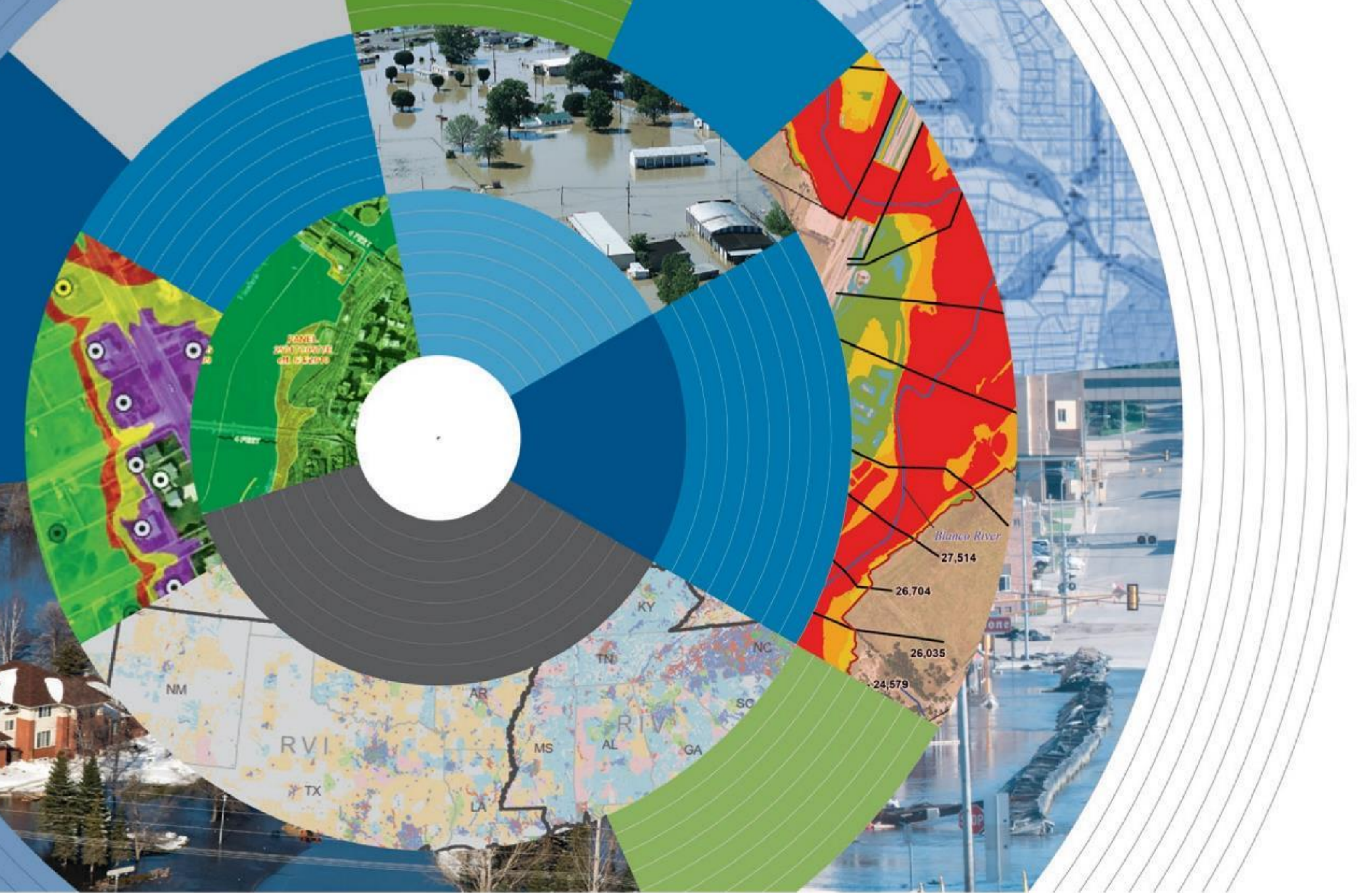

Base Level Engineering Report

Middle Colorado (12090106)

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

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1.0	November 30, 2024	Initial Report for the Estimated Base Flood Elevation Viewer	AtkinsRéalis USA, Inc.

FINAL REPORT FOR MIDDLE COLORADO (12090106)

PREPARED FOR:

Texas Water Development Board

Prepared By:

AtkinsRéalis USA, Inc.

STATE OF TEXAS
SHRINIVAS V. KAULGUD
143831
LICENSED
PROFESSIONAL ENGINEER

Texas Registered
Engineering FIRM # 474

06/12/2025

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Executive Summary

The Texas Water Development Board (TWDB) contracted with AtkinsRéalis USA, Inc. (AtkinsRéalis) to complete two-dimensional (2D) Base Level Engineering (BLE) in the Middle Colorado HUC-8 watershed (12090106). This watershed is located in Central Texas, northwest of Austin, between Ballinger and Goldthwaite, Texas. The watershed area is 2,012 square miles (mi^2). Approximately 2,050 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, July 2021)
- *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 Middle Colorado watershed was divided into nine HEC-RAS model domains — 0601_A1, 0601_A2, 0602_A3, 0602_A4, 0603_A5, 0603_A6, 0604_A7, 0605_A8, and 0606_A9. 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, 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 Middle Colorado 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	245.1
New Study Streams - CNMS	1,804.4
Total (BLE) Stream Miles	**2,049.5**

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	0.6
UNVERIFIED	BEING STUDIED	0	244.5
	TO BE STUDIED	241.6	0

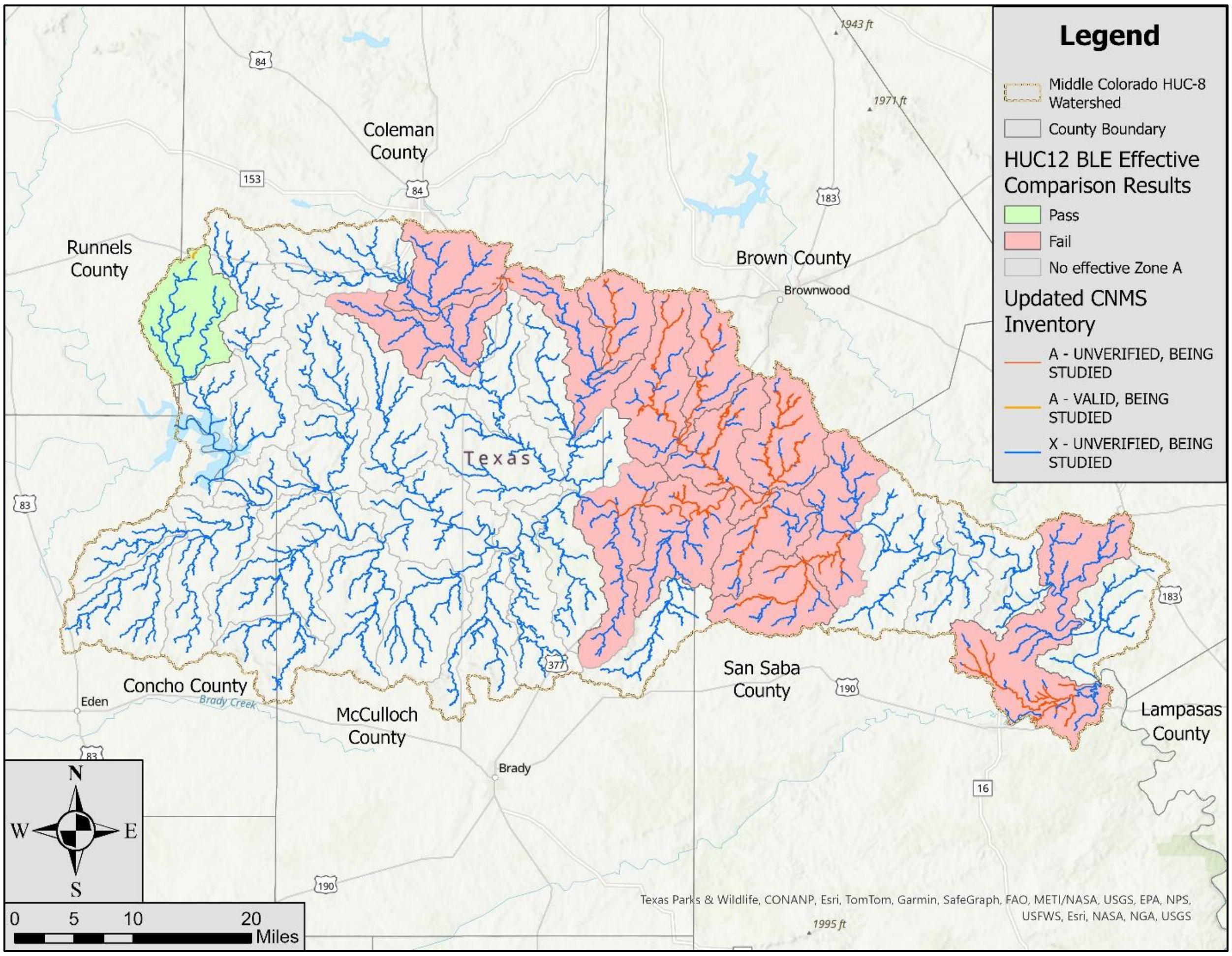


Figure 1: Middle Colorado - 12090106 CNMS Validation Results

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 Middle Colorado watershed (HUC-8 12090106). The watershed is mostly rural, and the land is predominantly used for farming and ranching. The watershed falls within Brown, Coleman, Concho, McCulloch, Mills, Runnels and San Saba counties. The city of Bangs and the town of Santa Anna reside within the watershed. See Figure 2 for a map of the Middle Colorado watershed.

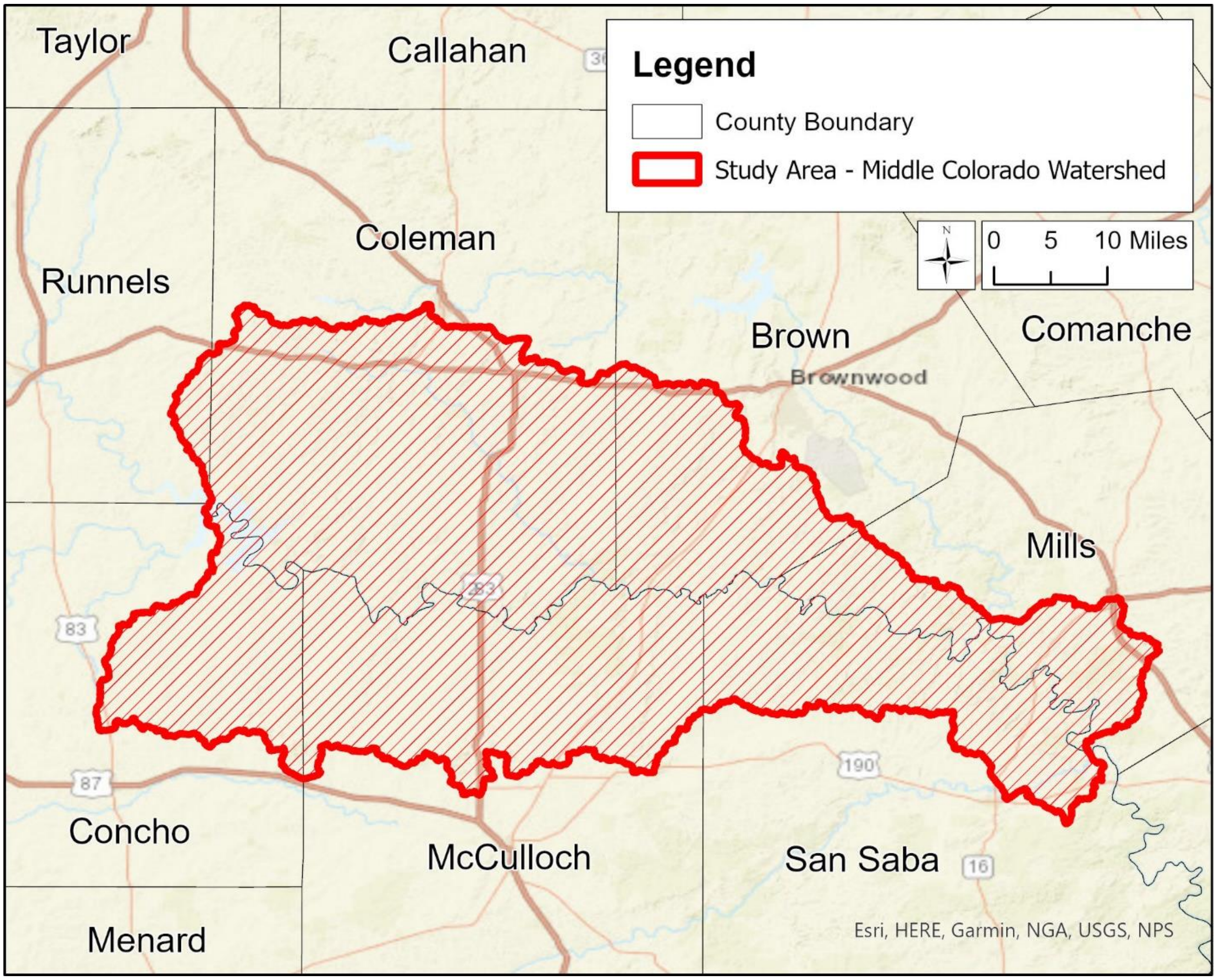


Figure 2: Middle Colorado Watershed – HUC-8 12090106

The BLE assessment prepared a cursory engineering analysis for approximately 2,050 miles of stream reaches within the Middle Colorado 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 datasets used to develop the terrain surface for the Middle Colorado watershed were the Texas West Central, Brown County, Hurricane, Lower Colorado San Bernard, and Bandera & Lampasas Counties LiDAR collections. These datasets, in the form of Digital Elevation Models (DEMs), were downloaded directly from the TNRIS website. A description of the terrain data sources used in this study is in Table 3.

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

- Texas West Central LiDAR
- Brown County LiDAR
- Hurricane LiDAR
- Lower Colorado San Bernard LiDAR
- Bandera & Lampasas Counties LiDAR

The above-mentioned LiDAR datasets were used to create a seamless set of tiled 5-foot DEMs for the Middle Colorado 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 2021. After projecting the terrain data 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.

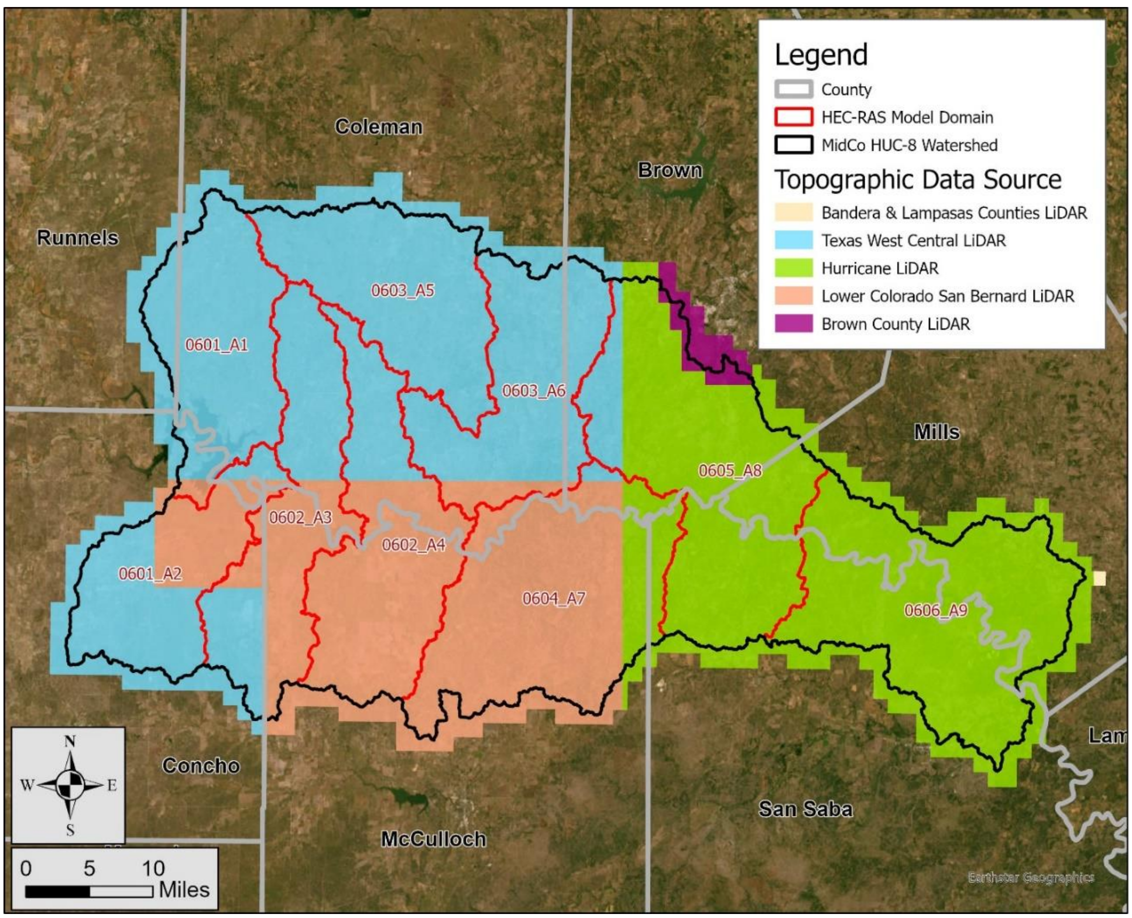


Figure 3: Topographic Data Extents in the Middle Colorado Watershed

Table 3: Topographic Data Sources

County	Year Acquired	Vertical Accuracy	Source	Approximate Footprint (mi^2)
Texas West Central LiDAR (Coleman, Concho, and Runnels counties)	2018	4.7 cm	USGS	970
Brown County LiDAR (Brown County)	2019	5.0 cm	Texas Strategic Mapping Program (StratMap)	29
Hurricane LiDAR (Brown, Mills, and San Saba counties)	2019	3.8 cm	USGS	734
Lower Colorado San Bernard LiDAR (Edwards, Kimble, Menard, and Sutton counties)	2018	4.9 cm	USGS	615
Bandera & Lampasas Counties LiDAR (Mills County)	2014	4.4 cm	StratMap	1

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

Dataset One – Texas West Central LiDAR

The USGS Texas West Central LiDAR captured in 2018 contains data for 42,557 mi^2 across 70 counties in Texas. In the Middle Colorado watershed, this dataset includes parts of Coleman, Concho, and Runnel counties. The vertical accuracy (RMSEz, or root mean square error in the z direction) of this dataset is 4.7 centimeters (cm). The native cell size of the data is 1 square meter (m^2).

Dataset Two – Brown County LiDAR

The Texas Strategic Mapping Program (StratMap) Brown County LiDAR dataset captured in 2019 covers approximately 182 mi^2 of Brown County. In the Middle Colorado watershed, this dataset resides within Brown County. The vertical accuracy (RMSEz) of this dataset is 5.0 cm. The native cell size of the data is 1 m^2.

Dataset Three – Hurricane LiDAR

The USGS Hurricane LiDAR dataset captured in 2019 contains data for 14,512 mi^2 across 45 counties in Texas. In the Middle Colorado watershed, this dataset includes parts of Brown, McCulloch, Mills, and San Saba counties. The vertical accuracy (RMSEz) of this dataset is 3.8 cm. The native cell size of the data is 1 m^2.

Dataset Four – Lower Colorado San Bernard LiDAR

The U.S. Geological Survey's (USGS) Lower Colorado San Bernard River LiDAR dataset captured in 2018 contains data for 17,942 mi^2 across 26 counties in Texas. In the Middle Colorado watershed, this dataset includes parts of Concho, Coleman, and McCulloch counties. The vertical accuracy (RMSEz) of this dataset is 4.9 cm. The native cell size of the data is 1 m^2.

Dataset Five – Bandera & Lampasas Counties LiDAR

The StratMap Bandera & Lampasas counties LiDAR dataset captured in 2014 covers approximately 3,054 mi^2 across 12 counties in Texas. In the Middle Colorado watershed, this dataset resides within Mills County. The vertical accuracy (RMSEz) of this dataset is 4.4 cm. The native cell size of the data is 1 m^2.

No modifications were made to the mosaicked DEM. 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, as described below.

The mosaicked DEM produced during the LiDAR date processing task was uploaded into the model as Terrain.hdf. The floodplain mapping for the watershed was based on this terrain.

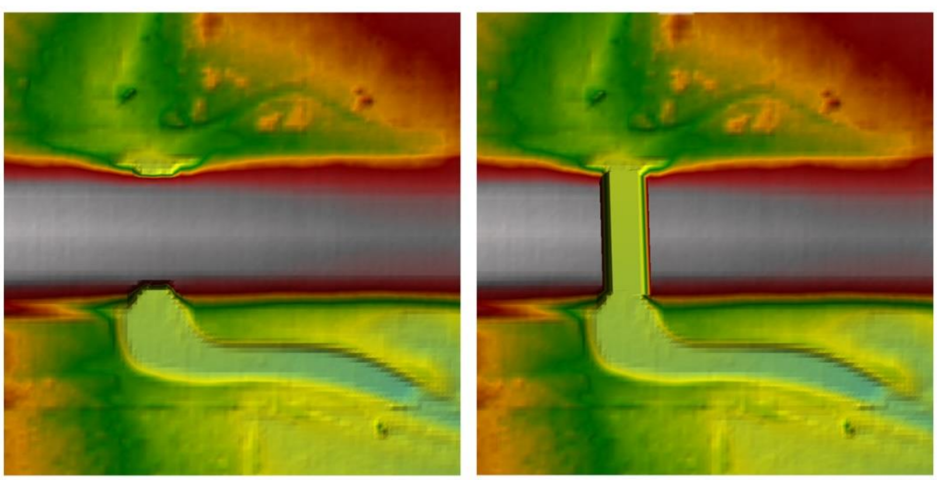
In the HEC-RAS model, Terrain.Hydroenforced.hdf is a modified version of Terrain.hdf. It was created by hydro-enforcing Terrain.hdf in HEC-RAS. The hydro-enforcement of this surface allowed water to drain properly at the bridges and culverts in the study area since the openings for these structures were not always able to be captured when the LiDAR data were collected. This terrain surface was only used for the model simulations. When the raw floodplain mapping rasters were exported, Terrain.hdf was used, not Terrain.hydroenforced.hdf.

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. See Figure 4 for an example. Terrain modifications, when applied, allowed flow through roadways.



(a) without terrain modifications (b) with terrain modifications

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

- The streamlines and watershed delineations were reviewed and burn lines were continually added and adjusted until the flow paths, basins, and computed drainage areas were reasonable and justifiable.
- A drainage area grid was computed along the flow paths.
- There were eight USGS gages with drainage areas greater than 1 mi^2 in the watershed. The table below summarizes the differences between the reported and computed values for the drainage area. The differences between the computed and reported drainage areas are less than 10 percent except at one location, gage 08140000. The topography and National Hydrography Dataset (NHD) flow lines and reservoirs were reviewed and support the computed drainage area of 7.55 mi^2, so no adjustments were made.

Table 4: Summary of Differences between Reported and Computed USGS Gage Drainage Areas

USGS Gages			Computed Values	
Site No.	Site Name	Drainage Area (mi^2)	Drainage Area (mi^2)	Difference
08136700	Colorado River near Stacy, TX	24,193*	24,193*	0.0%
08136900	Mukewater Ck WSW No.10-A nr Trickham, TX	21.8	21.6	-0.9%
08137000	Mukewater Ck SWS No.9 nr Trickham, TX	4.02	4.06	1.0%
08137500	Mukewater Ck at Trickham, TX	70	69	1.4%
08138000	Colorado Rv at Winchell, TX	25,179*	25,176*	-0.01%
08139000	Deep Ck SWS No. 3 nr Placid, TX	3.42	3.26	-4.7%
08140000	Deep Ck WSW No.6 nr Mercury, TX	5.41	7.55	40%
08147000	Colorado River near San Saba, TX	31,217*	31,217*	0.0%

* Includes the drainage area in the Middle Colorado watershed and upstream of the watershed.

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 Middle Colorado 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 Middle Colorado watershed was split into nine model domains — 0601_A1, 0601_A2, 0602_A3, 0602_A4, 0603_A5, 0603_A6, 0604_A7, 0605_A8, and 0606_A9, 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.

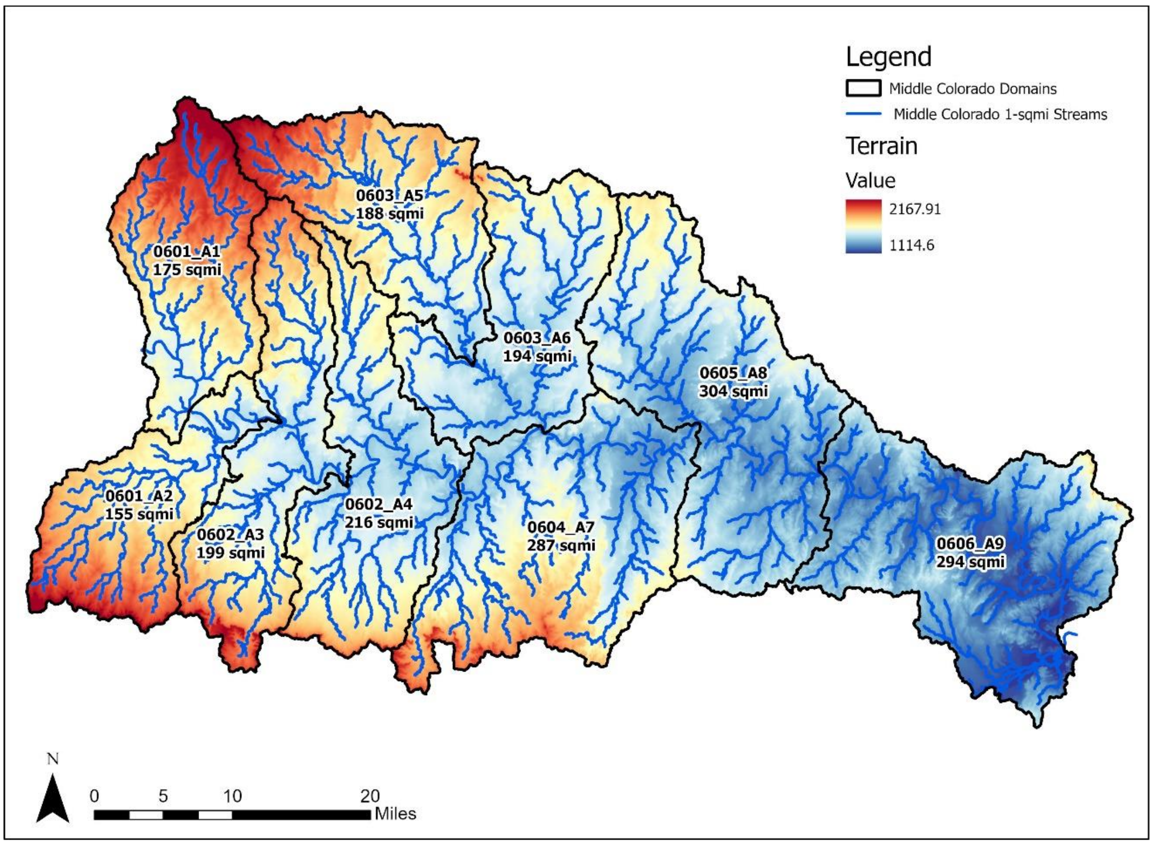


Figure 5: Middle Colorado Model Domains and Linkages

1.2.1 Total Precipitation

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

The 1% plus and 1% minus annual-chance rainfall totals were computed using the approach provided in subsection 2.2.3 of the TWDB's *2D BLE Guidance Version 1.0* (May 2022). The 1% plus and 1% minus storms were based on the NRCS temporal distribution described in Section 630.0407 of the *National Engineering Handbook* (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 by using gridded soils and gridded land cover data sets.

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

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

The infiltration layer was created in HEC-RAS by combining the soils and land cover gridded datasets. The CN values required for the loss rate computations were obtained from Table 2.4 of the TWDB's *2D Base Level Engineering Guidance Version 1.0* (May 2022) and are shown below in Table 4. An initial abstraction ratio of 0.2 was used to obtain the initial loss. For the Developed Low Intensity, Developed Medium Intensity, and Developed High Intensity land uses, the CN and the percent impervious cover presented for each land use in the TWDB guidance document were combined into an adjusted CN in the HEC-RAS model that took into account the impervious cover. These adjusted CNs were available in Table 2.2a of the NRCS's *Technical Release 55*.

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 6 for the AMC I CNs in the watershed. The AMC I CNs were computed from the AMC II CNs using the following equation (Chow, 1988):

$$CN(AMC\ I) = \frac{4.2 * CN(AMC\ II)}{10 - 0.058 * CN(AMC\ II)}$$

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. The Middle Colorado watershed resides within the transition from AMC II to AMC I. Therefore, the application of AMC I conditions to support validation was appropriate. See Section 1.2.9 for more information about the use of AMC I and AMC II CNs in the Middle Colorado watershed.

Table 5: AMC II Curve Number Values

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

Table 6: AMC I Curve Number Values

Land Use Grid Code	NLCD Land Use Description	CN for Each Hydrologic Soil Group			
		A	B	C	D
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 0.040 to 0.050.

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

Land Use Grid Code	NLCD Land Use Description	Normal N Value	Min N Value	Max N Value
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	0.03
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.
- As discussed in Subsection 1.1.2, the bridge/culvert crossing burn lines developed for this study were incorporated into the HEC-RAS terrain as terrain modification features to allow flow through roadways.

1.2.4 Model Boundary Conditions

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

Precipitation Boundary Conditions

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

Flow Hydrograph Boundary Conditions

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

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

Stage Hydrograph Boundary Conditions

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

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

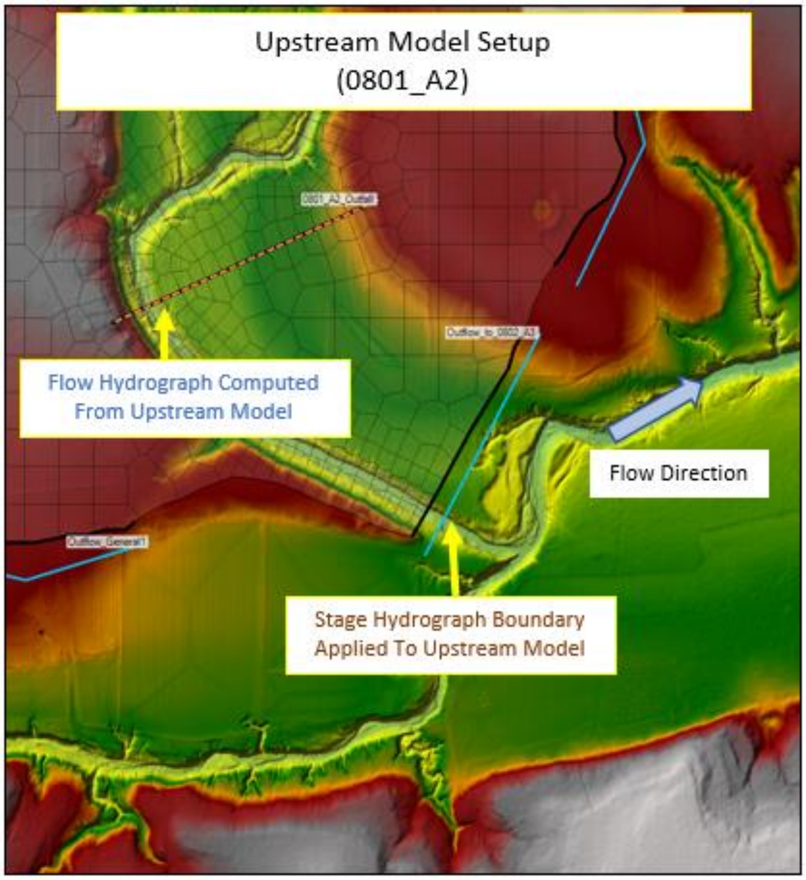


Figure 6: Extraction of Flow Hydrograph from the SA/2D Connection in the Upstream Domain for Use in the Downstream Domain

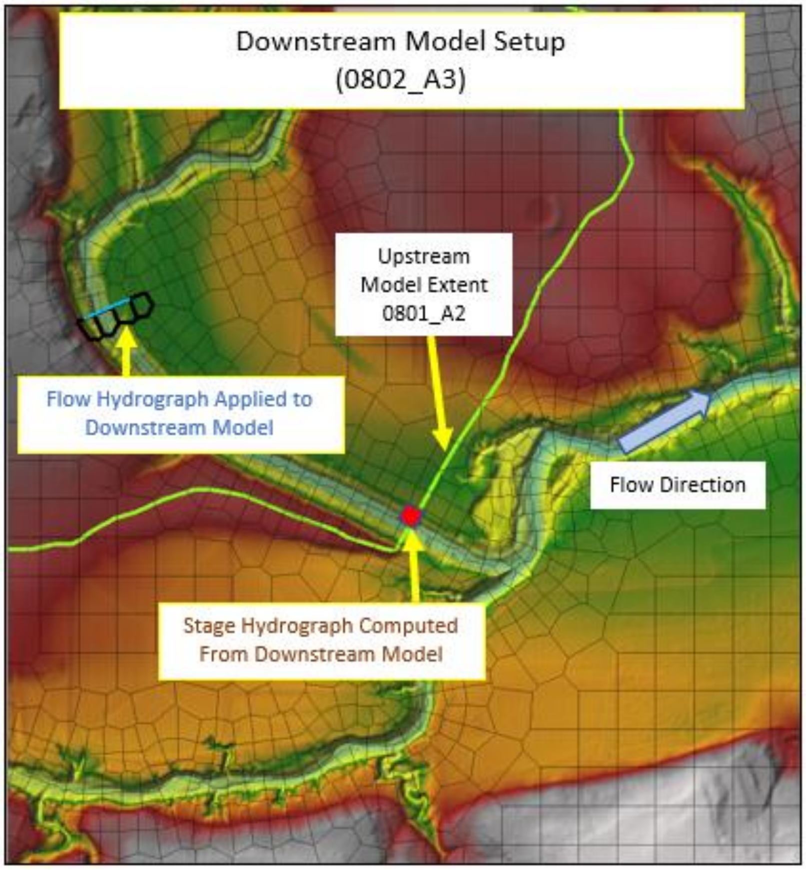


Figure 7: Application of Upstream Flow Hydrograph in the Downstream Domain

Although the TWDB's 2D BLE guidance recommended the use of normal depth boundary conditions at main channel outfalls, the use of a stage hydrograph as the downstream boundary is an acceptable alternative. This approach was used for two reasons. First, stage hydrographs account for simulated stages in the downstream model, whereas a single normal depth boundary condition slope may not mimic the temporal changes in the stage. Second, modeling the tie-ins is an iterative process, and stage hydrographs required fewer model iterations than normal depth to achieve acceptable tie-ins.

See Table 8 through Table 15 for a summary of the upstream and downstream peak discharges and WSELs at the downstream end of each domain in the Middle Colorado watershed. These tables have been included to demonstrate that at the downstream end of each model domain, the peak discharges are within 10% of one another and the WSELs are within 0.5 feet for each profile.

A table has not been included for domain 0601_A1. The dam for the O. H. Ivie Reservoir is located at the downstream end of this domain. Because of the dam, the WSELs between domains 0601_A1 and 0601_A2 differed by more than 0.5 feet. Since a decoupled modeling approach was applied at the dam, the discharges out of domain 0601_A1 and into domain 0602_A2 were not within 10% of one another. See Subsection 1.2.5 for more information about this decoupled approach.

Table 8: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0601_A2

Profile (AEP)	Upstream Outflow (cfs)	Downstream Inflow (cfs)	Difference (%)	Upstream WSEL (ft)	Downstream WSEL (ft)	Difference (ft)
10%	9,262	9,600	3.58%	1,411.40	1,411.54	0.14
4%	15,533	16,286	4.73%	1,415.61	1,415.82	0.21
2%	21,210	22,396	5.44%	1,418.82	1,418.99	0.17
1%	30,193	30,264	0.23%	1,422.02	1,422.23	0.21
0.2%	71,130	71,444	0.44%	1,432.26	1,432.46	0.20
1% minus	17,863	18,613	4.11%	1,416.90	1,417.08	0.18
1% plus	156,701	159,576	1.82%	1,444.48	1,444.69	0.21

Table 9: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0602_A3

Profile (AEP)	Upstream Outflow (cfs)	Downstream Inflow (cfs)	Difference (%)	Upstream WSEL (ft)	Downstream WSEL (ft)	Difference (ft)
10%	15,588	15,890	1.92%	1,386.16	1,386.17	0.01
4%	26,917	27,423	1.86%	1,391.42	1,391.45	0.03
2%	37,138	37,865	1.94%	1,394.81	1,394.87	0.06
1%	49,467	50,354	1.78%	1,398.02	1,398.08	0.06
0.2%	86,022	88,411	2.74%	1,405.64	1,405.75	0.11
1% minus	30,795	31,274	1.54%	1,392.75	1,392.82	0.07
1% plus	157,343	158,273	0.59%	1,413.35	1,413.32	0.03

Table 10: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0602_A4

Profile (AEP)	Upstream Outflow (cfs)	Downstream Inflow (cfs)	Difference (%)	Upstream WSEL (ft)	Downstream WSEL (ft)	Difference (ft)
10%	20,318	20,307	0.05%	1,342.03	1341.73	0.30
4%	32,784	32,812	0.09%	1,347.40	1,347.27	0.13
2%	44,219	44,315	0.22%	1,351.26	1,351.13	0.13
1%	57,663	57,942	0.48%	1,355.19	1,355.08	0.11
0.2%	98,137	98,868	0.74%	1,364.53	1,364.44	0.09
1% minus	37,238	37,254	0.04%	1,348.97	1,348.85	0.12
1% plus	144,090	150,491	4.35%	1,372.35	1,372.27	0.08

Table 11: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0603_A5

Profile (AEP)	Upstream Outflow (cfs)	Downstream Inflow (cfs)	Difference (%)	Upstream WSEL (ft)	Downstream WSEL (ft)	Difference (ft)
10%	11,073	11,067	0.05%	1,392.52	1,392.14	0.38
4%	16,953	16,956	0.02%	1,394.47	1,394.13	0.34
2%	22,825	22,809	0.07%	1,395.77	1,395.44	0.33
1%	29,507	29,516	0.03%	1,396.80	1,396.47	0.33
0.2%	59,507	59,531	0.04%	1,400.08	1,399.76	0.32
1% minus	19,722	19,745	0.11%	1,395.16	1,394.84	0.32
1% plus	42,310	42,252	0.14%	1,398.37	1,398.03	0.34

Table 12: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0603_A6

Profile (AEP)	Upstream Outflow (cfs)	Downstream Inflow (cfs)	Difference (%)	Upstream WSEL (ft)	Downstream WSEL (ft)	Difference (ft)
10%	18,763	19,063	1.58%	1,316.46	1,316.52	0.06
4%	26,962	28,625	5.99%	1,323.35	1,323.38	0.03
2%	34,411	37,153	7.66%	1,328.18	1,328.21	0.03
1%	43,787	47,869	8.91%	1,332.89	1,332.92	0.03
0.2%	85,066	87,367	2.67%	1,344.13	1,344.18	0.05
1% minus	30,783	32,734	6.14%	1,325.55	1,325.58	0.03
1% plus	66,663	65,625	1.57%	1,344.60	1,344.58	0.02

Table 13: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0604_A7

Profile (AEP)	Upstream Outflow (cfs)	Downstream Inflow (cfs)	Difference (%)	Upstream WSEL (ft)	Downstream WSEL (ft)	Difference (ft)
10%	34,605	34,609	0.01%	1,274.39	1,274.37	0.02
4%	55,323	55,412	0.16%	1,281.35	1,281.33	0.02
2%	73,442	73,658	0.29%	1,285.95	1,285.94	0.01
1%	95,446	95,790	0.36%	1,290.47	1,290.46	0.01
0.2%	172,641	172,579	0.04%	1,300.68	1,300.68	0.00
1% minus	63,180	63,390	0.33%	1,283.55	1,283.54	0.01
1% plus	140,783	145,796	3.50%	1,297.53	1,297.53	0.00

Table 14: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0605_A8

Profile (AEP)	Upstream Outflow (cfs)	Downstream Inflow (cfs)	Difference (%)	Upstream WSEL (ft)	Downstream WSEL (ft)	Difference (ft)
10%	34,151	34,685	1.55%	1,240.10	1,240.08	0.02
4%	53,432	55,003	2.90%	1,246.68	1,246.68	0.00
2%	70,170	72,300	2.99%	1,250.88	1,250.88	0.00
1%	90,776	93,532	2.99%	1,254.83	1,254.83	0.00
0.2%	167,735	172,341	2.71%	1,263.09	1,263.10	0.01
1% minus	62,206	64,134	3.05%	1,249.03	1,249.02	0.01
1% plus	137,261	138,429	0.85%	1,260.21	1,260.21	0.00

Table 15: Upstream and Downstream Discharges and WSELs at the Downstream End of Domain 0606_A9

Profile (AEP)	Upstream Outflow (cfs)	Downstream Inflow (cfs)	Difference (%)	Upstream WSEL (ft)	Downstream WSEL (ft)	Difference (ft)
10%	81,232	79,689	1.92%	1,144.58	1,144.54	0.04
4%	130,009	127,687	1.80%	1,153.72	1,153.42	0.30
2%	174,330	169,990	2.52%	1,158.53	1,158.42	0.11
1%	228,925	223,261	2.50%	1,163.51	1,163.54	0.03
0.2%	424,912	424,533	0.09%	1,177.82	1,178.05	0.23
1% minus	154,111	150,482	2.38%	1,156.42	1,156.24	0.18
1% plus	331,742	327,096	1.41%	1,171.43	1,171.60	0.17

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.

To minimize the effects that the model boundary conditions had on the model results within the HUC-8 boundary, a buffer of 1,000 feet was applied to the watershed boundary to establish the extents of the 2D computational mesh. Therefore, the 2D mesh extends beyond the high ground along the watershed boundary. Additionally, in the BLE model, rainfall was added to the model via a rain-on-grid approach that was applied over the entire 2D computational mesh, including the area outside the HUC-8 watershed boundary. The application of rainfall outside of the watershed boundary has led to some flow reaching the perimeter boundary. However, this flow does not represent flow that is leaving the HUC-8 watershed and entering the adjacent watershed. To simplify model setup, only one perimeter boundary condition line was used. The following figure shows an example of flow being captured at the perimeter boundary.

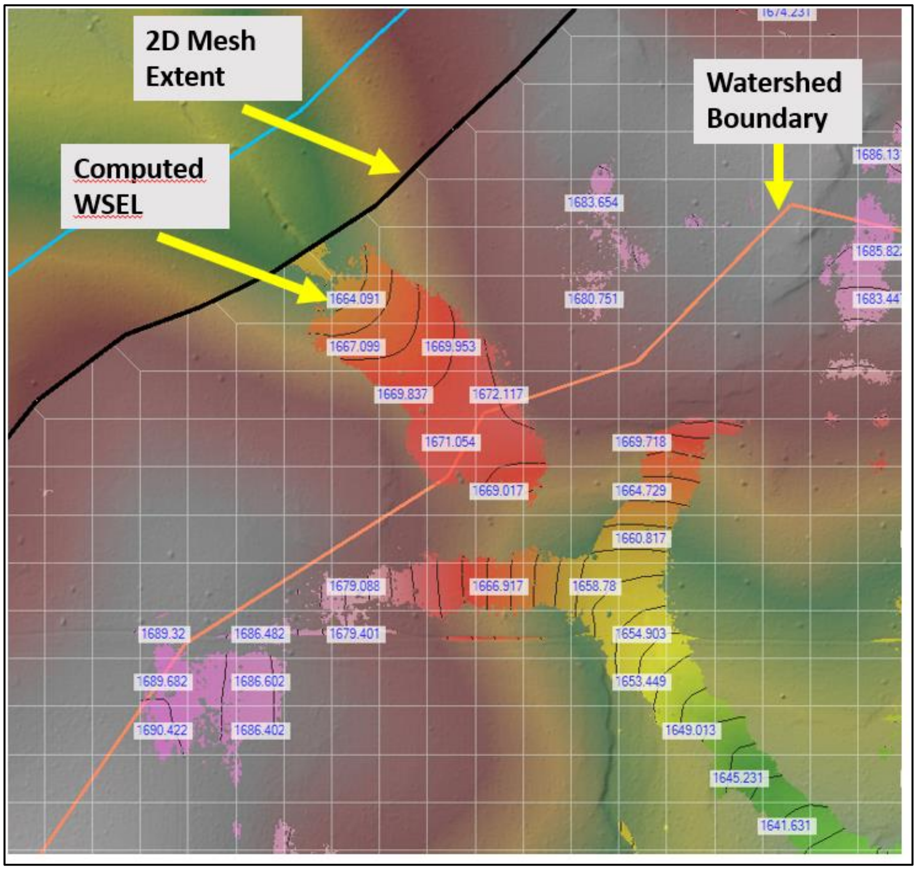


Figure 8: Flow Captured at the Perimeter Boundary

The topographic relief along the perimeter of the Middle Colorado watershed boundary is high enough that only negligible overflows leave the watershed. At locations where the floodplain extends to the watershed boundary, profile lines were drawn to verify that the flow leaving the watershed was negligible and did not need to be accounted for as an outflow into the neighboring watershed.

Adjustments to the Lengths of the Inflow Boundary Condition Lines

SA/2D connections were delineated at the downstream end of each domain to model the outflows into the downstream domain. The flows at these features were recorded in the model’s DSS output files. These connections are coincident with the inflow boundary location in the downstream model.

The lengths of the inflow lines were shortened so that they approximated the width of the floodplain limits of the 10% event. This was done to keep the flow from being distributed across the entire width of the valley. When the inflow line was initially set to the same length as the SA/2D connection, flooding was erroneously appearing at locations that were dry in the overlap area of the upstream model. Figure 9 shows an example of an outflow SA/2D connection near the outlet of an upstream domain. The results in Figure 10, which are based on the full-length coincident inflow boundary condition line in the receiving domain, show a floodplain that is much wider than what is shown in the upstream model in Figure 9. Figure 11 shows the mapping that results from applying a shortened inflow boundary condition. The width of the floodplain in Figure 11 is better aligned with the width shown in the overlap area between the two model domains in Figure 9.

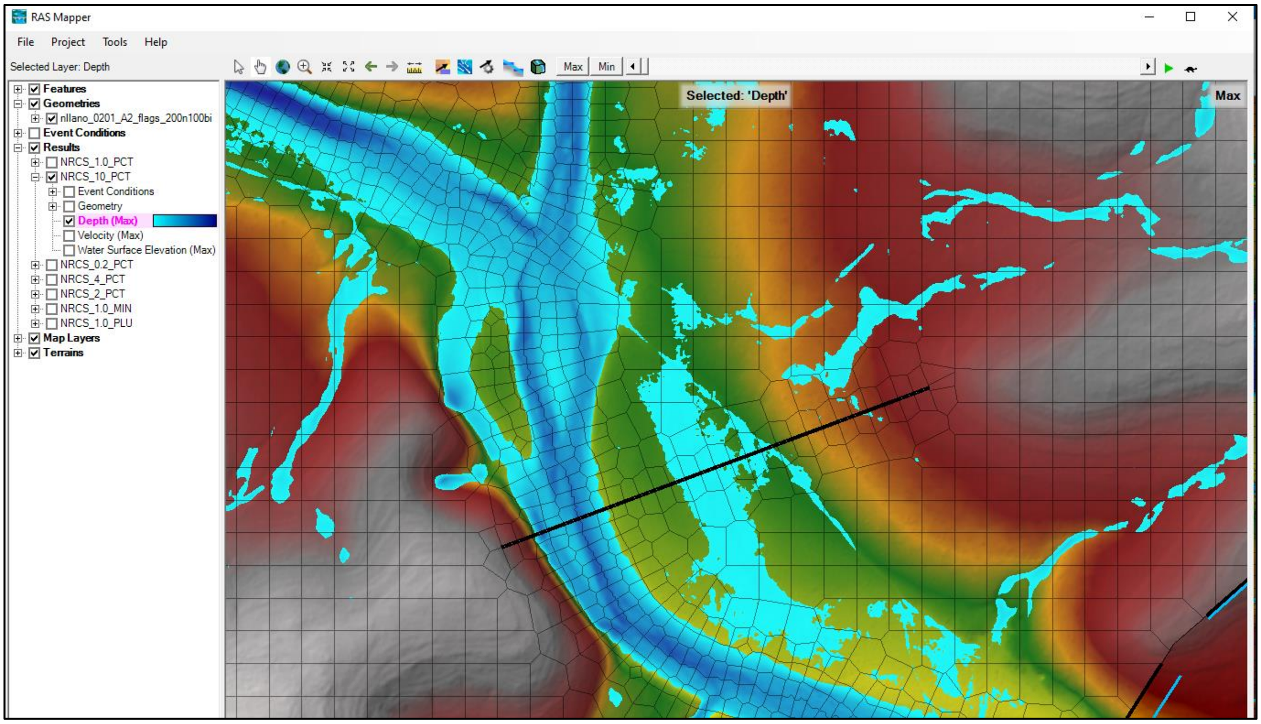


Figure 9: SA/2D Connection and Floodplain at the Outflow of an Upstream Domain

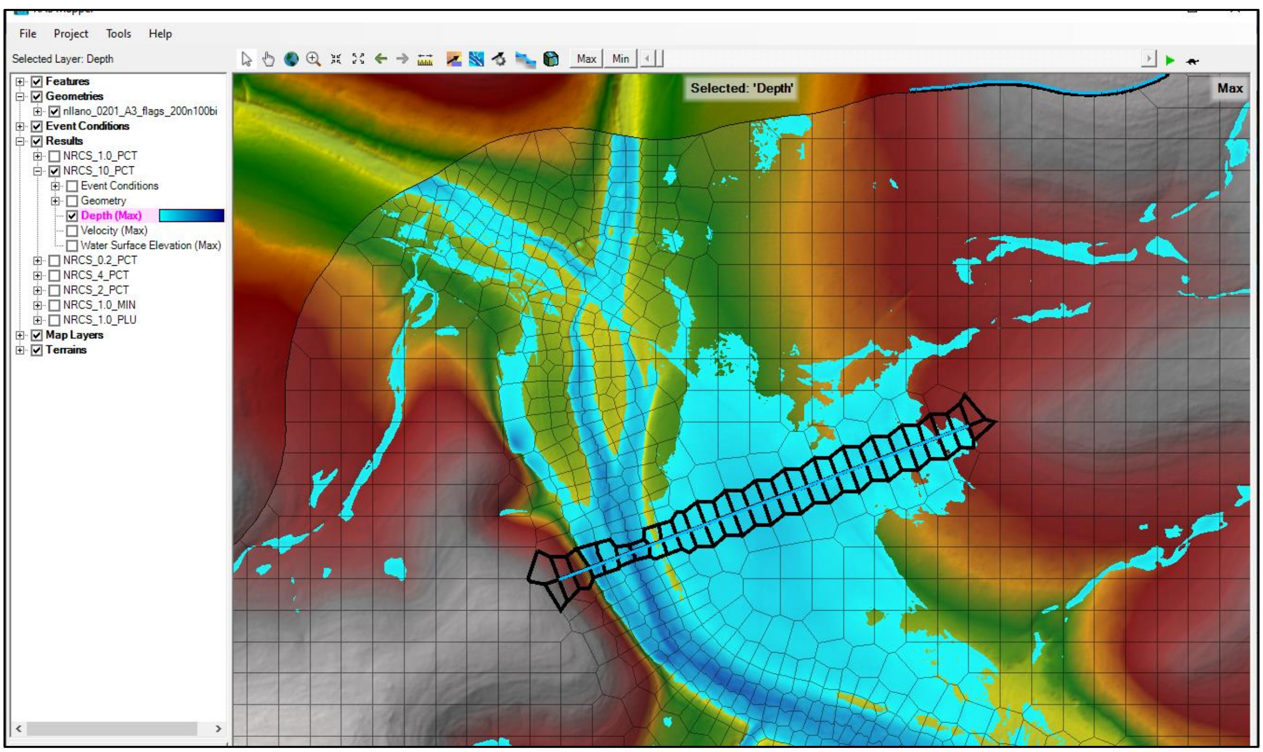


Figure 10: Application of a Full-length Inflow Boundary Condition Line in the Receiving Domain

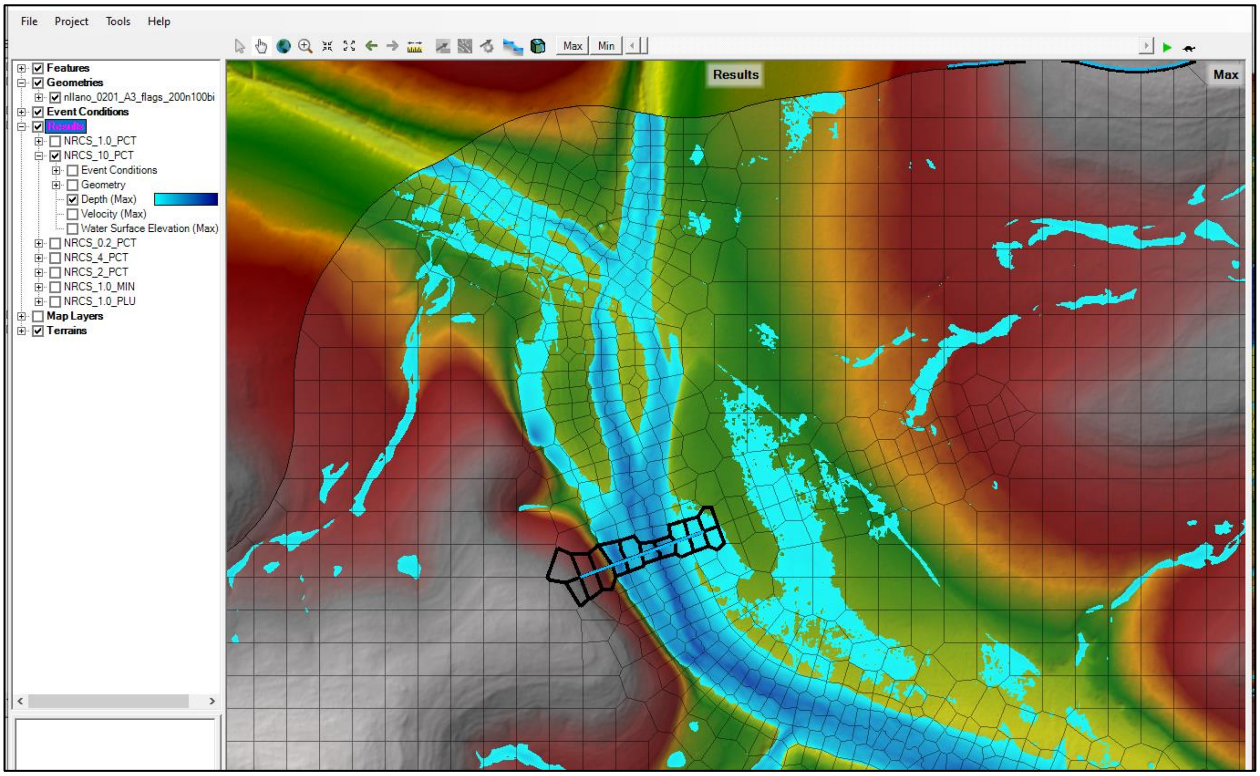


Figure 11: Application of a Shortened Inflow Boundary Condition Line in the Receiving Domain

1.2.5 Reservoir Modeling

The O. H. Ivie Reservoir is located at the confluence of the Colorado and Concho Rivers. Most of the reservoir is located within the Middle Colorado HUC-8 watershed, but the upper end of the reservoir extends into the Middle Colorado-Elm and Concho HUC-8 watersheds. The Middle Colorado model domains were delineated near the O. H. Ivie Reservoir dam crest such that the reservoir is mostly located in domain 0601_A1, and the reach downstream of the dam is located in domain 0601_A2.

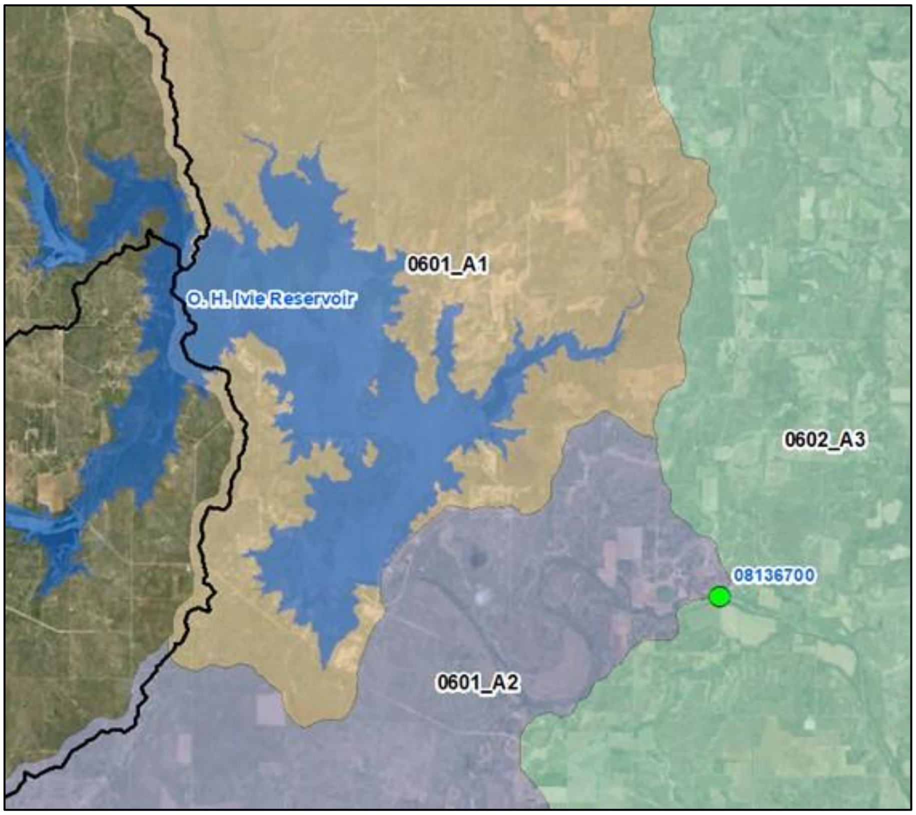


Figure 12: Domain Delineation near the O. H. Ivie Reservoir

The O. H. Ivie Reservoir was analyzed by the Interagency Flood Risk Management (InFRM) team's Watershed Hydrology Assessment (WHA) for the Lower Colorado River Basin. This study produced an updated pool-frequency curve for the reservoir. The results are included in the draft WHA report in Chapter 9 (March 2021). The results for O. H. Ivie Reservoir are summarized on page 67. A copy of this report has been included in the supplemental data folder for reference.

Domain 0601_A1 Inflow

The Colorado River enters the Middle Colorado watershed in domain 0601_A1. To model the river as it entered the domain, an inflow hydrograph had to be computed. USGS gages 08126380 (Colorado River near Ballinger, TX) and 08136500 (Concho River at Paint Rock, TX) are located just upstream of the O. H. Ivie Reservoir, outside of the BLE study area. The WHA completed a flow-frequency analysis for these two gages and a Reservoir Frequency Analysis (RFA) for the reservoir. To approximate the inflow peak discharges into domain 0601_A1, the flows computed by the gage analyses were added together. Although this approach did not take into consideration the timing of the hydrograph peaks, the combined flows were generally similar to the peak flows out of the reservoir that were computed by the RFA. See Table 16 for a summary of the gages analyses, the combined flow rates, and the RFA.

Table 16: Estimated Peak Inflows and Outflow for O. H. Ivie Reservoir

AEP	InFRM WHA Gage Analysis		Combined Peak Inflow Rate (cfs)	InFRM RFA Analysis	Reservoir Inflow Applied in the BLE Model (cfs)
	08126380 Colorado River near Ballinger (cfs)	08136500 Concho River at Paint Rock (cfs)		Total Release (cfs)	
10%	9,730	13,500	23,230	1,500	23,230
4%	14,900	23,000	37,900	32,700	37,900
2%	19,200	32,100	51,300	52,500	51,300
1%	24,000	43,300	67,300	67,350	67,300
0.2%	36,400	78,400	114,800	94,945	114,800
1% plus	64,000*	127,000*	191,000	-	191,000
1% minus	15,400*	24,600*	40,000	-	40,000

* 1% plus and 1% minus flows are from the gage's 95% confidence interval. Flows at the 84% confidence interval were not available.

A triangular inflow hydrograph shape for the domain, shown in Figure 13, was developed iteratively to obtain a pool elevation within 0.5 foot of the 1% stage estimated by the RFA. This hydrograph was scaled up or down for the other events.

The 1% plus discharge computed by the gage analysis at each gage is higher than the 0.2% discharge. On the other hand, the 0.2% rainfall total for the domain is higher than the 1% plus total. This is producing a phenomenon in the model where the 0.2% discharges near the beginning of the model run, where local runoff controls the discharges, are higher than the 1% plus discharges. Later in the model run, where the Colorado River inflow controls the discharges, the 1% plus discharges are higher than the 0.2% discharges. Although crossing profiles typically indicate something is amiss in a model, in this case they are acceptable as the flows into the reservoir shift from being dominated by Colorado River inflows to being dominated by rainfall runoff inflows. See the discussion in the Challenges section for more information about these crossing profiles.

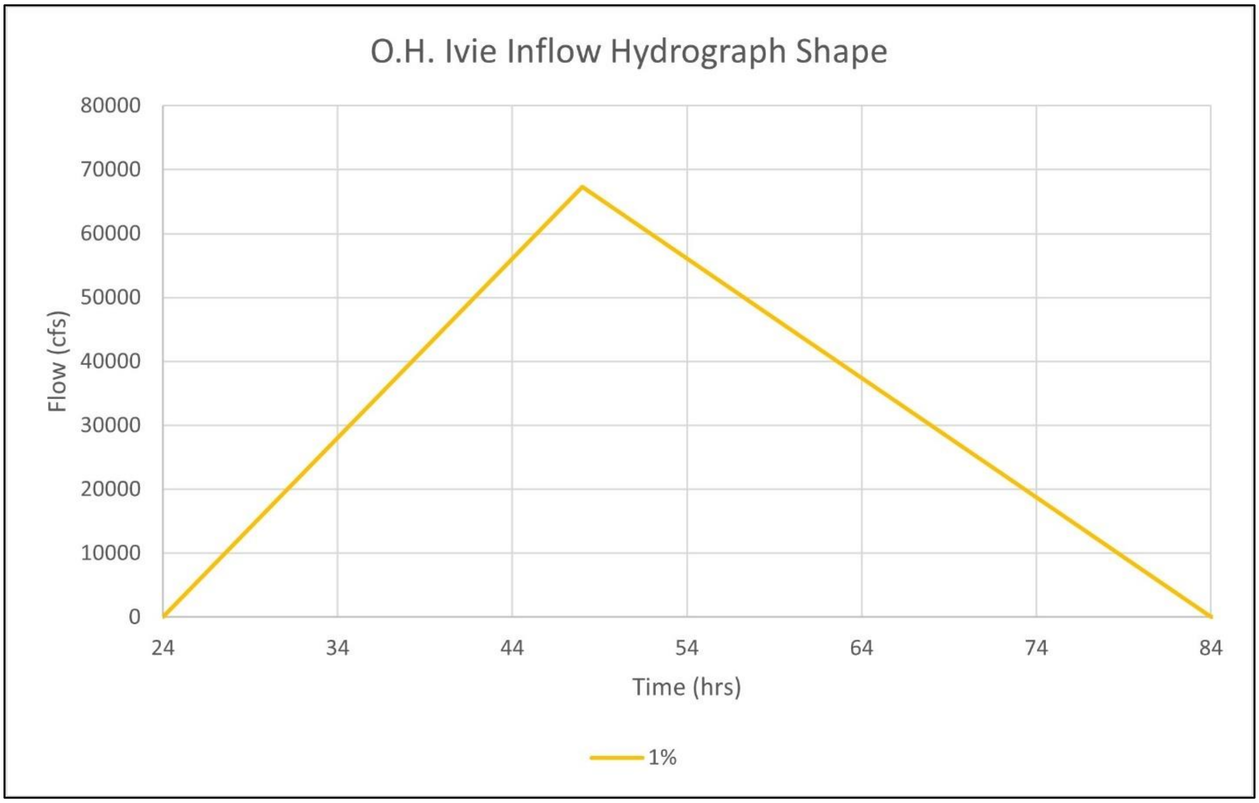


Figure 13: O. H. Ivie Inflow Hydrograph Shape

Model Setup at O. H. Ivie Dam

The O. H. Ivie dam in domain 0601_A1 was modeled as a hydraulic structure by adding an SA/2D connection in the HEC-RAS model. The outflow versus stage rating curve from the RFA, shown in Table 17, was applied at this connection. An overview of the model setup is shown in Figure 14. The elevations in the RFA were referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). A datum conversion of +0.147 foot was used to convert the elevations to NAVD 88.

Table 17: RFA Frequency-Outflow Curve for O. H. Ivie Reservoir

AEP	Elevation (ft, NGVD 29)	Elevation (ft, NAVD 88)	Spillway Release (cfs)	Gate Release (cfs)	Total Release (cfs)
10%	1,551.95	1,552.10	0	1,500	1,500
4%	1,552.12	1,552.27	0	32,700	32,700
2%	1,552.49	1,552.64	0	52,500	52,500
1%	1,552.74	1,552.89	0	67,350	67,350
0.2%	1,553.38	1,553.53	0	94,945	94,945

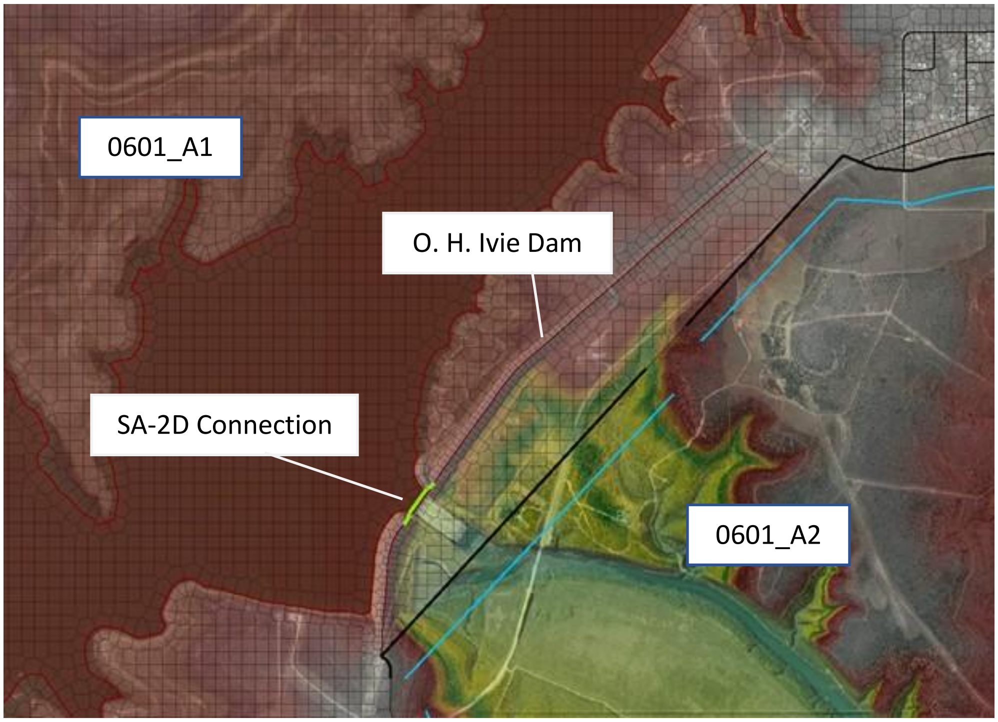


Figure 14: O. H. Ivie Dam at the Boundary of Domains 0601_A1 and 0601_A2

Domain 0601_A2 Inflow

The modeled outflow from domain 0601_A1 was not used as the inflow for domain 0601_A2. Instead, a decoupled modeling approach was used to establish the inflow into domain 0601_A2.

Gage 08136700 (Colorado River near Stacy, TX) is located approximately 10 river miles downstream of the reservoir outlet. The peak 1% flow at the gage from the WHA was 30,300 cfs, whereas the 1% outflow from the RFA analysis of O. H. Ivie Reservoir was 67,350 cfs. Because the reservoir was constructed in 1990, little historical performance data was available for the reservoir; only two releases have occurred since the reservoir was constructed. In addition, no operations data were available.

AtkinsRéalis compared the peak 1% flows computed by the RFA at the reservoir outlet (67,350 cfs) and the WHA at the gage (30,300 cfs). AtkinsRéalis concluded the gage flow was more reliable since the RFA was based on only two releases. In addition, the WHA noted in its gage analysis that the historical and ongoing construction of reservoirs in the Colorado River basin was contributing to a reduction in peak flow rates in the basin. See Subsection 1.2.8 for more information. In light of this observation, the WHA only included in it gage analysis flow from 1990, when the reservoir was constructed, to 2019. Since the gage analysis included more data and analyzed the existing conditions in the domain, it was considered the more reliable source of peak flow data.

As part of the WHA, USACE developed scalable hydrograph shapes at the reservoir outlet. These hydrograph shapes were combined with the peak flow data from the gage analysis to develop the hydrographs of the flow that exited the dam and entered domain 0601_A2. The construction of the inflow hydrographs for domain 0601_A2 is documented in the spreadsheet *Flow_Hydrograph_RatingCurve_OH_Ivie.xlsx* in the supplemental data folder.

Other Modeling Considerations for O. H. Ivie Reservoir

As discussed earlier in this section, the InFRM RFA established a pool-frequency curve for O. H. Ivie Reservoir. A goal of this BLE study was to compute reservoir stages similar to those in the RFA without building a detailed model of the dam.

The O. H. Ivie Reservoir is located at the confluence of the Colorado and Concho Rivers. A portion of the reservoir extends into the Concho River HUC-8 watershed and the Middle Colorado-Elm HUC-8 watershed, which are outside of the scoped study area of this BLE analysis. Although the model domain containing the reservoir does extend approximately 1,000 feet outside of the Middle Colorado HUC-8 boundary, it does not contain the entire footprint of the O. H. Ivie reservoir.

To obtain pool elevations similar to those in the RFA, a triangular inflow hydrograph shape was developed and was applied as an inflow to domain 0601_A1. The hydrograph shape was iterated to adjust the inflow hydrograph volume to produce elevations within 0.5 feet of the RFA 1% pool elevation (1552.90 feet, NAVD 88). The same hydrograph shape was scaled for the other AEP events.

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 15. 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.

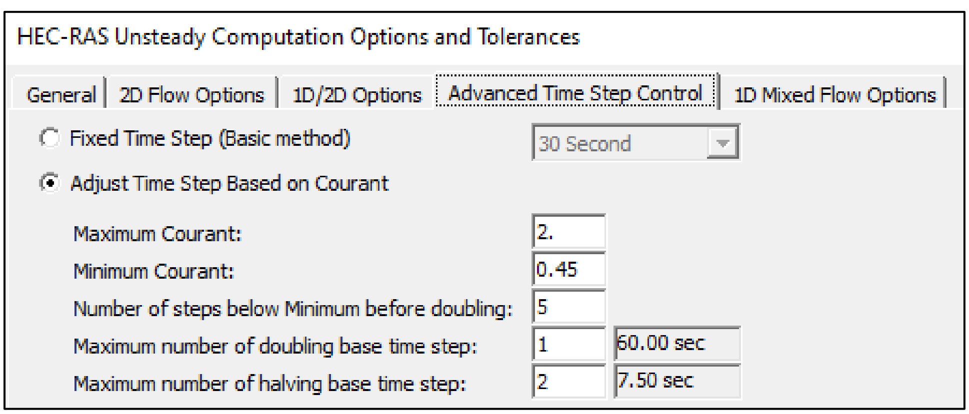


Figure 15: HEC-RAS Unsteady Computation Options and Tolerances

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 (Ω) were the input parameters for the regression equations. The regression equations are shown in Table 3 in the regression report (Asquith and Roussel 2009) and below on Figure 16.

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 16: Regression Equations for the Middle Colorado 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.

$$Q_{1\%Plus} = Q_{1\%} * 1.648$$

$$Q_{1\%Minus} = \frac{Q_{1\%}}{1.648}$$

Regression flows were not considered accurate downstream of flow-regulating reservoirs or along streams that routed inflows from other HUC-8 watersheds.

1.2.8 Gage Analysis

The Middle Colorado watershed was studied by the InFRM team's WHA for the Lower Colorado River Basin. The WHA analyzed USGS gages 08136700 (Colorado River near Stacy, TX), 08138000 (Colorado River at Winchell, TX), and 08147000 (Colorado River near San Saba, TX) using the methodology in USGS Bulletin 17C to determine frequency-discharge curves for each gage. The validation of the BLE results in the Middle Colorado watershed leveraged these frequency-discharge curves. See Subsection 1.2.9 for additional details. Table 18 documents the USGS gages located in the Middle Colorado watershed. Of the 8 gages in the watershed, flow-frequency analyses were completed for 3 gages. At the remaining gages, either the period of record was too short or the gage data were too suspect to produce a reliable flow-frequency analysis. See the table for more information about why flow-frequency analyses were not completed for these 5 gages.

Table 18: Summary of USGS Gages in the Middle Colorado Watershed

Site No.	Site Name	Computed Drainage Area (mi^2)	Was Gage Analysis Performed?	Source of Gage Analysis	Reason why gage analysis was not performed to support BLE validation
08136700	Colorado River near Stacy, TX	24,193	Yes	InFRM WHA	
08136900	Mukewater Ck WSW No.10-A nr Trickham, TX	21.6	No		The period of record was less than 10 years, and the flow data were old (1966-1973).
08137000	Mukewater Ck SWS No.9 nr Trickham, TX	4.1	No		The recorded flows were old (1961-1977). Records after 1966 were estimated flows, which may not be reliable.
08137500	Mukewater Ck at Trickham, TX	69	No		The recorded flows were old (1951-1973). Flows after 1961 were regulated flows. Period of record was short.
08138000	Colorado Rv at Winchell, TX	25,176	Yes	InFRM WHA	
08139000	Deep Ck SWS No. 3 nr Placid, TX	3.3	No		No streamflow data were available for this gage.
08140000	Deep Ck WSW No.6 nr Mercury, TX	7.6	No		No streamflow data were available for this gage.
08147000	Colorado River near San Saba, TX	31,217	Yes	InFRM WHA	

The remainder of Subsection 1.2.8 provides more background about the gage analyses included in the InFRM WHA.

The period of record for gage 08136700 (Colorado River near Stacy, TX) extended from 1969 to 2019. The WHA noted that peak annual discharge data prior to 1990 were not used in the analysis because of the construction of the O. H. Ivie Reservoir, which entered service in 1990 and had a noticeable effect on the annual peak discharge data at this gage.

The period of record for gage 08138000 (Colorado River at Winchell) extended from 1924 to 2020. The WHA reported that the Pettit test identified a change point in water year 1961, and there is an obvious change in the data after 1961, as documented in Figure 17. Twin Buttes Reservoir on the Concho River entered service in 1963. The WHA was concerned that this reservoir was still affecting peak discharges this far downstream since the Pettit test identified similar changes in 1961 at the gage along the Colorado River near San Saba. Because the Concho River is a major tributary to the Colorado River and the E.V. Spencer Reservoir was constructed in the 1960s (1969), the WHA assumed that the cumulative effects of these reservoirs and others constructed in the basin since then have contributed to a downward trend in the peak annual discharges at this gage. Therefore, peak discharge data prior to the construction of the Twin Buttes Reservoir in 1963 was removed from the gage analysis.

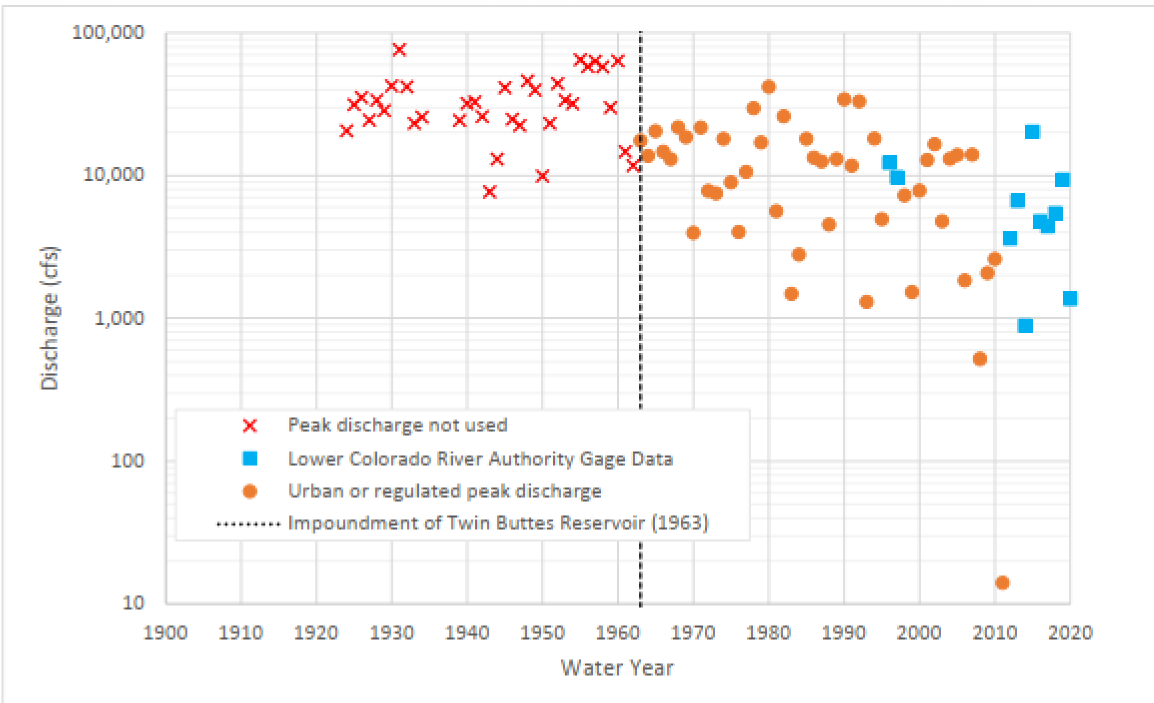


Figure 17: Annual Peak Discharge Data for USGS Gage 08138000

The WHA computed two sets of frequency-discharge curves for gage 08147000 (Colorado River near San Saba gage). One curve was derived using annual peak discharge data from 1963 to 2020. The second curve was based on the full record of annual peak discharges, which extended from 1916 to 2020.

The WHA reported that the Pettit test identified a change point in water year 1961, and there is an obvious change in the data after 1961, as documented in Figure 18. Twin Buttes Reservoir on the Concho River entered service in 1963. The WHA was concerned that this reservoir was still affecting peak discharges this far downstream since the Pettit test identified similar changes in 1961 at the gage along the Colorado River near Winchell. Because the Concho River is a major tributary to the Colorado River and the E.V. Spencer Reservoir was constructed in the 1960s (1969), the WHA assumed that the cumulative effects of these reservoirs and others constructed in the basin since then have contributed to a downward trend in the peak annual discharges at this gage. Therefore, peak discharge data prior to the construction of the Twin Buttes Reservoir in 1963 was removed from the initial gage analysis.

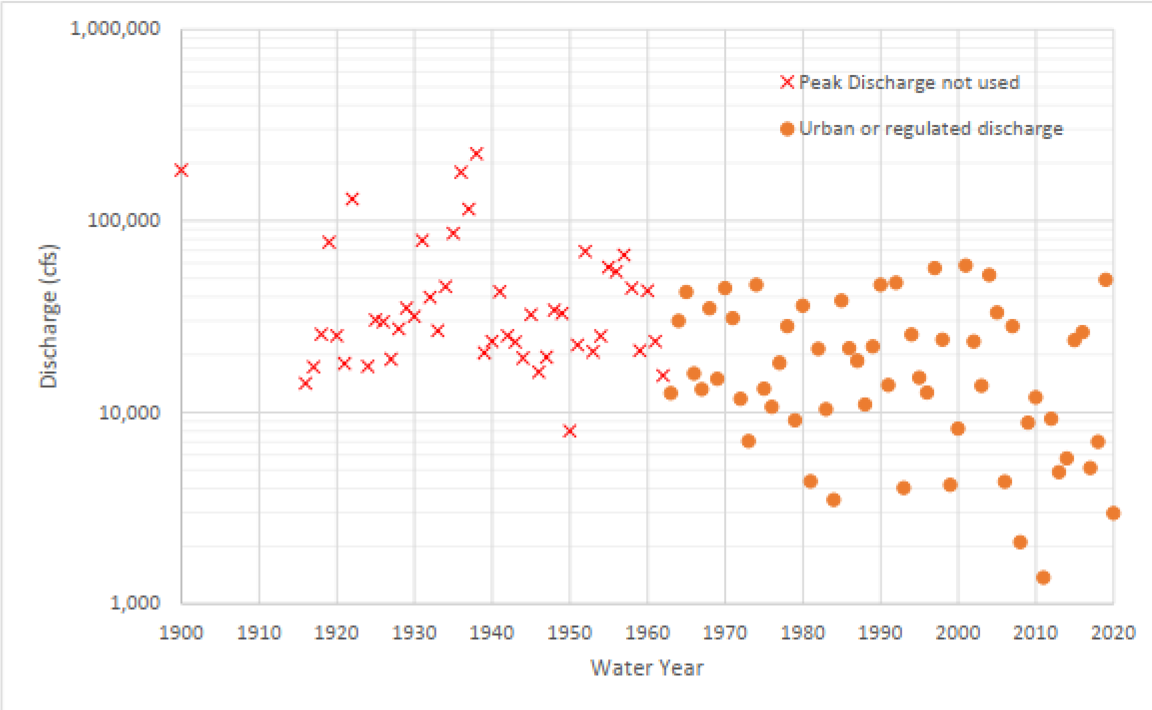


Figure 18: Annual Peak Discharge Data for USGS Gage 08147000

The WHA competed an alternate analysis at gage 08147000 (Colorado River near San Saba) to highlight the effects of including gage data from before 1963. This analysis included the entire period of record (1916 – 2020). Compared to the analysis that only used data from 1963 to 2020, the 1% peak discharge increased from 80,900 cfs to 158,000 cfs, and the 10% peak discharge increased from 44,000 cfs to 68,200 cfs. The WHA stated that the alternate results are only meant for comparison to the original results. Since the original results better reflect the current conditions at this gage, they are the WHA's recommended results for this gage.

A description of the gage analyses in the WHA, the WHA's assumptions, and its results are included on pages 62 to 65, 91 to 95, and 146 of Chapter 5 of the InFRM's draft WHA report. A copy of these pages has been included in Appendix B of this report.

No additional gage analyses were performed for this BLE study.

1.2.9 Model Validation

The Middle Colorado BLE hydraulic models were validated using peak flow information available in the draft InFRM WHA and outcomes from the regression analysis previously discussed in Subsection 1.2.7.

Validation checks were made at 87 locations throughout the Middle Colorado watershed. The locations may be grouped as follows:

- Eighty-four validation locations compared the 1% BLE flows with the 1% minus, 1%, and 1% plus regression flows.
- Three validation locations compared the 1% BLE flow with the 1% minus, 1%, and 1% plus gage flows.

The validation locations were scattered throughout the watershed in locations that provided a comprehensive coverage of drainage areas and stream characteristics. The model overview and results spreadsheet (*MidCo_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 this spreadsheet. 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 31,200 mi^2. At the 84 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 66 locations, and they were outside of this range at 18 locations. At the 3 locations where the 1% BLE flows were validated against the 1% plus and 1% minus USGS gage flows, the 1% BLE flows were between the 1% minus and the 1% plus regression flows at 1 location, and they were outside of this range at 2 USGS locations. The comparisons of the 1% BLE flows with the regression and gage flows is shown in Table 21.

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 7.

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.

For model domains 0604_A7 and 0606_A9, 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 AMCs were revised from AMC II to AMC I. The computed flow rates obtained by assuming AMC I conditions were lower than the 1% flows based on AMC II conditions, and in several locations, the computed BLE flows were even lower than the 1% minus flows. To increase the number of validation points with valid BLE flows, further refinements were necessary.

Research of published documentation on the topic of AMCs in Texas uncovered *Engineering Technical Note 210-18-TX5 – Estimating Runoff for Conservation Practices.* Published by the Soil Conservation Service (SCS), this document included a map showing how typical AMCs vary across Texas. As shown in Figure 19 and in Appendix B, typical AMCs range from AMC I (west Texas) to 40% of the way between AMC II and AMC III in far east Texas.

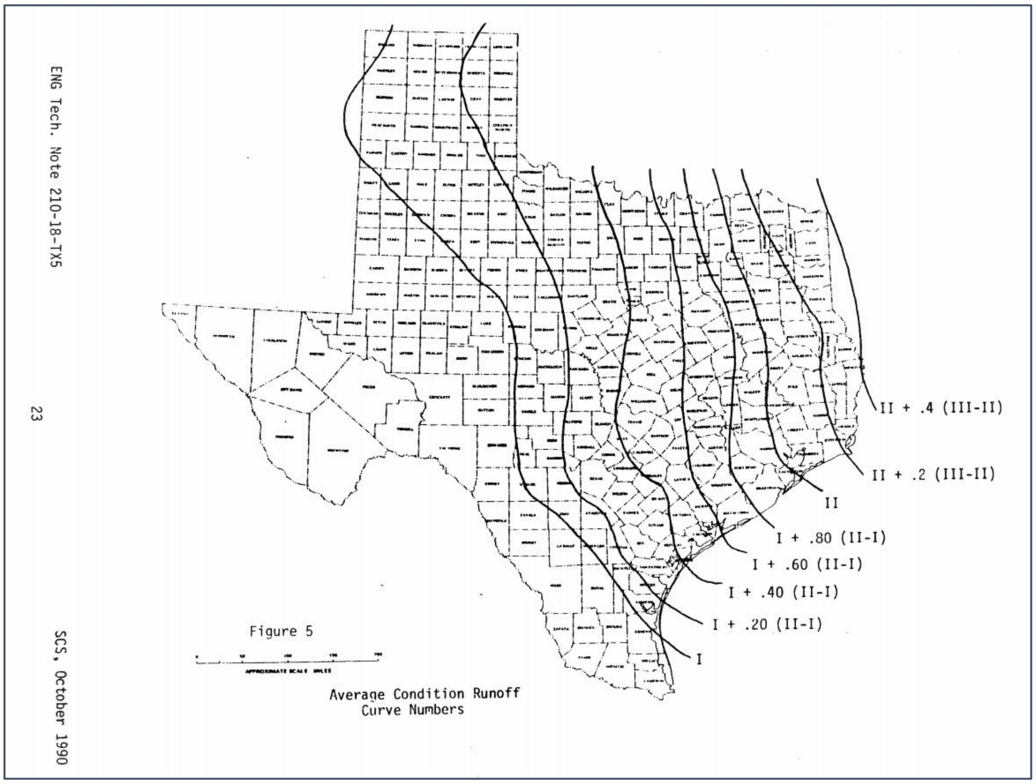


Figure 19: Typical Antecedent Moisture Conditions in Texas

Since the Middle Colorado watershed resides within the transition zone from AMC I to AMC II, a weighted AMC between AMC I and AMC II was used to compute the CNs for the next iteration of model runs. Based on the watershed's location, a weighted average of 70% AMC I and 30% AMC II was assumed to calculate the weighted CNs for model domains 0604_A7 and 0606_A9. Use of weighted CN values significantly improved the validation results for model domains 0604_A7 and 0606_A9.

A summary of the parameter adjustments made during the validation task is shown in Table 19.

Table 19: Summary of Parameter Adjustments Made During Validation in the Middle Colorado Watershed

Model Domain	CN Adjustment	Overland n Adjustment	Channel n Adjustment	Number of Validation Locations	Pass	Fail
0601_A1	Reduced by 10% from AMC II	No change (Baseline n)	Raised to 0.045	8	7	1
0601_A2	Reduced by 10% from AMC II	No change (Baseline n)	Raised to 0.045	10	9	1
0602_A3	Reduced by 10% from AMC II	No change (Baseline n)	Raised to 0.045	13	10	3
0602_A4	Reduced by 10% from AMC II	No change (Baseline n)	Raised to 0.045	12	8	4

Model Domain	CN Adjustment	Overland n Adjustment	Channel n Adjustment	Number of Validation Locations	Pass	Fail
0603_A5	No change (Baseline AMC II)	No change (Baseline n)	Raised to 0.045	6	5	1
0603_A6	Reduced by 5% from AMC II	No change (Baseline n)	No change (0.04)	13	9	4
0604_A7	Weighted – 70% AMC I and 30% AMC II	No change Baseline (Baseline n)	Raised to 0.045	7	6	1
0605_A8	Reduced by 10% from AMC II	No change (Baseline n)	Main channel raised to 0.05	6	5	1
0606_A9	Weighted - 70% AMC I and 30% AMC II	No change (Baseline n)	Main channel raised to 0.05. Tribs raised to 0.045.	12	9	3
			Total	87	68	19

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.

At the three USGS gages in the Middle Colorado watershed where flow-frequency data were available, the following observations were made:

- At USGS gage 08136700 (Colorado River near Stacy, TX), the 1% BLE flow was 0.4% lower than the InFRM 1% estimate.
- At USGS gage 08138000 (Colorado River at Winchell, TX), the 1% BLE flow was 131% higher than the InFRM 1% estimate and slightly higher (3%) than the 1% plus estimate.
- At USGS gage 08147000 (Colorado River near San Saba, TX), the 1% BLE flow was 185% higher than the InFRM 1% estimate and 60% higher than the 1% plus estimate.

Table 20 includes more details about how the BLE flows compared to the flows computed by the WHA gage flow-frequency analysis.

Table 20: Comparison of 1% BLE and Gage Flows along the Colorado River in the Middle Colorado Watershed

Gage ID	Location	Computed Area (mi^2)	BLE 1% Flow	InFRM Bulletin 17C Analysis Gage Flows (cfs)			% Difference
				1% Minus	1%	1% Plus	BLE Vs. Gage
08136700	Colorado River near Stacy, TX	24,193	30,193	11,700	30,300	160,000	-0.4
08138000	Colorado River at Winchell, TX	25,176	102,207	32,100	44,200	99,200	131
08147000	Colorado River near San Saba, TX	31,217	230,518	57,400	80,900	145,000	185
				Alternate Analysis 115,000*	Alternate Analysis 158,000*	Alternate Analysis 254,000*	46

* See Subsection 1.2.8 and Appendix B for details regarding the two analyses completed for USGS gage 08147000. The WHA concluded the initial analysis is more accurate

USGS gage 08138000 (Colorado River at Winchell, TX) is located near the downstream end of domain 0604_A7. The drainage area at this gage is 25,176 mi^2, which includes 1,314 mi^2 from the Middle Colorado watershed and 23,662 mi^2 upstream of O. H. Ivie Reservoir, where the Colorado River enters the watershed.

Gage 08138000 is near the downstream end of domain 0605_A7, so roughly 7 different domains drain to this gage. These domains are small enough that the Atlas 14 point rainfall totals applied in each domain did not need to be reduced using areal-reduction factors. The BLE peak flows in the tributaries in these domains (i.e., the streams other than the Colorado River) are reasonable since there is good agreement with the regression flows at many locations. However, along the Colorado River, as the drainage area accumulates as flow moves downstream, the runoff volumes in the river start to become unrealistically high. This is happening because the watershed is large enough that it is not realistic to assume that the point rainfall totals in each domain will fall across the entire watershed at once. Although techniques such as a joint probability analysis or an elliptical rainfall distribution could have been applied to reduce the volumes along the Colorado River, those approaches were beyond the scope of this BLE project and were not applied.

Figure 20 provides an illustration of the 1% inflow hydrographs that enter domain 0605_A7 from domains 0602_A4 (green) and 0603_A6 (orange) and the resulting 1% flow hydrograph at the USGS gage (gold). This figure shows that the rainfall over the local watershed drives the first peak, which controls the maximum flows and WSELs along Colorado River at the gage. The second peak in the hydrograph at the gage represents the arrival of the outflows from the O. H. Ivie Reservoir. This peak arrives much later than the peak caused by the local rainfall, and it does not control the maximum flows or WSEL at the gage.

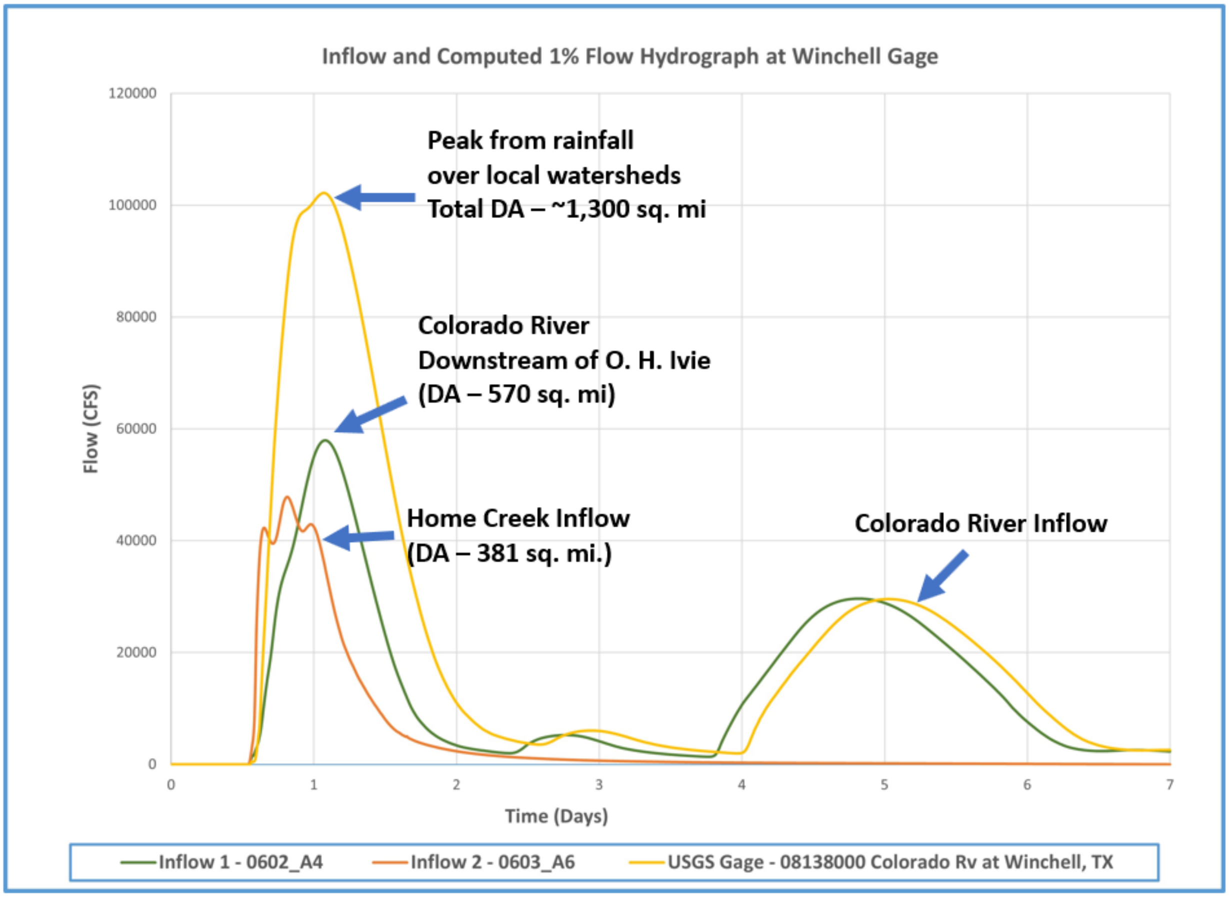


Figure 20: Inflows and Computed 1% Peak Flows at USGS Gage 08138000 (Winchell)

USGS gage 08147000 (Colorado River near San Saba, TX) is located at the downstream end of domain 0606_A9. It is the most downstream gage on the Colorado River in this HUC-8 watershed. In addition to including all of the Middle Colorado watershed and the watersheds contributing to the O. H. Ivie reservoir (~24,000 sq. mi), the gage's drainage area also includes the Brady watershed (HUC-8 12090110), the San Saba watershed (HUC-8 12090109), the Jim Ned watershed (HUC-8 12090108), and the Pecan Bayou watershed (HUC-8 12090107).

For the Middle Colorado 1% BLE simulation, three inflows were applied to domain 0606_A9, one from the San Saba River (which included the Brady watershed), one from Pecan Bayou (which included the Jim Ned watershed), and one from the Colorado River. The inflows from the San Saba River and Pecan Bayou were available in other BLE studies AtkinsRéalis had completed for the TWDB. The 1% inflow from the San Saba River was approximately 245,000 cfs, the 1% inflow from Pecan Bayou was roughly 40,000 cfs, and the 1% inflow from the Colorado River was approximately 93,000 cfs. Furthermore, the BLE model for domain 0606_A9 received 1% local rainfall as an additional hydrologic input. The combined peak 1% BLE flow at the gage was approximately 230,000 cfs. See Figure 21 for these inflow and outflow hydrographs. When these hydrographs combine at the outlet of the Middle Colorado watershed, they produce high flows and high volumes at the gage. As explained in the previous paragraphs, assuming that uniform rainfall occurs over the entire watershed at once is unrealistic for large rivers such as the Colorado River; therefore, peak flow rates and volumes along portions of the Colorado River are overestimated in this BLE study. Although other approaches such as the application of an elliptical rainfall distribution or a joint probability analysis could have been applied to reduce the volumes in the Colorado River, those approaches were beyond the scope of this BLE project and were not applied. Even though the flows were overpredicted along portions of the main steam of the Colorado River, the flows estimated along the river's tributaries were not overestimated and align well with regression flows.

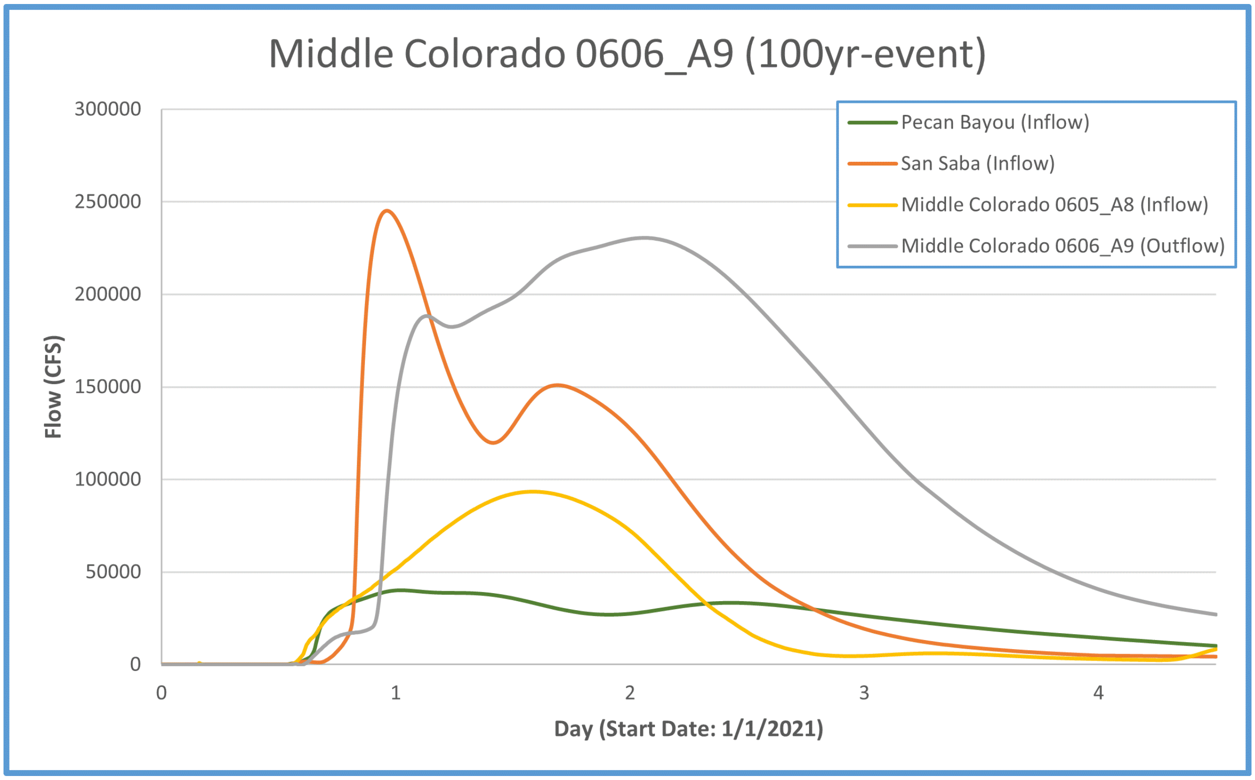


Figure 21: Comparison of inflow and outflow hydrographs for domain 0606_A9

The model overview and results spreadsheet (*MidCo_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 are also available on the validation location maps in the model overview and results spreadsheet for each domain.

See Figure 22 and Table 21 for a summary of the 1% validation results at the validation points throughout the Middle Colorado watershed. The model validation for this watershed was achieved by adjusting the Curve Numbers, the Manning's n values, and the AMCs. No aerial reduction factors were applied to the precipitation data for any of the model domains.

There were no effective detailed studies in the Middle Colorado HUC-8 watershed, so the computed BLE WSELs could not be compared to the WSELs in any effective studies.

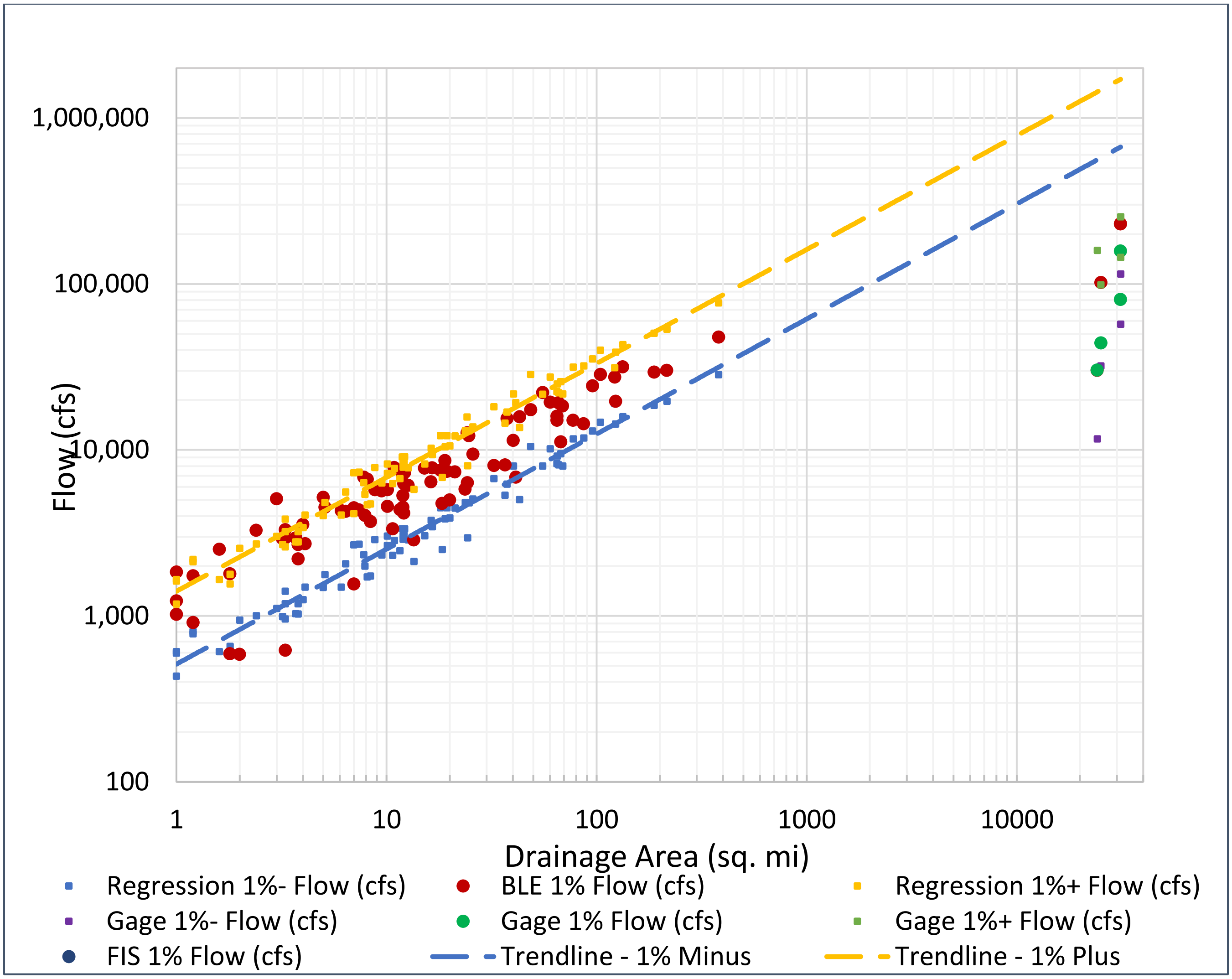


Figure 22: Computed Flows vs Drainage Areas for Select 1% BLE Flows, 1% Gage Flows, and 1% Regression Flows

Table 21: 1% Peak Flow Validation Results for the Middle Colorado 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 0601_A1										
Pt 1	Grape Creek	11.9	3352	5,525	9,104	7,129	-	-	-	-
Pt 2	Grape Creek	1.0	435	717	1,182	1,024	-	-	-	-
Pt 3	Elm Creek	41.3	7,108	11,713	19,304	6,850	-	-	-	-
Pt 4	Elm Creek	16.5	3,455	5,693	9,383	7,812	-	-	-	-
Pt 5	Little Grape Creek	4.0	1,255	2,068	3,408	3,559	-	-	-	-
Pt 6	Grape Creek	32.5	6,725	11,082	18,263	8,083	-	-	-	-
Pt 7	Spring Creek	1.0	599	987	1,626	1,231	-	-	-	-
Pt 8	Unnamed Creek	3.3	1,410	2,324	3,830	2,961	-	-	-	-
Domain 0601_A2										
Pt 1	West Fork Mustang Creek	8.8	2,888	4,760	7,844	5,771	-	-	-	-
Pt 2	East Fork Mustang Creek	25.8	5,074	8,362	13,780	9,441	-	-	-	-
Pt 3	Unnamed Creek	3.8	1,029	1,696	2,796	2,207	-	-	-	-
Pt 4	Unnamed Creek	6.1	1,496	2,466	4,064	4,300	-	-	-	-
Pt 5	Mustang Creek	133.4	15,881	26,172	43,132	31,698	-	-	-	-
Pt 6	Unnamed Creek	7.9	1,997	3,290	5,422	4,030	-	-	-	-

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)
Pt 7	Mustang Creek	77.4	11,669	19,230	31,691	15,115	-	-	-	-
Pt 8	Unnamed Creek	3.8	1,186	1,955	3,222	2,691	-	-	-	-
Pt 9	East Fork Mustang Creek	19.4	4,493	7,405	12,203	7,437	-	-	-	-
Outfall	08136700 Colorado River near Stacy, TX	24,193	-	-	-	30,193	11,700	30,300	160,000	-
Domain 0602_A3										
Pt 1	Salt Branch	4.1	1495	2,464	4,061	2,723	-	-	-	-
Pt 2	Salt Branch	12.1	3,049	5,026	8,282	6,284	-	-	-	-
Pt 3	Salt Creek	95.7	13,025	21,466	35,376	24,400	-	-	-	-
Pt 4	Salt Creek	7.4	2,710	4,466	7,361	4,365	-	-	-	-
Pt 5	Unnamed Creek	11.6	2,483	4,092	6,744	4,382	-	-	-	-
Pt 6	Salt Creek	40.2	8,014	13,208	21,766	11,419	-	-	-	-
Pt 7	Unnamed Creek	3.2	992	1,634	2,693	2,927	-	-	-	-
Pt 8	Bois d'Arc Creek	8.1	1,723	2,840	4,681	6,666	-	-	-	-
Pt 9	Mercer Creek	7.8	2,340	3,857	6,356	6,857	-	-	-	-
Pt 10	Panther Creek	64.9	9,203	15,166	24,993	16,016	-	-	-	-
Pt 11	Little Panther Creek	16.3	3,783	6,235	10,275	6,427	-	-	-	-

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)
Pt 12	Unnamed Creek	10.1	2,663	4,389	7,233	5,772	-	-	-	-
Pt 13	Unnamed Creek	23.7	4,825	7,952	13,105	5,814	-	-	-	-
Domain 0602_A4										
Pt 1	Unnamed Creek	1.6	610	1,006	1,658	2,525	-	-	-	-
Pt 2	Bull Creek	9.5	2,336	3,850	6,345	5,667	-	-	-	-
Pt 3	Unnamed Creek	3.3	962	1,586	2,614	3,312	-	-	-	-
Pt 4	Unnamed Creek	3.7	1,032	1,701	2,803	2,961	-	-	-	-
Pt 5	Unnamed Creek	12.7	2,884	4,753	7,833	6,137	-	-	-	-
Pt 6	Bull Creek	36.7	5,358	8,830	14,552	8,127	-	-	-	-
Pt 7	Bull Creek	64.8	8,282	13,648	22,492	15,101	-	-	-	-
Pt 8	Saddle Creek	6.4	2,062	3,398	5,600	4,278	-	-	-	-
Pt 9	West Fork Big Elm Creek	12.2	3,361	5,540	9,129	7,326	-	-	-	-
Pt 10	Saddle Creek	24.7	4,812	7,931	13,070	12,170	-	-	-	-
Pt 11	Saddle Creek	37.5	6,233	10,272	16,928	15,468	-	-	-	-
Pt 12	Elm Creek	55.4	8,003	13,189	21,735	22,153	-	-	-	-
Domain 0603_A5										
Pt 1	Home Creek	104.3	14717.87	24,255	39,972	28,501	-	-	-	-
Pt 2	Home Creek	60.2	10,161	16,746	27,597	19,454	-	-	-	-
Pt 3	Home Creek	24.2	5,830	9,608	15,834	12,672	-	-	-	-

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)
Pt 4	Red Bank Creek	10.9	2,860	4,713	7,767	7,856	-	-	-	-
Pt 5	Red Bank Creek	1.2	782	1,288	2,123	1,746	-	-	-	-
Outfall	Home Creek	187.9	18,594	30,642	50,499	29,507	-	-	-	-
Domain 0603_A6										
Pt 1	Mukewater Creek	69.0	8,017	13,211	21,772	18,453	-	-	-	-
Pt 2	Home Creek	216.0	19,705	32,474	53,518	30,139	-	-	-	-
Pt 3	Camp Creek	7.0	1,524	2,511	4,138	1,561	-	-	-	-
Pt 4	Mukewater Creek	122.0	19,062	11,567	31,415	27,529	-	-	-	-
Pt 5	Hay Creek	20.0	3,900	6,427	10,591	4,996	-	-	-	-
Pt 6	Mukewater Creek	66.0	8,146	13,424	22,123	19,300	-	-	-	-
Pt 7	Unnamed	5.0	1,485	2,447	4,032	5,194	-	-	-	-
Pt 8	East Fork Mukewater Creek	2.0	944	1,556	2,564	587	-	-	-	-
Pt 9	Unnamed	1.0	610	1,005	1,657	1,843	-	-	-	-
Pt 10	Mukewater Creek	12.0	3,051	5,028	8,286	5,322	-	-	-	-
Pt 11	Dry Creek	3.0	1,110	1,830	3,016	5,094	-	-	-	-
Pt 12	Mukewater Creek	19.0	3,859	6,359	10,479	8,650	-	-	-	-
Outfall	Home Creek	381.0	28,434	46,859	77,224	47,869	-	-	-	-

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)
Domain 0604_A7										
Pt1	Unnamed	1.2	808	1,332	2,196	913	-	-	-	-
Pt2	Unnamed	7.0	2,685	4,422	7,292	4,485	-	-	-	-
Pt3	West Fork Cow Creek	10.1	3,039	5,011	8,258	4,574	-	-	-	-
Pt4	Cedar Creek	18.1	4,502	7,420	12,228	7,563	-	-	-	-
Pt5	Cow Creek	48.6	10,537	17,365	28,618	17,473	-	-	-	-
Pt6	Rough Branch	67.6	9,500	15,657	25,803	11,210	-	-	-	-
Pt7	08138000 Colorado River at Winchell, TX	25,179	-	-	-	102,207	32,100	44,200	99,200	-
Domain 0605_A8										
Pt 1	Unnamed	5.1	1,777	2,929	4,827	4,516	-	-	-	-
Pt 2	Unnamed	12.1	3,179	5,240	8,635	4,178	-	-	-	-
Pt 3	Antelope Creek	21.2	4,480	7,386	12,168	7,371	-	-	-	-
Pt 4	Indian Creek	43.0	5,041	8,307	13,690	15,844	-	-	-	-
Pt 5	Clear Creek	86.8	11,825	19,488	32,118	14,415	-	-	-	-
Pt 6	Clear Creek	123.2	14,341	23,634	38,949	19,691	-	-	-	-
Domain 0606_A9										
Pt 1	Browns Branch	1.8	656	1,082	1,783	1,799	-	-	-	-
Pt 2	Rocky Creek	3.3	1,187	1,956	3,224	621	-	-	-	-
Pt 3	Nabors Creek	12.0	2,903	4,783	7,883	4,515	-	-	-	-
Pt 4	Bull Creek	15.2	3,043	5,015	8,265	7,767	-	-	-	-

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)
Pt 5	Prescott Creek	10.7	2,319	3,822	6,299	3,356	-	-	-	-
Pt 6	Unnamed	1.8	576	949	1,564	592	-	-	-	-
Pt 7	Cottonwood Creek	24.3	2,965	4,887	8,053	6,365	-	-	-	-
Pt 8	Jerrys Branch	13.5	2,137	3,521	5,803	2,872	-	-	-	-
Pt 9	Jerrys Branch	18.4	2,521	4,154	6,846	4,764	-	-	-	-
Pt 10	Spring Creek	8.4	1,745	2,879	4,744	3,710	-	-	-	-
Pt 11	North Fork Bull Creek	2.4	1,004	1,654	2,725	3,277	-	-	-	-
Outfall/US GS Gage	08147000 Colorado River near San Saba, TX	31,217	-	-	-	230,518	57,400 Alternate Analysis 115,000*	80,900 Alternate Analysis 158,000*	145,000 Alternate Analysis 254,000*	-

* See Subsection 1.2.8 and Appendix B for details regarding the two analyses completed for USGS gage 08147000. The WHA concluded the initial analysis is more accurate.

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 23, 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.

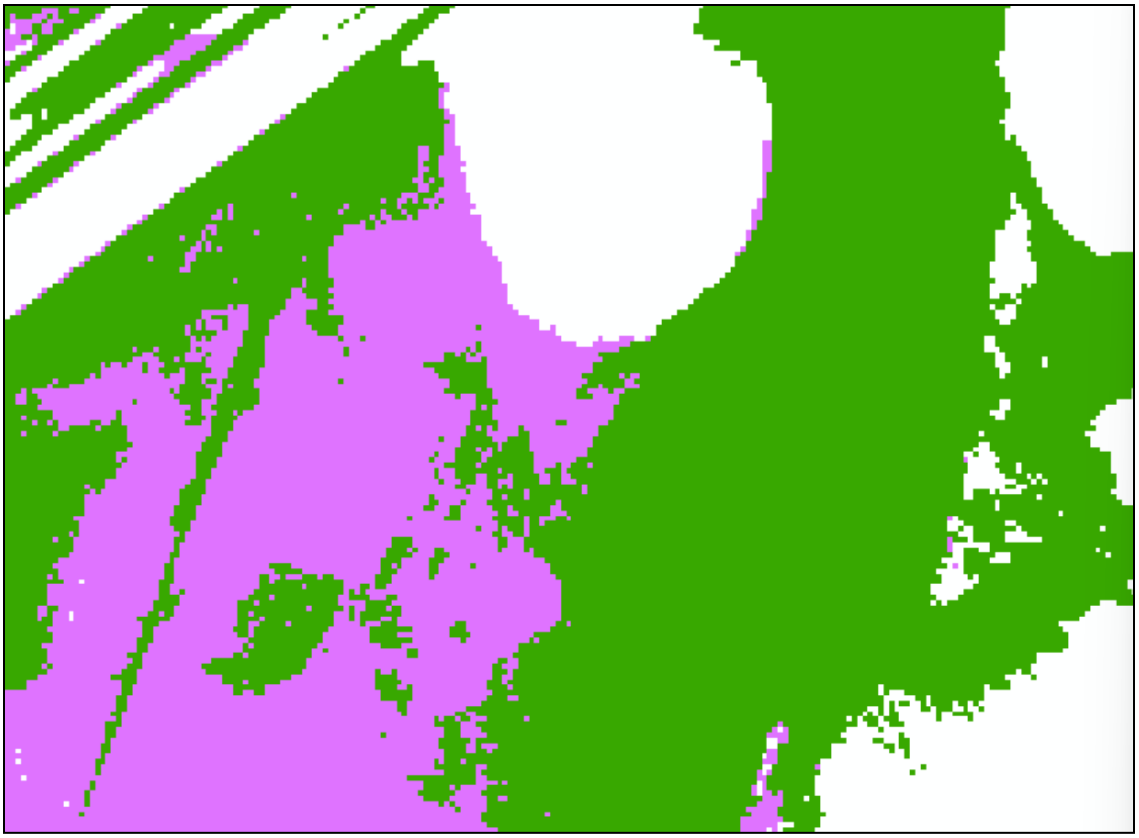


Figure 23: Example of overlapping mapping along a model domain boundary

Figure 24 shows what the difference raster looks like for the area in Figure 23. 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 23 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.

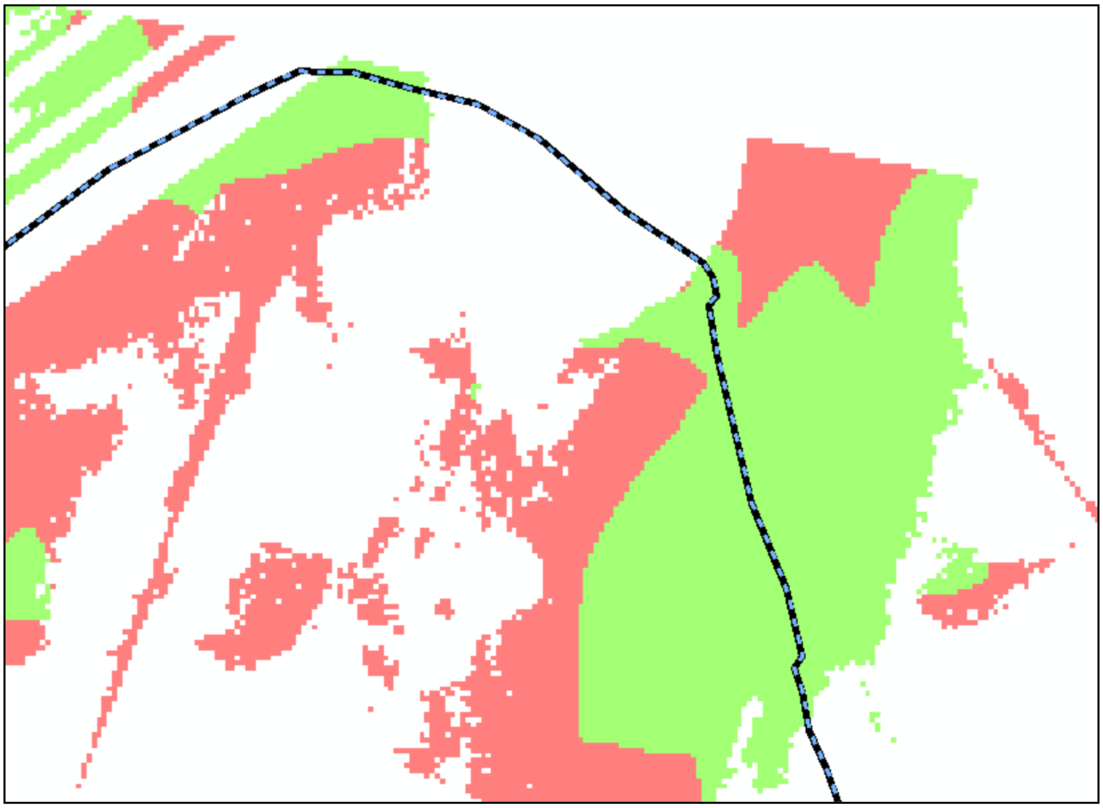


Figure 24: WSEL difference raster and split line for the overlap area

- The merged raw raster grids included connected and disconnected areas of potential flood hazard. To reduce the extent of these disconnected flood areas, process the rasters to filter and remove disconnected small, shallow areas of flooding. To do this, apply the TWDB's mapping threshold matrix to remove shallow depths, small areas of flood risk, and disconnected areas. According to Figure 3.1 in TWDB's 2D BLE guidelines, the watershed falls in the Inland Areas of Texas. Therefore, disconnected areas were removed if they met ***both*** of the criteria in Table 22.

Table 22: Inland mapping threshold matrix

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

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

- Convert each WSEL raster to a floodplain polygon.
- Many ponding areas were present throughout the watershed. Due to the large mesh cells used in the 2D modeling, the extent of the smaller ponds was not always mapped properly in the model output. To properly identify the flood hazard in these areas, transfer the ponding extents available in the National Hydrography Dataset into the 1% and 0.2% floodplain polygons. Do not transfer them into the 10% floodplain polygon.
- If any dams are present that have been catalogued by the National Inventory of Dams and include a normal pool storage of 200 acre-feet or more, review the spillway mapping along each dam. If the 1% and/or the 0.2% model output did not include any flooding along the spillway, manually revise the floodplain polygon(s) to flood the spillway.
- Add waterbodies of lake and reservoir inundation areas of 20 acres or greater to the WTR-LN and FLD_HAZ_AR feature classes. The National Inventory of Dams was used to identify dams with inundation areas greater than 20 acres. The areas of inundation were computed by measuring the areas of the normal pools visible on the aerial photography.
- Clean up each polygon by simplifying it and smoothing it. The intent of the simplify and smooth processes is to eliminate unnecessary/erroneous vertices, remove rough edges, and reduce the size and complexity of the raw floodplain polygons. Apply professional judgement to determine the appropriate tolerance for simplifying and smoothing the floodplain polygons. Set initial thresholds to 5 feet for simplifying and 25 feet for smoothing.
- Merge the 1%, and 0.2% ACE polygons into one feature class. Keep the 10% ACE polygon as a separate feature class.
- The extents of the final depth and WSEL grids must match the extents of the flood inundation polygons. Because of the clipping and smoothing procedures applied to the floodplain polygons, they will no longer match the extents of the rasters. Clip the depth and WSEL grids to each respective flood frequency inundation polygon to align the extents of the rasters with the extents of the floodplain polygons.
- Clip the rasters and the floodplain polygons using the HUC-8 watershed boundary.

2.0 Challenges

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

Crossing of 1% Plus and 0.2% AEP Profiles

As discussed in the reservoir modeling section, the peak flows in the BLE study along the Colorado River that exit the O. H. Ivie Reservoir are based on the InFRM's WHA gage analysis of USGS gage 08136700 (Colorado River near Stacy, TX). The 1% plus discharge computed by the gage analysis is higher than the 0.2% discharge as shown in Table 23.

Table 23: InFRM Gage Analysis Summary for Gage 08136700

InFRM WHA Gage Analysis	
AEP	**Peak Discharge (cfs)**
10%	5,540
4%	12,000
2%	19,600
1%	30,300
0.2%	71,500
1% plus	160,000*
1% minus	11,700*

* 1% plus and 1% minus flows are from the gage's 95% confidence interval. Flows at the 84% confidence interval were not available.

The 0.2% point rainfall totals in the watershed are higher than the 1% plus point rainfall totals. As a result, the flow and stage hydrographs for the 1% plus and 0.2% AEP events along the Colorado River cross during the model run. In the domains immediately downstream of the dam, the runoff flows from the local watershed are significantly less than the Colorado River inflows. Therefore, the peak WSELs along the river are driven by the river inflows, not the local precipitation runoff. See Figure 25, Figure 26, and Figure 27 for examples of crossing hydrographs at the outlets of domains 0601_A2, 0605_A8, 0606_A9, respectively.

As one moves downstream from domain 0601_A2 to domain 0605_A8 to domain 0606_A9, the precipitation runoff volume and the drainage area increase, and eventually the precipitation runoff discharges exceed the Colorado River inflow discharges from upstream.

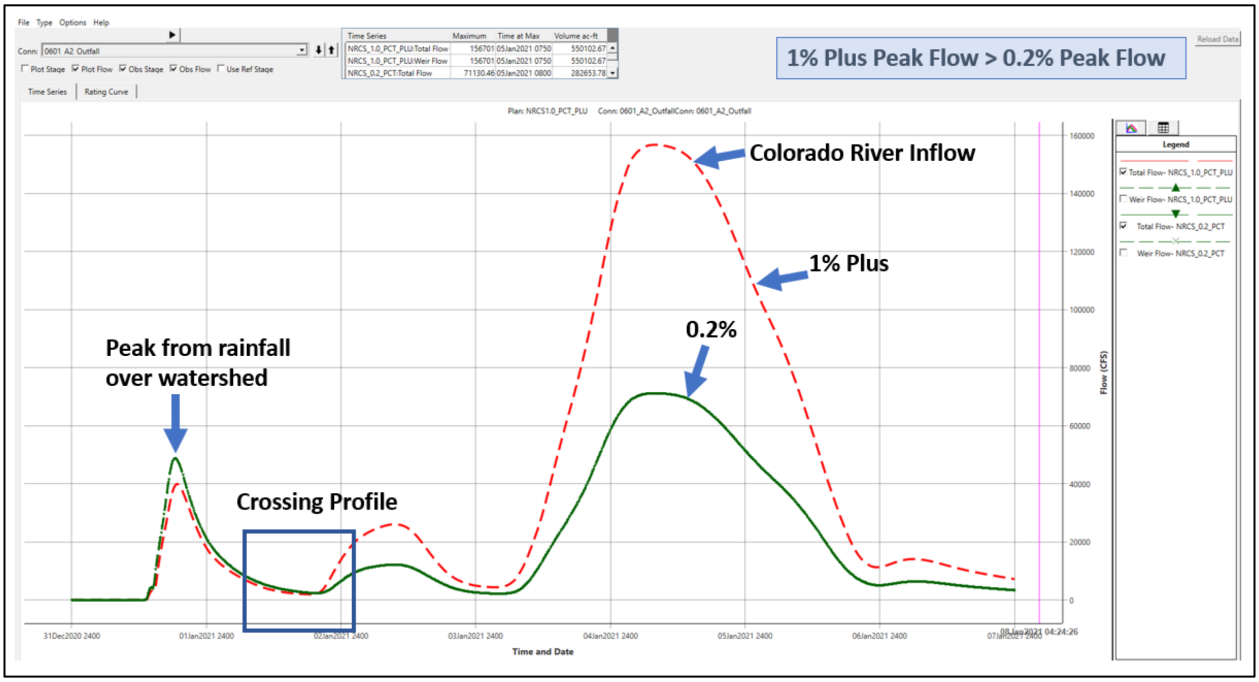


Figure 25: BLE Outflow Hydrographs for Domain 0601_A2

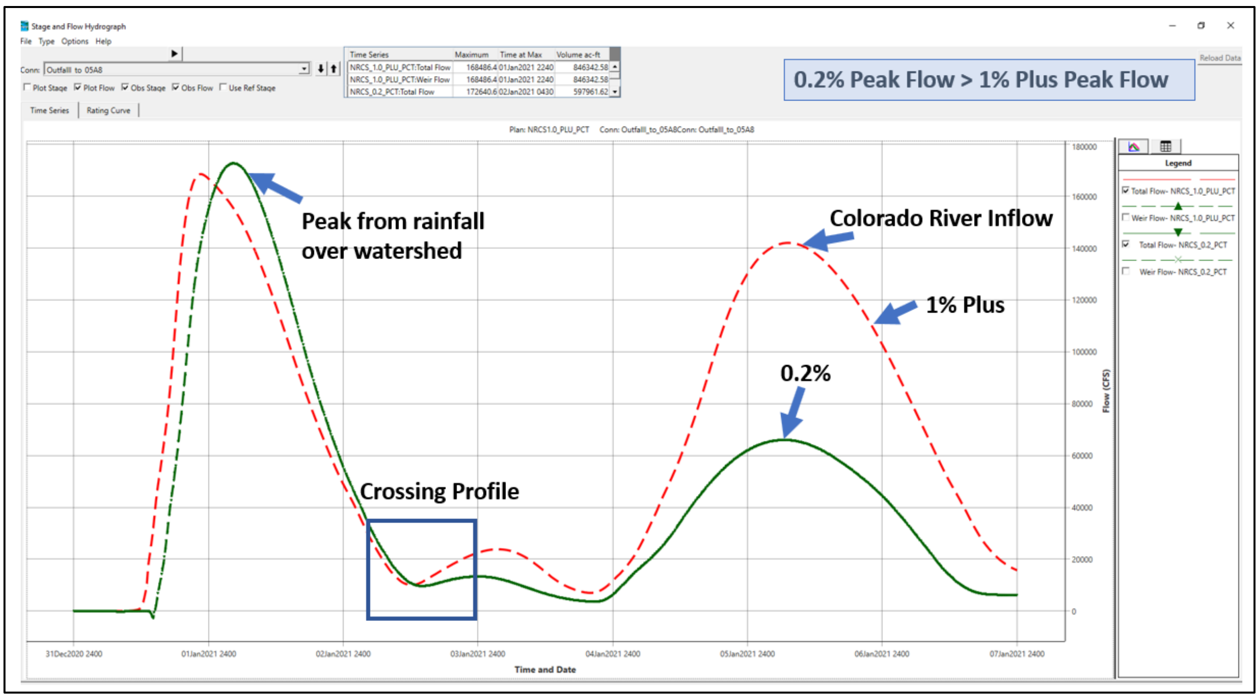


Figure 26: BLE Outflow Hydrographs for Domain 0605_A8

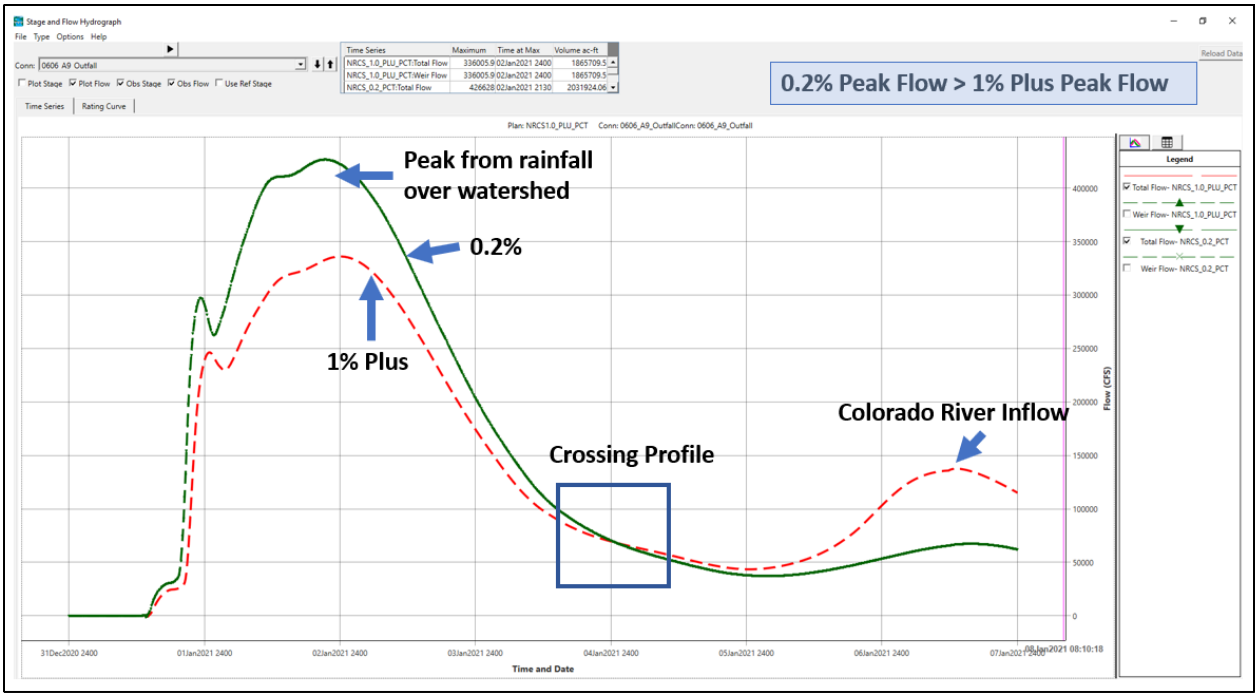


Figure 27: BLE Outflow Hydrographs for Domain 0606_A9

Modeling of O.H. Ivie Reservoir

The O. H. Ivie Reservoir is located at the confluence of the Colorado and Concho Rivers. Most of the reservoir is located within the Middle Colorado HUC-8 watershed, but the upper end of the reservoirs extends into the Middle Colorado-Elm and Concho HUC-8 watersheds. Modeling this reservoir was not a straight-forward process. See Subsection 1.2.5 for details regarding how the reservoir was modeled.

Balancing Flows between Small and Large Streams

The BLE models developed for the Middle Colorado 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.

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 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 28. The areas of cupping will not be removed or cleaned beyond the extents of the mapping cleanup process discussed herein. There is significant topographic relief throughout the Middle Colorado watershed. Therefore, cupping is prevalent throughout the BLE mapping.

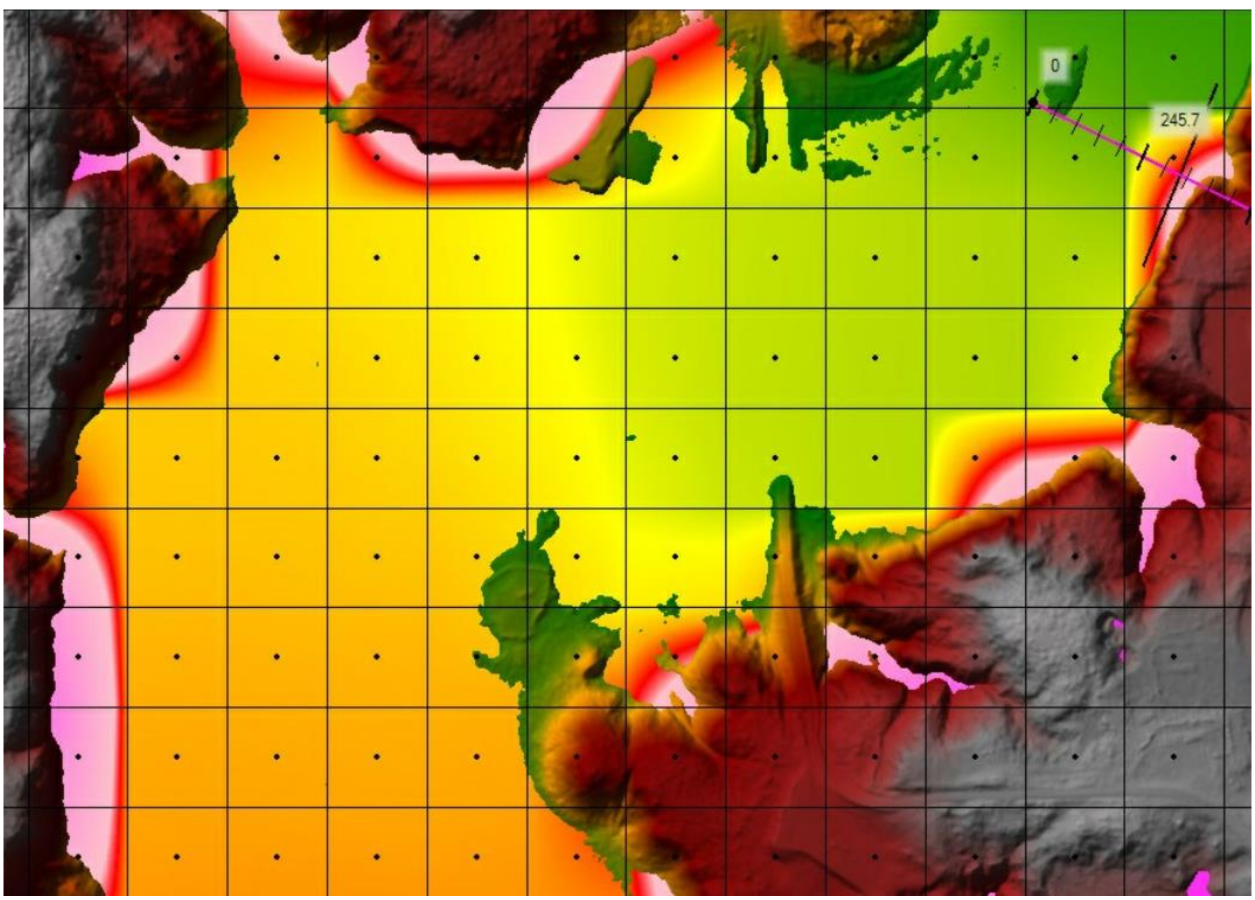


Figure 28: An Example of Cupping in 2D BLE Mapping

3.0 Results and Recommendations

The BLE floodplain mapping for the Middle Colorado watershed compared 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 Middle Colorado watershed has been included as Appendix A.

The BLE floodplains were compared with the effective floodplains in the Middle Colorado watershed. No digital mapping data was available in the National Flood Hazard Layer (NFHL) for the watershed. However, digitized effective floodplain mapping was available in a proprietary dataset developed by RMSI and acquired by AtkinsRéalis. The RMSI dataset included digital floodplain boundaries for Kimble and Sutton counties. A comparison of the digitized FEMA mapping with the BLE 1% boundaries revealed that the updated BLE floodplain boundaries were more defined than the effective floodplains. The BLE floodplains exhibited generally good agreement with the effective mapping, although occasionally the effective floodplains were wider while, at other times, the BLE floodplains were wider.

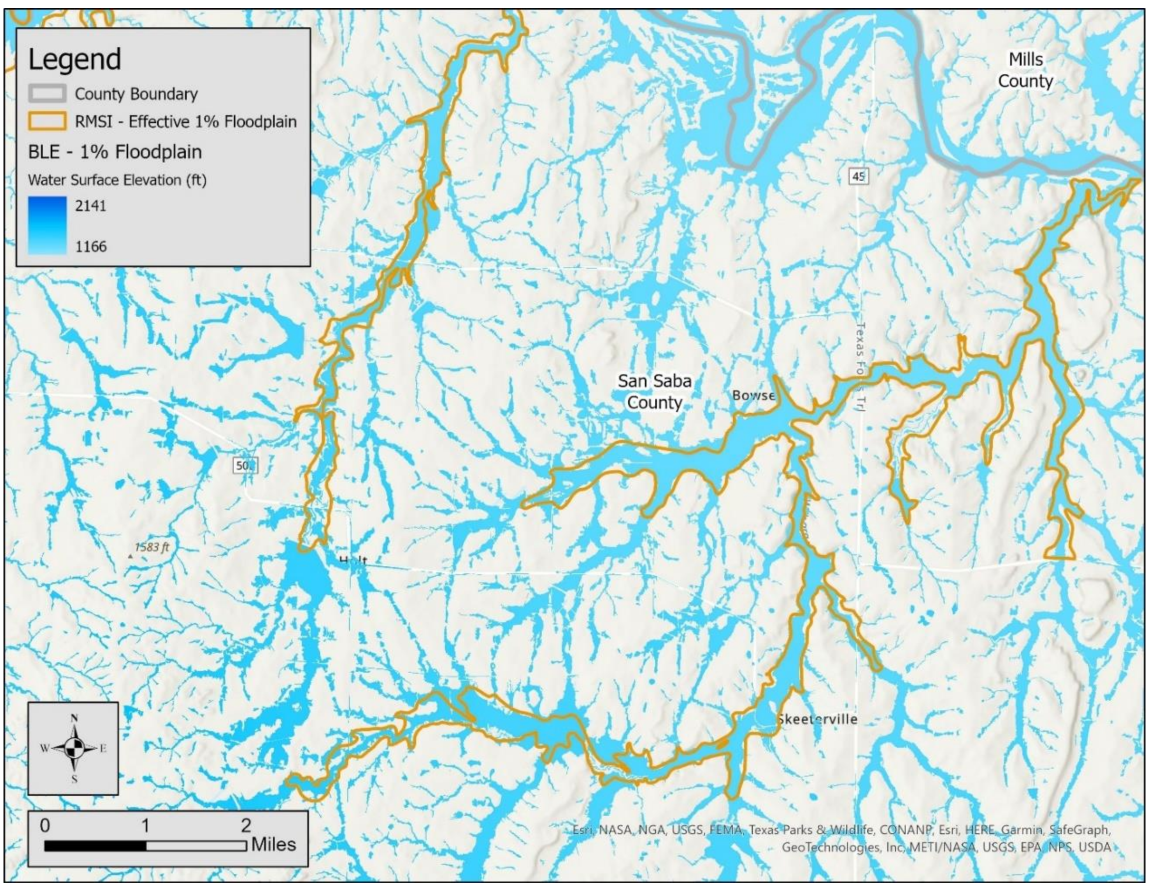


Figure 29: The Effective 1% Floodplain and the 1% BLE Floodplain in San Saba County, TX

Floodplain mapping for the Middle Colorado 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 Middle Colorado watershed were compared with the Fathom floodplain mapping. Figure 30 shows the 1% BLE mapping in blue with a transparency applied and the 1% Fathom mapping in black in the same area that is shown in Figure 29. 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.

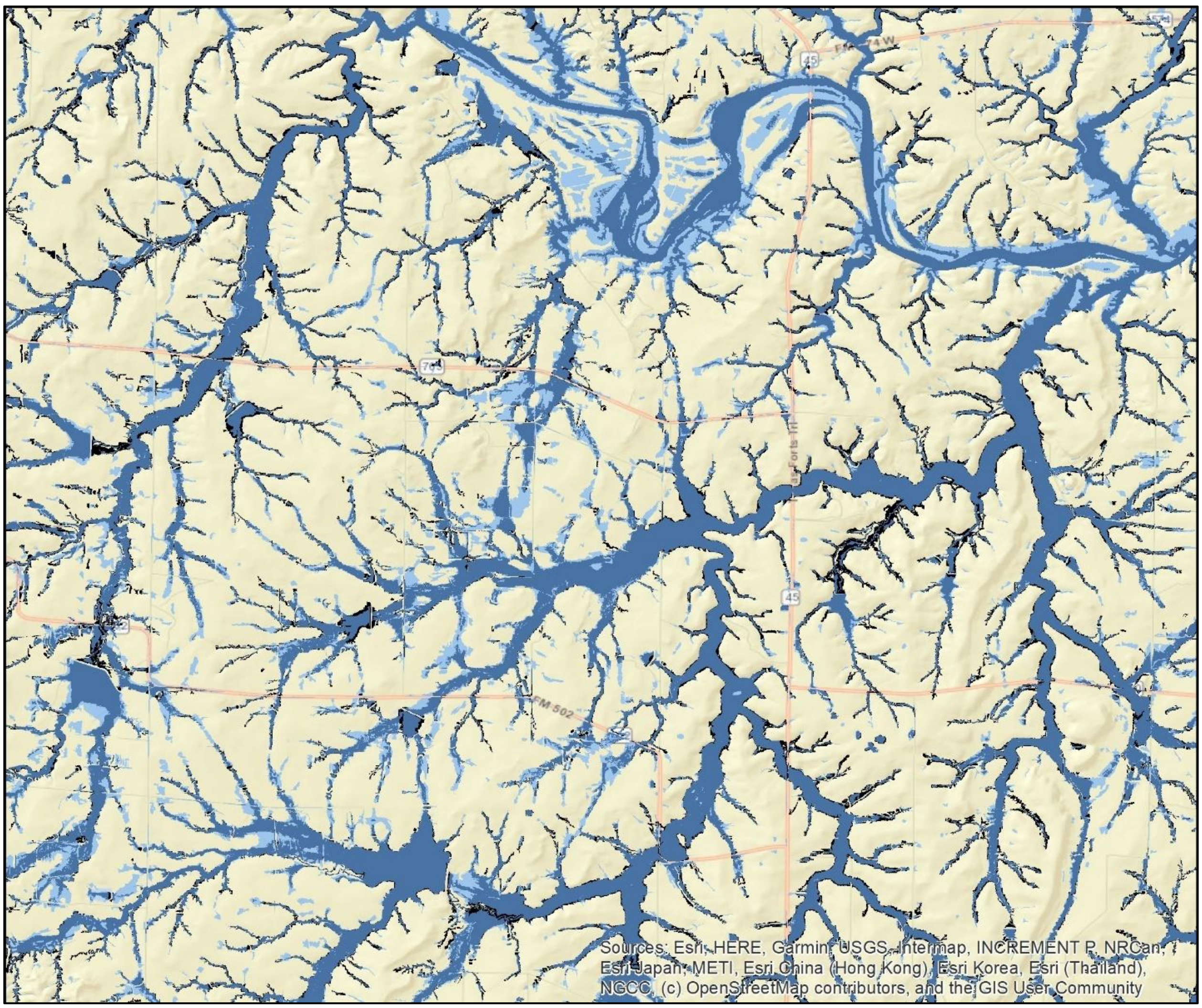


Figure 30: Comparison of 1% BLE mapping (light blue with transparency) with Fathom 1% mapping (black)

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

All of the Zone A streams (245.1 miles) in the Middle Colorado watershed were classified as “UNVERIFIED” 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 Middle Colorado 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 24: 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 for a smaller portion of the reaches (93.8 miles). The A4 check was set to fail for those reaches. The majority of the effective reaches, however, were model-backed (151.3 miles). The A4 check for those reaches was set to pass.

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 Middle Colorado BLE analysis.

The contour interval for the vertical tolerance was taken from the USGS 1:24,000-scale topographic maps of the Middle Colorado 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 26 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 Zone A studies in the Middle Colorado watershed study area has been updated. The total miles in each of these categories are summarized in Table 25 and illustrated on Figure 31. The findings from the Initial Assessment A5 are in Table 26.

Table 25: Zone A Validation Results

Validation Status	CNMS Validation Status	CNMS Project Start	CNMS Post-BLE Assessment
VALID	NVUE COMPLIANT	0	0
	BEING STUDIED	0	0.6
UNVERIFIED	BEING STUDIED	0	244.5
	TO BE STUDIED	239.1	0

Table 26: BLE Comparison Results

HUC-12 Watershed		Total FBS Points	Fail	Pass	% Pass	BLE Comparison Pass? (>85%)
Watershed Name	HUC-12 ID					
Corn Creek-Colorado River	120901060404	861	657	204	23.69	Fail
Mukewater Creek	120901060307	87	36	51	58.62	Fail
Headwaters Wilbarger Creek	120901060506	1,760	808	952	54.09	Fail
East Fork Mukewater Creek	120901060306	1,367	299	1,068	78.13	Fail
Coggin Lake-Colorado River	120901060503	3,142	1,598	1,544	49.14	Fail
Red Bank Creek-Home Creek	120901060303	131	49	82	62.60	Fail
Antelope Creek-Colorado River	120901060505	1,138	492	646	56.77	Fail
Headwaters Clear Creek	120901060502	2,317	725	1,592	68.71	Fail
Rough Creek-Indian Creek	120901060504	3,277	1,580	1,697	51.79	Fail
Headwaters Grape Creek	120901060101	74	7	67	90.54	Pass
Deep Creek-Colorado River	120901060406	2,178	1,287	891	40.91	Fail
Wilbarger Creek-Colorado River	120901060507	1,291	535	756	58.56	Fail
West Fork Clear Creek	120901060501	2,630	829	1,801	68.48	Fail
Loss Creek-Home Creek	120901060302	62	39	23	37.10	Fail
Horse Creek-Colorado River	120901060604	2,942	1,448	1,494	50.78	Fail

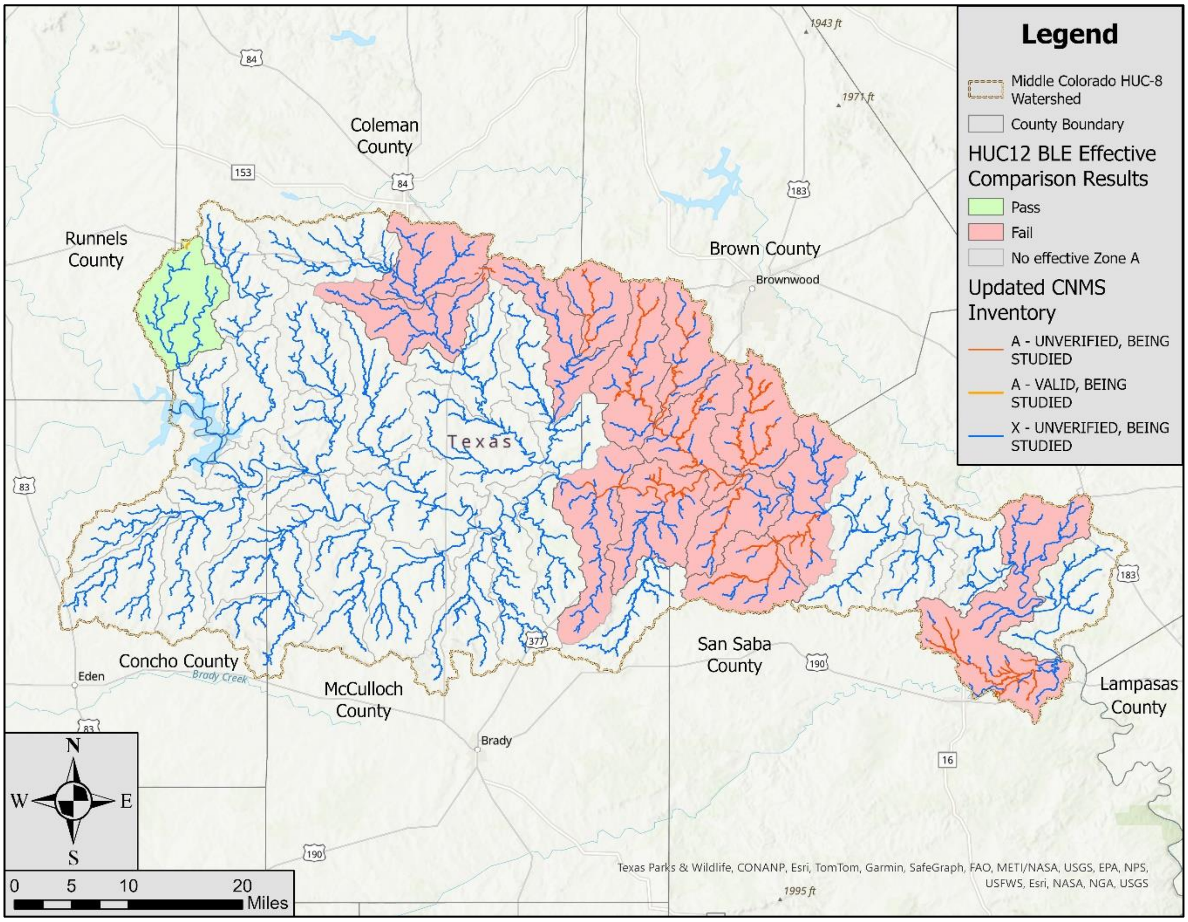


Figure 31: CNMS Validation Results

3.3 Flood Risk Analysis

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

Additional inputs for the analysis were as follows.

S_AOMI_Ar

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

Areas typically identified by this feature class include:

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

- Intersections of significant streams with major roadways – Since structures were not explicitly included in the BLE models, these areas were identified as areas where additional analysis may be useful for refining the outcomes of the BLE study.
- Floodplain mapping tie-ins along the HUC-8 watershed boundary – Along the HUC-8 watershed boundaries where AtkinsRéalis completed BLE assessments for both watersheds, the floodplain mapping includes smooth tie-ins across the watershed boundaries. Along those HUC-8 watershed boundaries where AtkinsRéalis did not study both watersheds, the mapping tie-ins could not be smoothed since the BLE floodplain mapping in the neighboring watershed was not available. AoMIs were placed along these HUC-8 watershed boundaries to identify those tie-ins that potentially could be refined by a future modeling effort.

S_AOMI_Pt

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

Outputs from the analysis were as follows.

S_FRACT_Ar

This is the flood risk assessment polygon feature class. It is the output for a flood level 2 analysis using Hazus Version 5.1, which is based on a 1% annual-chance depth grid. The calculated loss results from Hazus are stored in the polygon feature and are based on dasymetric census blocks. Dasymetric census blocks have had additional “undeveloped” land areas (primarily wetlands and forest) clipped out of the original census block boundaries based on USGS land use/land cover data. Loss values are reported in whole dollar amounts. See Table 27 below for a summary of the losses computed by Hazus.

L_Source_Cit

The data sources used for S_AOMI_Pt and AOMI_Ar are documented in the L_Source_Cit table.

Table 27: Hazus Results for the Middle Colorado Watershed

County	Full Replacement – Total Loss	Dollar Exposure (Replacement Value) - Buildings	Dollar Exposure (Replacement Value) - Contents
Brown County	$61,555,000	$403,237,000	$230,597,000
Coleman County	$19,242,000	$305,441,000	$177,250,000
Concho County	$4,592,000	$45,382,000	$24,165,000
McCulloch County	$9,345,000	$126,786,000	$72,462,000
Mills County	$20,614,000	$282,237,000	$196,937,000
Runnels County	$0	$521,000	$261,000
San Saba County	$14,282,000	$123,936,000	$68,083,000
Total	$129,630,000	$1,287,540,000	$769,755,000

4.0 References

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

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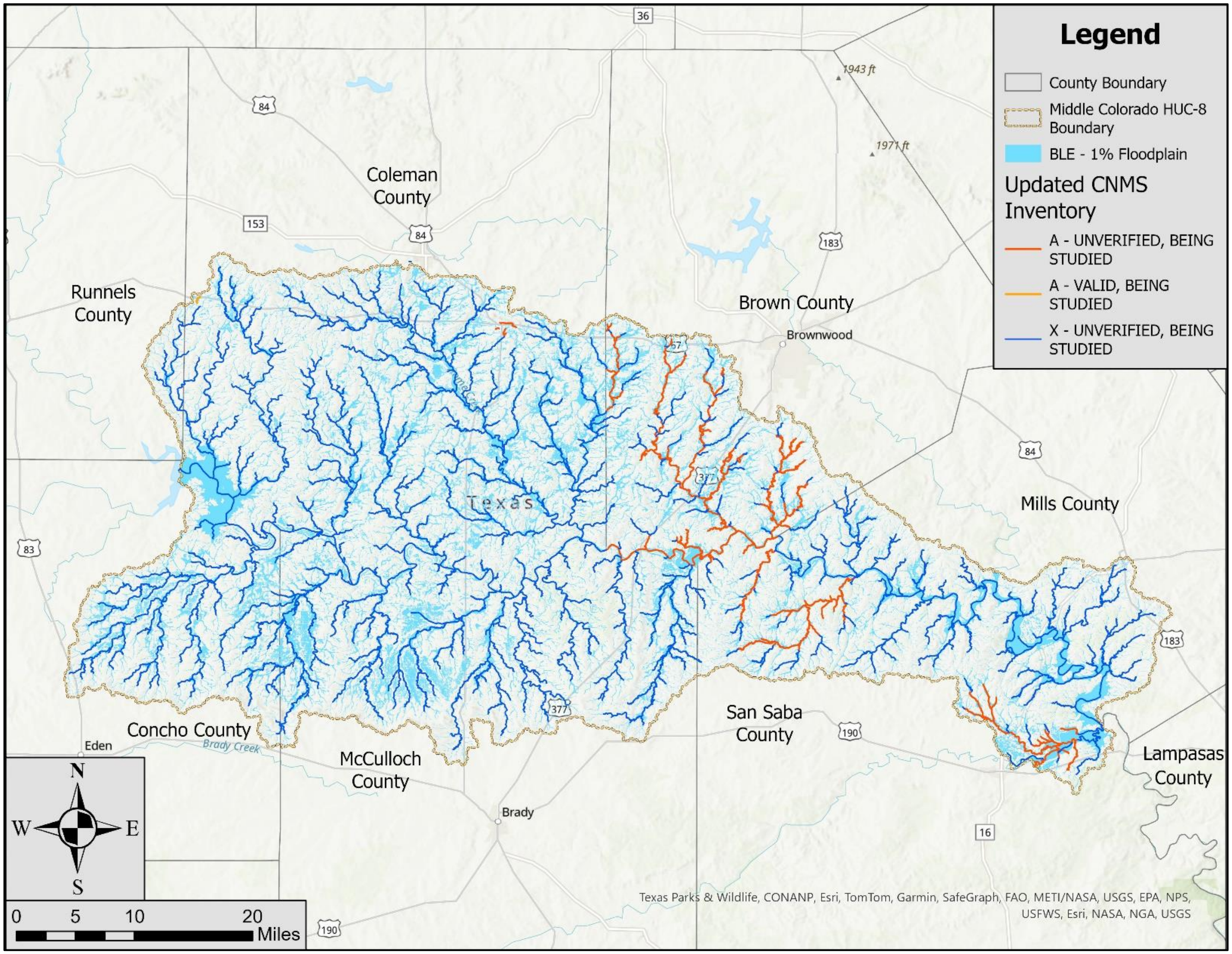
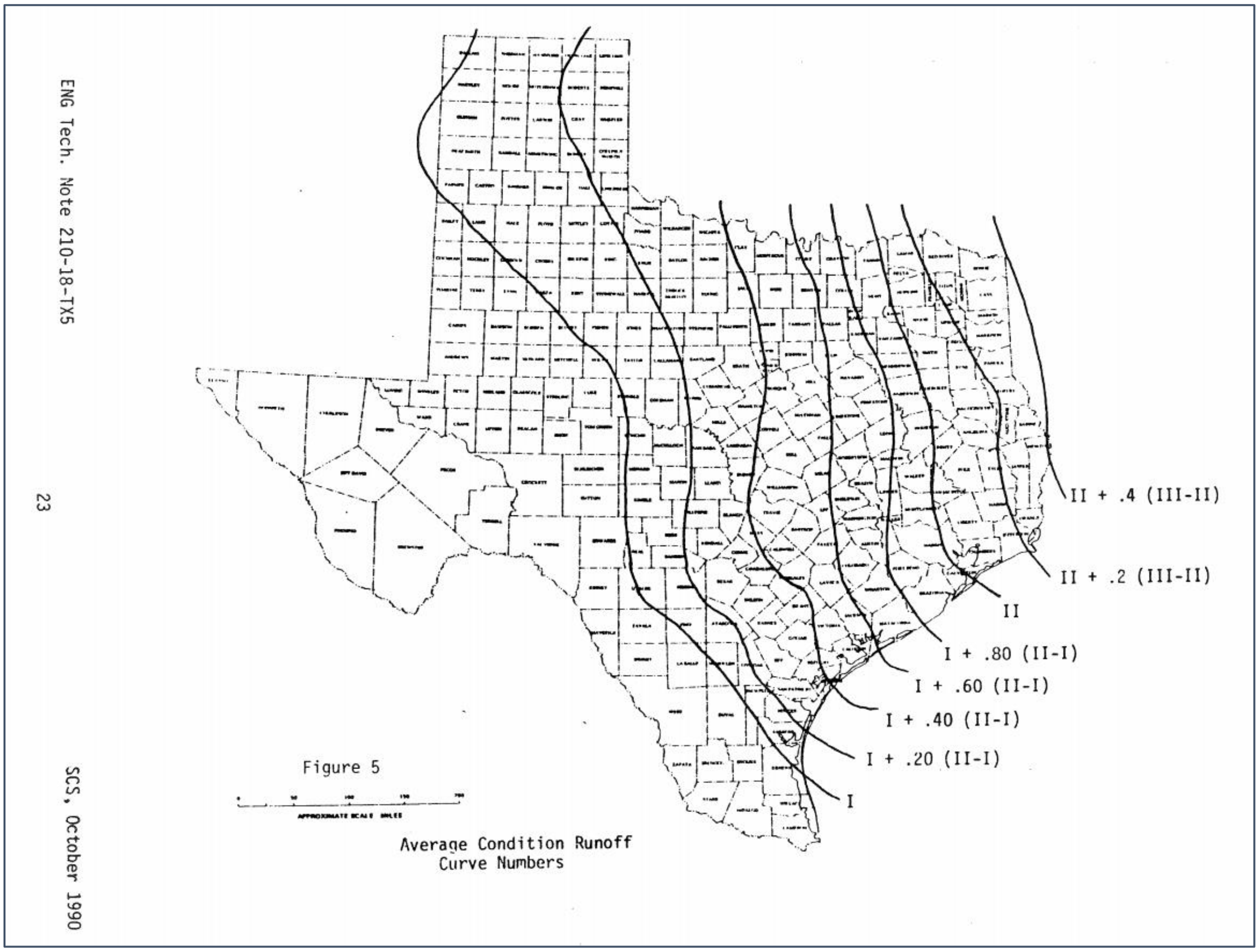
Appendix A: Base Level Engineering Results



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 Middle Colorado watershed.

- Page 23 from *Engineering Technical Note No. 210-18-TX5 - 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 62 to 65, 91 to 95, and 146 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 analyses for USGS gages 08136700 (Colorado River near Stacy, TX), 08138000 (Colorado River at Winchell, TX), and 08147000 (Colorado River near San Saba, TX).
- Pages 67 through 70 from Chapter 9 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 data for the O. H. Ivie Reservoir. The scalable hydrograph created by the USACE during a simulation of the flood of 1936 is shown in the figure below.