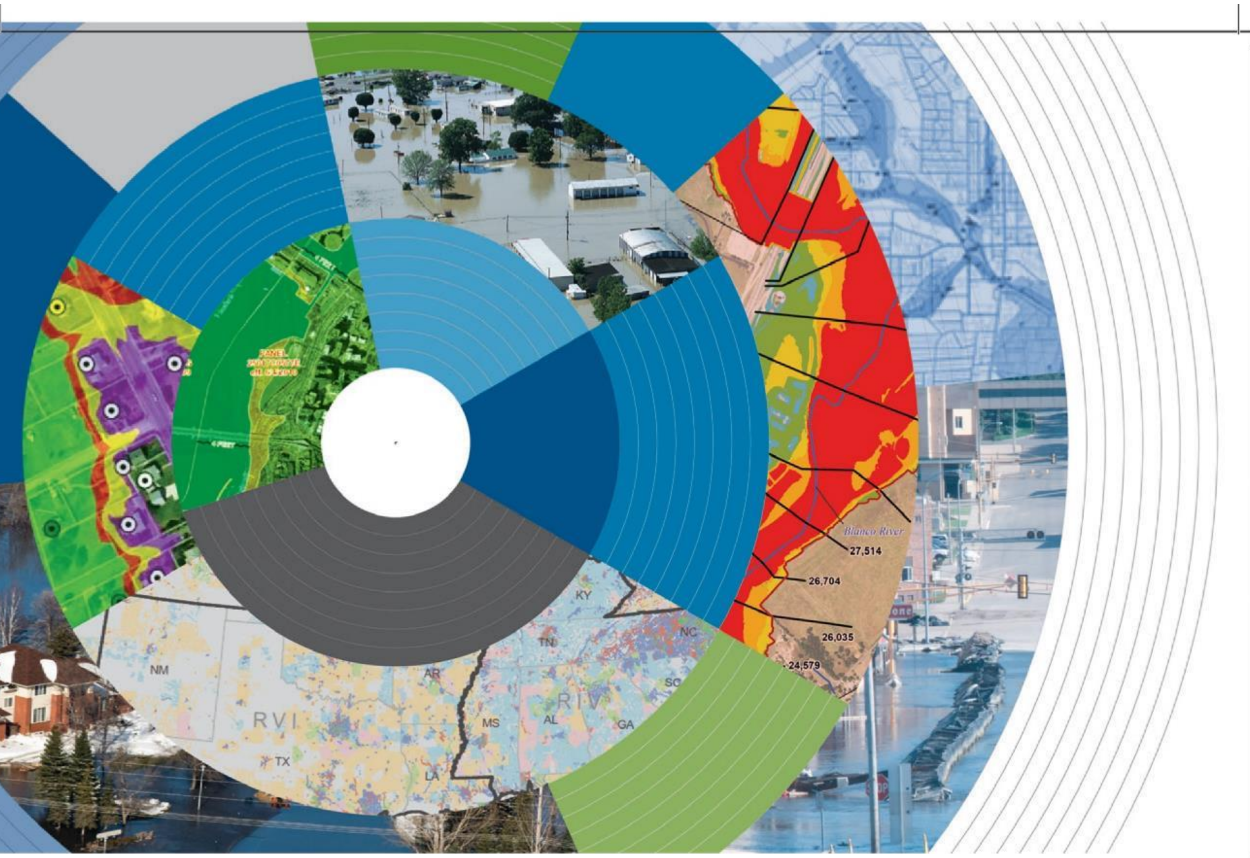



# Base Level Engineering Report

## North Llano (12090202)

Texas Water Development Board

November 30, 2024

Version 1.0

**Report Prepared for:**

Texas Water Development Board
1700 North Congress Avenue
Austin, TX 78701

**Report Prepared by:**

AtkinsRéalis USA, Inc.
11801 Domain Boulevard
Suite 500
Austin, TX 78758

## Document History

### Document Storage Location

K:/FY2022/22-06-0047S/Hydraulics – BLE|FY21|North Llano (12090202)

### Revision History

| Version No. | Version Date | Summary of Changes | Author |
|---|---|---|---|
| 1.0 | November 30, 2024 | Initial Report for the Estimated Base Flood Elevation Viewer | AtkinsRéalis USA, Inc. |

**Commented [AS1]:** Changes I've already made are to fix things I discovered while working on san saba v 4.

# Table of Contents

## List of Tables

Page

## List of Figures

# 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 North Llano HUC-8 watershed (12090202). This watershed is located in Central Texas, between Sonora and Junction, Texas. The watershed area is 920 square miles ($mi^2$). Approximately 694 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 Service's (NRCS) Curve Number (CN) loss rate method.

The North Llano watershed was divided into eight HEC-RAS model domains — 0201_A1, 0201_A2, 0201_A3, 0202_A4, 0202_A5, 0202_A6, 0203_A7, and 0203_08. 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 North 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 | 430.8 |
| **New Study Streams** - CNMS | 245.2 |
| **Total (BLE) Stream Miles** | **676.0** |

**Table 2: Zone A Validation Results**

| Validation Status | CNMS Validation Status | CNMS Project Start | CNMS Post-BLE Assessment |
|---|---|---|---|
| VALID | NVUE COMPLIANT | 0 | 0 |
| | BEING STUDIED | 0 | 2.9 |
| UNVERIFIED | BEING STUDIED | 0 | 426.2 |
| | TO BE STUDIED | 404.2 | 0 |

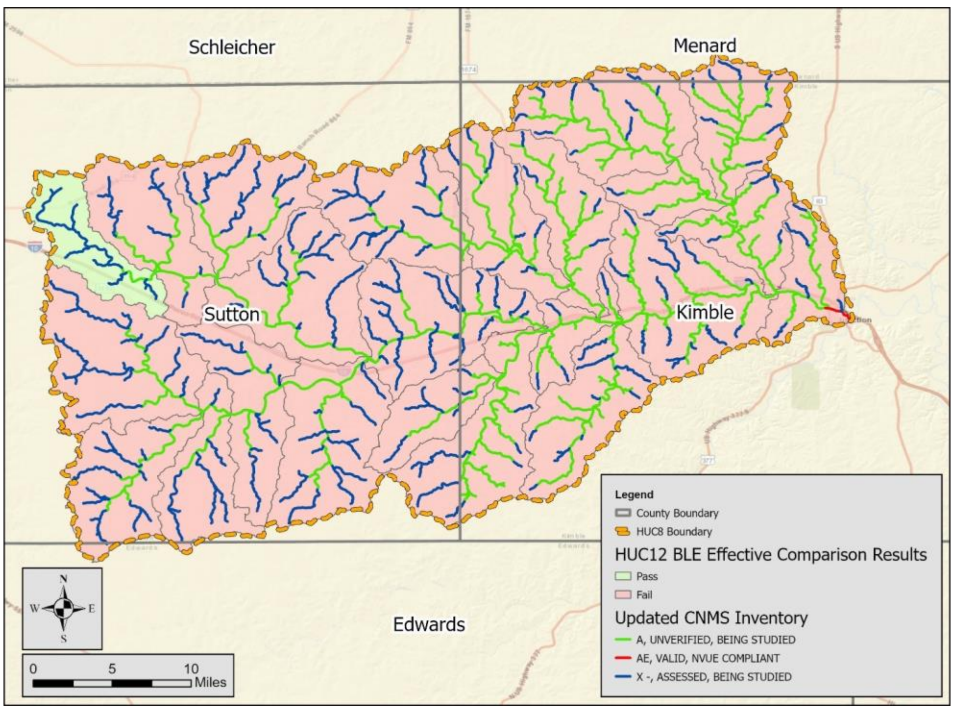



**Figure 1: North Llano - 12090202 CNMS Validation Results**

## 1.0 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 North Llano watershed (HUC-8 12090202). The watershed is mostly rural and the land is predominantly used for farming and ranching. The vast majority of the watershed is located in Kimble and Sutton counties. A small portion of the watershed falls within Edwards and Menard counties. The city of Junction and the town of Roosevelt reside within the watershed. See Figure 2 for a map of the North Llano watershed.

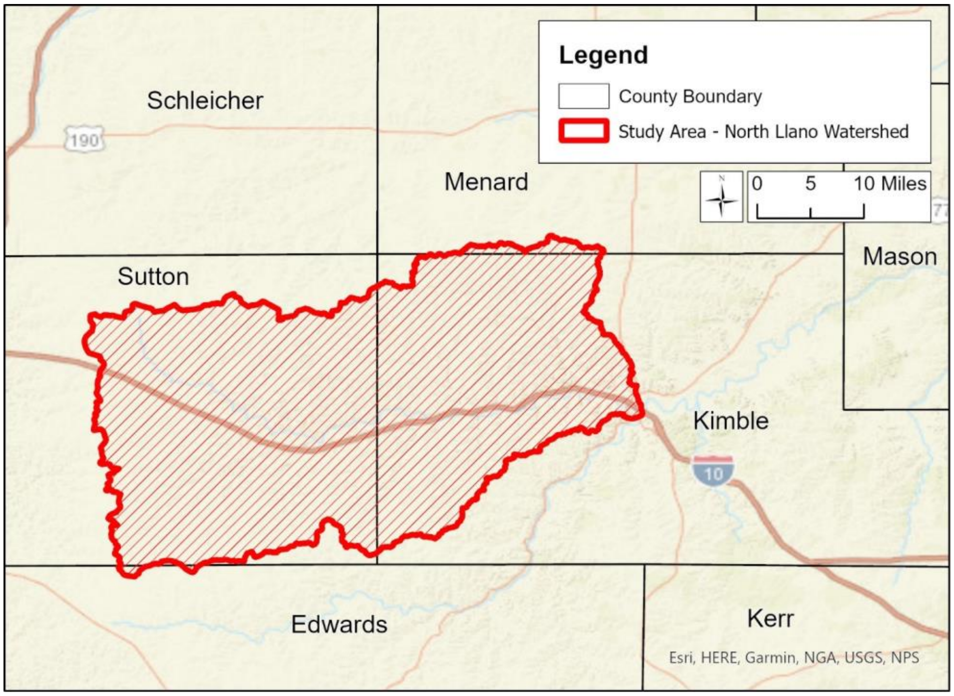



**Figure 2: North Llano Watershed – HUC-8 12090202**

The BLE assessment prepared a cursory engineering analysis for approximately 715 miles of stream reaches within the North 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 dataset used to develop the terrain surface for the North Llano watershed was the Lower Colorado San Bernard LiDAR collection. This dataset, in the form of Digital Elevation Models (DEMs), was downloaded directly from the TNRIS website. A description of this data source is in Table 3.

The above-mentioned LiDAR data set was used to create a seamless set of tiled 5-foot DEMs for the North 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 10-foot cell size criterion outlined in FEMA's

Region 6 BLE guidance from 2019. 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 source and extents of the original DEMs used to create the mosaicked DEM are shown on Figure 3.

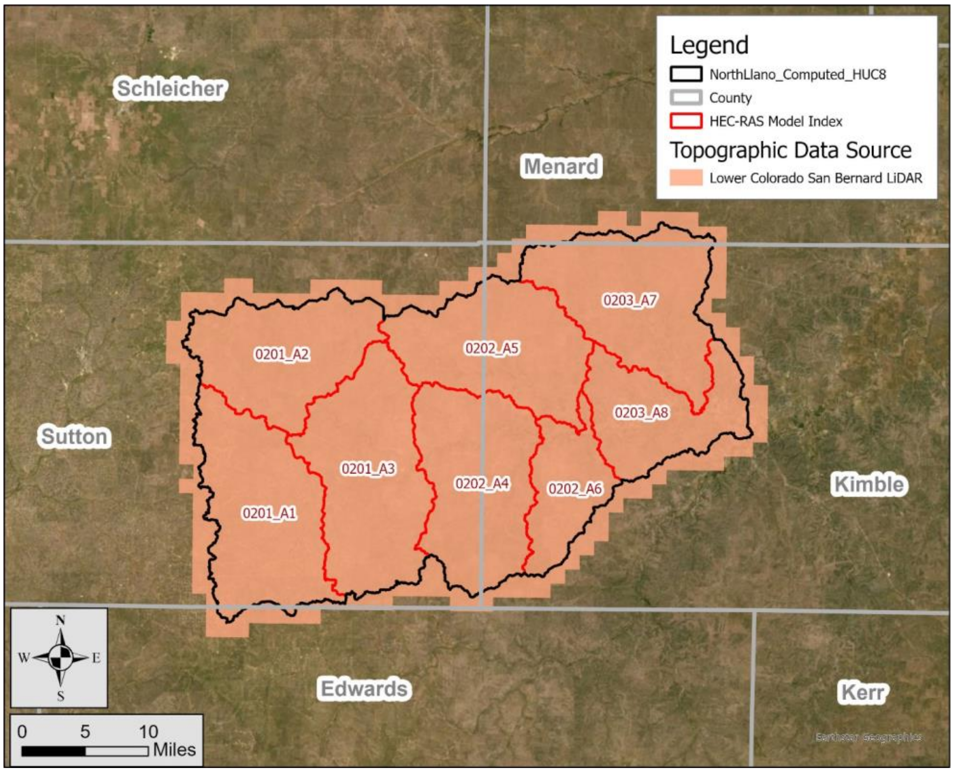



**Figure 3: Topographic Data Extents in the North Llano Watershed**

**Table 3: Topographic Data Sources**

| County | Year Acquired | Vertical Accuracy | Source | Approximate Footprint (mi²) |
|---|---|---|---|---|
| Lower Colorado San Bernard LiDAR (Edwards, Kimble, Menard, and Sutton Counties) | 2018 | 4.9 cm | USGS | 920 |

The U.S. Geological Survey's (USGS) Lower Colorado San Bernard River LiDAR dataset captured in 2018 contains data for 17,942 mi² across 26 counties in Texas. In the North Llano watershed, this dataset includes all of Edwards, Kimble, Sutton, and Menard 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 $m^2$. The vertical datum was the North American Vertical Datum of 1988 (NAVD 88).

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.

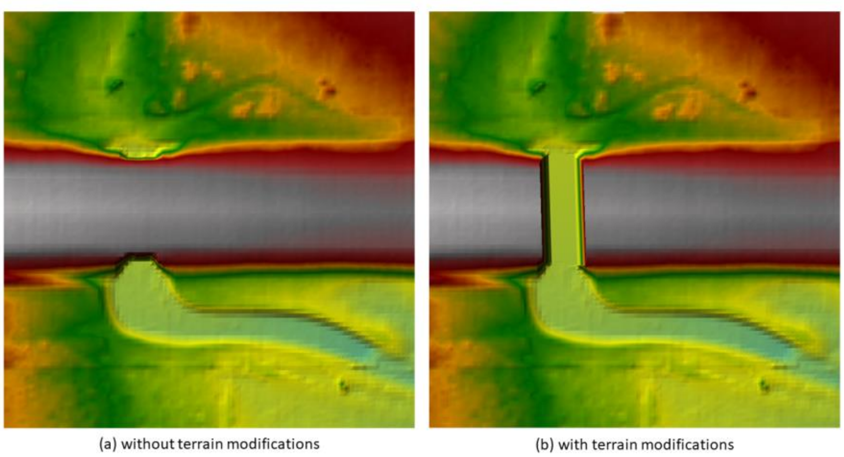



**Figure 4: HEC-RAS Terrain Modification at a Culvert Crossing to Allow Flow through a Roadway**

- 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 was one USGS gage in the watershed. This gage was located on the North Llano River (08148500 N Llano Rv nr Junction, TX). The reported drainage area for this gage is 914 $mi^2$. The computed drainage area was 902 $mi^2$. The difference of 1 percent is acceptable. There were no other locations for comparison in the Flood Insurance Study (FIS).

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 North 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 North Llano watershed was split into eight model domains — 0201_A1, 0201_A2, 0201_A3, 0202_A4, 0202_A5, 0202_A6, 0203_A7, and 0203_08, 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.

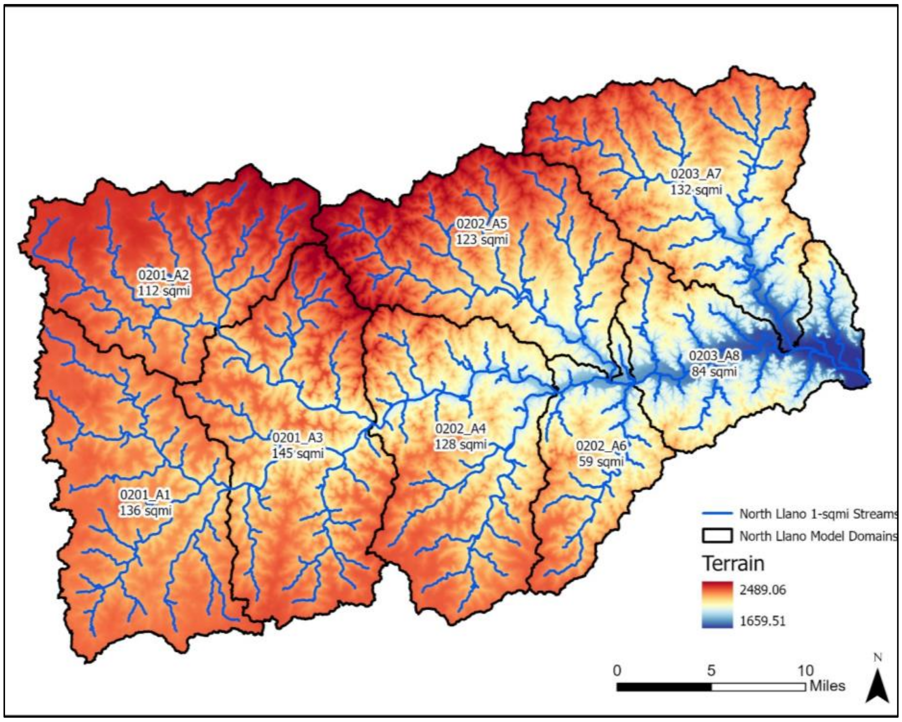



Figure 5: North Llano Model Domains and Linkages

### 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* (August 2019). 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* (August 2019). 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 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 4. An initial abstraction ratio of 0.2 was used to obtain the initial loss. During the model validation phase, the CN values were adjusted to bring the model results into alignment with the validation data (e.g., stream gage data, effective discharges, etc.). The CN values presented in Table 4 are 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 of the AMC II CN values produced flows that continued to be too high to be considered valid. For these model domains, CN values corresponding to AMC I conditions were used to achieve model validation. See Table 5 for the AMC I CNs in the watershed.

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 North 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 North Llano watershed.

**Table 4: AMC II Curve Number Values**

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

**Table 5: AMC I Curve Number Values**

| Land Use Grid Code | NLCD Land Use Description | CN for Each Hydrologic Soil Group | | | |
|---|---|---|---|---|---|
| | | A | B | C | D |
| 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), as shown below. 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 0.04 to 0.05.

**Table 6: Manning's n Values for Overland and Overbank Areas**

| Land Use Grid Code | NLCD Land Use Description | Typical N Value | N Value Range |
|---|---|---|---|
| 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 | 0.060–0.12 |
| 23 | Developed, Medium Intensity | 0.12 | 0.080–0.14 |
| 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 (100 feet on either side) 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 they 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.

### 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.

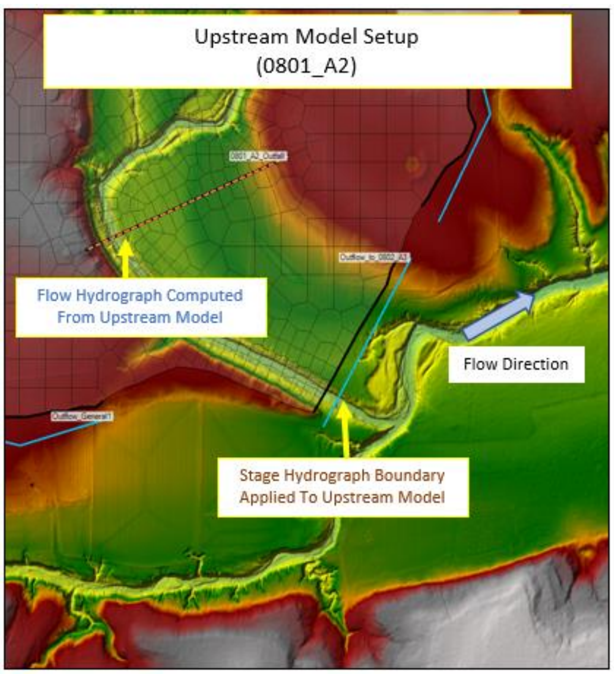



**Figure 6: Extraction of Flow Hydrograph from the SA/2D Connection in the Upstream Domain for Use in the Downstream Domain**

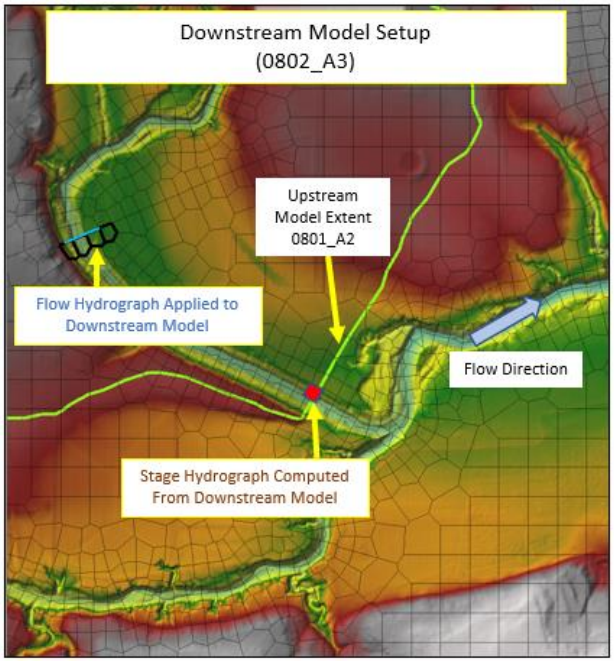



**Figure 7: Application of Upstream Flow Hydrograph in the Downstream Domain**

At the downstream end of the North Llano watershed, the North Llano River and the South Llano River merge to form the Llano River. North Llano (12090202), South Llano (12090203), and Llano (12090204) are three separate HUC-8 watersheds, and it was required to achieve a 0.5-foot tie-in among the three watersheds at their confluence. It was also necessary to consider the backwater effects of the Llano River on the North Llano River and the South Llano River. To simplify the modeling of this complex tie-in, a small portion of the HUC-8 watersheds for the Llano River and the South Llano River were included in North Llano River model domain 0203_A8 as shown on Figure 8. A stage hydrograph was applied at the main stem outflow location of domain 0203_A8 to account for the downstream backwater elevations from the Llano River. An inflow hydrograph at the downstream end of the South Llano River was added so that the combined outflow from the North Llano River and the South Llano River equalled the inflow into the Llano River. Because AtkinsRéalis was concurrently performing BLE analyses for the South Llano and Llano HUC-8 watersheds, the stage hydrograph for the Llano River and the inflow hydrograph for the South Llano River were leveraged from these analyses. 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.

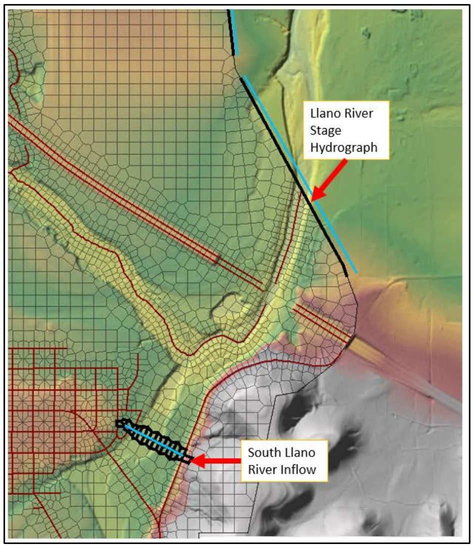



Figure 8: HEC-RAS Model Setup at the Confluence of the North Llano, South Llano, and Llano Rivers

See Table 7 through Table 14 for a summary of the upstream and downstream peak discharges and WSELs at the downstream end of each domain in the North Llano watershed. These tables have been included to demonstrate that at the downstream end of each model domain, the peak discharges are within 5% of one another and the WSELs are within 0.5 feet for each profile.

Table 7: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0201_A1

| Profile (AEP) | Upstream Outflow (cfs) | Downstream Inflow (cfs) | Difference (%) | Upstream WSEL (ft) | Downstream WSEL (ft) | Difference (ft) |
|---|---|---|---|---|---|---|
| 10% | 6,065 | 6,065 | 0.00% | 2,117.78 | 2,117.69 | 0.09 |
| 4% | 12,537 | 12,537 | 0.00% | 2,120.25 | 2,120.21 | 0.04 |
| 2% | 19,491 | 19,491 | 0.00% | 2,122.17 | 2,122.11 | 0.06 |
| 1% | 28,442 | 28,442 | 0.00% | 2,124.18 | 2,123.98 | 0.20 |
| 0.2% | 58,671 | 58,671 | 0.00% | 2,128.82 | 2,128.66 | 0.16 |
| 1% minus | 15,597 | 15,597 | 0.00% | 2,121.15 | 2,121.10 | 0.05 |
| 1% plus | 43,669 | 43,669 | 0.00% | 2,126.61 | 2,126.51 | 0.10 |

Table 8: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0201_A2

| Profile (AEP) | Upstream Outflow (cfs) | Downstream Inflow (cfs) | Difference (%) | Upstream WSEL (ft) | Downstream WSEL (ft) | Difference (ft) |
|---|---|---|---|---|---|---|
| 10% | 4,728 | 4,728 | 0.00% | 2,160.47 | 2,160.35 | 0.12 |
| 4% | 9,900 | 9,900 | 0.00% | 2,162.72 | 2,162.65 | 0.07 |
| 2% | 15,324 | 15,324 | 0.00% | 2,164.58 | 2,164.51 | 0.07 |
| 1% | 22,520 | 22,520 | 0.00% | 2,166.54 | 2,166.45 | 0.09 |
| 0.2% | 48,043 | 48,044 | 0.00% | 2,171.45 | 2,171.26 | 0.19 |
| 1% minus | 12,006 | 12,006 | 0.00% | 2,163.51 | 2,163.43 | 0.08 |
| 1% plus | 34,726 | 34,726 | 0.00% | 2,169.09 | 2,169.00 | 0.09 |

Table 9: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0201_A3

| Profile (AEP) | Upstream Outflow (cfs) | Downstream Inflow (cfs) | Difference (%) | Upstream WSEL (ft) | Downstream WSEL (ft) | Difference (ft) |
|---|---|---|---|---|---|---|
| 10% | 18,293 | 18,293 | 0.00% | 2,024.25 | 2,024.09 | 0.16 |
| 4% | 35,270 | 35,270 | 0.00% | 2,028.24 | 2,028.01 | 0.23 |
| 2% | 51,944 | 51,944 | 0.00% | 2,031.16 | 2,030.87 | 0.29 |
| 1% | 73,028 | 73,028 | 0.00% | 2,034.25 | 2,033.78 | 0.47 |
| 0.2% | 142,366 | 142,366 | 0.00% | 2,041.67 | 2,041.18 | 0.49 |
| 1% minus | 42,146 | 42,146 | 0.00% | 2,029.53 | 2,029.18 | 0.35 |
| 1% plus | 108,926 | 108,926 | 0.00% | 2,038.33 | 2,037.90 | 0.43 |

Table 10: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0202_A4

| Profile (AEP) | Upstream Outflow (cfs) | Downstream Inflow (cfs) | Difference (%) | Upstream WSEL (ft) | Downstream WSEL (ft) | Difference (ft) |
|---|---|---|---|---|---|---|
| 10% | 26,605 | 26,605 | 0.00% | 1,881.79 | 1,881.58 | 0.21 |
| 4% | 46,452 | 46,452 | 0.00% | 1,885.04 | 1,885.08 | -0.04 |
| 2% | 64,970 | 64,970 | 0.00% | 1,887.24 | 1,887.41 | -0.17 |
| 1% | 87,312 | 87,312 | 0.00% | 1,889.50 | 1,889.71 | -0.21 |
| 0.2% | 164,188 | 164,188 | 0.00% | 1,894.79 | 1,895.08 | -0.29 |
| 1% minus | 53,478 | 53,478 | 0.00% | 1,885.93 | 1,886.03 | -0.10 |
| 1% plus | 127,550 | 127,550 | 0.00% | 1,892.61 | 1,892.81 | -0.20 |

Table 11: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0202_A5

| Profile (AEP) | Upstream Outflow (cfs) | Downstream Inflow (cfs) | Difference (%) | Upstream WSEL (ft) | Downstream WSEL (ft) | Difference (ft) |
|---|---|---|---|---|---|---|
| 10% | 7,855 | 7,855 | 0.00% | 1,871.74 | 1,871.26 | 0.48 |
| 4% | 17,328 | 17,328 | 0.00% | 1,875.04 | 1,874.79 | 0.25 |
| 2% | 27,373 | 27,373 | 0.00% | 1,877.82 | 1,877.38 | 0.44 |
| 1% | 40,621 | 40,621 | 0.00% | 1,880.79 | 1,880.37 | 0.42 |
| 0.2% | 84,629 | 84,628 | 0.00% | 1,886.73 | 1,886.41 | 0.32 |
| 1% minus | 21,445 | 21,445 | 0.00% | 1,876.31 | 1,875.98 | 0.33 |
| 1% plus | 62,540 | 62,540 | 0.00% | 1,884.16 | 1,883.99 | 0.17 |

Table 12: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0202_A6

| Profile (AEP) | Upstream Outflow (cfs) | Downstream Inflow (cfs) | Difference (%) | Upstream WSEL (ft) | Downstream WSEL (ft) | Difference (ft) |
|---|---|---|---|---|---|---|
| 10% | 35,294 | 35,141 | -0.44% | 1,836.73 | 1,836.25 | 0.48 |
| 4% | 61,234 | 61,248 | 0.02% | 1,841.15 | 1,840.73 | 0.42 |
| 2% | 85,704 | 84,816 | -1.05% | 1,843.70 | 1,843.38 | 0.32 |
| 1% | 118,185 | 116,932 | -1.07% | 1,846.59 | 1,846.23 | 0.36 |
| 0.2% | 218,776 | 214,757 | -1.87% | 1,852.54 | 1,852.13 | 0.41 |
| 1% minus | 70,141 | 70,295 | 0.22% | 1,842.14 | 1,841.81 | 0.33 |
| 1% plus | 170,340 | 167,570 | -1.65% | 1,850.18 | 1,849.76 | 0.42 |

Table 13: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0203_A7

| Profile (AEP) | Upstream Outflow (cfs) | Downstream Inflow (cfs) | Difference (%) | Upstream WSEL (ft) | Downstream WSEL (ft) | Difference (ft) |
|---|---|---|---|---|---|---|
| 10% | 9,719 | 9,719 | 0.00% | 1,768.24 | 1,767.80 | 0.44 |
| 4% | 21,405 | 21,405 | 0.00% | 1,771.38 | 1,770.94 | 0.44 |
| 2% | 34,111 | 34,111 | 0.00% | 1,773.43 | 1,773.20 | 0.23 |
| 1% | 51,393 | 51,396 | 0.01% | 1,775.57 | 1,775.50 | 0.07 |
| 0.2% | 108,793 | 106,842 | -1.83% | 1,780.30 | 1,780.46 | -0.16 |
| 1% minus | 27,393 | 27,393 | 0.00% | 1,772.43 | 1,772.06 | 0.37 |
| 1% plus | 78,244 | 78,244 | 0.00% | 1,778.08 | 1,778.15 | -0.07 |

Table 14: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0203_A8

| Profile (AEP) | Upstream Outflow (cfs) | Downstream Inflow (cfs) | Difference (%) | Upstream WSEL (ft) | Downstream WSEL (ft) | Difference (ft) |
|---|---|---|---|---|---|---|
| 10% | 9,719 | 9,719 | 0.00% | 1,768.24 | 1,767.80 | 0.44 |
| 4% | 21,405 | 21,405 | 0.00% | 1,771.38 | 1,770.94 | 0.44 |
| 2% | 34,111 | 34,111 | 0.00% | 1,773.43 | 1,773.20 | 0.23 |
| 1% | 51,393 | 51,396 | 0.01% | 1,775.57 | 1,775.50 | 0.07 |
| 0.2% | 108,793 | 106,842 | -1.83% | 1,780.30 | 1,780.46 | -0.16 |
| 1% minus | 27,393 | 27,393 | 0.00% | 1,772.43 | 1,772.06 | 0.37 |
| 1% plus | 78,244 | 78,244 | 0.00% | 1,778.08 | 1,778.15 | -0.07 |

#### 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 North 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 9. This option was chosen to decrease run times while generally maintaining Courant number values less than 1.
- 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.

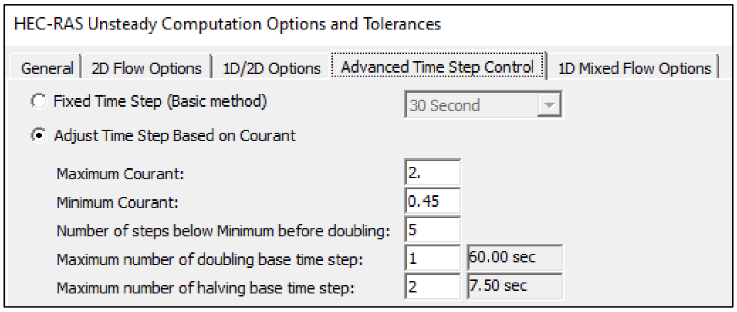



**Figure 9: HEC-RAS Unsteady Computation Options and Tolerances**

### 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 ($\Omega$) 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 10.

| 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 10: Regression Equations for the North 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

The North Llano watershed was being studied as part of the Interagency Flood Risk Management (InFRM) team's Watershed Hydrology Assessment (WHA) for the Lower Colorado River Basin. USGS gage 08148500 (North Llano River nr Junction, TX) was analyzed by the WHA using Bulletin 17C methodology. This InFRM gage analysis was leveraged to support flow validation in the North Llano BLE model.

A description of the analysis, its assumptions, and its results is included on pages 96, 97, and 152 of Chapter 5 of the InFRM's draft WHA report. A copy of these pages has been included in Appendix B of this report.

There were no other USGS flow gages in the North Llano watershed. Therefore, no additional gage analysis was performed for this BLE study.

### 1.2.9 Model Validation

The North Llano BLE hydraulic models were validated using peak flow information available in the draft InFRM WHA and the effective FIS report. For the streams where no InFRM or FIS flow information was available, the regression analysis previously discussed was used to validate the HEC-RAS models.

Validation checks were made at 62 locations throughout the North Llano watershed. The locations may be grouped as follows:

- Sixty-one 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 1% minus, 1%, and 1% plus regression flows; and the 1% gage 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 gage and effective flow information were available. The drainage areas of the validation points ranged from approximately 1 $mi^2$ to 906 $mi^2$. At the 61 locations where the 1% BLE flows were validated against the 1% plus and 1% minus regression flows, the 1% BLE flows were between the 1% minus and the 1% plus regression flows at 49 locations, and they were outside of this range at 12 locations. At the single location where regression flows, the 1% effective flow, and 1% flows from a gage analysis were available, the 1% BLE flow was 39% less than the effective flow, and it fell between the 1% minus and 1% plus regression and gage flows. The comparisons of the 1% BLE flows with the regression, effective, and gage flows is shown in Table 18.

The first step of the validation effort was to review the initial 1% BLE results. When the initial BLE flows fell outside the range between the 1% minus and 1% plus gage or regression flows, the Manning's n and CN values were adjusted iteratively until the computed flows were within this range. The Manning's n values were revised as needed, provided they remained within the ranges specified in Table 6. The AMC II CN values were adjusted by no more than ±10% of their initial values. Following these adjustments, if the computed flows were between the 1% minus and 1% plus flows and were similar to the 1% flow, then the revised Manning's n and AMC II CN 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 sufficiently reduce the flows. 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 North 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 11 and Appendix B for a map from the SCS report showing the average antecedent moisture conditions across Texas. The application of AMC I CN values in the BLE models increased the number of locations where valid 1% BLE flows were computed to an acceptable level (50 out of 62).

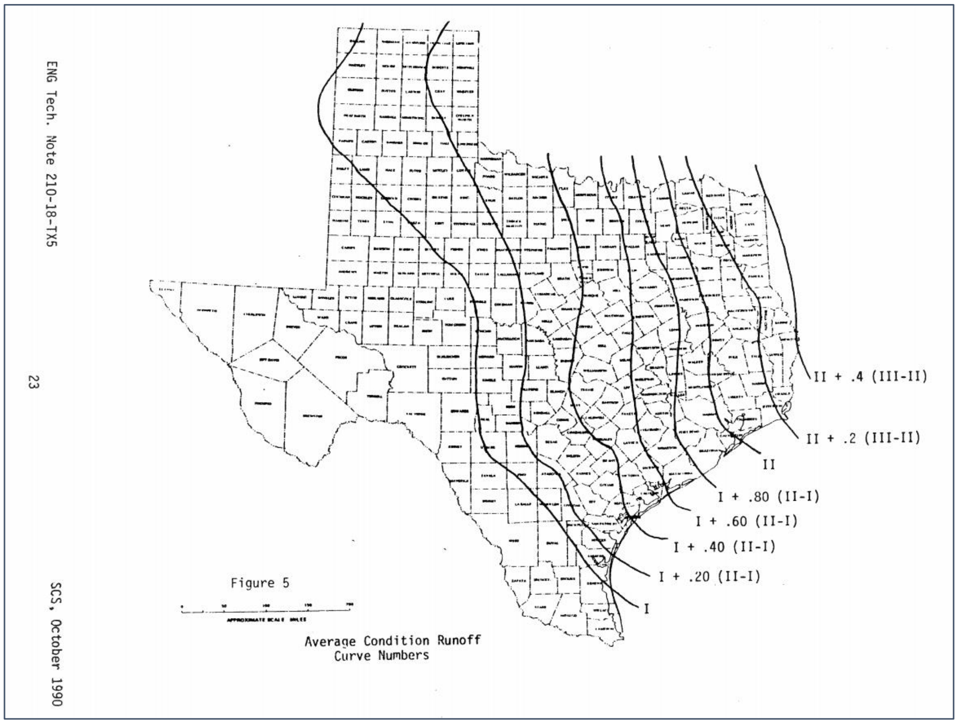



**Figure 11: Typical Antecedent Moisture Conditions in Texas**

A summary of the parameter adjustments made during the validation task is shown in Table 15.

**Table 15: Summary of Parameter Adjustments Made During Validation in the North Llano Watershed**

| Model Domain | CN Adjustment | Overland n Adjustment | Channel n Adjustment | Number of Validation Locations | Pass | Fail |
|---|---|---|---|---|---|---|
| 0201_A1 | AMC I | No Change (Baseline n) | No Change (Baseline n) | 6 | 4 | 2 |
| 0201_A2 | AMC I | No Change (Baseline n) | No Change (Baseline n) | 7 | 5 | 2 |
| 0201_A3 | Reduced by 10% from AMC II | Maximum n | Increased to 0.045 | 7 | 7 | 0 |
| 0202_A4 | Reduced by 10% from AMC II | Maximum n | Increased to 0.045 | 6 | 6 | 0 |
| 0202_A5 | AMC I | No Change (Baseline n) | No Change (Baseline n) | 7 | 5 | 2 |
| 0202_A6 | Reduced by 10% from AMC II | No Change (Baseline n) | No Change (Baseline n) | 12 | 9 | 3 |
| 0203_A7 | AMC I | No Change (Baseline n) | No Change (Baseline n) | 8 | 6 | 2 |
| 0203_A8 | Reduced by 10% from AMC II | No Change (Baseline n) | No Change (Baseline n) | 9 | 8 | 1 |
| | | | **Total** | **62** | **50** | **12** |

During the validation process, domain-wide parameter adjustments were applied to the CN values 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/gage 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, effective, gage, 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 0201_A1 is described as follows. Iterative results from this process are presented in Table 16. This description is representative; a similar process was applied to all domains in the North Llano watershed. In Table 16, the flows in green fall between the 1% minus and 1% plus regression flows, and the values in red are outside this range.

For Iteration 1, baseline AMC II CN values and Manning's n values were applied. The Iteration 1 results showed that a majority of the computed 1% BLE flows were higher than the 1% plus regression flows. To reduce the computed flows, Iteration 2 lowered the AMC II CN values by 10%, which brought most of the 1% BLE flows within the range of the 1% minus and 1% plus regression flows. However, the 1% BLE flows remained above the 1% regression flows by 40% to 90%. In addition, at two locations, the 1% BLE flows continued to be higher than the 1% plus regression flows.

To bring the 1% BLE flows into better alignment with the 1% regression flows, Iteration 3 increased the overland Manning's n values to their maximum values, as documented in Table 6. The CN values remained unrevised from Iteration 2 (90% of baseline AMC II). The 1% BLE flows from Iteration 3 were lower than those from Iteration 2; however, they were still generally higher than the 1% regression estimates by 19% to 63%, and 1% BLE flows at two locations fell outside the regression bounds.

To reduce the flows further, Iteration 4 reset the CN values from 90% of 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 smaller tributaries, the 1% BLE flow values were lower than the 1% regression estimates, and for larger streams such as the North Llano River, the 1% BLE flows were higher than the 1% regression estimates. In addition, there were two locations where the 1% BLE flows were lower than the 1% minus regression flows. To further refine the validation, Iteration 5 continued to use the baseline AMC I CN values but lowered the Manning's n values to their minimum values. The 1% BLE flows from Iteration 5 were a slight improvement over the results from Iteration 4.

For the final model for domain 0201_A1, AMC I CN values and baseline Manning's n values were applied for the following reasons:

- The flow values that were computed using the 90% AMC II CN values were too high, particularly along the larger streams.
- The AMC I CN values combined with the baseline Manning's n values produced reasonable results in all four headwater domains (0201_A1, 0201_A2, 0202_A5, and 0203_A7).
- The initial model runs showed that the 1% BLE flows along the main stem were increasing significantly in the downstream direction as each domain was added to the river. Adjusting the 0201_A1 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 16: Summary of the Model Validation Process for Domain 0201_A1

| Validation Location | Name | Drainage Area (mi²) | Regression | | | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1%- | 1% | 1%+ | Initial CN and n | 90% CN | 90% CN + Max n | AMC1 | AMC1 + Min n |
| Pt1 | Pt1 | 4.5 | 1,709 | 2,816 | 4,641 | 3,388 | 2,429 | 1,984 | 1,136 | 1,513 |
| Pt2 | Pt2 | 18.19 | 4,682 | 7,716 | 12,716 | 14,572 | 10,810 | 9,148 | 5,325 | 6,777 |
| Pt3 | Pt3 | 34.1 | 6,543 | 10,782 | 17,769 | 22,688 | 17,117 | 15,040 | 9,043 | 10,956 |
| Pt4 | Pt4 | 106.5 | 13,839 | 22,806 | 37,585 | 55,240 | 42,553 | 38,269 | 23,543 | 27,389 |
| Pt5 | Pt5 | 1.14 | 841 | 1,385 | 2,283 | 1,419 | 1,041 | 880 | 514 | 647 |
| SA2DConn_0201_A1 | Pt6 | 135.88 | 16,235 | 26,755 | 44,093 | 66,041 | 50,768 | 45,932 | 28,442 | 32,621 |

At USGS gage 08148500 (North Llano River nr Junction, TX), the InFRM WHA reported a 1% flow of 126,000 cubic feet per second (cfs), and the BLE model computed a 1% flow of 140,656 cfs. The BLE 1% flow compares favorably with the InFRM WHA study at this location, with a difference of 12% between the two flows. The effective 1% flow at the gage was 231,000 cfs, which was 61% higher than the BLE 1% flow. However, for the validation check, the InFRM discharges were given higher priority over the effective flows since the InFRM WHA considered a significantly longer period of record than the gage analysis in the effective study.

The model overview and results spreadsheet (*NLlano_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 in the model overview and results spreadsheet for each domain.

A comparison between the 1% BLE WSELs and select effective 1% WSELs for the North Llano River is presented in Table 17. The effective 1% WSELs were estimated using BFEs available in the RMSI digitized floodplain mapping dataset. For the North Llano River, the BLE WSELs were lower than the effective WSELs, which was expected since the 1% BLE flow was 39% lower than the 1% effective flow.

**Table 17: Comparison of Effective 1% WSELs with 1% BLE WSELs**

| Location | Effective 1% WSEL (feet) | BLE 1% WSEL (feet) | Difference (Eff. - BLE) (feet) |
|---|---|---|---|
| At the mouth of the North Llano River | 1,700.4 | 1,697.9 | 2.5 |
| North Llano River at Main Street / US 377 (Junction, TX) | 1,708.1 | 1,704.8 | 3.3 |

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

See Figure 12 and Table 18 on the following pages for a summary of the 1% validation results at the validation points in the North Llano watershed.

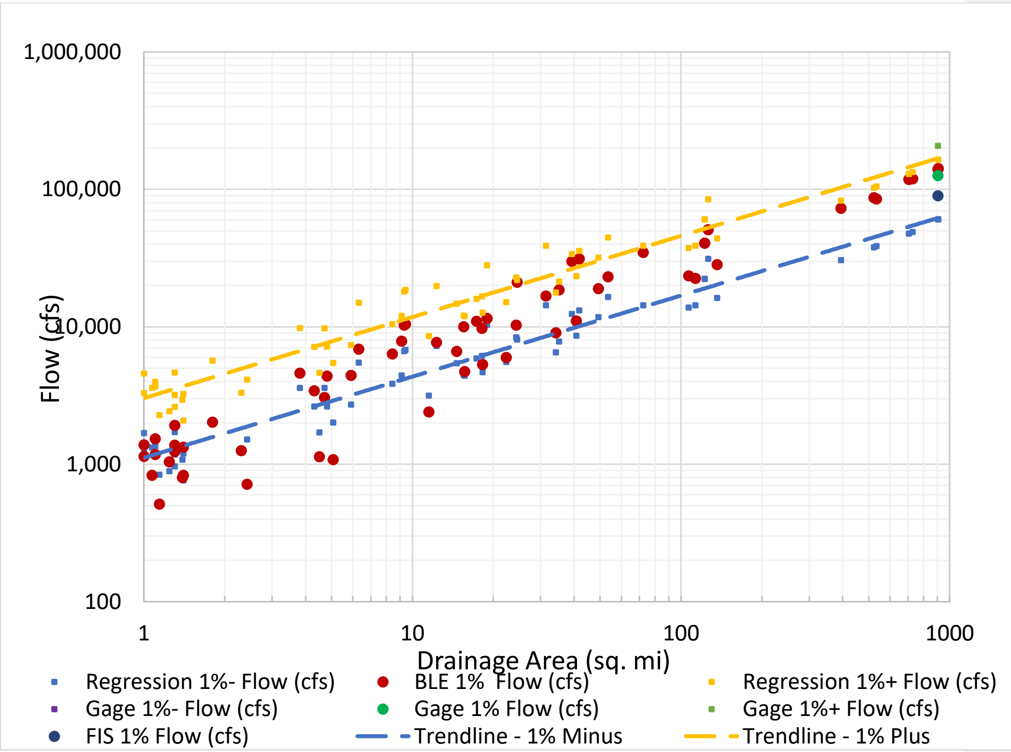



**Figure 12: Computed Flow vs Drainage Area of Select 1% BLE, 1% Regression, and 1% Gage Flows**

**Table 18: 1% Peak Flow Validation Results for the North 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 0201_A1** | | | | | | | | | | |
| Pt1 | Pt1 | 4.5 | 1,709 | 2,816 | 4,641 | 1,136 | - | - | - | - |
| Pt2 | Pt2 | 18.19 | 4,682 | 7,716 | 12,716 | 5,325 | - | - | - | - |
| Pt3 | Pt3 | 34.1 | 6,543 | 10,782 | 17,769 | 9,043 | - | - | - | - |
| Pt4 | Pt4 | 106.5 | 13,839 | 22,806 | 37,585 | 23,543 | - | - | - | - |
| Pt5 | Pt5 | 1.14 | 841 | 1,385 | 2,283 | 514 | - | - | - | - |
| SA2D Connection | Pt6 | 135.88 | 16,235 | 26,755 | 44,093 | 28,442 | - | - | - | - |
| **Domain 0201_A2** | | | | | | | | | | |
| Pt1 | Unnamed | 1.4 | 764 | 1,260 | 2,076 | 832 | - | - | - | - |
| Pt2 | Unnamed | 15.6 | 4,409 | 7,265 | 11,973 | 4,721 | - | - | - | - |
| Pt3 | Unnamed | 22.3 | 5,568 | 9,177 | 15,117 | 5,982 | - | - | - | - |
| Pt4 | Unnamed | 5.06 | 2,014 | 3,318 | 5,463 | 1,081 | - | - | - | - |
| Pt5 | North Llano River | 11.5 | 3,167 | 5,218 | 8,600 | 2,400 | - | - | - | - |
| Pt6 | Unnamed | 40.67 | 8,608 | 14,187 | 23,380 | 11,067 | - | - | - | - |
| Outfall | Unnamed | 113.02 | 14,345 | 23,641 | 38,960 | 22,520 | - | - | - | - |
| **Domain 0201_A3** | | | | | | | | | | |
| Pt1 | Unnamed | 2.3 | 1,225 | 2,019 | 3,328 | 1,255 | - | - | - | - |
| Pt2 | Unnamed | 15.5 | 4,464 | 7,357 | 12,124 | 10,017 | - | - | - | - |
| Pt3 | Dry Llano River | 35.1 | 7,849 | 12,936 | 21,318 | 18,536 | - | - | - | - |
| Pt4 | Unnamed | 4.3 | 2,638 | 4,347 | 7,163 | 3,431 | - | - | - | - |
| Pt5 | Unnamed | 8.4 | 3,860 | 6,362 | 10,484 | 6,359 | - | - | - | - |

| 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) |
|---|---|---|---|---|---|---|---|---|---|---|
| Pt6 | Unnamed | 1.3 | 968 | 1,595 | 2,628 | 1,237 | - | - | - | - |
| Outfall | North Llano River | 393 | 30,568 | 50,376 | 83,019 | 73,028 | - | - | - | - |
| **Domain 0202_A4** | | | | | | | | | | |
| Pt1 | Unnamed | 9.1 | 4,428 | 7,297 | 12,026 | 7864 | - | - | - | - |
| Pt2 | Unnamed | 1.3 | 1,178 | 1,941 | 3,200 | 1376 | - | - | - | - |
| Pt3 | West Fork Maynard Creek | 17.3 | 5,891 | 9,708 | 15,999 | 10978 | - | - | - | - |
| Pt4 | Maynard Creek | 72.2 | 14,378 | 23,694 | 39,048 | 34710 | - | - | - | - |
| Pt5 | Maynard Creek | 18.1 | 6,159 | 10,150 | 16,728 | 9742 | - | - | - | - |
| Outfall | North Llano River | 521 | 37,930 | 62,509 | 103,015 | 87313 | - | - | - | - |
| **Domain 0202_A5** | | | | | | | | | | |
| Pt1 | Copperas Creek | 122.3 | 22,274 | 36,702 | 60,494 | 40,680 | - | - | - | - |
| Pt2 | West Copperas Creek | 49.1 | 11,756 | 19,374 | 31,928 | 19,016 | - | - | - | - |
| Pt3 | Unnamed | 1.39 | 1,084 | 1,786 | 2,944 | 799 | - | - | - | - |
| Pt4 | Unnamed | 2.42 | 1,519 | 2,508 | 4,127 | 715 | - | - | - | - |
| Pt5 | East Copperas Creek | 14.6 | 5,444 | 8,972 | 14,785 | 6,638 | - | - | - | - |

| 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) |
|---|---|---|---|---|---|---|---|---|---|---|
| Pt6 | East Copperas Creek | 24.3 | 8,418 | 13,873 | 22,862 | 10,295 | - | - | - | - |
| Outfall | Copperas Creek | 122.2 | 22,428 | 36,961 | 60,912 | 40,622 | - | - | - | - |
| **Domain 0202_A6** | | | | | | | | | | |
| Pt1 | Unnamed | 1.1 | 1,467 | 2,419 | 3,986 | 1,181 | - | - | - | - |
| Pt2 | Unnamed | 1.8 | 2,094 | 3,452 | 5,689 | 2,024 | - | - | - | - |
| Pt3 | Unnamed | 1.0 | 1,215 | 2,002 | 3,299 | 1,139 | - | - | - | - |
| Pt4 | Bois d'Arc Creek | 41.7 | 13,163 | 21,692 | 35,748 | 31,319 | - | - | - | - |
| Pt5 | Bois d'Arc Creek | 5.9 | 2,726 | 4,491 | 7,402 | 4,424 | - | - | - | - |
| Pt6 | Unnamed | 4.8 | 2,640 | 4,351 | 7,171 | 4,389 | - | - | - | - |
| Pt7 | Bois d'Arc Creek | 24.5 | 8,084 | 13,323 | 21,955 | 21,148 | - | - | - | - |
| Pt8 | North Llano River | 533.0 | 38,712 | 63,758 | 105,140 | 85,403 | - | - | - | - |
| Pt9 | Unnamed | 1.4 | 1,195 | 1,970 | 3,247 | 1,334 | - | - | - | - |
| Pt10 | Bois d'Arc Creek | 39.2 | 12,451 | 20,520 | 33,832 | 29,971 | - | - | - | - |
| Pt11 | Unnamed | 1.1 | 1,357 | 2,236 | 3,685 | 1,531 | - | - | - | - |
| Outfall | North Llano River | 703.0 | 47,723 | 78,648 | 129,612 | 118,438 | - | - | - | - |
| **Domain 0203_A7** | | | | | | | | | | |
| Pt1 | Unnamed | 1.07 | 1,327 | 2,187 | 3,604 | 833 | - | - | - | - |

| 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) |
|---|---|---|---|---|---|---|---|---|---|---|
| Pt2 | West Bear Creek | 53.37 | 16,479 | 27,157 | 44,755 | 23,163 | - | - | - | - |
| Pt3 | Unnamed | 4.7 | 3,601 | 5,935 | 9,781 | 3,063 | - | - | - | - |
| Pt4 | Unnamed | 1.24 | 893 | 1,472 | 2,426 | 1,041 | - | - | - | - |
| Pt5 | Bear Creek | 31.35 | 14,344 | 23,638 | 38,956 | 16,777 | - | - | - | - |
| Pt6 | Bear Creek | 18.91 | 10,358 | 17,070 | 28,131 | 11,502 | - | - | - | - |
| Pt7 | Bear Creek | 12.25 | 7,283 | 12,002 | 19,780 | 7,725 | - | - | - | - |
| Outfall | Bear Creek | 126 | 31,222 | 51,454 | 84,796 | 50,876 | - | - | - | - |
| **Domain 0203_A8** | | | | | | | | | | |
| Pt1 | Elm Slough | 6.3 | 5,510 | 9,080 | 14,963 | 6,878 | - | - | - | - |
| Pt2 | Unnamed | 1.0 | 1,689 | 2,784 | 4,588 | 1,388 | - | - | - | - |
| Pt3 | Falls Creek | 3.8 | 3,607 | 5,944 | 9,796 | 4,607 | - | - | - | - |
| Pt4 | Falls Creek | 1.3 | 1,715 | 2,827 | 4,658 | 1,921 | - | - | - | - |
| Pt5 | Star Creek | 9.3 | 6,650 | 10,959 | 18,061 | 10,279 | - | - | - | - |
| Pt6 (USGS 08148500) | North Llano River | 901.8 | 60,594 | 99,859 | 164,568 | 140,656 | 90,100 | 126,000 | 208,000 | 231,000 |
| Pt7 | North Llano River | 727.6 | 49,188 | 81,062 | 133,591 | 119,234 | - | - | - | - |
| Pt8 | Calf Creek | 9.4 | 6,823 | 11,244 | 18,530 | 10,465 | - | - | - | - |
| 0203_A8_Outfall | North Llano River | 905.8 | 60,788 | 100,603 | 165,093 | 141,839 | - | - | - | - |

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

## 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 13, 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.

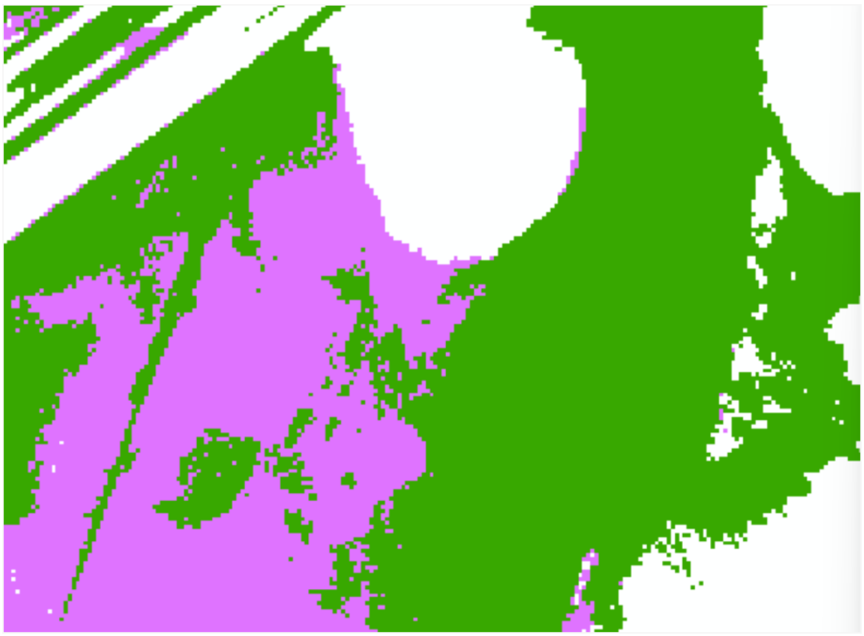


Figure 13: Example of Overlapping Mapping along a Model Domain Boundary

Figure 14**Error! Reference source not found.** shows what the difference raster looks like for the area in Figure 13. 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 13 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.

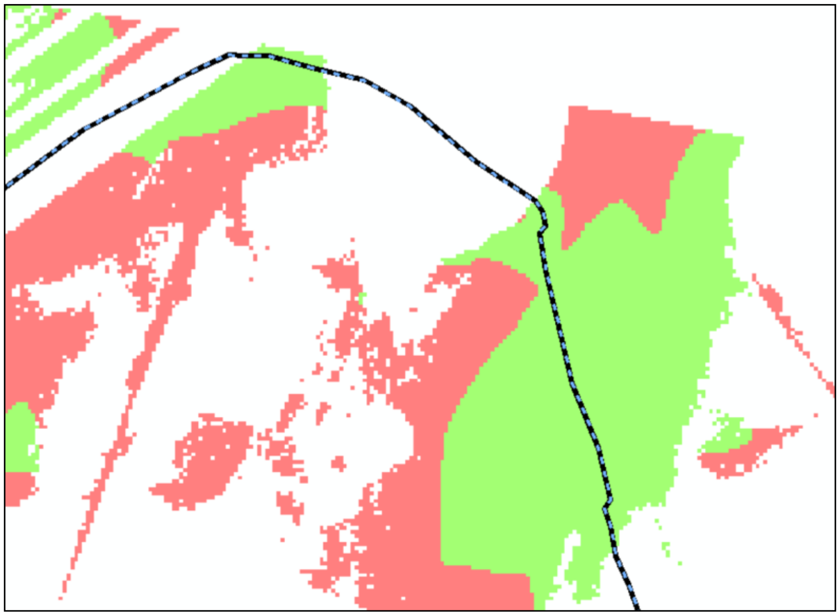


Figure 14: WSEL Difference Raster and Split Line for the Overlap Area

- 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 **Error! Reference source not found.**.

Table 19: Inland Mapping Thresholds 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.

## 2.0 Challenges

A handful of challenges were encountered during the North 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 North 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 CN values were revised 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 CN values 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 too heavily in favor of the larger streams or the smaller streams. Balancing the validation needs between the small and large streams 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, completely ignoring the structures would have produced invalid model results. Therefore, hydraulic structures were modeled using a 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.

### Downstream Tie-in with the South Llano River and the Llano River

At the downstream end of the North Llano watershed, the North Llano River and the South Llano River merge to form the Llano River. North Llano (12090202), South Llano (12090203), and Llano (12090204) are three separate HUC-8 watersheds, and it was required to achieve a 0.5-foot tie-in among the three watersheds at their confluence. It was also necessary to consider the backwater effects of the Llano River on the North Llano River and the South Llano River. To simplify the modeling of this complex tie-in, a small portion of the HUC-8 watersheds for the Llano River and the South Llano River were included in

North Llano River model domain 0203_A8. See the *Stage Hydrograph Boundary Conditions* discussion in Subsection 1.2.4 for details regarding how this area was modeled.

### 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 15. The areas of cupping will not be removed or cleaned beyond the extents of the mapping clean-up process discussed herein. There is significant topographic relief throughout the North Llano watershed. Therefore, cupping is prevalent throughout the BLE mapping.

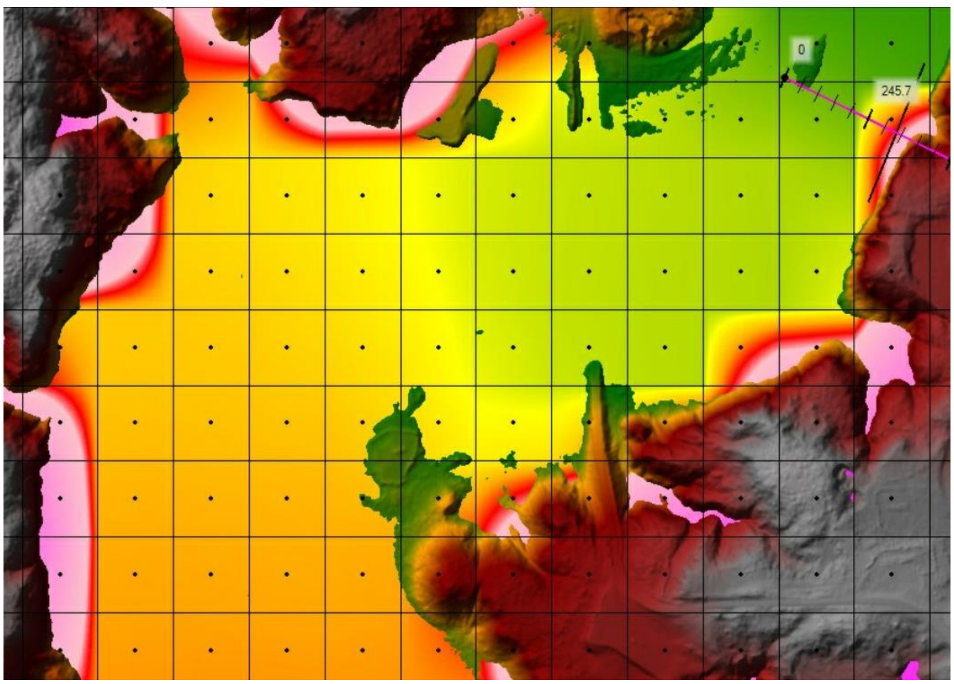



**Figure 15: An Example of Cupping in 2D BLE Mapping**

## 3.0 Results and Recommendations

The BLE results for the North 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 North Llano watershed has been included as Appendix A.

The BLE floodplains were compared with the effective floodplains in the North 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 16, which shows the downstream part of the watershed near Junction, Texas.

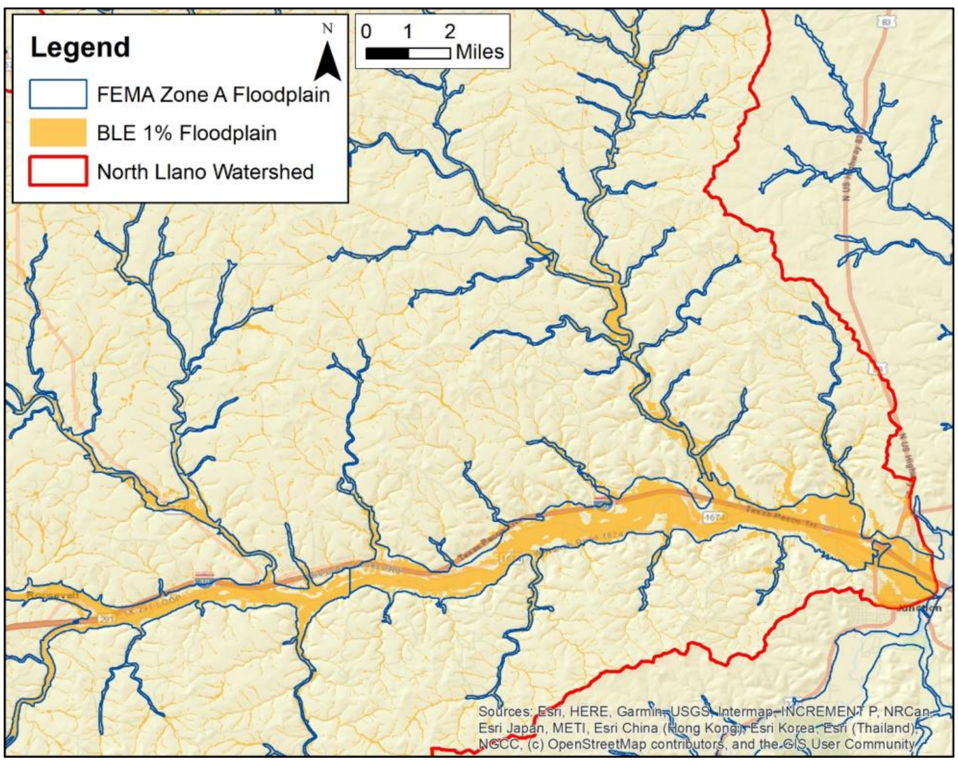



Figure 16: The Effective 1% Floodplain and the 1% BLE Floodplain in the vicinity of Junction, TX

Floodplain mapping for the North 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 North Llano watershed were compared with the Fathom floodplain mapping. Figure 17 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 16. 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.

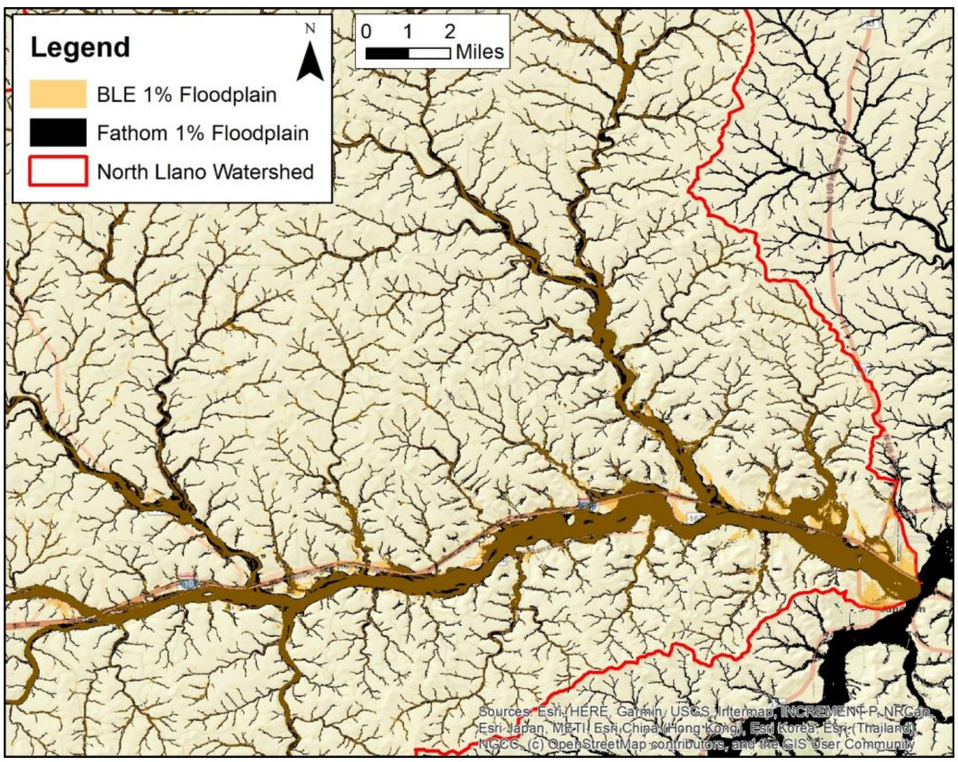



Figure 17: Comparison of 1% BLE Mapping with Fathom 1% Mapping

The BLE floodplains were compared with the effective floodplains in the North Llano watershed. No

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.

## 3.1 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.

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.

## 3.2 CNMS Validation of Effective Zone A Special Flood Hazard Area

The majority of the Zone A streams in the North Llano watershed (426.2 miles) were classified as "UNVERIFIED" with a status type of "BEING STUDIED." One stream (2.9 miles) was classified as "VALID" with a status type of "BEING STUDIED".

### 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 North 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. 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 HUC-12 watersheds with Zone A studies. If the percentage of urban area within the watershed containing the 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. This watershed is generally rural with few villages, and there has not been significant development in the watershed. A significant development check for the study areas 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 20: 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 of the initial assessment checks described above were categorized as "Valid" in the CNMS Inventory when 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 North Llano BLE analysis.

The contour interval for the vertical tolerance was taken from the USGS 1:24,000-scale topographic maps of the North 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 22 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 North Llano watershed study area has been updated. The total miles in each of these categories are summarized in Table 21 and illustrated on Figure 18. The findings from Initial Assessment A5 are in Table 22.

**Table 21: Zone A Validation Results**

| Validation Status | CNMS Validation Status | CNMS Project Start | CNMS Post-BLE Assessment |
|---|---|---|---|
| VALID | NVUE COMPLIANT | 0 | 0 |
| | BEING STUDIED | 0 | 2.9 |
| UNVERIFIED | BEING STUDIED | 0 | 426.2 |
| | TO BE STUDIED | 404.2 | 0 |

**Table 22: BLE Comparison Results**

| HUC-12 Watershed | | Total FBS Points | Fail | Pass | % Pass | BLE Comparison Pass? (>85%) |
|---|---|---|---|---|---|---|
| Watershed Name | HUC-12 ID | | | | | |
| Headwaters Eightmile Draw | 120902020101 | 1,211 | 216 | 995 | 82.2 | Fail |
| Bull Hollow | 120902020102 | 1,305 | 329 | 976 | 74.8 | Fail |
| Tenmile Draw-Eightmile Draw | 120902020103 | 787 | 229 | 558 | 70.9 | Fail |
| Live Oak Draw-Eightmile Draw | 120902020104 | 1,129 | 299 | 830 | 73.5 | Fail |
| Eightmile Draw-Dry Llano River | 120902020105 | 1,835 | 472 | 1,363 | 74.3 | Fail |
| Allison Ranch | 120902020106 | 326 | 8 | 318 | 97.5 | Pass |
| Headwaters North Llano River | 120902020107 | 1,659 | 437 | 1,222 | 73.7 | Fail |
| Bufallo *sic* Draw | 120902020108 | 1,280 | 527 | 753 | 58.8 | Fail |
| Tenmile Draw-North Llano River | 120902020109 | 2,196 | 841 | 1,355 | 61.7 | Fail |
| Bell Hollow-North Llano River | 120902020201 | 2,009 | 1,056 | 953 | 47.4 | Fail |
| West Maynard Creek | 120902020202 | 988 | 511 | 477 | 48.3 | Fail |
| Maynard Creek | 120902020203 | 2,970 | 1,091 | 1,879 | 63.3 | Fail |
| Upper West Copperas Creek | 120902020204 | 1,484 | 585 | 899 | 60.6 | Fail |
| Lower West Copperas Creek | 120902020205 | 2,921 | 1,318 | 1,603 | 54.9 | Fail |

| HUC-12 Watershed | | Total FBS Points | Fail | Pass | % Pass | BLE Comparison Pass? (>85%) |
|---|---|---|---|---|---|---|
| Watershed Name | HUC-12 ID | | | | | |
| East Copperas Creek-Copperas Creek | 120902020206 | 2,783 | 1,089 | 1,694 | 60.9 | Fail |
| Frog Creek-North Llano River | 120902020207 | 1,186 | 596 | 590 | 49.7 | Fail |
| Bois d'Arc Creek | 120902020208 | 2,503 | 798 | 1,705 | 68.1 | Fail |
| Stark Creek-North Llano River | 120902020301 | 3,485 | 1,373 | 2,112 | 60.6 | Fail |
| Upper West Bear Creek | 120902020302 | 3,637 | 1,306 | 2,331 | 64.1 | Fail |
| Lower West Bear Creek | 120902020303 | 1,482 | 539 | 943 | 63.6 | Fail |
| Upper Bear Creek | 120902020304 | 2,830 | 1,151 | 1,679 | 59.3 | Fail |
| Lower Bear Creek | 120902020305 | 2,491 | 927 | 1,564 | 62.8 | Fail |
| Elm Slough-North Llano River | 120902020306 | 1,557 | 564 | 993 | 63.8 | Fail |

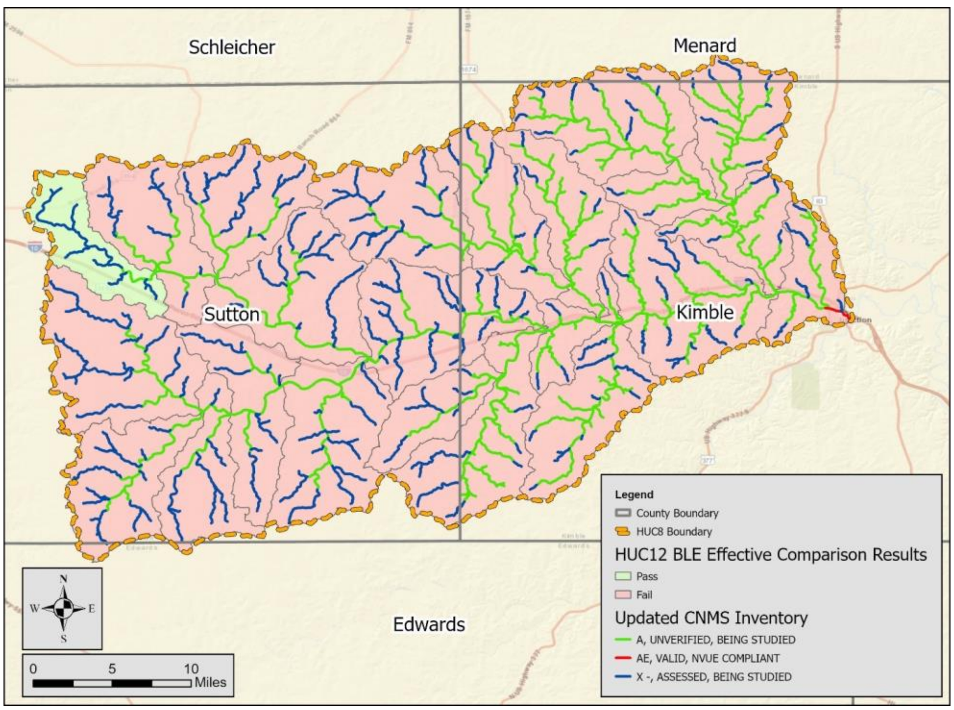



Figure 18: CNMS Validation Results

## 3.3 Flood Risk Analysis

A flood risk analysis was performed for the North 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 AtkinsRéalisRéalis completed BLE assessments for both watersheds, the floodplain mapping includes smooth tie-ins across the watershed boundaries. Along those HUC-8 watershed boundaries where AtkinsRéalisRéalis 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.

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 23 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 23: Hazus Results for the North Llano Watershed**

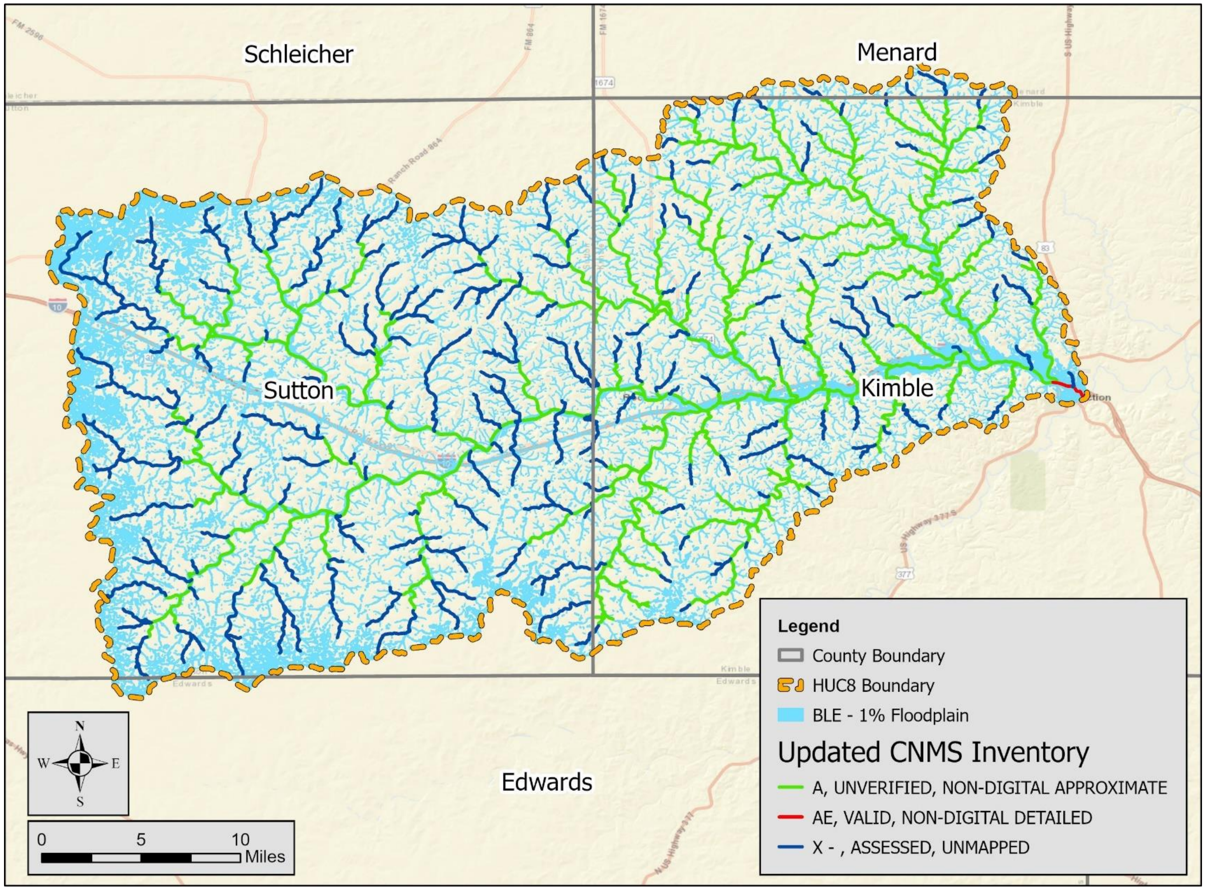
| County | Full Replacement – Total Loss | Dollar Exposure (Replacement Value) - Buildings | Dollar Exposure (Replacement Value) - Contents |
|---|---|---|---|
| Edwards County | $0 | $657,000 | $329,000 |
| Kimble County | $44,862,000 | $246,638,000 | $153,158,000 |
| Menard County | $44,000 | $21,113,000 | $10,609,000 |
| Sutton County | $3,177,000 | $67,000,000 | $46,774,000 |
| **Total** | **$48,083,000** | **$335,408,000** | **$210,870,000** |

## 4.0 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 96, 97, and 152. 2021-08-13.
6. National 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. National 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 Service. *Engineering Technical Note No. 210-18-TX5*. 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). 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
13. 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
14. 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.

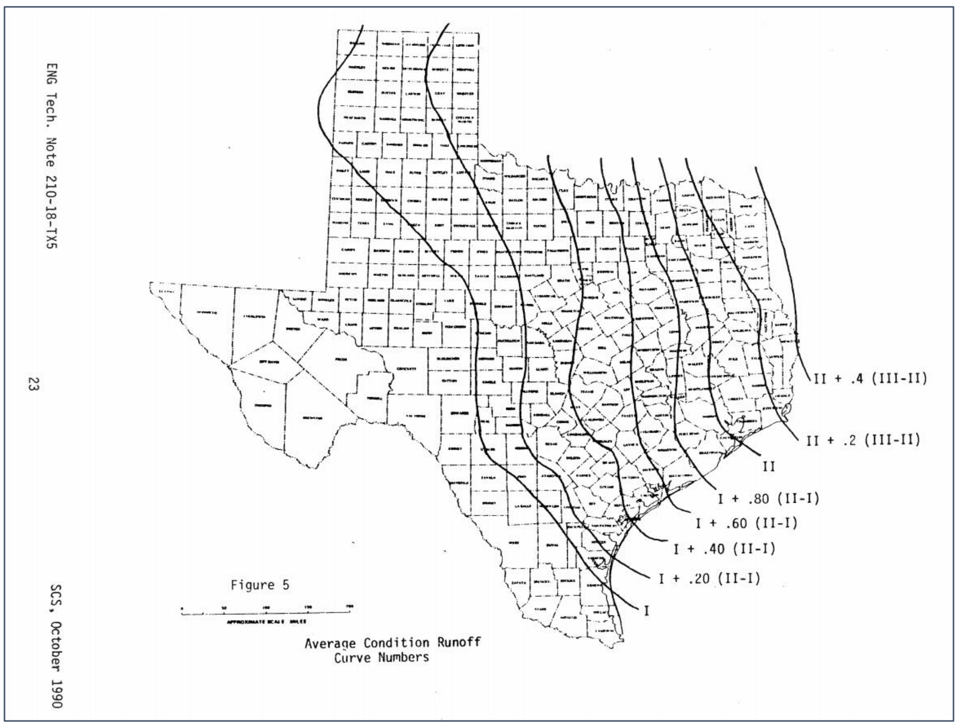
## Appendix A: Base Level Engineering Results



## 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 North 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.




- Pages 96, 97, and 152 from Chapter 5 of the InFRM team's draft *Watershed Hydrology Assessment for the Lower Colorado River Basin.* This is an excerpt from a draft copy of this report. This excerpt includes the gage analysis for USGS gage 08148500 (North Llano River near Junction, TX).