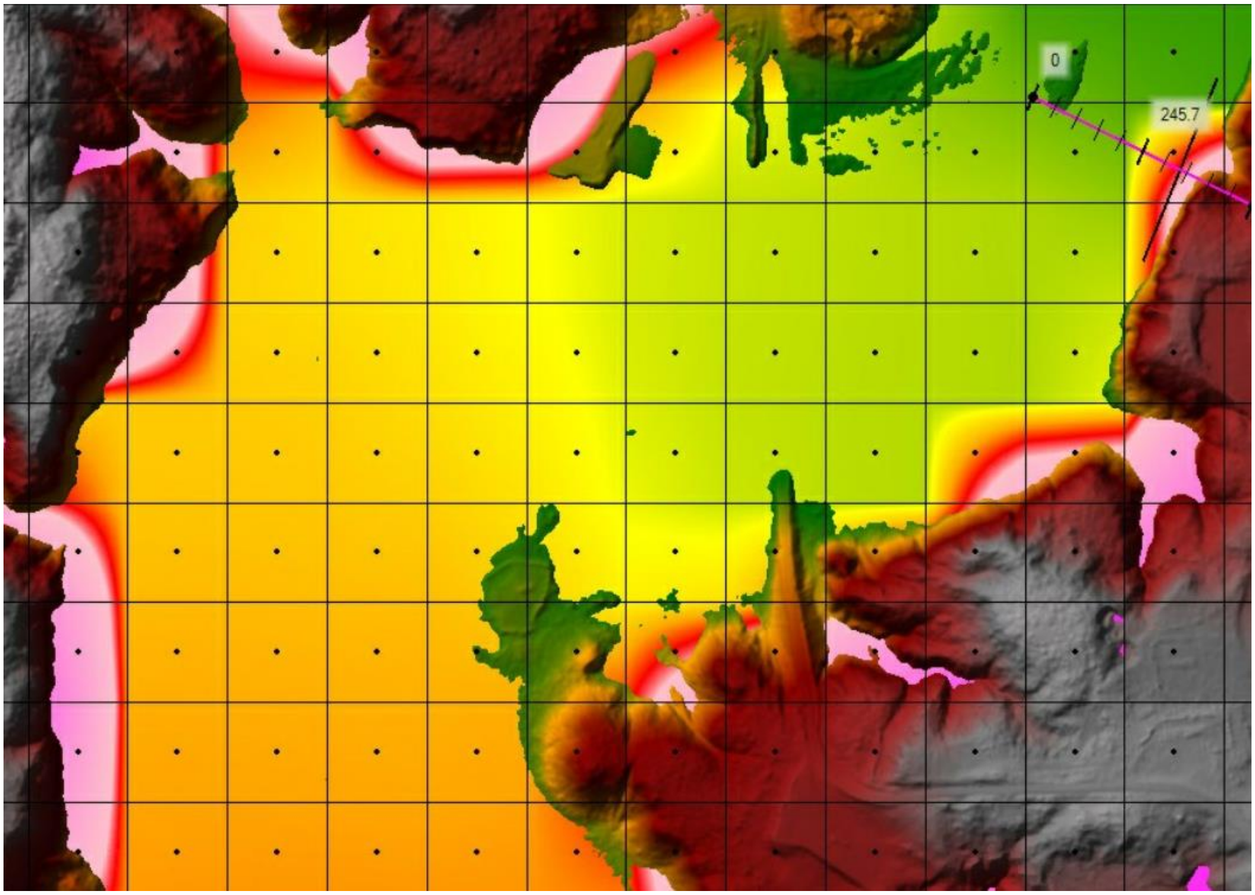


Figure 14: An Example of Cupping in 2D BLE Mapping

Results and Recommendations

The BLE results for the South Llano watershed produced floodplain boundaries that compare reasonably well with the effective Special Flood Hazard Area (SFHA) in most cases, and provides an estimated 1% annual-chance floodplain in areas currently not mapped by FEMA. These results provide context for flood risk communication as part of the Discovery process and should be verified through community work map meetings before application to a regulatory product.

A map showing the BLE results for the South Llano watershed has been included as Appendix A.

The BLE floodplains were compared with the effective floodplains in the South Llano watershed. No digital mapping data was available in the National Flood Hazard Layer (NFHL) for the watershed. Digitized effective floodplain mapping was available in a proprietary dataset developed by RMSI and acquired by AtkinsRéalis. The RMSI dataset included digital floodplain boundaries throughout the watershed. A comparison of the effective and BLE 1% boundaries revealed that the updated BLE floodplain boundaries matched well, as shown in Figure 15, which shows the area in the vicinity of Telegraph, Texas.

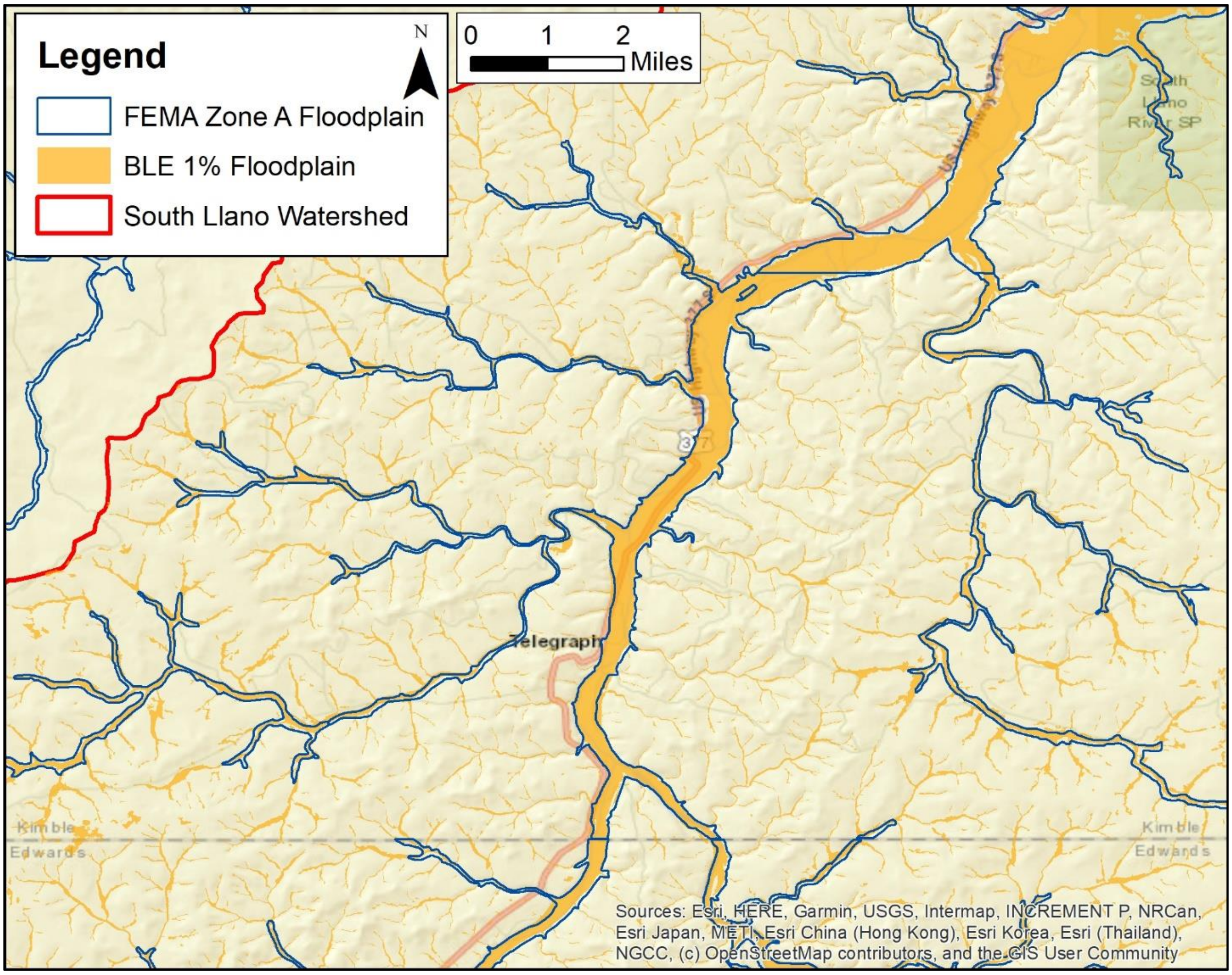


Figure 15: The Effective 1% Floodplain and the 1% BLE Floodplain near Telegraph, TX

Floodplain mapping for the South Llano watershed was also available from a contractor called Fathom. The TWDB acquired cursory floodplain data from Fathom to fill gaps in areas where no floodplain mapping was available in Texas. The Fathom floodplain dataset included pluvial, fluvial, and coastal storm surges produced using models developed at a 30-meter resolution for the entire state of Texas. The 30-meter Fathom models incorporated LiDAR data provided by the TWDB and NOAA Atlas 14 rainfall data in all areas of the state. Fathom model results were mapped to a 3-meter resolution. Fluvial and pluvial cells with depths less than 0.5 feet were removed from the results of the mapping dataset. The use of this dataset should be limited to areas where no other data source has been identified or areas where flood hazard information is outdated or unreliable. Limited use of this dataset is recommended due to limitations with accuracy, resolution, and age of the underlying datasets.

The 2D BLE results for the South Llano watershed were compared with the Fathom floodplain mapping. Figure 16 shows the 1% BLE mapping in orange with a transparency applied and the 1% Fathom mapping in black in the same area that is shown in Figure 15. In general, there was good agreement between the mapping from these two sources. However, there are examples of pluvial mapping in the figure that are more extensive in the BLE mapping than in the Fathom mapping.

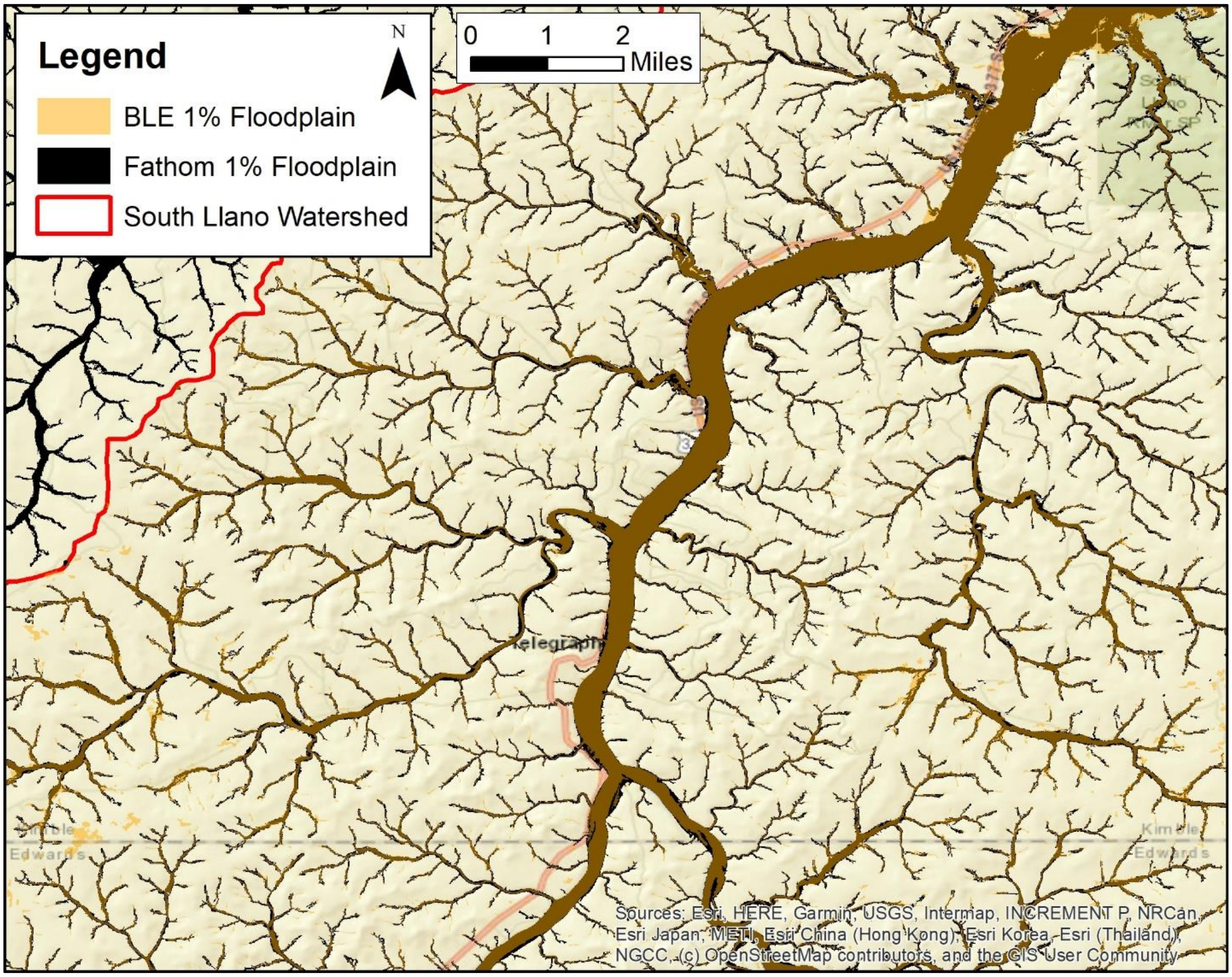


Figure 16: Comparison of 1% BLE Mapping with Fathom 1% Mapping

As part of the BLE assessment effort, a polygon file was prepared to detail areas where model refinements may be warranted. These areas may be found in the feature class S_AOMI_AR in the mapping database.

1.4. Quality Control

To guide its quality control (QC) reviews, AtkinsRéalis developed three custom QC checklists for its TWDB 2D BLE studies. The checklists were for the terrain processing, the modeling, and the mapping tasks. The terrain processing checklist included 17 items, and the modeling checklist included 51 items. The mapping checklist included 20 checks for the spatial data and 244 checks for the attributes in the mapping database. These robust checklists documented the QC review process, capturing reviewer comments and originator feedback throughout the comment resolution process. Checklists were not considered final until reviewed and approved by project leadership.

As part of this QC process, the flood hazard area delineations created by the BLE analysis were reviewed for areas where the results were not ideal.

A major component of the QC process was an automated check that identified locations where the 1% annual-chance WSELs were crossed by another frequency or by the 1% plus or 1% minus profile. Significant effort was made to reasonably resolve all of these instances.

An Independent Technical Review (ITR) was completed on all BLE deliverables by a representative of the TWDB. AtkinsRéalis resolved all ITR comments prior to uploading the project deliverables to the MIP.

1.5. CNMS Validation of Effective Zone A Special Flood Hazard Area

All of the Zone A streams in the South Llano watershed were classified as "UNVERIFIED" with a status type of "BEING STUDIED" (631.5 miles).

Initial Assessment A1 – Significant Topography Update Check

This check involved determining whether a topographic data source was available that was significantly better than that used for the effective Zone A modeling and mapping. For the South Llano watershed, USGS 1:24,000-scale topographic maps were used for the effective Zone A analysis. The LiDAR data used in the BLE analysis was a significant improvement over the effective data's terrain data source. Therefore, the A1 check failed for all effective Zone A reaches.

Initial Assessment A2 – Check for Significant Hydrology Changes

This check involved first determining whether regression equations were used in the effective study. If they were, then it was determined whether new regression equations had become available since the date of the effective Zone A study. If newer regression equations existed for the area of interest, then an engineer determined whether these regression equations would significantly affect the 1% annual-chance flow. The effective hydrologic analysis was not based on a regression analysis, therefore the A2 check was set to pass.

Initial Assessment A3 – Check for Significant Development

This check involved using the National Urban Change Indicator (NUCI) dataset to assess increased urbanization in the watersheds with Zone A studies. If the percentage of urban area within a HUC-12 watershed containing an effective Zone A study was 15% or more, and had increased by 50% or more since the effective analysis, then the study would fail this check. Although the NUCI data provided year-to-year changes in urbanization, the NLCD also was needed to establish a baseline of urban land cover for this analysis. The South Llano watershed is generally rural with few villages, and there had not been significant development in the watershed. A significant development check for the study area was carried out using the NUCI dataset, which did not meet the urban change criteria. Therefore, the A3 check was set to pass for all reaches.

Table 14: Zone A Initial Assessment Results

Assessment Check	Pass/Fail	Comments/Notes
A1 - Topography	Fail	The LiDAR terrain data is a significant improvement over the terrain data used to develop the effective mapping.
A2 - Hydrology	Pass	The effective hydrologic analysis was not regression based.
A3 - Development	Pass	No significant development has occurred in the study area.

Initial Assessment A4 – Check of Studies Backed by Technical Data

Zone A studies that passed all initial assessment checks described above were categorized as "Valid" in the CNMS Inventory only if the effective Zone A study was supported by modeling or sound engineering judgment and all regulatory products were in agreement. If the effective Zone A study passed all initial assessment checks but was not supported by modeling, or if the original engineering method used was unsupported or undocumented, then a comparison of the BLE results and effective Zone A mapping was performed. There was no adequate documentation regarding how the engineering analysis supporting the effective study was performed. Therefore, the A4 check was set to fail for all reaches in this study.

Initial Assessment A5 – Comparison of BLE and Effective Zone A Floodplains

The BLE/effective Zone A comparison method leveraged the existing Floodplain Boundary Standard (FBS) certification procedures described in FEMA SID 113, but with a slight modification. This modified FBS comparison approach used the 1% plus and 1% minus flood extents and the horizontal and vertical tolerances described in the CNMS Technical Reference. For the comparison of the BLE mapping and effective Zone A mapping in the study area, the following vertical and horizontal tolerances were used to conduct the modified FBS procedure. These comparisons were made at points spaced at a 100-foot interval along the outer extents of the effective Zone A mapping.

Vertical Tolerance: Plus or minus 5 or 10 feet (one-half contour interval of assumed effective topographic source). See the shapefile USGS_24K_Index.shp in the Supplemental data folder to see how the vertical tolerance varied throughout the watershed.

Horizontal Tolerance: Plus or minus 75 feet (standard horizontal tolerance for BLE comparison testing).

The terrain data used to complete Initial Assessment A5 was the terrain surface created from the LiDAR data that was acquired for the South Llano BLE analysis.

The contour interval for the vertical tolerance was acquired from the USGS 1:24,000-scale topographic maps of the South Llano watershed.

The source of the effective Zone A mapping was FEMA's NFHL and mapping that was digitized from FEMA's paper FIRMs.

See Table 16 for a summary of the outcomes of Initial Assessment A5.

CNMS Validation Results

Based on the validation assessments and BLE comparisons described above, the CNMS Inventory of the Zone A studies in the South Llano watershed study area has been updated. The total miles in each of these categories are summarized in Table 15 and illustrated on Figure 17. The findings from the Initial Assessment A5 are in Table 16.

Table 15: Zone A Validation Results

Validation Status	CNMS Validation Status	CNMS Project Start	CNMS Post-BLE Assessment
VALID	TO BE STUDIED	0	0
	BEING STUDIED	0	0
UNVERIFIED	TO BE STUDIED	552.1	0
	BEING STUDIED	0	631.5

Table 16: BLE Comparison Results

HUC-12 Watershed		Total FBS Points	Fail	Pass	% Pass	BLE Comparison Pass? (>85%)
Watershed Name	HUC-12 ID					
120902030101	120902030101	3,827	913	2,914	76.1%	Fail
120902030103	120902030103	2,927	756	2,171	74.2%	Fail
120902030104	120902030104	1,266	323	943	74.5%	Fail
Bluff Creek-South Llano River	120902030206	1,517	702	815	53.7%	Fail
Cajac Creek-South Llano Creek	120902030402	2,210	942	1,268	57.4%	Fail
Cedar Creek	120902030404	3,593	908	2,685	74.7%	Fail
Chalk Creek	120902030403	2,512	858	1,654	65.8%	Fail
Cloudt Draw-South Llano River	120902030102	3,025	712	2,313	76.5%	Fail
Contrary Creek	120902030205	3,583	984	2,599	72.5%	Fail
Dragoo Hollow	120902030107	1,499	578	921	61.4%	Fail
Dry Hollow-South Llano River	120902030204	1,191	440	751	63.1%	Fail
Elbow Lake-South Llano River	120902030106	1,936	548	1,388	71.7%	Fail
Headwaters Paint Creek	120902030301	4,103	909	3,194	77.8%	Fail
Hunger Creek	120902030303	2,696	732	1,964	72.8%	Fail
Joy Creek-South Llano River	120902030405	1,923	942	981	51.0%	Fail
Knust Draw-South Llano River	120902030108	4,004	1,689	2,315	57.8%	Fail

HUC-12 Watershed		Total FBS Points	Fail	Pass	% Pass	BLE Comparison Pass? (>85%)
Watershed Name	HUC-12 ID					
Little Pain Creek-South Llano River	120902030401	3,266	1,255	2,011	61.6%	Fail
Lower Dry Draw	120902030203	3,838	1,215	2,623	68.3%	Fail
Lower Paint Creek	120902030305	2,624	945	1,679	64.0%	Fail
Middle Dry Draw	120902030202	2,124	812	1,312	61.8%	Fail
Middle Paint Creek	120902030304	3,881	1,408	2,473	63.7%	Fail
Phillips Draw-South Llano River	120902030105	3,372	1,141	2,231	66.2%	Fail
Upper Dry Draw	120902030201	3,240	892	2,348	72.5%	Fail
Upper Paint Creek	120902030302	1,375	478	897	65.2%	Fail

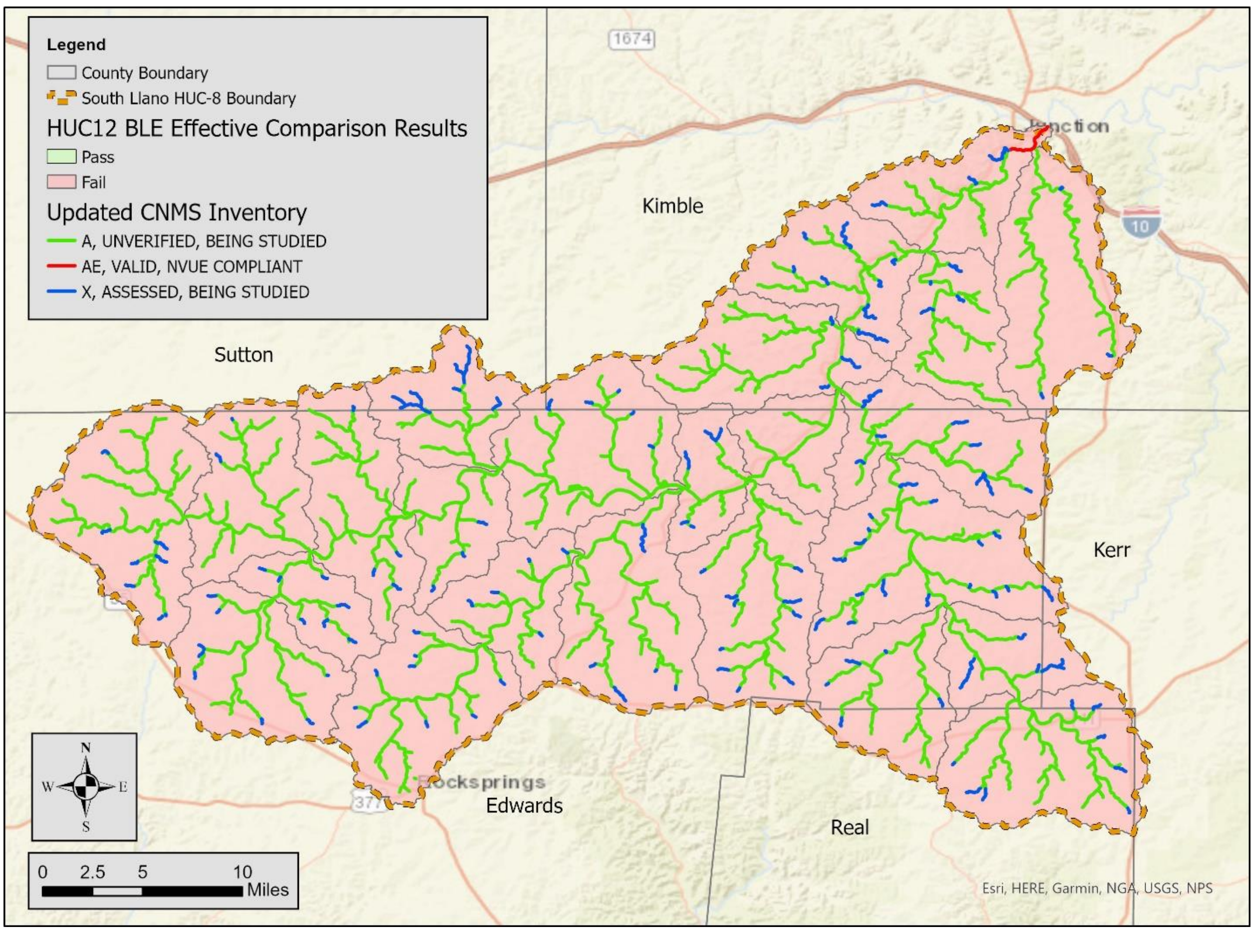


Figure 17: CNMS Validation Results

1.6. Flood Risk Analysis

A flood risk analysis was performed for the South Llano watershed. This analysis was completed using Hazus Version 5.1. Flood losses were based on the 1% annual-chance depth grids from the BLE analysis.

Additional inputs for the analysis were as follows.

S_AOMI_Ar

AoMIs are Areas of Mitigation Interest. This polygon feature class is intended to be used as a communication tool to direct users to areas that warrant further investigation or research for possible mitigation. The intent of this coverage area is to allow a visualization and depiction of areas that may be refined in future local, state, regional, or federal modeling efforts.

Areas typically identified by this feature class include:

- Areas of significant land use change – The source of land use data for this BLE assessment was the 2019 NLCD. The land uses captured by this database were compared with the land uses shown in the aerial imagery available in Google Earth when the floodplain mapping was being developed. Areas where the land use had changed significantly since 2019 were documented in the feature class.

- Intersections of significant streams with major roadways – Since structures were not explicitly included in the BLE models, these areas were identified as areas where additional analysis may be useful for refining the outcomes of the BLE study.

- Floodplain mapping tie-ins along the HUC-8 watershed boundary – Along the HUC-8 watershed boundaries where AtkinsRéalis completed BLE assessments for both watersheds, the floodplain mapping includes smooth tie-ins across the watershed boundaries. Along those HUC-8 watershed boundaries where AtkinsRéalis did not study both watersheds, the mapping tie-ins could not be smoothed since the BLE floodplain mapping in the neighboring watershed was not available. AoMIs were placed along these HUC-8 watershed boundaries to identify those tie-ins that potentially could be refined by a future modeling effort.

S_AOMI_Pt

This point feature class depicts hydraulic structures (e.g., bridges, culverts, dams, etc.), highwater marks, and low water crossings. Hydraulic structures data was obtained from available Texas GIS data sites. Essential facilities such as schools, police stations, and emergency centers were obtained from the Hazus essential facilities inventory.

Outputs from the analysis were as follows.

S_FRACT_Ar

This is the flood risk assessment polygon feature class. It is the output for a flood level 2 analysis using Hazus Version 5.1, which is based on a 1% annual-chance depth grid. The calculated loss results from

Hazus are stored in the polygon feature and are based on dasymetric census blocks. Dasymetric census blocks have had additional "undeveloped" land areas (primarily wetlands and forest) clipped out of the original census block boundaries based on USGS land use/land cover data. Loss values are reported in whole dollar amounts. See Table 17 below for a summary of the losses computed by Hazus. Note that the full replacement loss (total loss) column is limited to those structures in the 1% floodplain while the dollar exposure columns considered all structures in the watershed.

L_Source_Cit

The data sources used for S_AOMI_AR and S_AOMI_PT are documented in the L_Source_Cit table.

Table 17: Hazus Results for the South Llano Watershed

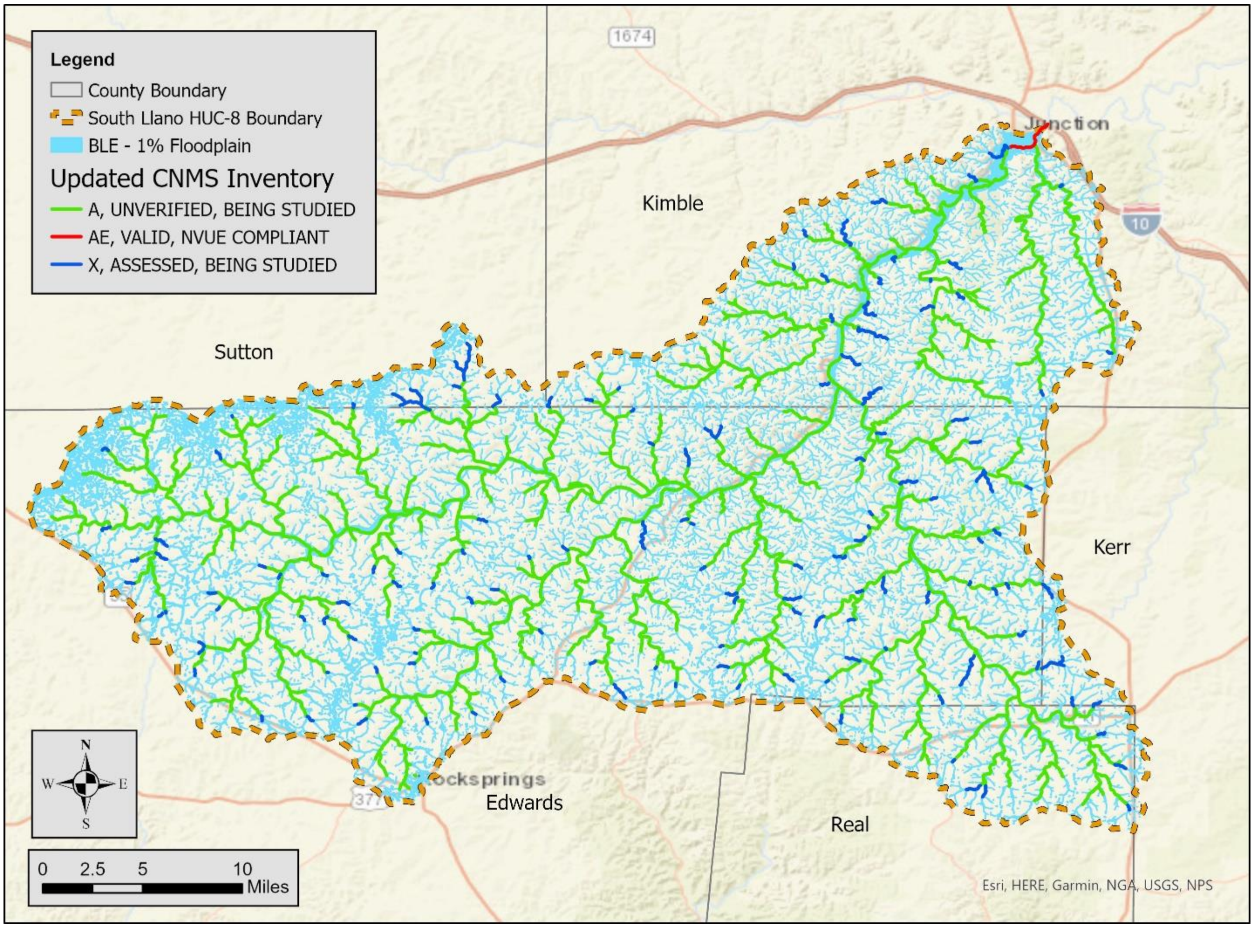
County	Full Replacement – Total Loss	Dollar Exposure (Replacement Value) - Buildings	Dollar Exposure (Replacement Value) - Contents
Edwards County	$14,308,000	$163,543,000	$94,965,000
Kerr County	$12,000	$5,397,000	$2,701,000
Kimble County	$53,886,000	$240,456,000	$143,380,000
Real County	$777,000	$11,856,000	$6,545,000
Sutton County	$71,000	$3,532,000	$1,795,000
Total	**$69,054,000**	**$424,784,000**	**$249,386,000**

References

This section includes a bibliographic list of the documents referenced throughout this document or used during the preparation of the BLE analysis.

1. Chow, Ven T. *Open Channel Hydraulics*. Caldwell, NJ: Blackburn, 1959. *Development of Uniform Flow and Its Formulas*, pages 109-113. Print.
2. Federal Emergency Management Agency (FEMA). *Base Level Engineering – Region 6 Submittal Guidance*. January 2019. Main report and Appendix A. PDF.
3. Federal Emergency Management Agency (FEMA). *Coordinated Needs Management Strategy (CNMS) Technical Reference*. November 2021. Web. https://www.fema.gov/flood-maps/guidance-reports/guidelines-standards
4. Federal Emergency Management Agency (FEMA). National Flood Hazard Layer (NFHL). Web. https://hazards-fema.maps.arcgis.com/apps/webappviewer/index.html?id=8b0adb51996444d4879338b5529aa9cd
5. Interagency Flood Risk Management (InFRM) Team. *Watershed Hydrology Assessment for the Lower Colorado River Basin*. DRAFT PDF. Chapter 5, pages 67, 68, and 151. 2021-08-13.
6. Natural Resources Conservation Service. Gridded Soil Survey Geographic Database (gSSURGO). 2021 version. Web. https://data.nal.usda.gov/dataset/gridded-soil-survey-geographic-database-gssurgo
7. Natural Resources Conservation Service. *National Engineering Handbook*, Title 210, Section 630, Chapter 4. August 2019 Version. Web. https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=43924.wba
8. Sanja Perica, Sandra Pavlovic, Michael St. Laurent, Carl Trypaluk, Dale Unruh, Orlan Wilhite. *NOAA Atlas 14 Volume 11 Version 2, Precipitation-Frequency Atlas of the United States, Texas*. 2018. NOAA, National Weather Service, Silver Spring, MD.
9. Soil Conservation Services, *Engineering Technical Note No. 210-18-TX5 - Estimating Runoff For Conservation Practices*, October 1990.
10. Texas Water Development Board (TWDB). *Texas Two-Dimensional Base Level Engineering Guidelines, Version 1.0*. May 21, 2022. PDF.
11. United States Army Corps of Engineers (USACE). Hydrologic Engineering Center-River Analysis System (HEC-RAS), Version 6.2. March 11, 2022.
12. United States Geological Survey (USGS). Hurricane LiDAR, 2019-02-20. Web. https://data.tnris.org/collection?c=6ddcc1e6-2059-4fa2-a2cf-4ab163e2c97e#6.55/29.436/-97.594
13. United States Geological Survey (USGS). Lower Colorado San Bernard LiDAR, 2018-06-17. Web. https://data.tnris.org/collection?c=b246f8f7-9c79-4c89-91f7-9c7f44955fca#5.37/29.889/-99.969
14. United States Geological Survey (USGS). Multi-Resolution Land Characteristics Consortium. National Land Cover Database 2019. https://www.mrlc.gov/data/nlcd-2019-land-cover-conus
15. William H. Asquith, Meghan C. Roussel. *Regression Equations for Estimation of Annual Peak-Streamflow Frequency for Undeveloped Watersheds in Texas Using an L-moment-Based, PRESS-Minimized, Residual-Adjusted Approach.* USGS Scientific Investigations Report 2009-5087. June 2009.

Appendix A – Base Level Engineering Results



Appendix B – Supporting Documentation

The following information may be found in Appendix B. These documents provide further details regarding the methodology and outcomes of the BLE analysis for the South Llano watershed.

- Page 23 from Engineering Technical Note No. 210-18-TX5 titled Estimating Runoff For Conservation Practices – This is an excerpt showing a map of Average Runoff Conditions (ARC) across Texas. The term Antecedent Runoff Condition (ARC) used in the older literature is analogous to Antecedent Moisture Condition (AMC), which is the term that is commonly accepted today.