Evaluation of Subsidence Impacts in the Spring Creek Watershed

Technical Memorandum 2: Development of Hydrologic and Hydraulic Models for Subsidence Scenarios

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Technical Memorandum #2:

Development of Hydrologic and Hydraulic Models for Subsidence Scenarios

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List of Tables

List of Figures

Acronyms and Abbreviations

1D	:	*One-dimensional*
2D	:	*Two-dimensional*
AEP	:	*Annual Exceedance Probability*
Baseline	:	*Baseline without Future Development (2020)*
BDF	:	*Basin Development Factor*
DSS	:	*Data Storage System*
FEMA	:	*Federal Emergency Management Agency*
FIS	:	*Flood Insurance Study*
FM	:	*Farm to Market*
GIS	:	*Geographic Information System*
H&H	:	*Hydrologic and Hydraulic*
HCFCD	:	*Harris County Flood Control District*
HEC-HMS	:	*Hydrologic Engineering Center - Hydrologic Modeling System*
HEC-RAS	:	*Hydrological Engineering Center – River Analysis System*
H-GAC	:	*Houston-Galveston Area Council*
HGSD	:	*Harris-Galveston Subsidence District*
IH-45	:	*Interstate Highway-45*
LOMR	:	*Letters of Map Revision*
MBI	:	*Michael Baker International*
NFHL	:	*National Flood Hazard Layer*
NOAA	:	*National Oceanic and Atmospheric Administration*
PAD	:	*Protected Areas Database*
PCPM	:	*Policy Criteria and Procedure Manual*
QAQC	:	*Quality Assessment and Quality Control*
R	:	*Storage Coefficient*
RS	:	*River Station*
SA-2D	:	*Storage Area 2-dimensional*
SFD	:	*Subsidence with Future Development*
SJRA	:	*San Jacinto River Authority*
SWFD	:	*Subsidence without Future Development*
Tc	:	*Time of Concentration*
TSDN	:	*Technical Support Data Notebook*
USGS	:	*United States Geological Survey*
WSE	:	*Water Surface Elevation*

1 Introduction

1.1 Overview of the Study

Michael Baker International (MBI) is evaluating the impacts of future subsidence in the Spring Creek watershed for the Harris-Galveston Subsidence District (HGSD). The project aims to quantify flood risk and economic impacts attributable to future subsidence in the Spring Creek watershed. **Figure 1** shows the boundaries of the watershed and the study area.

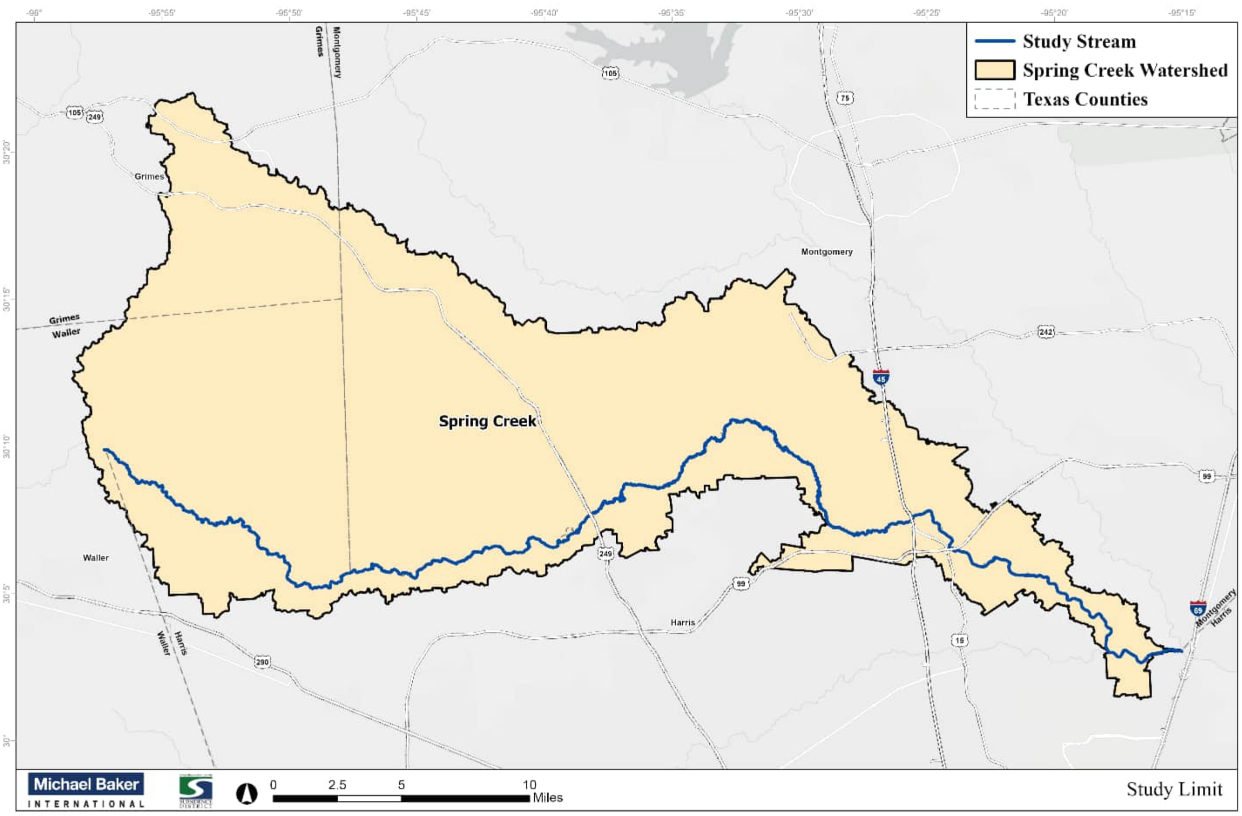

Figure 1: Spring Creek Watershed Showing Study Limits

1.2 Summary of Technical Memorandum #1

Technical Memorandum #1 (MBI, Technical Memorandum #1: Methodology for Subsidence Grid Development, 2024) discusses the development of the cumulative subsidence grid from 2019 through 2070 using HGSD's Joint Regulatory Plan Review[i] documentation. Tech Memo 1 also discusses the various interpolation methodologies to interpolate the HGSD provided 1 kilometer x 1 kilometer (0.62 miles x 0.62 miles) subsidence grid to the same resolution as that of the Harris County Flood Control District's (HCFCD) model's LiDAR resolution (3 feet x 3 feet), which was

[i] https://hgsubsidence.org/planning/regulatory-plan/

surveyed in 2018. Finally, the Kriging interpolation method was selected as the most robust of the four tested methods for developing an interpolated (3 feet x 3 feet) subsidence raster (**Figure 2**). Tech Memo 1 also discussed the development of the subsidence terrain for 2070 using the HCFCD's LiDAR. Tech Memo 1 further discussed the modification of the Hydrologic and Hydraulic (H&H) model parameters, such as hydraulic structures and building elevations, for incorporating subsidence in the development of subsidence scenario models.

1.3 Purpose and Scope of Technical Memorandum #2

The purpose of this Technical Memorandum #2 (Tech Memo 2) is to document the development of baseline and subsidence scenario H&H models. These models are developed to understand the flood risk associated with the projected subsidence in the Spring Creek watershed. The modeling for this project is accomplished with pluvial modeling, which is based on the Rain-on-Mesh (RoM) methodology, which is a new model developed for this study, which covers the entire Spring Creek watershed.

The RoM model was developed from scratch for this project and was also developed using HEC-RAS latest version 6.6 (as of September 2024), to use the latest advancements in the RAS modeling software. The RoM model functions as both the hydrologic as well as the hydraulic model and is calibrated against Hurricane Harvey-2017 (100-500-year recurrence interval) and validated against Hurricane Beryl-2024 (5-10-year recurrence interval). One baseline and two different scenarios (**Figure 3**). These two scenarios are based on the subsidence and population projections from 2020 to 2070. The calibrated Baseline model serves as the benchmark for 2020 and is used to compare results with Subsidence without future development (SWFD) and Subsidence with future development (SFD) scenarios. After the modeling impacts are developed, it will be assessed to estimate the economic impact on the Spring Creek watershed.

This memo describes the development of Baseline and Subsidence scenarios for pluvial models. This includes modification of hydrologic input like inflows from Willow Creek and Cypress Creek watersheds and land cover projection to estimate future development, as well as modification of hydraulic components like terrain, structures (bridges, culverts, inline structures) due to future subsidence. These methodologies related to pluvial modeling are described in detail in Sections **2**, **3**, and **4.**

1.3.1 Organization of Technical Memorandum #2

There are five (5) chapters in Tech Memo 2. The first chapter introduces Tech Memo 2, while Chapter two (2) discusses modeling scenarios for pluvial modeling approaches. Chapter three (3) discusses details on the modeling support or input data used to develop models. Chapter four (4) discusses model development. Chapter five (5) concludes Tech Memo 2.

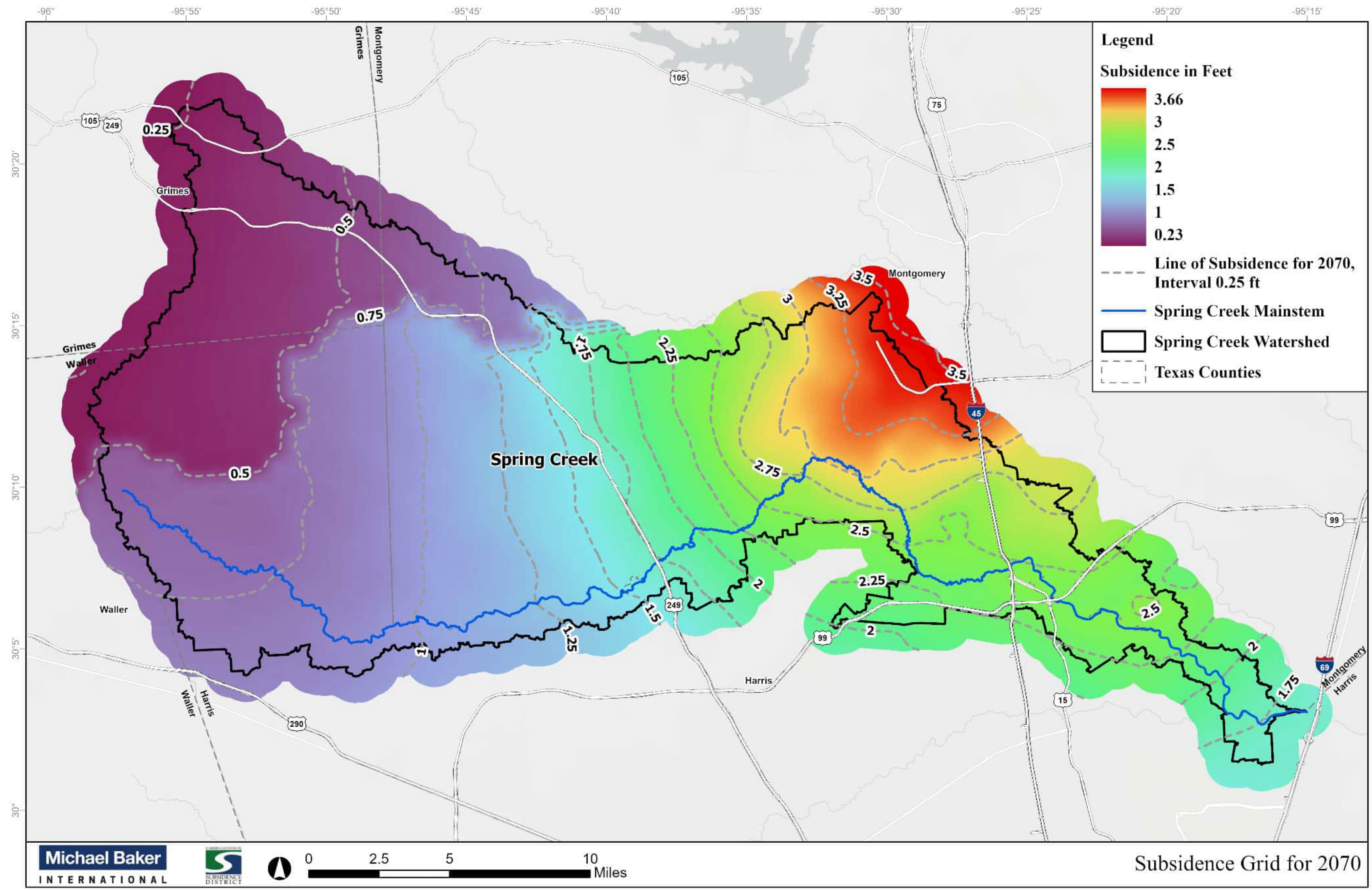

Figure 2: Total Projected Subsidence from 2018-2070 from HGSD's Joint Regulatory Plan Review

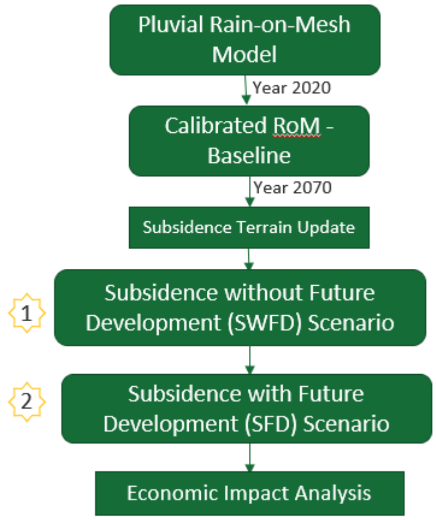

Figure 3: Modeling Scenarios for Pluvial (Rain-on-Mesh) Model Development in Spring Creek Watershed. Two Proposed Condition Scenarios are Represented by Numbers One and Two.

2 Modeling Scenarios

H&H modeling is a critical tool for understanding the movement of water in a watershed. It involves simulating the movement and distribution of water within a watershed using data on rainfall, streamflow, topography, and land use. These models help predict how water will flow and accumulate, which is essential for assessing flood risks and mitigation.

As discussed briefly in Section **1.3**, to evaluate the flood risk associated with subsidence, the three H&H models were developed based on the subsidence and future projections for pluvial modeling:

(i) Baseline Model (benchmark for the year 2020 for existing conditions)

(ii) Subsidence without Future Development (SWFD) Model (projected subsidence scenario for the year 2070, everything else the same as Baseline)

(iii) Subsidence with Future Development (SFD) Model (subsidence + future development scenario for the year 2070)

Six model simulations were formulated – three for 1% Annual Exceedance Probability (AEP) or 100-Year return period, and three for 10% AEP or 10-Year return period for the pluvial approach were developed as shown in **Table 1** below.

Table 1: Model Simulation Scenarios for Pluvial Modeling Approach

Simulations/Scenarios	Pluvial Modeling Approach		
	Historical Event	1% AEP	10% AEP
Calibration Event - Harvey-2017	✓		
Check Event -Beryl-2024	✓		
Baseline		✓	✓
Subsidence without Future Development		✓	✓
Subsidence with Future Development		✓	✓

As shown in **Table 1**, there are 8 simulations for the pluvial model, including 2 historical events for calibration and check events.

2.1 Baseline Model

The baseline model represents the current or existing conditions of a watershed, which includes data on current topography, land use, precipitation, and infrastructure, providing a reference point for understanding how the system behaves under existing conditions.

To evaluate changes in the watershed's flood risk due to future subsidence, a good baseline model is essential. This baseline model serves as the benchmark for comparing subsidence scenario models. Since the study projects change from 2020 to 2070, a baseline model was developed for the year 2020.

The pluvial or Rain-on-Mesh (RoM) model in HEC-RAS is a relatively new approach for simulating precipitation directly on a 2D mesh, allowing for detailed analysis of how precipitation impacts surface runoff and flow patterns. This method integrates H&H modeling by applying precipitation directly to the computational grid, which can represent complex terrain and land cover variations. The model can incorporate different precipitation events, such as design storms or real-time weather data, and simulate the resulting flow dynamics across the landscape. This makes it particularly useful for flood risk assessment, urban drainage planning, and environmental impact.

Pluvial modeling is particularly important since it covers the entire Spring Creek watershed. One limitation of fluvial modeling (commonly used) is that it only focuses on riverine flood risk (fluvial flooding), where the channel overtops its banks and spills over into the over banks. It does not capture localized urban flooding, where rainfall runs off from yards, roofs, streets, and parking lots, creates shallow overland flow and ponding as it tries to find its way to the channel (pluvial flooding). The pluvial approach shows the inundation and localized ponding due to pluvial flooding, where the fluvial approach does not accurately account for potentially localized flooding that may occur due to insufficient conveyance capacity of the local stormwater drainage systems. The fluvial approach underestimates potential inundation, which could be separated/disconnected or disassociated with the 1% AEP area of inundation, whereas the pluvial approach captures the potential inundation anywhere within the modeled area. Hence, the economic impact assessment based on fluvial modeling may underestimate potentially flooded properties. Hence, pluvial modeling provides a better estimate of flooding hazards outside of fluvial flooding.

The baseline model was developed from scratch for this project using the latest HEC-RAS 6.6 (as of September 2024), precipitation, land cover, and land use, as well as available relevant data from HCFCD (LiDAR, hydraulic structures, etc.). The baseline model is calibrated against Hurricane Harvey 2017 to increase model reliability. The performance of the model has also been assessed for Hurricane Beryl-2024. More details of baseline model development are discussed in Section **4**.

2.2 Subsidence without Future Development Model

In contrast to the baseline model, the scenarios model, on the other hand, explores potential future conditions or changes. These scenarios might include proposed or projected changes (in this case, projected subsidence as in this study). By comparing the baseline model with subsidence scenarios, the changes in flood risks, water quality, and thus economic impact can be assessed.

Because future development and future subsidence both affect flood risk, it is important to differentiate the impacts associated with future development from those associated with subsidence, which is the goal of this subsidence without Future Development scenario. Hence, the subsidence without future development model examines the impact on flooding due to projected subsidence when compared with the baseline model. The SWFD scenario model for the pluvial approach is discussed briefly below.

The subsidence model was developed from the calibrated baseline model. The subsidence model uses the 2070 subsidence terrain along with the changes in the hydraulic components. These hydraulic components, like hydraulic structure elevation (bridges, culverts, etc.), are updated to reflect the adjusted elevations of the subsidence terrain (discussed in Section **4**). By comparing this SWFD scenario with the baseline scenario, the impact on pluvial flooding risk due to subsidence only can be isolated, without the effect of future development. Though it is an unrealistic scenario, as future development is inevitable, future subsidence most likely will be affected by that.

2.3 Subsidence with Future Development Model

The subsidence without future development scenario model only considers the subsidence of terrain between the baseline 2020 and the future 2070. However, between 2020 and 2070, urban development is expected to significantly increase the number of impervious surfaces, such as new buildings and structures, roads, rooftops, parking lots, etc. This expansion will reduce natural land cover, typically leading to more impervious surfaces, such as roads and buildings. This will lead to decreased infiltration of rainwater into the soil and increased surface runoff, and consequently, urban areas will face higher risks of flooding.

Hence, SFD examines the compound impact on flooding due to both subsidence and future development when compared with the baseline model. The SFD model is developed from the subsidence model. The pluvial modeling approach does not have a separate hydrologic model; hence, the future development is incorporated by using projected land cover and land use for 2070. More details are discussed in Section **4**.

3 Modeling Support Data

H&H modeling support data is essential in building accurate models. This data includes information on topography, rainfall, streamflow, land use, and soil characteristics, which are used to simulate the movement and distribution of water within a watershed. This section discusses the process for formulating the data that was collected during Task 2: Data Collection.

3.1 Pluvial Modeling Support Data

3.1.1 Precipitation

For pluvial modeling, there are two different sets of precipitation data used for calibration and design events, which are discussed below.

3.1.1.1 Precipitation Data for Calibration Event

The Analysis of Record for Calibration (AORC) provides a detailed record of historical precipitation data over the continental United States. The data was obtained from the NOAA website and converted into DSS files for two historical events (Harvey and Beryl). Hurricane Harvey, which occurred August 25-29, 2017, was a major event with a 100–500-year recurrence interval, while Hurricane Beryl, which occurred on July 7-9, 2024, was a much smaller event, 5–10-year recurrence interval for the Spring Creek watershed. The AORC gridded precipitation data in DSS format was used as 2D rain-on-mesh precipitation data for historical storm simulations. Hurricane Harvey was modeled as a calibration event, while Hurricane Beryl as a check event.

3.1.1.2 Precipitation Data for Design Events

The same precipitation data that was used in the HCFCD model was used as the design rainfall data for 100 and 10-year recurrence intervals for consistency. The precipitation hyetographs from the HCFCD hydrology model (HEC-HMS) were used as a 2D boundary condition for the watershed for 100 and 10-year simulations of all scenarios. Changes in precipitation were not considered for the future, and all the future subsidence with and without future development scenarios used the same precipitation hyetographs for design rainfall as in the baseline model.

3.1.2 Soil Data

The soil data for the Spring Creek watershed were obtained from the Soil Survey Geographic Database (SSURGO) and used to create a gridded soil layer based on the hydrologic soil groups. According to this data, 33.44 percent of the Spring Creek watershed has soil group A, 30.39 percent belongs to soil group B, 15.09 percent of the watershed is soil group D, and 2.88 percent belongs to soil group C. **Figure 4** shows the different types of soil group data for the watershed.

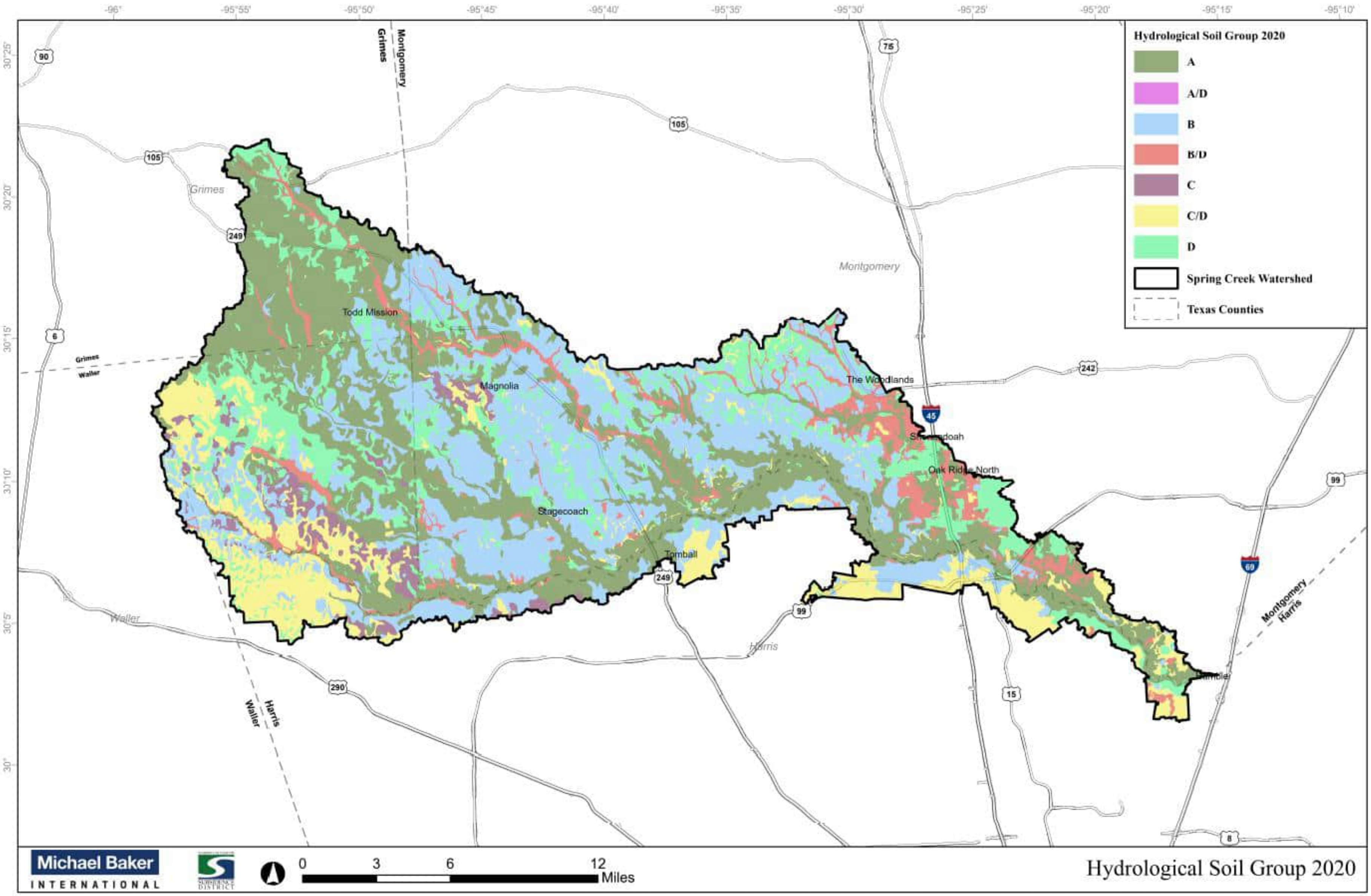

Figure 4: Existing Hydrological Soil Group (2020) for Spring Creek Watershed.

3.1.3 *Infiltration Data*

A 2D gridded infiltration layer was created using HEC-RAS tools using SSURGO soil data and land cover (2020) data. The infiltration layer was created using the Soil Conservation Service (SCS) curve number method. The infiltration layer was used in the 2D model to simulate losses for the 2D rain-on-mesh rainfall runoff. The curve number values were incorporated based on land cover information (SCS[ii]). The abstraction ratio values were used based on land use and soil data according to the HEC-RAS 2D user manual. The curve number and abstraction ratio used for the 2D model are shown in **Table 2**.

Table 2: Curve Number and Abstraction Ratio as used for the Pluvial Model based on Land Classification

Name	Curve Number	Abstraction Ratio	Name	Curve Number	Abstraction Ratio
No Data	86	0.00	Scrub-Shrub: A	67	0.05
Pasture-Hay: A	49	0.05	Scrub-Shrub: CD	85	0.05
Pasture-Hay: CD	84	0.05	Scrub-Shrub: BD	85	0.05
Pasture-Hay: BD	84	0.05	Scrub-Shrub: B	67	0.20
Pasture-Hay: B	69	0.20	Scrub-Shrub: C	80	0.10
Pasture-Hay: C	79	0.10	Scrub-Shrub: D	85	0.05
Pasture-Hay: D	84	0.05	Scrub-Shrub: AD	85	0.05
Pasture-Hay: AD	84	0.05	Palustrine Forested Wetland: A	100	0.00
Developed - High Intensity: A	77	0.00	Palustrine Forested Wetland: CD	100	0.00
Developed - High Intensity: CD	92	0.00	Palustrine Forested Wetland: BD	100	0.00
Developed - High Intensity: BD	92	0.00	Palustrine Forested Wetland: B	100	0.00
Developed - High Intensity: B	85	0.00	Palustrine Forested Wetland: C	100	0.00
Developed - High Intensity: C	90	0.00	Palustrine Forested Wetland: D	100	0.00
Developed - High Intensity: D	92	0.00	Palustrine Forested Wetland: AD	100	0.00
Developed - High Intensity: AD	92	0.00	Cultivated Crops: A	60	0.05
Developed - Open Space: A	49	0.05	Cultivated Crops: CD	84	0.05
Developed - Open Space: CD	84	0.05	Cultivated Crops: BD	84	0.05
Developed - Open Space: BD	84	0.05	Cultivated Crops: B	72	0.20
Developed - Open Space: B	69	0.20	Cultivated Crops: C	80	0.10
Developed - Open Space: C	79	0.10	Cultivated Crops: D	84	0.05
Developed - Open Space: D	84	0.05	Cultivated Crops: AD	84	0.05
Developed - Open Space: AD	84	0.05	Palustrine Emergent Wetland: A	100	0.00

[ii] https://www.hec.usace.army.mil/confluence/hmsdocs/hmstrm/cn-tables

Name	Curve Number	Abstraction Ratio	Name	Curve Number	Abstraction Ratio
Mixed Forest: A	43	0.05	Palustrine Emergent Wetland: CD	100	0.00
Mixed Forest: CD	82	0.05	Palustrine Emergent Wetland: BD	100	0.00
Mixed Forest: BD	82	0.05	Palustrine Emergent Wetland: B	100	0.00
Mixed Forest: B	65	0.20	Palustrine Emergent Wetland: C	100	0.00
Mixed Forest: C	76	0.10	Palustrine Emergent Wetland: D	100	0.00
Mixed Forest: D	82	0.05	Palustrine Emergent Wetland: AD	100	0.00
Mixed Forest: AD	82	0.05	Palustrine Scrub-Shrub Wetland: A	100	0.00
Barren Land: A	77	0.05	Palustrine Scrub-Shrub Wetland: CD	100	0.00
Barren Land: CD	94	0.05	Palustrine Scrub-Shrub Wetland: BD	100	0.00
Barren Land: BD	94	0.05	Palustrine Scrub-Shrub Wetland: B	100	0.00
Barren Land: B	86	0.20	Palustrine Scrub-Shrub Wetland: C	100	0.00
Barren Land: C	91	0.10	Palustrine Scrub-Shrub Wetland: D	100	0.00
Barren Land: D	94	0.05	Palustrine Scrub-Shrub Wetland: AD	100	0.00
Barren Land: AD	94	0.05	Unconsolidated Shore: A	77	0.05
Open Water: A	100	0.00	Unconsolidated Shore: CD	94	0.05
Open Water: CD	100	0.00	Unconsolidated Shore: BD	94	0.05
Open Water: BD	100	0.00	Unconsolidated Shore: B	86	0.20
Open Water: B	100	0.00	Unconsolidated Shore: C	91	0.10
Open Water: C	100	0.00	Unconsolidated Shore: D	94	0.05
Open Water: D	100	0.00	Unconsolidated Shore: AD	94	0.05
Open Water: AD	100	0.00	Evergreen Forest: A	36	0.05
Developed - Low Intensity: A	51	0.05	Evergreen Forest: CD	79	0.05
Developed - Low Intensity: CD	84	0.05	Evergreen Forest: BD	79	0.05
Developed - Low Intensity: BD	84	0.05	Evergreen Forest: B	60	0.20
Developed - Low Intensity: B	68	0.05	Evergreen Forest: C	73	0.10
Developed - Low Intensity: C	79	0.05	Evergreen Forest: D	79	0.05
Developed - Low Intensity: D	84	0.05	Evergreen Forest: AD	79	0.05
Developed - Low Intensity: AD	84	0.05	Deciduous Forest: A	30	0.05
Grassland-Herbaceous: A	71	0.05	Deciduous Forest: CD	77	0.05
Grassland-Herbaceous: CD	89	0.05	Deciduous Forest: BD	77	0.05
Grassland-Herbaceous: BD	89	0.05	Deciduous Forest: B	55	0.20
Grassland-Herbaceous: B	71	0.20	Deciduous Forest: C	70	0.10
Grassland-Herbaceous: C	81	0.10	Deciduous Forest: D	77	0.05
Grassland-Herbaceous: D	89	0.05	Deciduous Forest: AD	77	0.05
Grassland-Herbaceous: AD	89	0.05	Building: A	100	0.00

Name	Curve Number	Abstraction Ratio	Name	Curve Number	Abstraction Ratio
Palustrine Aquatic Bed: A	100	0.00	Building: CD	100	0.00
Palustrine Aquatic Bed: CD	100	0.00	Building: BD	100	0.00
Palustrine Aquatic Bed: BD	100	0.00	Building: B	100	0.00
Palustrine Aquatic Bed: B	100	0.00	Building: C	100	0.00
Palustrine Aquatic Bed: C	100	0.00	Building: D	100	0.00
Palustrine Aquatic Bed: D	100	0.00	Building: AD	100	0.00
Palustrine Aquatic Bed: AD	100	0.00			

3.1.4 Land Cover Data

3.1.4.1 Land Cover 2020

Coastal Change Analysis Program (C-CAP) high-resolution land cover data dated 2024 was obtained from the NOAA Coastal Management website[iii]. The C-CAP is 1 meter x 1 meter resolution data, but does not cover the small northwest portion, which is Grimes County of the Spring Creek watershed (**Figure 5**). To cover this missing area, land cover data were also obtained from the National Land Cover Database [NLCD developed by the Multi-Resolution Land Characteristics (MRLC) Consortium] for the year 2021. This data has a resolution of 10 meters x 10 meters. Land cover data from both sources were combined to create integrated data for the whole watershed to be used for the baseline model. The comparison between NLCD and C-CAP classification provided by the NOAA Coastal Management website was used to create the combined land cover data. **Table 3** shows the comparison and the **Figure 5** shows the landcover classification for 2020, which was used for the baseline and subsidence without future development scenario models.

[iii] https://coast.noaa.gov/digitalcoast/data/ccapregional.html

Table 3: Comparison between NLCD and C-CAP Land Use Category

Anderson Level 1 Category	NLCD Category	C-CAP Category
Urban or Built-up Land (1)	Developed, High Intensity (24)	High Intensity Developed (2)
	Developed, Medium Intensity (23)	Medium Intensity Developed (3)
	Developed, Low Intensity (22)	Low Intensity Developed (4)
	Developed, Open Space (21)	Open Space Developed (5)
Agricultural Land (2)	Cultivated Crops (82)	Cultivated Land (6)
	Pasture/Hay (81)	Pasture/Hay (7)
Rangeland (3)	Grassland / Herbaceous (71)	Grassland (8)
	Scrub / Shrub (52)	Scrub Shrub (12)
Forest (4)	Deciduous Forest (41)	Deciduous Forest (9)
	Evergreen Forest (42)	Evergreen Forest (10)
	Mixed Forest (43)	Mixed Forest (11)
Wetlands (6)	Woody Wetlands (90)	Palustrine Forested Wetlands (13)
		Palustrine Scrub Shrub Wetlands (14)
		Estuarine Forested Wetlands (15)
		Estuarine Scrub Shrub Wetlands (16)
	Emergent Herbaceous Wetlands (95)	Palustrine Emergent Wetlands (17)
		Estuarine Emergent Wetlands (18)
Open Water (5)	Open Water (11)	Open Water (21)
		Palustrine Aquatic Bed (22)
		Estuarine Aquatic Bed (23)
Barren Land (7)	Barren Land (31)	Unconsolidated Shore (19)
		Barren Land (20)
Tundra (8)		Tundra (24)
Perennial Ice/Snow (9)	Perennial Ice/Snow (12)	Perennial Ice/Snow (25)

For the land cover data, we also incorporated channels such as open water and buildings using building footprint data.

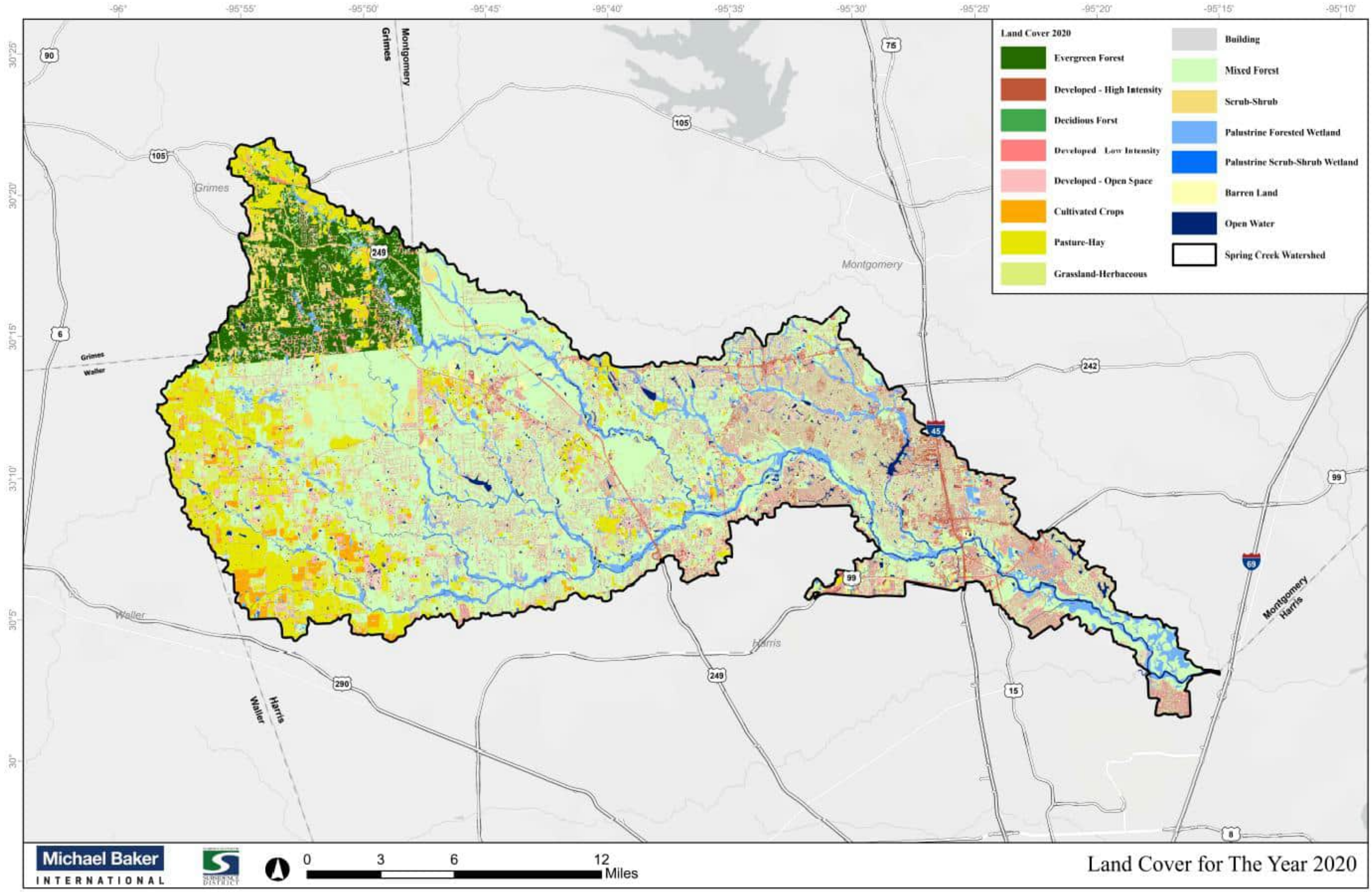

Figure 5: Land Cover Land Use (2020) Data for Spring Creek Watershed.

3.1.4.2 Land Cover 2070

The land cover for 2070 was used to estimate future development in the Spring Creek watershed. The land cover projection was developed by the United States Geological Survey (USGS's) FOREcasting SCEnarios of Land-use Change (FORE-SCE)[iv] model that provides land-use and land-cover (LULC) projections for the conterminous United States (Sohl, 2014). This projection was developed based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES). Out of 4 SRES (A1B, A2, B1, and B2) scenarios, the A2 scenario projection was used, which is more relevant to current climate conditions. The projection was available only at a coarser 250-meter scale, compared to the 1-meter resolution of the current CCAP LULC dataset. It was also based on older 1992 LULC data. If a grid showed developed land in 2020 but undeveloped in 2070, it was corrected to reflect development. Land cover classes in the future dataset were updated to match the current dataset (**Table 4**). This land cover data was used for SFD scenarios. Figure 6 shows the land cover data for 2070.

Table 4: Land Cover Classes in Future Projected Land Cover

Future Projected Landcover Classes	Land Cover Classes Used in HEC-RAS
Developed	Developed - High Intensity
Mechanically Disturbed Private	Developed - High Intensity
Mechanically Disturbed Other Public Lands	Developed - Open Space
Mining	Developed - Open Space
Barren	Barren Land
Hay/Pasture Land	Pasture-Hay
Cropland	Cultivated Crops
Grassland	Grassland-Herbaceous
Shrubland	Scrub-Shrub
Deciduous Forest	Deciduous Forest
Evergreen Forest	Evergreen Forest
Mixed Forest	Mixed Forest
Mechanically Disturbed National Forests	Mixed Forest
Herbaceous Wetland	Palustrine Scrub-Shrub Wetland
Woody Wetland	Palustrine Forested Wetland
Water	Open Water
Perennial Ice/Snow	Open Water

3.1.5 Boundary Conditions (Inflows/Outflows)

Inflow and outflow boundary conditions are the main boundary conditions for the Spring Creek watershed, which are taken from the HCFCD model for consistency. Please refer to Section **4.2.3** for details.

[iv] https://www.sciencebase.gov/catalog/item/5b96c2f9e4b0702d0e826f6d

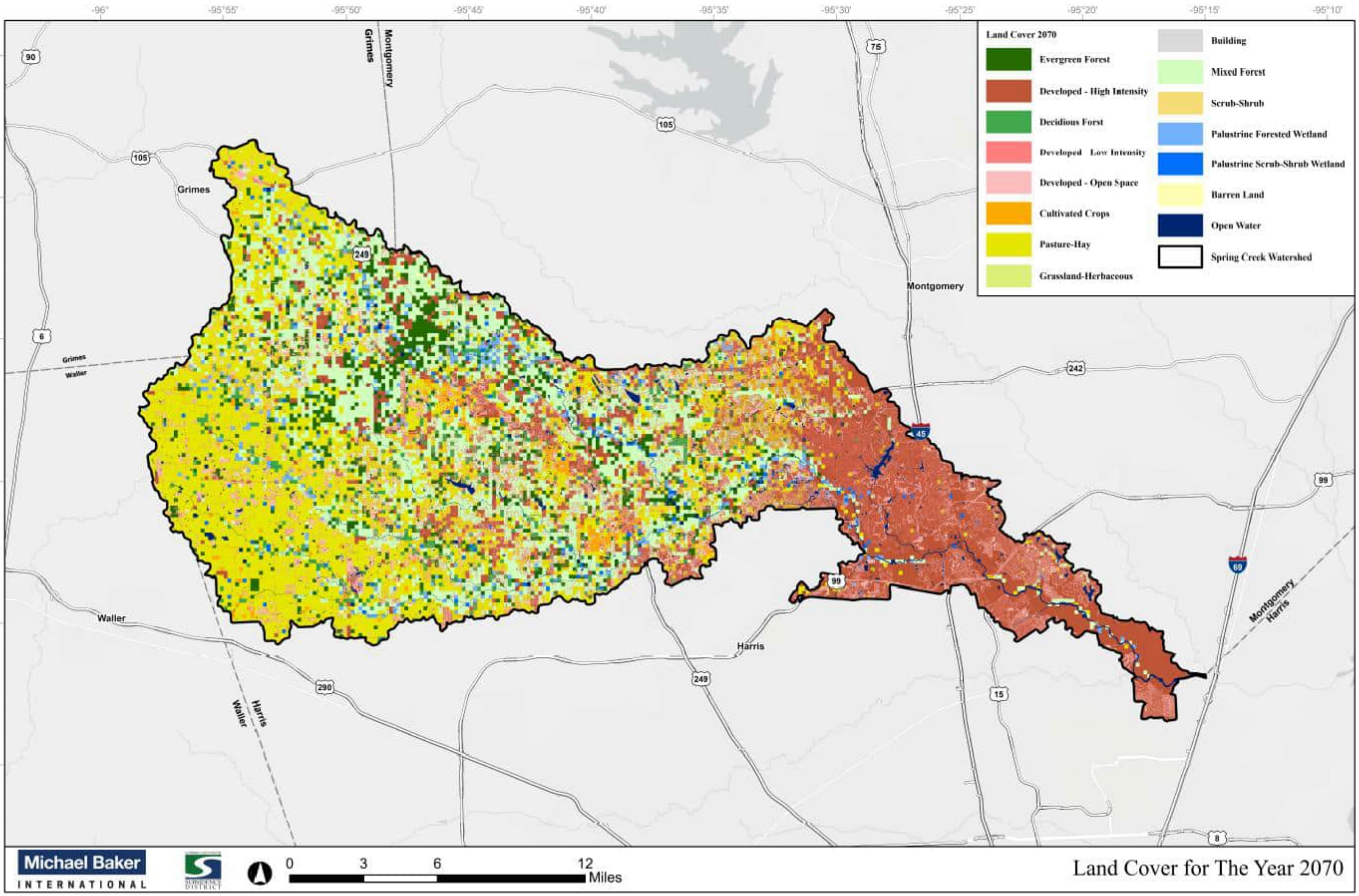

Figure 6: Projected Land Cover Land Use (2070) Data for Spring Creek Watershed.

4 Pluvial-Hydraulic Analysis

As discussed in earlier sections, the pluvial modeling domain covers the entire watershed. The total area of the Spring Creek watershed is 392 square miles, which includes urban areas like Conroe-Woodlands, parts of Tomball, Magnolia, etc, and lies in four (4) counties (Harris, Montgomery, Waller, and Grimes). As shown in **Figure 1**, only 15% of the total area of the Spring Creek watershed falls in Harris County, while 51%, 22%, and 12% fall in Montgomery, Waller, and Grimes counties, respectively. Hence, almost 85% of the watershed area falls outside of the HCFCD model scope, even though the model includes a few tributaries in Montgomery and other counties with limited details. Hence, the pluvial modeling will cover areas both in and outside of the HCFCD model study domain. However, a detailed study at the watershed scale could be optimized using informed information of future projections of subsidence, population growth, and thus economic activity, which is discussed in the subsequent section on the tier-based modeling resolution approach as discussed below.

4.1 Tier-based Modeling Approach

For the 2D hydraulic analysis, a tier-based prioritization approach was adopted, ensuring that the level of detail used in the modeling approach matches the level of potential risks to the population and infrastructure in the Spring Creek watershed. The pluvial domain of the Spring Creek watershed was divided into three tiers: high, mid, and low tiers (**Figure 7)**. This tier-based approach prioritizes detailed modeling (high-tier areas with finer mesh size, detailed modeling of hydraulic structures, breaklines, etc.) for areas with higher population density or higher projected subsidence, or urbanized areas. These areas typically have more infrastructure and assets at risk, and the potential impact on human lives is greater. Detailed modeling in these regions ensures that the potential flood risk is captured with greater detail. Conversely, in areas with lower population density or lower projected subsidence, a reduced level of detailed modeling (low-tier areas with coarser mesh size, less detail, or no modeling of hydraulic structures, etc.) can be sufficient. These areas generally have fewer assets at risk, and the lower population density means that the potential impact of flooding is less severe. By allocating modeling details efficiently, it can be ensured that the most vulnerable areas receive the attention they need while still maintaining an appropriate level of modeling details in all areas of the watershed.

High-Tier: The high-tier modeling area is located at the easternmost part of the Spring Creek watershed, which shows a higher projection for subsidence depth as well as population density (**Figure 7**). The projected subsidence depth in this area varies from 2 to 3.5 feet. This area is also urbanized as the Conroe-Woodland urban area falls under this tier. Detailed modeling will be done for this area with a finer cell size (**Table 5**).

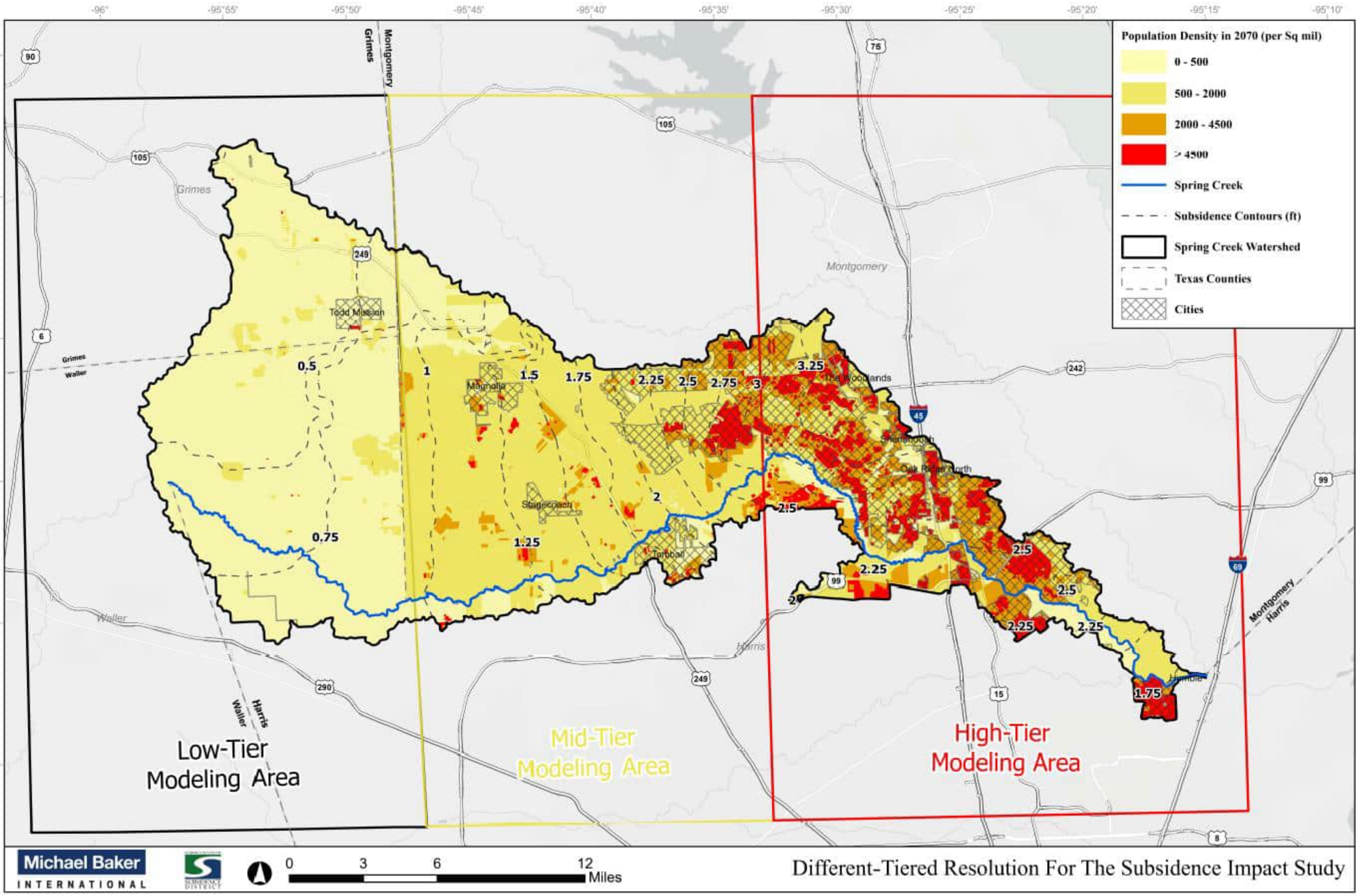

Figure 7: Different Tiered Resolution for the Subsidence Impact Study for Pluvial Model

Mid-Tier: The mid-tier modeling area is the mid-section of the Spring Creek watershed (**Figure 7**), which starts at the end of Grimes County and the start of Montgomery County and stops at the beginning of the high-tier area. The cities within this area are Magnolia and Tomball. This area shows medium subsidence projection in 2070, varying within 1-2 feet, as well as medium population growth to a density between 500-4,500 people per square mile. **Table 5** shows the medium mesh resolution used for the modeling of this area.

Low-Tier: The low-tier modeling area is located on the western portion of the Spring Creek watershed (**Figure 7**). This area shows minimal subsidence projection as well as population growth in 2070 and hence is modeled with less detail (coarser mesh as shown in **Table 5**).

Table 5: Different Cell Sizes used for different Tiers for Modeling

Model Tier	Default 2D Cell Size
High Tier	500 feet
Mid-Tier	1000 feet
Low-Tier	2000 feet

4.2 Model Development

The pluvial model was set up to cover the entire Spring Creek watershed with relevant modeling data from the HCFCD fluvial model as well as other sources. If the data used in the HCFCD model were updated, the updated version of the data was used in the pluvial model (for example, LULC data). Please refer to Section **3.1** for details on pluvial model input and supporting data. The model geometry, computation methods, and parameters are discussed in the subsequent sections.

The setup of the hydraulic 2D model is within the Spring Creek boundary with many structures, spillways, cities, and major roads. Since the model is set to solve the full momentum equation set using a ROM hydrological input, the advanced time step control that utilizes the Courant condition was used. The Courant condition in HEC-RAS is a numerical accuracy criterion that determines the time step used in hydraulic modeling. It's based on the Courant–Friedrichs–Lewy (CFL) condition, which is a mathematical criterion that determines the time step size in computational fluid dynamics simulations to avoid instabilities. The limits of the Courant condition were chosen based on various simulation trials. The details of the Courant parameters are discussed in Section **4.2.2** and detailed in **Appendix A1.**

The 2D geometry was set up to capture the inherent details of the watershed such as the channels, levees, major roadways, high grounds, bridges, culverts, etc. Using a default mesh cell size of 2000 feet x 2000 feet with different refinement zones and breaklines of varied resolution, the number of computation points is ~68,000. Different mesh size details of the model can be seen in the exhibit called the pluvial model domain details in **Appendix B.**

4.2.1 Model Geometry

As discussed in the earlier sections, the pluvial model is a 2D-only model with varying mesh sizes based on a prioritized tier-based approach (Section **4.1**). The main channels, major roads and grade breaks, etc., were modeled as breaklines. The hydraulic structures were modeled as SA-2D connections within the 2D model. Various components of the 2D geometry are discussed below:

Refinement Regions – As discussed earlier, different tiers are modeled with refinement regions. The easternmost part of the Spring Creek watershed was modeled as a refinement region to have a finer cell size of 500 feet x 500 feet. For the mid-tier location, another refinement region with a cell size of 1000 feet x 1000 feet was used. The low-tier modeling region used the default mesh size of 2000 feet x 2000 feet, with exceptions to channels, and structures modified to a finer mesh as needed to represent those structures. **Figure 8** showing the refinement regions in the 2D model.

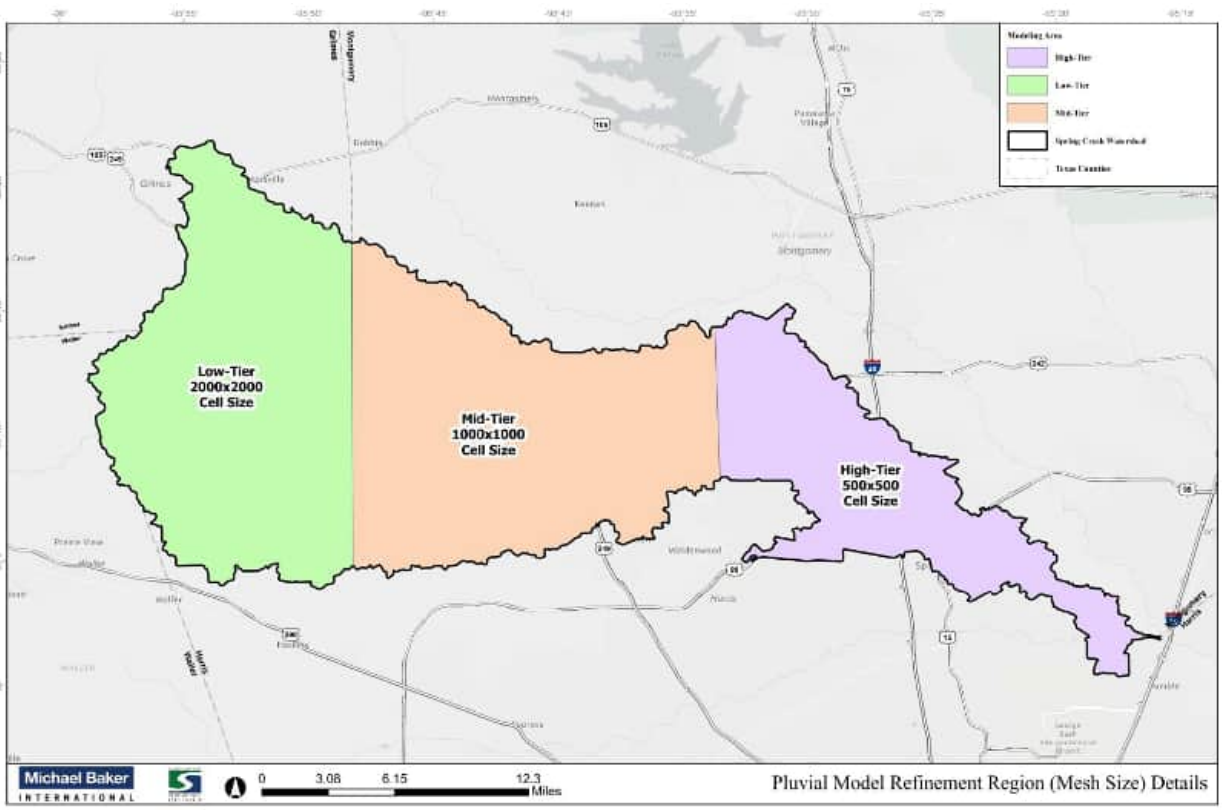

Figure 8: Refinement Regions for the Pluvial Model

2D Breaklines – Breaklines were used for depicting major roads, main streams, levees, high grounds, etc. The 2D breaklines for streams represent the channel's centerline, and various mesh sizes from 200 ft x 200 ft to 50 ft x 50 ft were enforced with near repeats of 1 or 2 cells to depict the channel width. Details of the 2D breaklines location and mesh size are shown in the exhibit showing the 2D model details in **Appendix B.**

Similarly, a 2D breakline representing a major roadway, high ground, and levee was modeled based on the terrain and satellite imagery. The breakline represents the highest point along the feature to properly simulate the overtopping.

2D Breaklines were also applied at spillway and weir locations, which are elevated areas. These breaklines ensure that the computational mesh cells represent the underlying terrain accurately and direct the flow appropriately.

2D Bridges: Bridges were modeled as SA/2D connections in the model, the data of which was acquired from the HCFCD fluvial model. The mesh cells around the bridge centerline were enforced with a finer cell size of 50-200 feet as needed based on the bridge width. A near repeat of one (1) or two (2) was used for cell enforcement to have cells align well with the SA/2D connection. As per the HEC-RAS manual, the cells don't need to have a rectangular shape around the SA/2D connections. Please see the pluvial model domain details exhibit in **Appendix B**, which shows the locations of the 2D bridges in the model.

2D culverts: Culverts that were modeled in the HCFCD model were also modeled in the 2D model as SA/2D connections. The input data for these culverts were acquired from the HCFCD model. The same approach as the 2D bridges was taken to enforce the 2D culverts, and the same exhibit shows the location of the culverts in the model.

Channel Modification: Channel modifications were used based on the visual inspection of the terrain and aerial imagery to depict small culverts. The invert elevations for these small culvert barrels were assumed from the channel bathymetry. These locations are shown in the exhibit, which depicts the model details.

4.2.2 Computation Methods

The diffusion wave equations were set to solve the 2D model flow. The maximum water surface elevation (WSE) error of a cell was set to 0.01 feet. Any WSE errors less than 0.01 feet were ignored since they were found to be insignificant for the given large scale of the model.

A base time step of thirty (30) seconds was selected for the model simulation. The advanced time step control with a Courant condition for efficient run times. The courant condition with the shortest run time, higher model stability, and accurate simulation results were selected.

4.2.3 Model Parameters

Model parameters for different hydraulic components used in the model are discussed in **Appendix A1.** Manning's n is a crucial coefficient that effectively measures the roughness of a channel or surface, directly influencing the friction encountered by flowing water. A higher Manning's n value means more friction, which slows down the flow of water, whereas a lower value means a faster flow of water.

Spatially varying Manning's n Layer: For Manning's n layer, the land cover 2020 data was used. Details of the land cover data were discussed in Section **3.1.4.1**. Along with Manning's n, impervious percentages were determined based on land cover data. A classification polygon was also used to depict the waterbodies of the watershed, as well as the building footprints. For water bodies (channels, ponds, etc.), a value of 0.05 was used based on the calibration, which is discussed in more detail in Section **4.3**. For buildings, a high Manning's n value of 10 was used to represent the obstruction to the flow caused by the structure's walls. The Manning's n values and the impervious percentage that were used based on land classification for the 2D model are shown in **Table 6**.

Table 6: Manning's n and Impervious percentage used in the Model

NLCD/CCAP ID	Land Classification	Manning's n	Percent Impervious
0	NoData	0.035	0
2	Developed - High Intensity	0.12	90
9	Building	10	100
4	Developed - Low Intensity	0.1	35
5	Developed - Open Space	0.05	10
6	Cultivated Crops	0.08	0
7	Pasture-Hay	0.08	0
8	Grassland-Herbaceous	0.08	0
3	Deciduous Forest	0.15	0
1	Evergreen Forest	0.2	0
11	Mixed Forest	0.2	0
12	Scrub-Shrub	0.1	0
13	Palustrine Forested Wetland	0.2	50
14	Palustrine Scrub-Shrub Wetland	0.2	50
15	Palustrine Emergent Wetland	0.2	75
19	Unconsolidated Shore	0.07	0
20	Barren Land	0.03	0
21	Open Water	0.15	100
22	Palustrine Aquatic Bed	0.07	100

4.2.4 HEC-RAS Boundary Condition Options

The HEC-RAS model uses boundary conditions to define the inflows and outflows. The boundary condition locations that were used for this model can be seen in the **Figure 9** and **Figure 10**. The following are the types of boundary conditions that were used for the model:

4.2.4.1 Outflow Boundary Conditions

Multiple boundary conditions depict the outflow condition of the Spring Creek watershed. The outflow boundary conditions are the same for all scenarios (baseline, SWFD, and SFD). **Figure 9** shows the location of different outflow boundary conditions. For the Spring Creek 2D model, we have used two types of outflow boundary conditions, which are; Rating Curve and Normal Depth, and are discussed below.

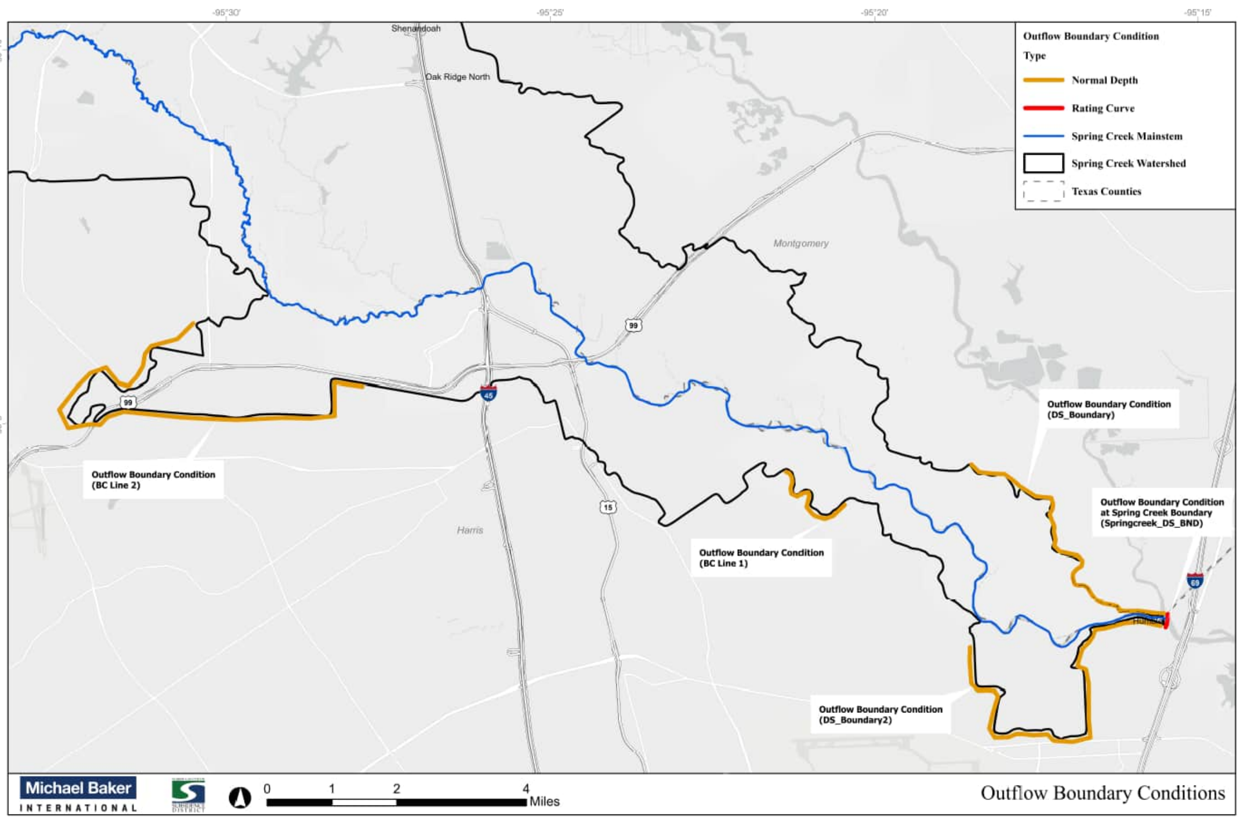

Figure 9: Outflow boundary condition locations for Pluvial Model

Rating Curve: Generally, rating curves are used as a downstream boundary condition. Rating curves show the relationship between a river's stage (water surface elevation) and flow (discharge of river). The downstream rating curve boundary condition used for all the model scenarios (baseline, SWFD, and SFD) is the same and is consistent with the downstream boundary condition used by the HCFCD model. The location of the outflow boundary conditions on the 2D model can be seen in **Figure 9.**

Normal Depth: Another type of boundary condition that was used to represent the outflow boundary conditions for the watershed was normal depth, which was used when the 2D mesh showed an overflow of water at the perimeter. For normal depth, the slope of the energy grade line for the reach in the vicinity of the boundary condition is needed. However, the average bed slope in the vicinity of the boundary condition location can be used as the friction slope when the flow is uniform. Under normal depth boundary conditions, Manning's n equation is used to estimate the stage for each calculated flow.

4.2.4.2 Inflow boundary conditions

For inflow boundary conditions, HEC-RAS offers multiple options such as flow hydrograph, and stage hydrograph, for the 2D model. Both flow and stage hydrographs are used as inflow boundary conditions for the 2D model. The inflow boundary conditions vary based on the model runs (calibration and design runs' scenario).

Design Events (1% and 10% AEP): As discussed in earlier sections, tributaries - Willow Creek and Cypress Creek flow into the Spring Creek watershed, which need to be accounted for as inflow boundary conditions. For the design events for each scenario, the output from the fluvial model is used as the inflow boundary condition for the pluvial model for the respective scenario. The HCFCD model included a portion of Willow Creek and Cypress Creek, and the results from the cross-sections nearest to the 2D boundary location were used. Flow from the cross-section (RS 359) of Cypress Creek, while that of the cross-section (RS 495) of Willow Creek was used as the input into the pluvial domain at the respective confluence for respective scenarios.

Calibration Event: For the historical events (Hurricane Harvey-2017 for calibration and Hurricane Beryl-2024 for check event), observed data from the nearest gage data at the confluence of Willow Creek and Cypress Creek were downloaded. However, these gages were still located far from the confluence, where inflow boundary conditions were needed as input to the pluvial model for each historical event. Using the HCFCD model, the flow translation (changes in peak and lag in time to peak) was estimated from the location of the gage to the confluence between each tributary and Spring Creek. Hence, the gage data for each historical event was translated and used as the inflow boundary condition for the respective historical event run. For the Willow Creek boundary condition, USGS gage 08068325 (Willow Creek near Tomball, TX) was the closest gage near the confluence between Willow Creek and Spring Creek. For the Cypress Creek boundary condition, HCFCD gage 1110 (Cypress Creek at Cypresswood Drive) was the closest gage near the confluence between Cypress Creek and Spring Creek. **Figure 10** shows the locations of the inflow boundary condition and gage location from which data was obtained.

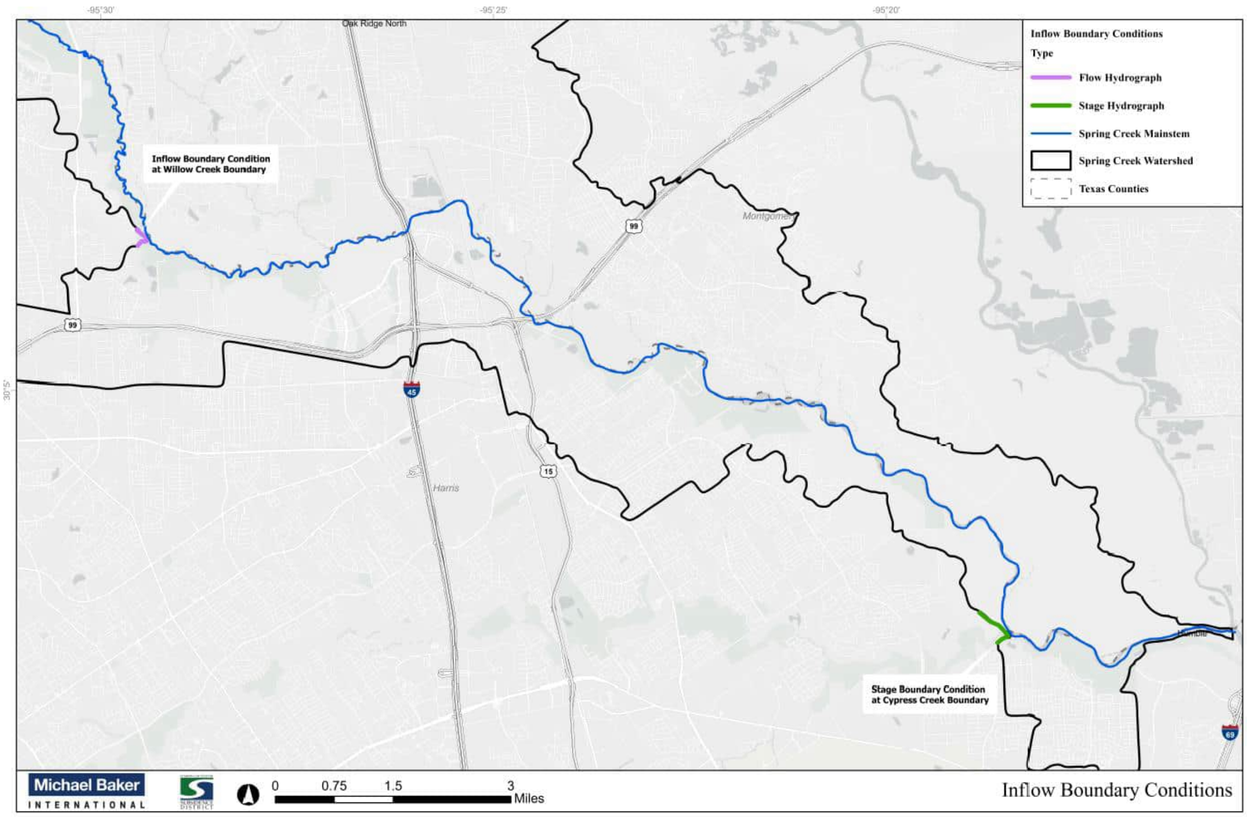

Figure 10: Inflow boundary conditions used in the Pluvial Model

4.3 Model Calibration

H&H model calibration is crucial for ensuring the accuracy and reliability of flood predictions. Calibration involves adjusting model parameters to match observed data such as streamflow, stage, or high-water marks (HWM), which helps to fine-tune the model's performance. Properly calibrated models can predict the timing, extent, and severity of flooding more accurately. This is important for increasing model reliability in predicting flood peaks, floodplains, and timing response to precipitation.

Goals for good calibration were generally established as follows.

- 50%, 75%, and 90% of the modeled peak stage must fall within 5%, 10%, and 20% respectively of the observed value.
- 50% and 70% of the modeled peak discharge must fall within 10%, and 20% respectively of the observed value.
- Time of Peak should fall within 9 hours and 12 hours of the observed value at least 60% and 80% of the gages.
- The runoff volume of the modeled value should fall within 20 % of the observed values for at least 70 % of the gages.

For calibrating the pluvial model, we have used the historical event of Hurricane Harvey in 2017, which was one of the most impactful events for this area. The model was also checked for its performance for a much smaller event, Hurricane Beryl-2024. Multiple USGS and HCFCD gage records (streamflow, stage, HWM) within the Spring Creek watershed were obtained for the calibration of the model. The location of the gages that were used in the 2D model for calibration purposes can be seen in **Figure 11**. The USGS locations provided both observed stage and flow, whereas the HCFCD gages only provided stage data and rainfall data.

For calibration, multiple iterations of Manning's n value were tested for different land use types. For initial runs, Manning's n value of 0.035 for water bodies, 0.04 for grassland, and 0.045 for Pasture/Hay, etc, were used, which showed significantly faster time response in peak stage and peak flow than observed gage records. After multiple iterations with a higher range of Manning's n values for each land cover (particularly open water bodies/channels), the final Manning's n values were selected (**Table 6**) which provided results within acceptable limits.

The peak stage data for both the USGS gage and HCFCD gage match well with the modeled peak stage data. All peak stage falls within 20% of the observed peak stage data, which satisfies the criteria well and is documented in **Appendix A2**. **Figure 12** shows the comparison of observed and simulated data time series for water surface elevation at the HCFCD Gage 1070, where the modeled peak stage is within 1 foot of the observed peak. It also shows a correlation coefficient of 0.99 between observed and simulated data.

Similarly, peak discharge data for USGS gages match well with the modeled peak discharge data. For Hurricane Harvey, the modeled peak discharge falls within 20 % of the observed peak discharge 80 % of the time, which falls within the criteria. **Figure 13** shows the comparison of observed and simulated flow data time-series at USGS gage 08068275, though the modeled flow peaks earlier than the observed flow, it is within the calibration criteria. The peak discharge difference is detailed in **Appendix A2.**

Hurricane Beryl was also modeled to compare the observed and simulated data as a check event to assess how the model performs for a smaller event (5-10 recurrence interval). Hurricane Beryl occurred from July 6 to 9, 2024, in Spring Creek with a total precipitation of 6-8 inches. The correlation coefficient for the time series of the stage and flow for USGS and HCFCD gages are satisfactory and within criteria.

A comparison of gridded AORC precipitation (which is the meteorological input for the calibration event as discussed in Section **3.1.1.1**) with HCFCD gage data was done to evaluate if the rainfall data were comparable. **Figure 14** shows the AORC gridded precipitation data matches well with the rain gage at HCFCD gage 1050, with very similar total rainfall depth for Hurricane Harvey from the two observed sources.

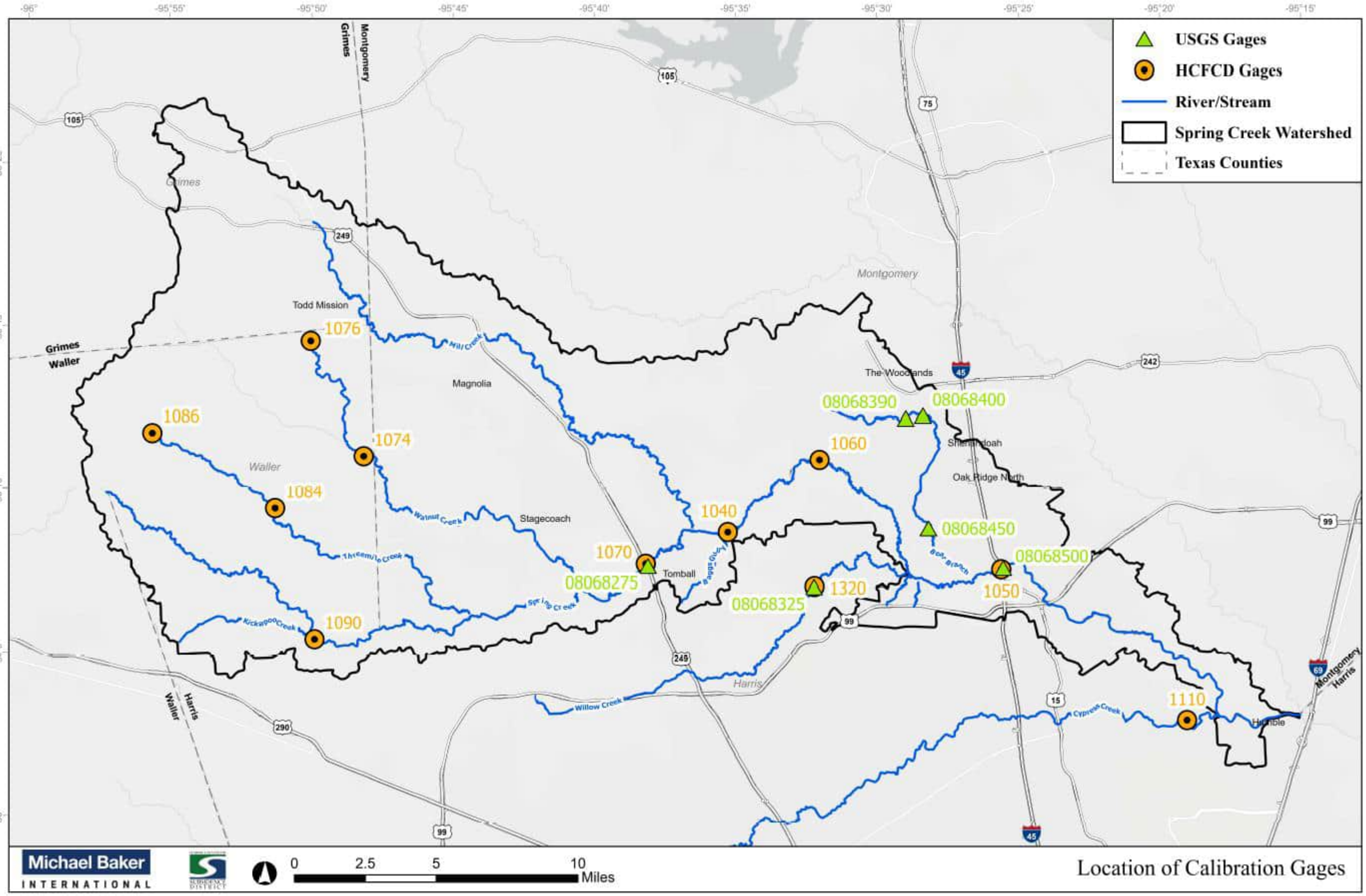

Figure 11: Location of calibration gages used for the Pluvial model

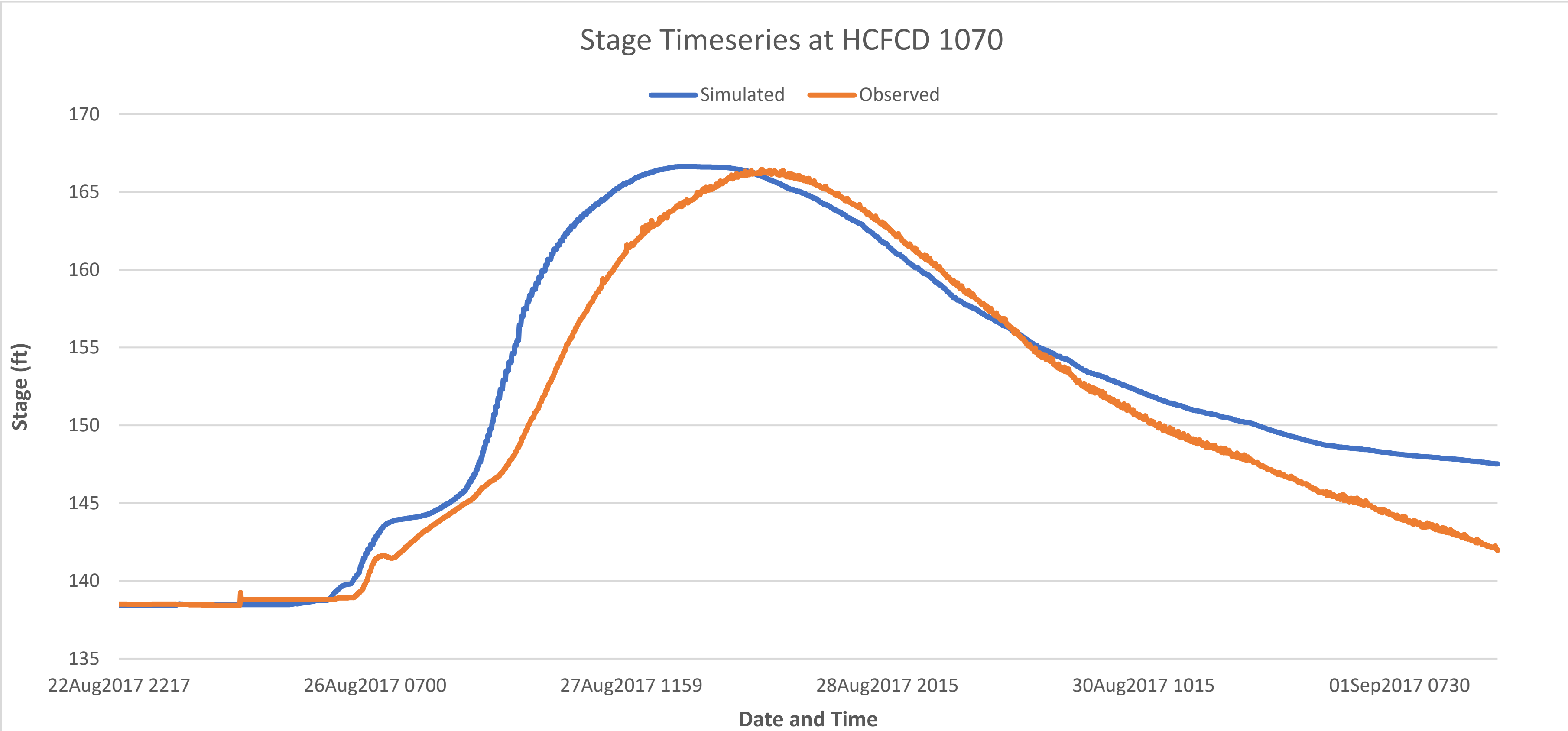

Figure 12: Comparison between Observed and Simulated Stage at HCFCD 1070 for Hurricane Harvey

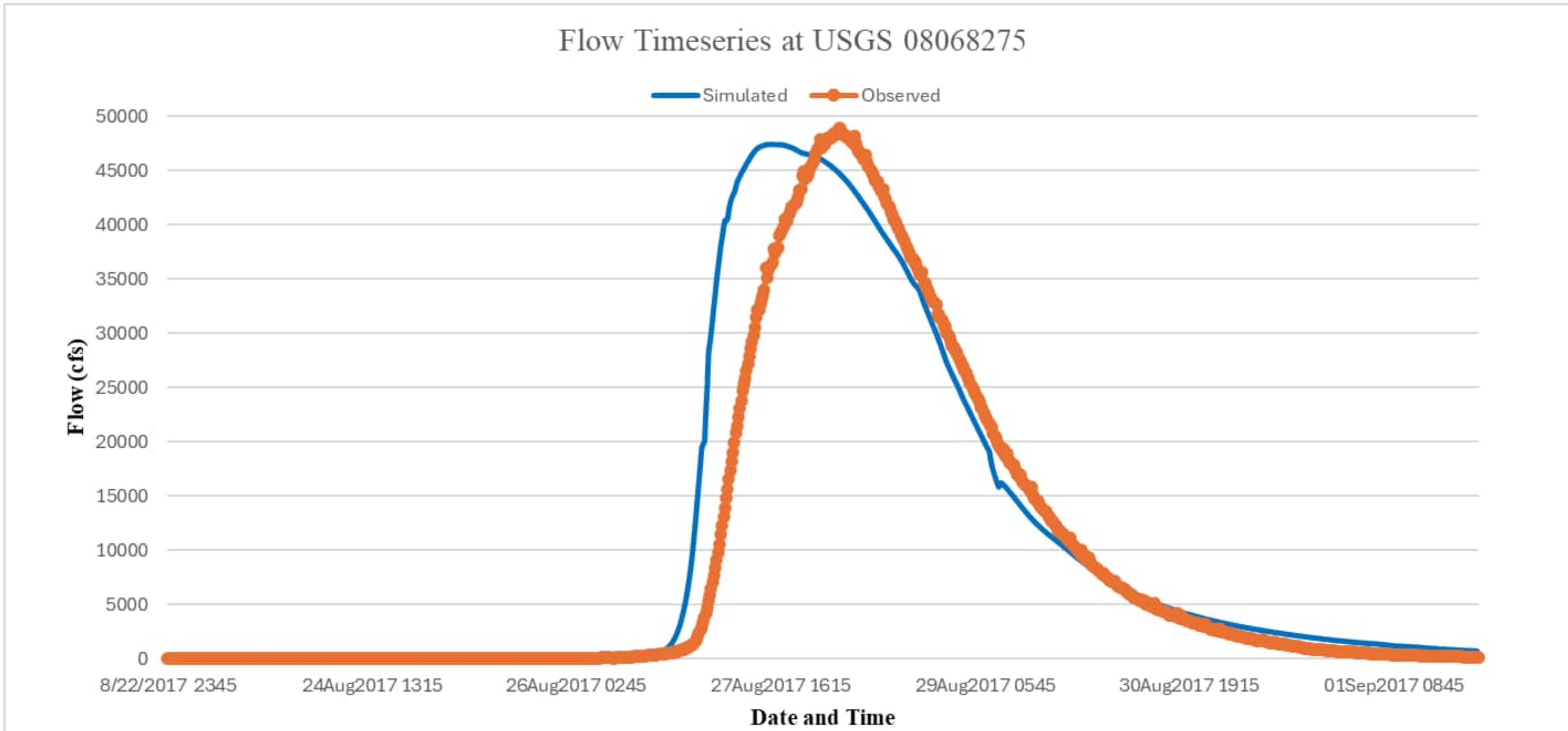

Figure 13: Comparison between Observed and Simulated Flow at USGS 08068275 for Hurricane Harvey

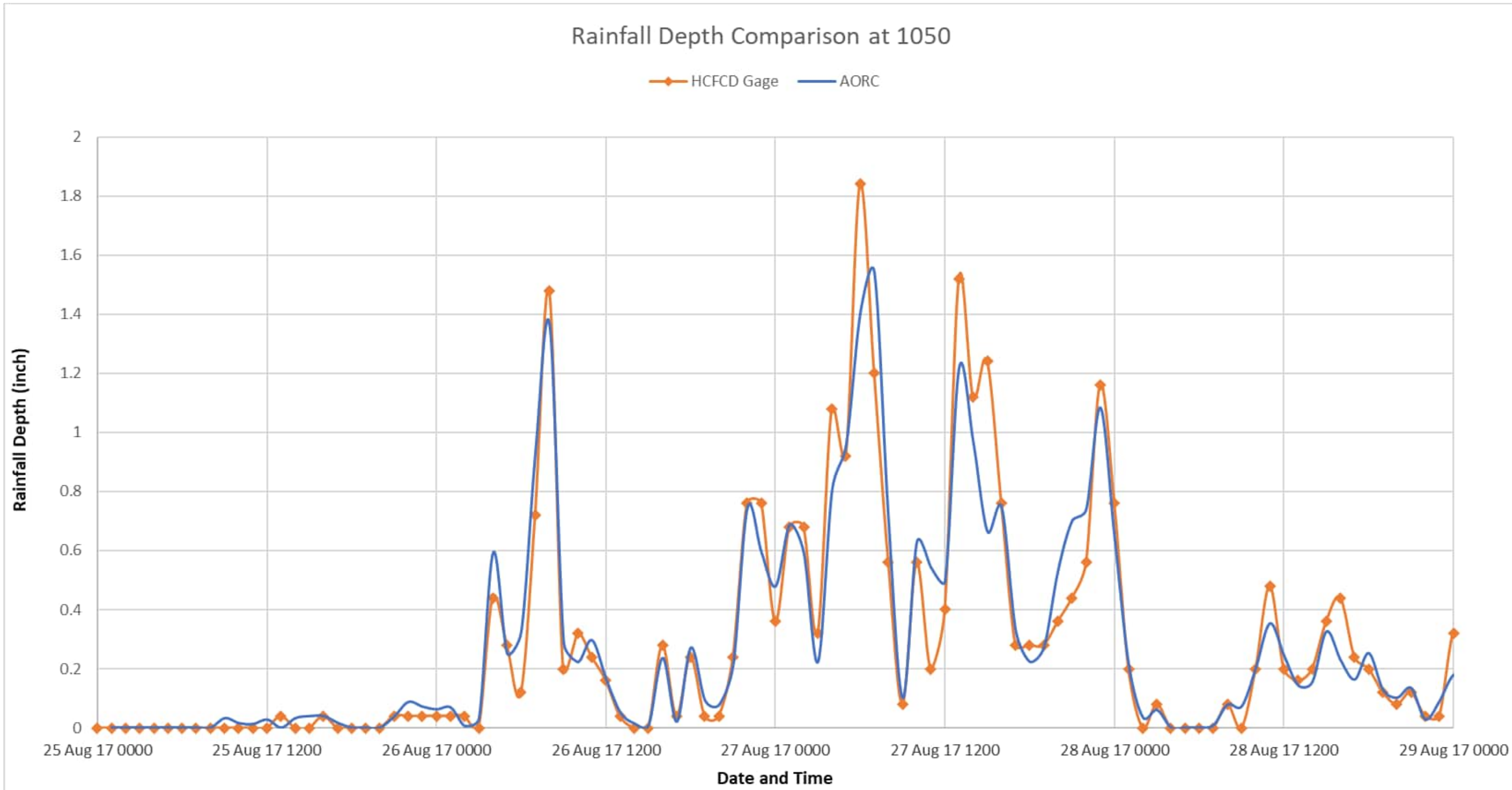

Figure 14: Rainfall Depth Comparison for Hurricane Harvey between Harris County Flood Control District gage data and Analysis of Record for Calibration (AORC) data

4.4 Baseline Scenario Model Development

After the model had been satisfactorily calibrated to Harvey, the model was deemed fine-tuned to represent the current conditions of the watershed. The same calibrated model geometry with fine-tuned hydraulic parameters like Manning's roughness coefficient, rainfall loss methods, etc., was used to create the baseline model to run design events for 1% and 10% AEPs. The existing condition terrain, LULC data, soil data, infiltration data, and outflow boundary conditions are kept the same as the calibrated model, while design rainfall for 1% and 10% AEPs were extracted from the HCFCD fluvial model. Please refer to Sections **3.1.1.2** for details on design precipitation. Similarly, the inflow boundary conditions from tributaries Willow Creek and Cypress Creek for 1% and 10% AEPs were incorporated as discussed in detail in Section **4.2.4.2**.

4.5 Subsidence without Future Development Scenario Model Development

The baseline pluvial model was converted to the SWFD pluvial model by incorporating the 2070 projected subsidence terrain instead of the baseline (existing 2020) terrain. All the hydraulic structures (and associated features like bridge deck, piers, culvert inverts, aprons, etc.) were lowered based on subsidence projections. **Figure 15** shows the comparison of the baseline and subsided structure at the Grand Parkway Bridge across Spring Creek. Similarly, the inflow boundary conditions from tributaries Willow Creek and Cypress Creek for 1% and 10% AEPs were incorporated as discussed in detail in Section **4.2.4.2**. All other input parameters, like LULC data, soil data, infiltration data, and outflow boundary conditions, are kept the same as the baseline model, along with the design rainfall for 1% and 10% AEPs.

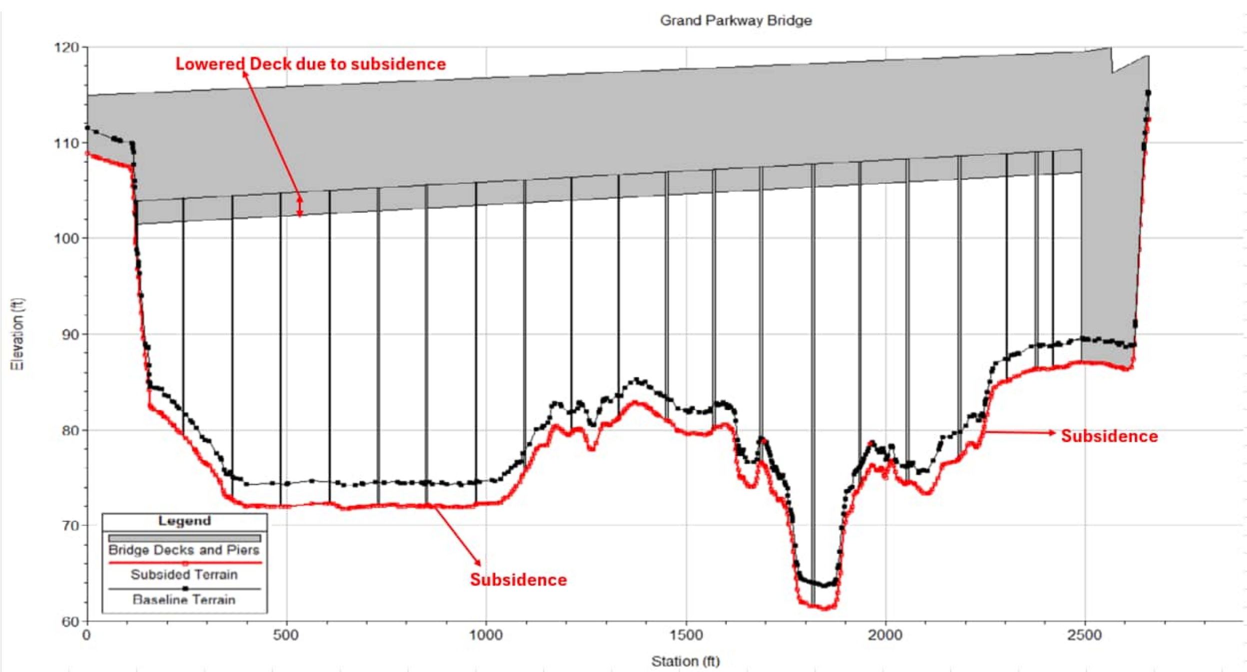

Figure 15: Cross-sectional view of Grand Parkway Bridge showing the Effects of Subsidence on the Roadway, Bridge Decks, Pier, and Bathymetry Elevations between Baseline and Subsidence without Future Development Scenario

4.6 Subsidence with Future Development Scenario Model Development

The SWFD pluvial model was converted to the SFD pluvial model by incorporating 2070 projected LULC data instead of the baseline (existing 2020) LULC. The 2070 projected LULC is discussed in detail in Section **3.1.4.2**. Similarly, the inflow boundary conditions from tributaries Willow Creek and Cypress Creek for 1% and 10% AEPs were incorporated as discussed in detail in Section **4.2.4.2**. All other input parameters like subsidence terrain, soil data, infiltration data, and outflow boundary conditions, are kept the same as the SWFD model along with the design rainfall for 1% and 10% AEPs.

5 Conclusion

Hydrologic and hydraulic model was developed to assess flood risks and impacts due to land subsidence in the Spring Creek watershed. A pluvial modeling approach, which covers the entire watershed, was developed based on the Rain-on-Mesh methodology. The modeling approach had three scenarios: Baseline, Subsidence without future development, and Subsidence with future development scenarios. The baseline model represents the existing conditions (year 2020) of a watershed, which includes data on current topography, land use, precipitation, and infrastructure, providing a benchmark for comparing subsidence scenario models. The Subsidence without future development model was developed based on the Baseline scenario by incorporating the 2070 projected subsidence terrain, and structures were subsided based on subsidence projections. Hence, the SWFD model represents the condition of subsidence within the watershed for the year 2070 without considering any future development. The SFD model was developed using both the subsidence terrain as well as the 2070 projected LULC data to depict the subsidence with future development conditions.

The model also includes two events for calibration and validation (Harvey-2017 and Beryl-2024). Both modeled peak stage and peak discharge were found to be within 20% of the observed data for more than 80% gages (HCFCD and USGS). The model was also checked with Hurricane Beryl data and found to perform satisfactorily. Since the model was calibrated for Hurricane Harvey, which was an approximately 500-year storm event for the watershed, while Hurricane Beryl was a 10-year event, the model results generally show an overestimation of the Beryl model results. However, the model results are still within the calibration criteria set in this model study. Overall, the pluvial model is well-calibrated based on the observed storm events, which is important for increasing model reliability in predicting flood risk changes due to subsidence and future development.

The subsidence and as well as future development show changes in model hydrology independently as well as collectively. The change in hydrology due to subsidence is evident in the increase in flows, which in turn affects the hydraulics of the watershed. The change in hydraulics affects the water surface elevation, which in turn affects flooding and thus causes economic consequences in the watershed. Due to projected subsidence in 2070, the projected change in channel/overland slope upstream of the watershed to Kuykendahl Road is higher than that of the slope towards the east of Kuykendahl Road to the outlet of the watershed at the downstream end. These differential changes in slope lead to an increase in velocity towards Kuykendahl Road, while the flattening of the slope east of Kuykendahl Road decreases the velocity, resulting in increased water surface elevation. This leads to an increase in flood risk in the eastern part of the watershed (east of Kuykendahl Road), where the population is projected to increase more in the watershed. This potentially leads to an increase in the vulnerable population to flood risk in the future. The detailed analysis of hydraulic, flood, and economic impacts is discussed in Technical Memorandum #3: Hydraulic and Economic Impact Assessment for Subsidence Scenarios.

6 References

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Appendix A: Supporting Document and Tables

Appendix A1: Pluvial Model – Parameters for Hydraulic Component

Bridge Modeling approach: The bridge modeling approach consists of the highest energy answer between Energy (Standard Step) and Momentum for low flow, and Pressure and/or Weir with Submerged Inlet + Outlet Cd for high flows, as shown in **Figure 1**. The coefficient of drag (Cd) for the momentum equation was based on the shape of the piers and the look-up table in the HEC-RAS manual. Two types of piers were present – circular with a Cd of 1.2 and square with a Cd of 2. The Submerged inlet + Outlet Cd is the HEC-RAS default value of 0.8.

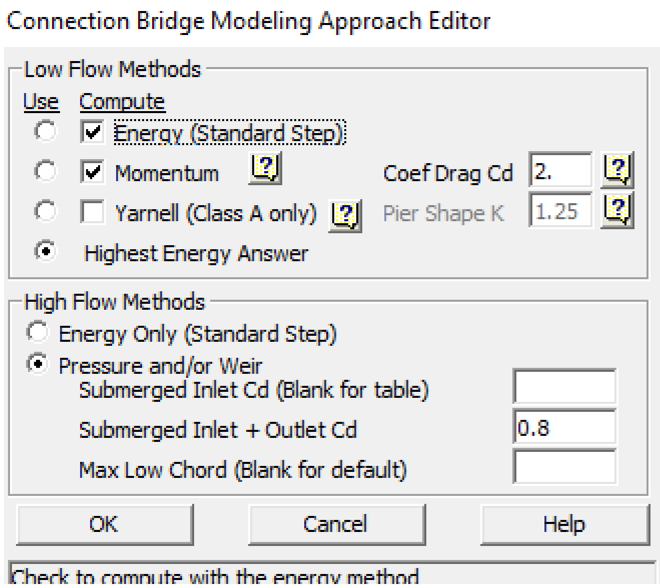


Figure 1: SA/2D Bridge Modeling Approach Details

Weir Coefficient and Max Submergence: The weir coefficient used for the bridges varies between 2.6-3.0, and the maximum submergence is 0.95. These values can be found in the deck/roadway editor of the SA/2D connections, as shown in **Figure 2**. The broad-crested weir shape was selected for the weir. For culverts, these data can be found in the weir/embankment data of the SA/2D connection. These values are consistent in all bridges in the model.

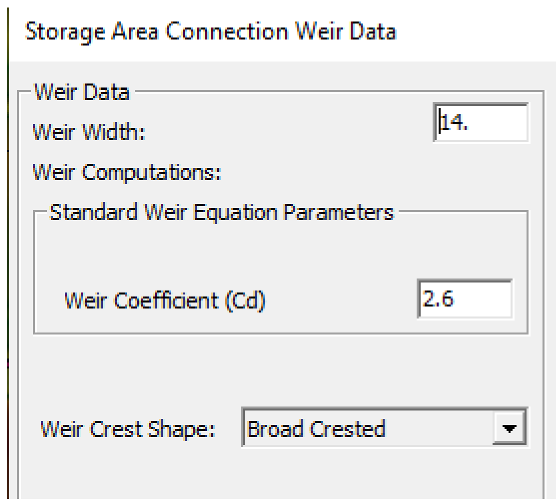


Figure 2: Weir Coefficient for SA/2D Connections

The deck and sloping abutment information for the bridges were obtained from the HCFCD model and incorporated within the SA/2D connections. **Figure 3** shows how the deck data was incorporated into the model.

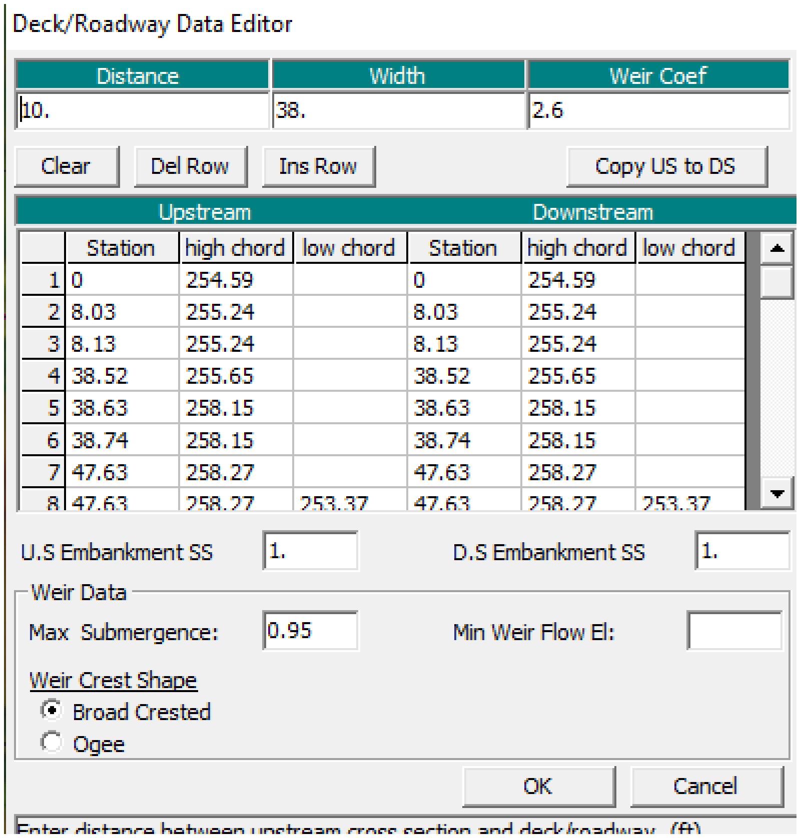


Figure 3: Bridge Deck data and other relevant data for SA/2D Bridge connection

Contraction and Expansion Losses: The losses associated with contracted flow through the bridge are represented by a contraction coefficient of 0.3. The losses associated with expansion are represented by an expansion coefficient of 0.5.

Manning's n in Bridge Cross Sections: Manning's n in the internal bridge cross sections is defined based on the underlying land cover. Currently, these values are set at a value of 0.05 for all bridges and culverts at the start and then calibrated to appropriate values through different trials.

Hydraulic Property Table Parameters: The hydraulic property table parameters are used for the SA/2D connections to define the number of points on the free flow curve, the number of submerged curves, and the number of points on each submerged curve for the connections. The following numbers were used for all the SA/2D connections as shown in the figure.

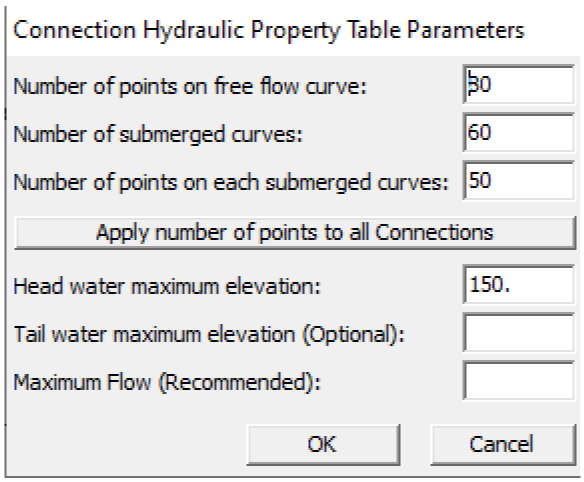


Figure 4: Hydraulic Property Table used for SA/2D connections

Appendix A2: Pluvial Model – Calibration Data Summary

Peak Stage Difference Summary Table

Gage Number	Location	Datum Adjustment applied	Storm Event				Error Percentage	
			Harvey 2017		Beryl 2024		Storm Event	
		NAVD88, 2001 to Geoid12b	Measured*	Modeled	Measured*	Modeled	Harvey 2017	Beryl 2024
USGS 8068390	Bear Br at Research Blvd, The	-0.012	140.26	142.59	138.43	137.93	1.7	0.4
USGS 8068400	Panther Br at Gosling Rd, The	-0.011	137.48	139.83	135.32	134.65	1.7	0.5
USGS 8068500	Spring Ck nr Spring, TX	-0.026	111.49	116.86	87.35	97.91	4.8	12.1
USGS 8068275	Spring Ck nr Tomball, TX	-0.039	165.61	167.08	148.11	152.20	0.9	2.8
USGS 8068450	Panther Br nr Spring, TX	-0.023	117.10	123.81	107.44	108.41	5.7	0.9
HCFCD 1074	Walnut Creek at Joseph Road	-0.006	225.59	230.79	218.89	222.76	2.3	1.8
HCFCD 1090	Spring Creek at Hegar Road	-0.015	223.04	222.90	212.93	217.03	0.1	1.9
HCFCD 1086	Threemile Creek at FM 362	-0.004	272.87	274.36	268.72	273.08	0.5	1.6
HCFCD 1084	Threemile Creek at Joseph Road	-0.004	242.10	244.09	238.30	241.49	0.8	1.3
HCFCD 1076	Birch Creek at Riley Road	-0.007	263.56	264.04	259.11	260.75	0.2	0.6
HCFCD 1060	Spring Creek at Kuykendahl Road	-0.02	140.86	143.61	121.60	125.04	2.0	2.8
HCFCD 1050	Spring Creek at I-45	-0.026	111.43	117.51	87.35	98.67	5.5	13.0
HCFCD 1040	Spring Creek at FM 2978	-0.037	154.26	155.96	136.06	140.91	1.1	3.6
HCFCD 1070	Spring Creek at SH 249	-0.039	166.41	166.65	148.09	152.64	0.1	3.1
Total Gages	**14**		**Within 5%**				**86%**	
Total Storms	**2**		**Within 10%**				**93%**	
No Data	**0**		**Within 20%**				**100%**	
Data Points	**28**		**Greater than 20%**				**0%**	

*Datum adjustment applied

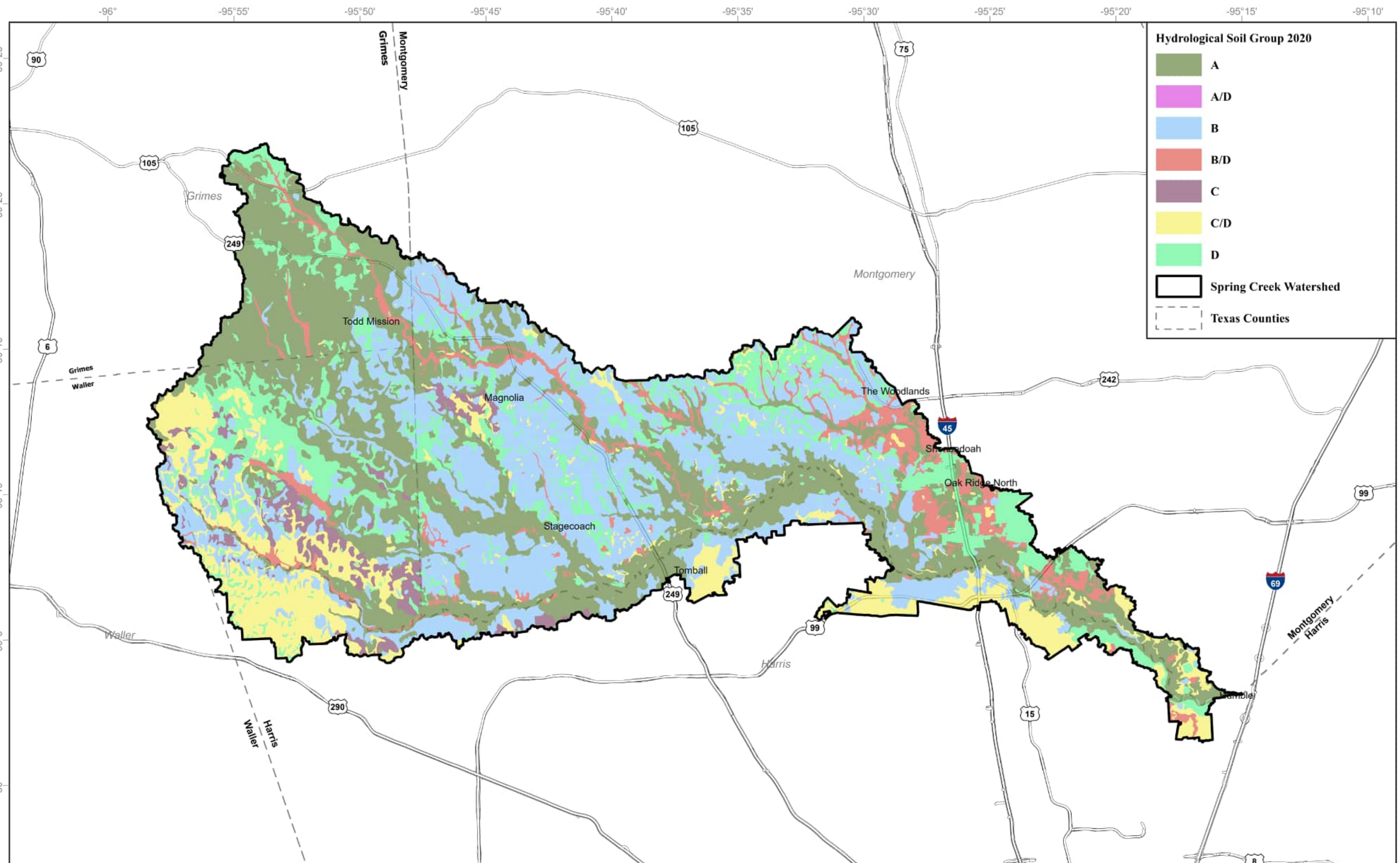
Peak Flow Difference Summary Table

Gage Number	Location		Harvey 2017		
			Measured	Modeled	Error Percentage
USGS 8068390	Bear Br at Research Blvd, The		3660	4009	9.5
USGS 8068400	Panther Br at Gosling Rd, The		6300	8487	34.7
USGS 8068500	Spring Ck nr Spring, TX		78400	70896	9.6
USGS 8068275	Spring Ck nr Tomball, TX		48900	47410	3.0
USGS 8068450	Panther Br nr Spring, TX		12500	11462	8.3
Total Gages	**5**		**Within 5%**		**20%**
Total Storms	**1**		**Within 10%**		**80%**
No Data	**0**		**Within 20%**		**80%**
Data Points	**5**		**Greater than 20%**		**20%**

Time to Peak Difference Summary Table

Gage Number	Location	Storm Event				Error Percentage	
		Harvey 2017		Beryl 2024		Storm Event	
		Measured	Modeled	Measured	Modeled	Harvey 2017	Beryl 2024
USGS 8068390	Bear Br at Research Blvd, The	28Aug2017 0045	27Aug2017 1645	08Jul2024 1030	08Jul2024 1445	8.0	4.3
USGS 8068400	Panther Br at Gosling Rd, The	28Aug2017 0045	27Aug2017 1730	08Jul2024 1200	08Jul2024 1645	7.3	4.8
USGS 8068500	Spring Ck nr Spring, TX	28Aug2017 2015	28Aug2017 0830	08Jul2024 1215	9Jul2024 0915	11.8	9.0
USGS 8068275	Spring Ck nr Tomball, TX	28Aug2017 0300	27Aug2017 1815	09Jul2024 0230	09Jul2024 2315	8.8	20.8
USGS 8068450	Panther Br nr Spring, TX	28Aug2017 1845	28Aug2017 0515	08Jul2024 1045	09Jul2024 0430	13.6	17.8
HCFCD 1086	Threemile Creek at FM 362	27Aug2017 0537	26Aug2017 2200	08Jul2024 2116	08Jul2024 1215	7.5	9.0
HCFCD 1084	Threemile Creek at Joseph Road	27Aug2017 0958	27Aug2017 0330	08Jul2024 1400	08Jul2024 2215	6.5	8.3
HCFCD 1076	Birch Creek at Riley Road	27Aug2017 0259	27Aug2017 0245	08Jul2024 1146	08Jul2024 1115	0.3	0.5
HCFCD 1060	Spring Creek at Kuykendahl Road	28Aug2017 1016	28Aug2017 0115	10Jul2024 0546	10Jul2024 1345	9.0	8.0
HCFCD 1050	Spring Creek at I-45	28Aug2017 1950	28Aug2017 0830	08Jul2024 1216	8Jul2024 2100	11.3	8.8
HCFCD 1040	Spring Creek at FM 2978	28Aug2017 0430	27Aug2017 2315	09Jul2024 1442	10Jul2024 0515	4.8	9.3
HCFCD 1070	Spring Creek at SH 249	28Aug2017 0311	27Aug2017 1815	09Jul2024 0230	09Jul2024 2315	8.8	20.8
Total Gages	**12**		**Within 6 hrs**			**21%**	
Total Storms	**2**		**Within 9 hrs**			**71%**	
No Data	**0**		**Within 12 hrs**			**83%**	
Data Points	**24**		**Greater than 12 hrs**			**17%**	

Appendix B: Exhibits



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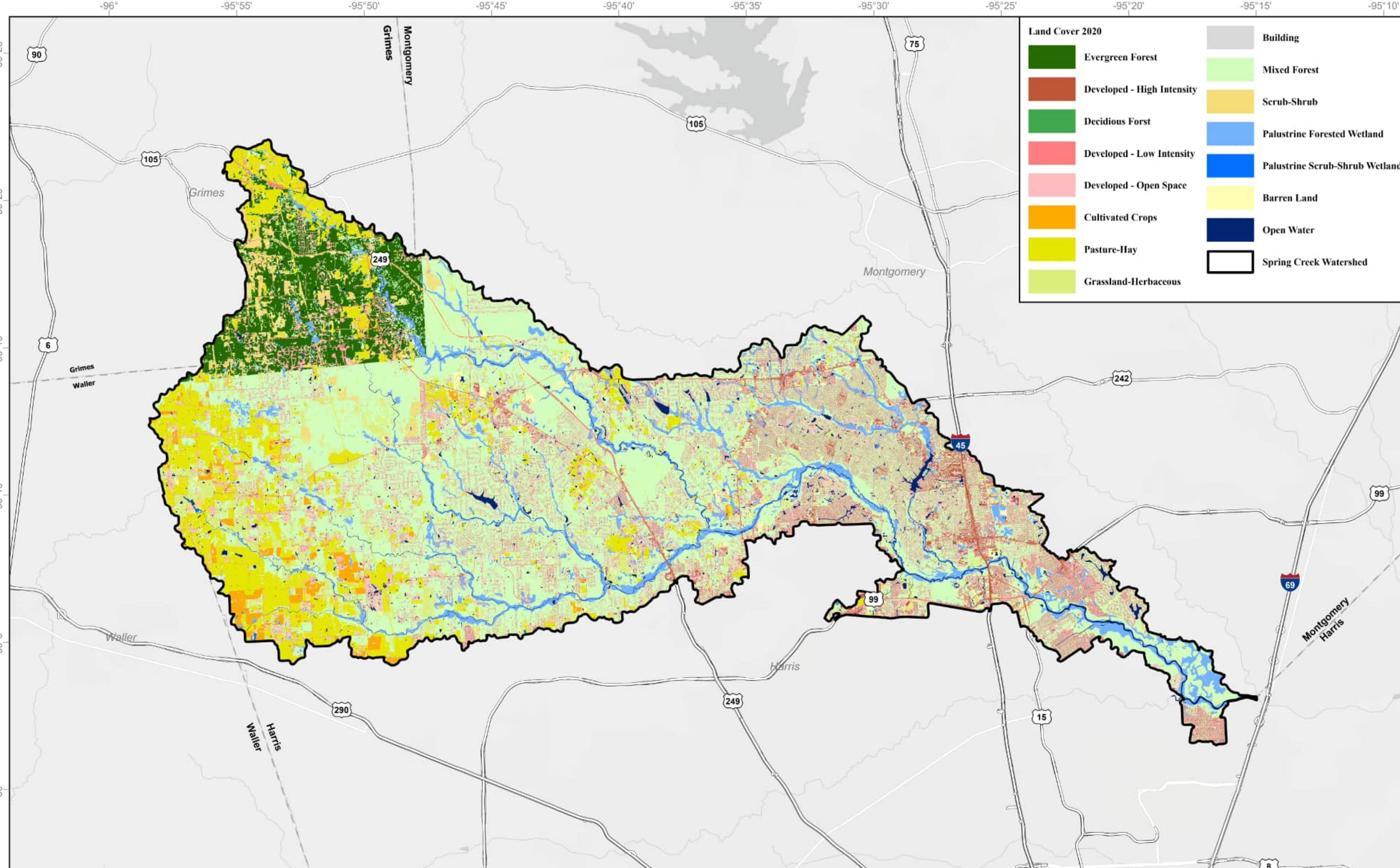
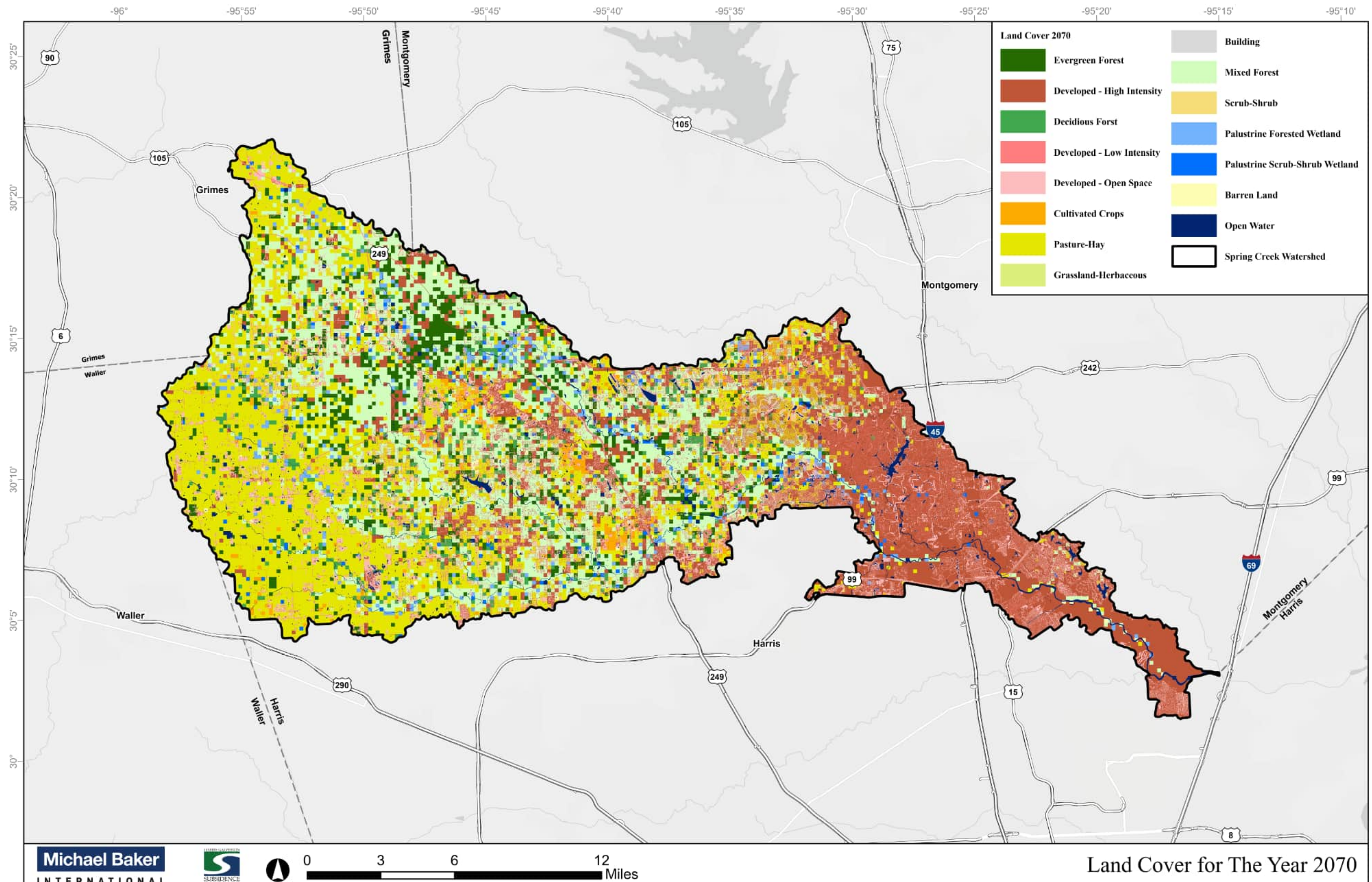
Hydrological Soil Group 2020



Land Cover for The Year 2020



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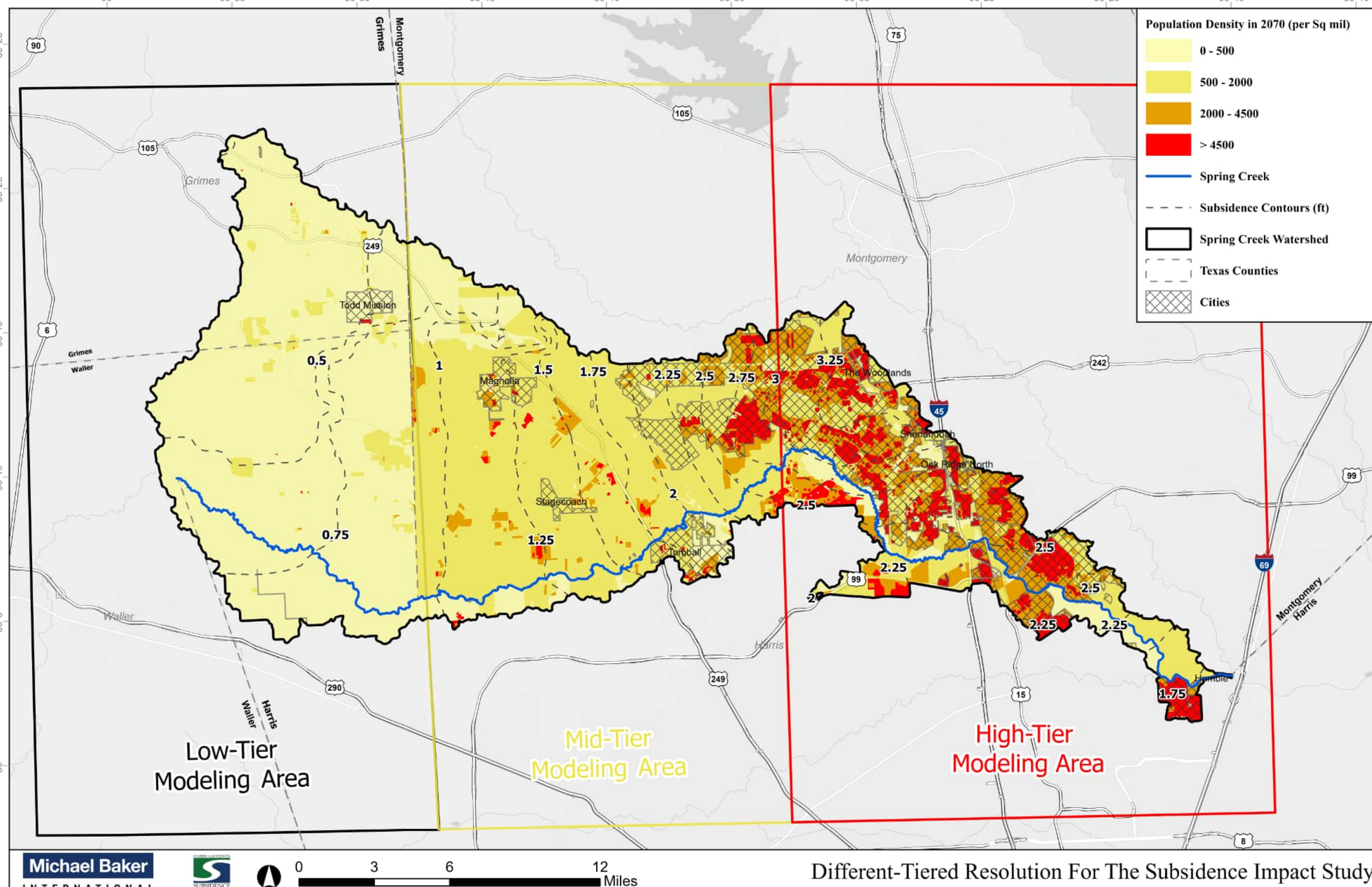
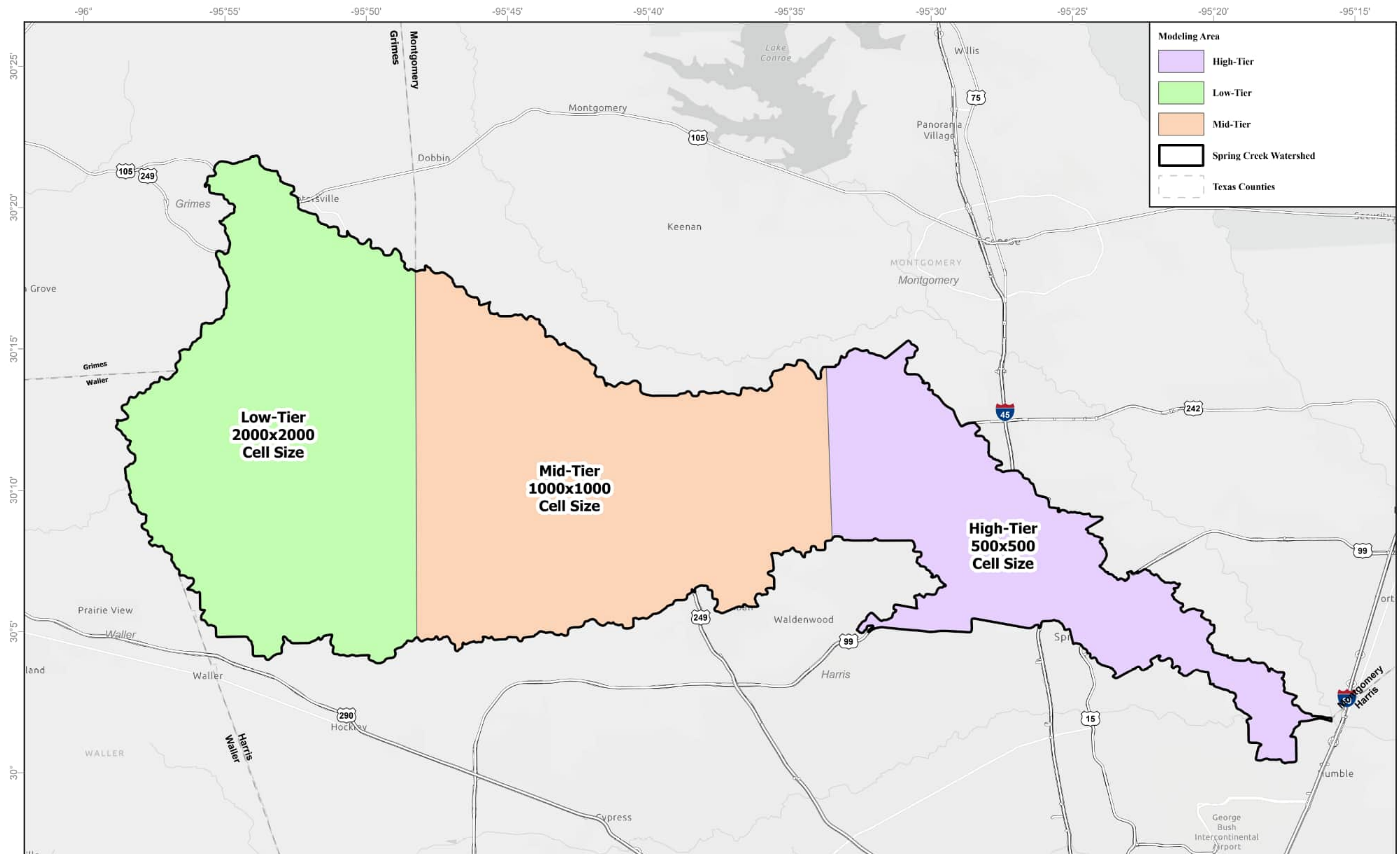
Land Cover for The Year 2070



Different-Tiered Resolution For The Subsidence Impact Study



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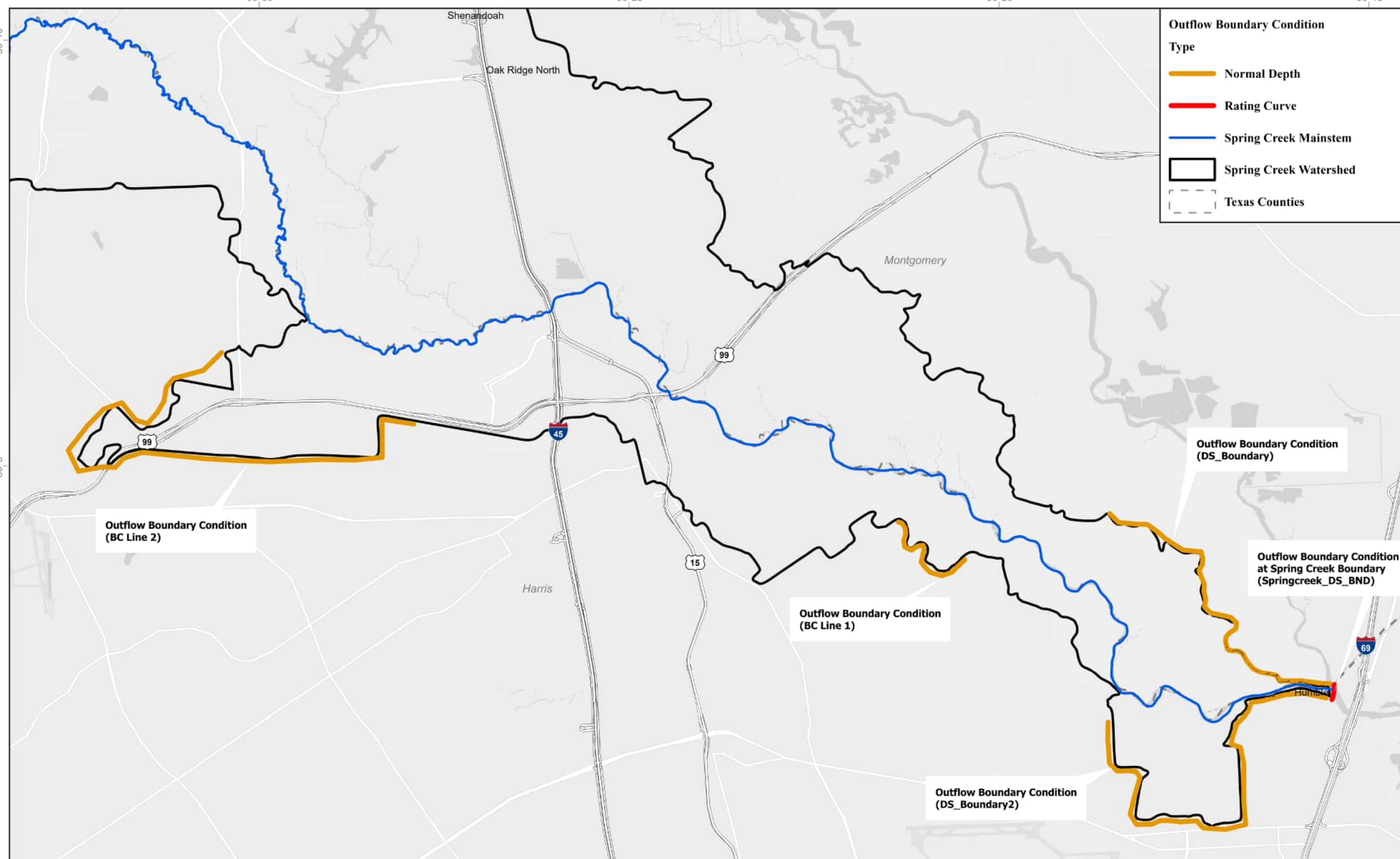
0 3.08 6.15 12.3 Miles

Pluvial Model Refinement Region (Mesh Size) Details



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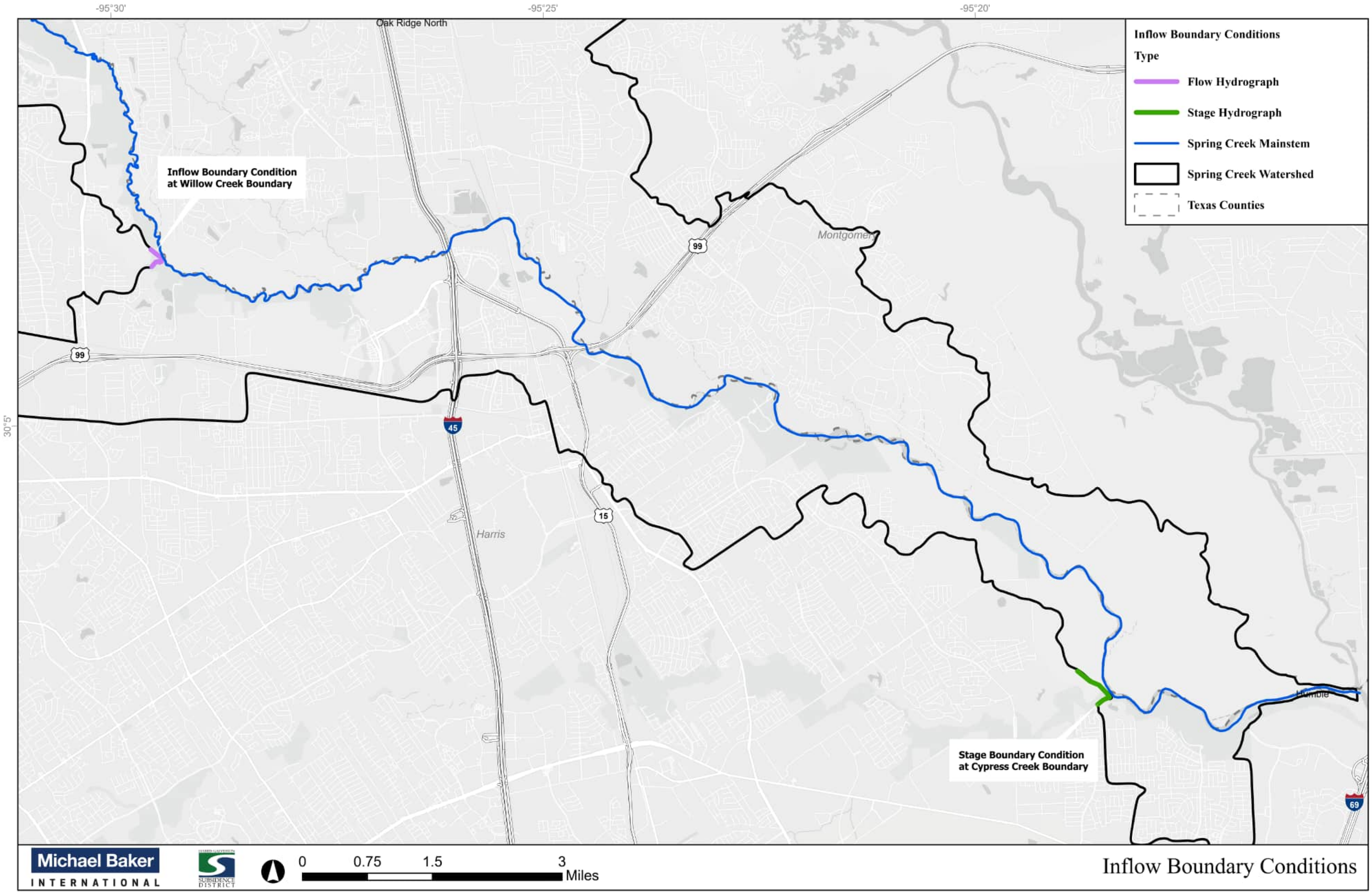
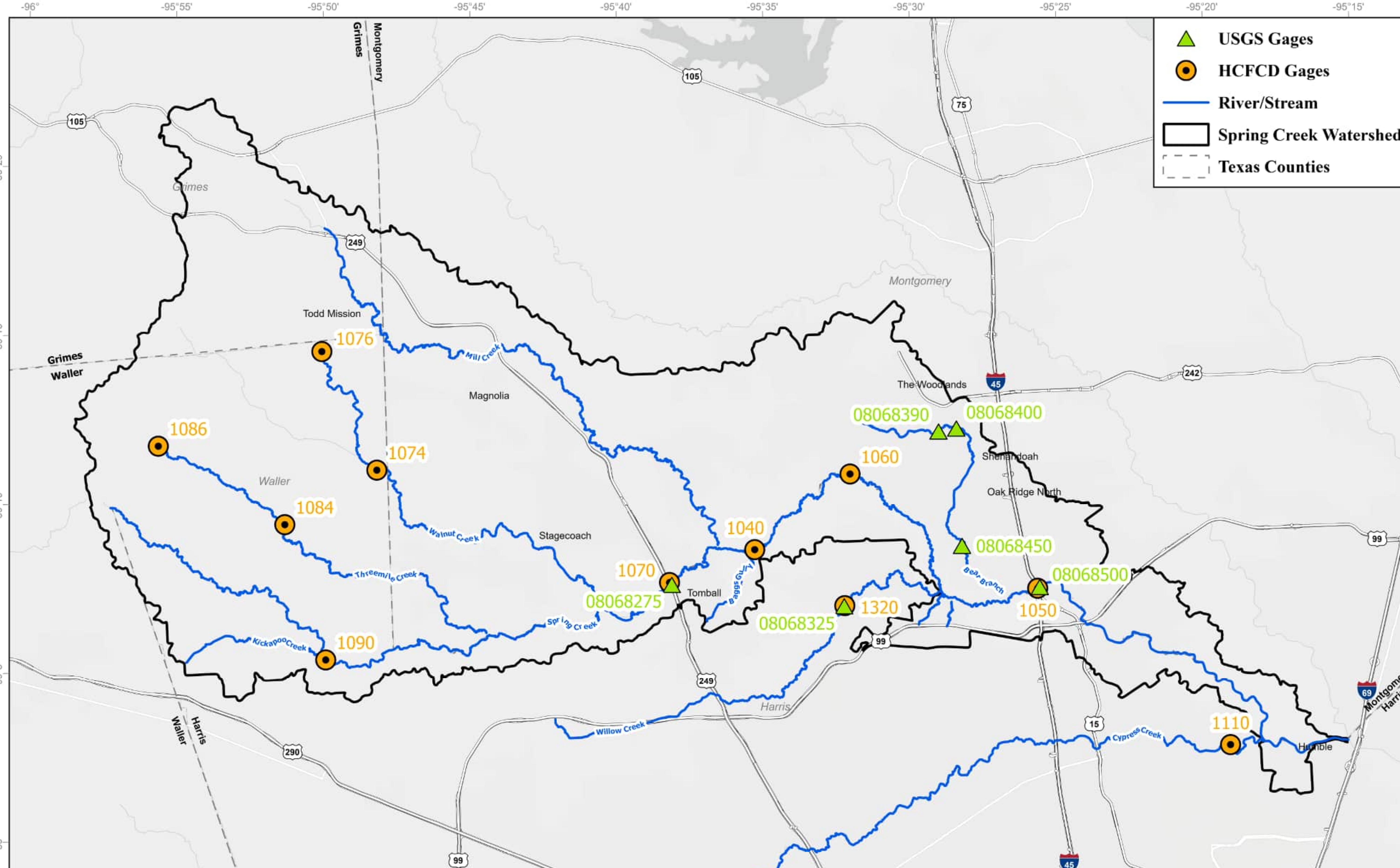
Outflow Boundary Conditions


-95°30'
-95°25'
-95°20'
30°5'
Oak Ridge North
Inflow Boundary Conditions
Type
Flow Hydrograph
Stage Hydrograph
Spring Creek Mainstem
Spring Creek Watershed
Texas Counties
Inflow Boundary Condition
at Willow Creek Boundary
Montgomery
Harris
Humble
99
45
15
69
Stage Boundary Condition
at Cypress Creek Boundary
Michael Baker
INTERNATIONAL
0
0.75
1.5
3
Miles
Inflow Boundary Conditions



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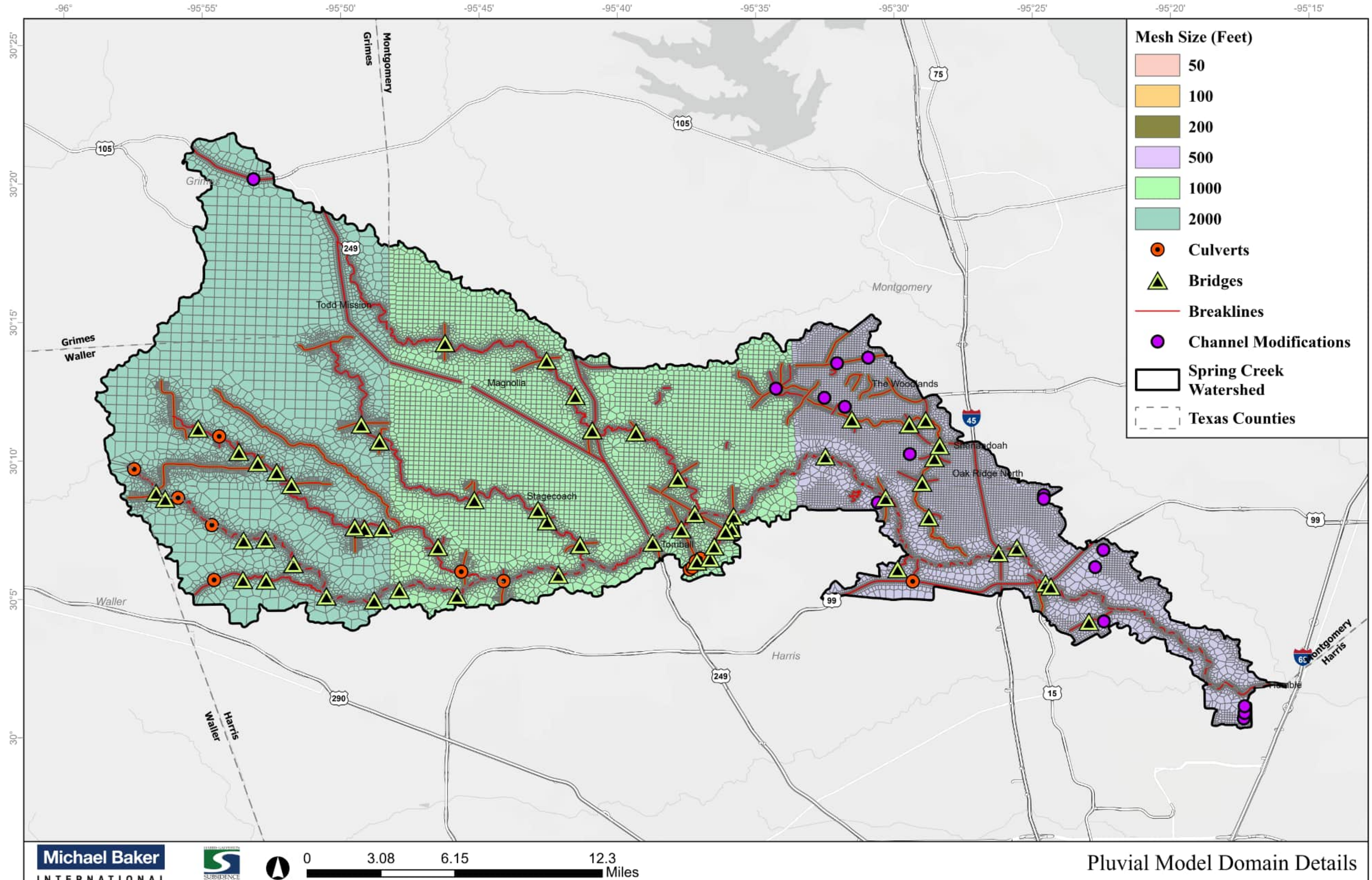
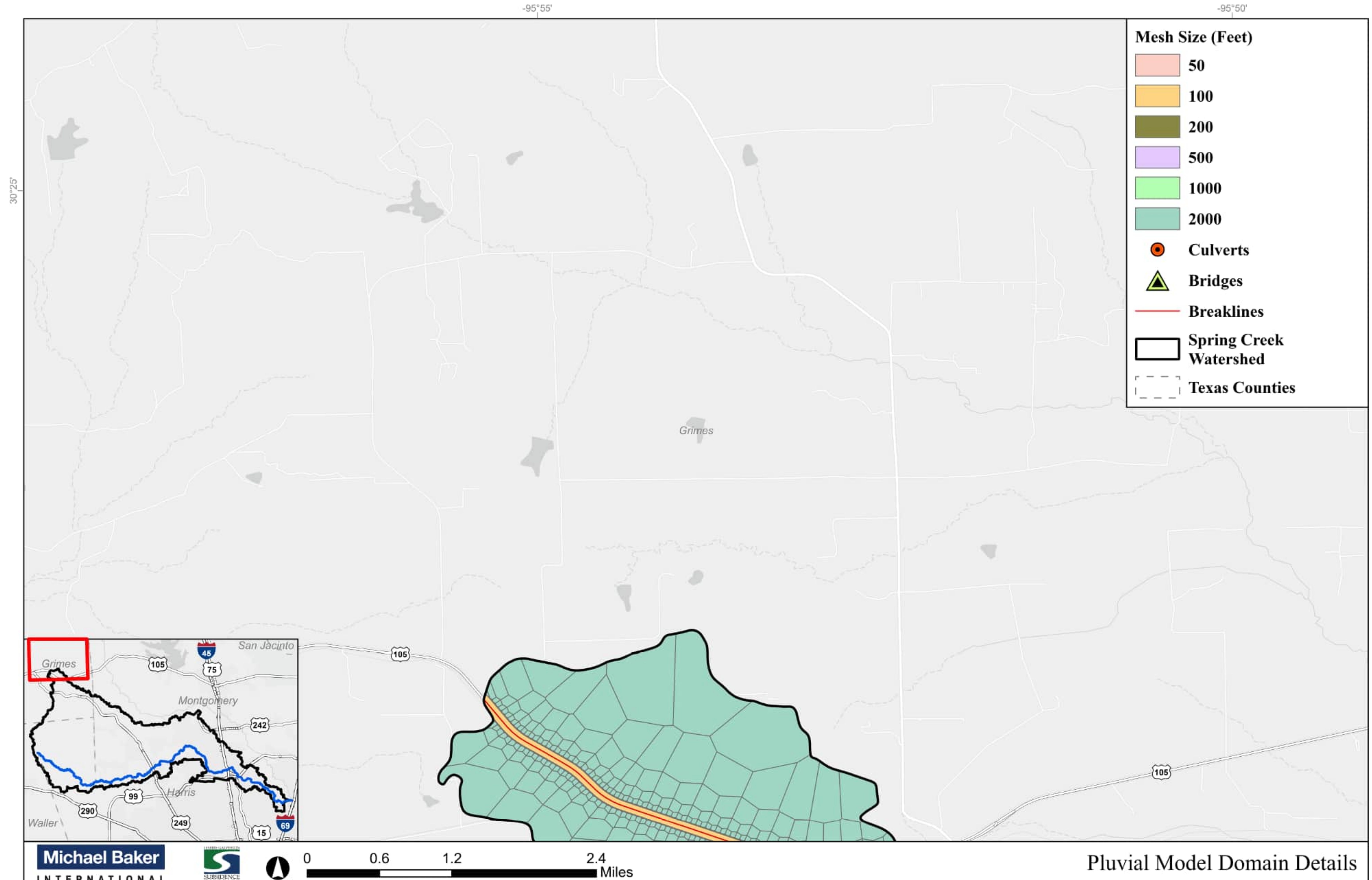
Location of Calibration Gages



Pluvial Model Domain Details



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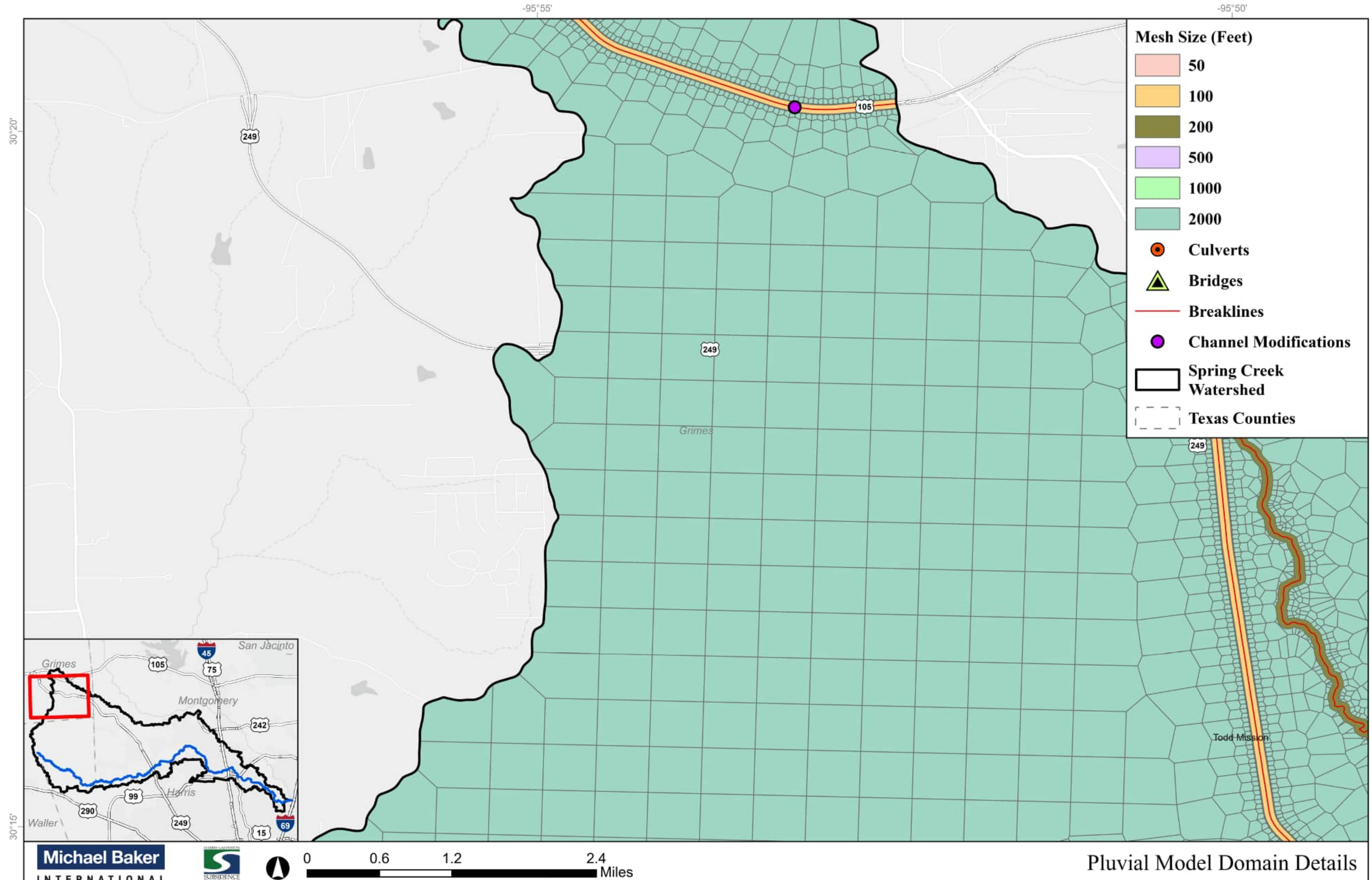

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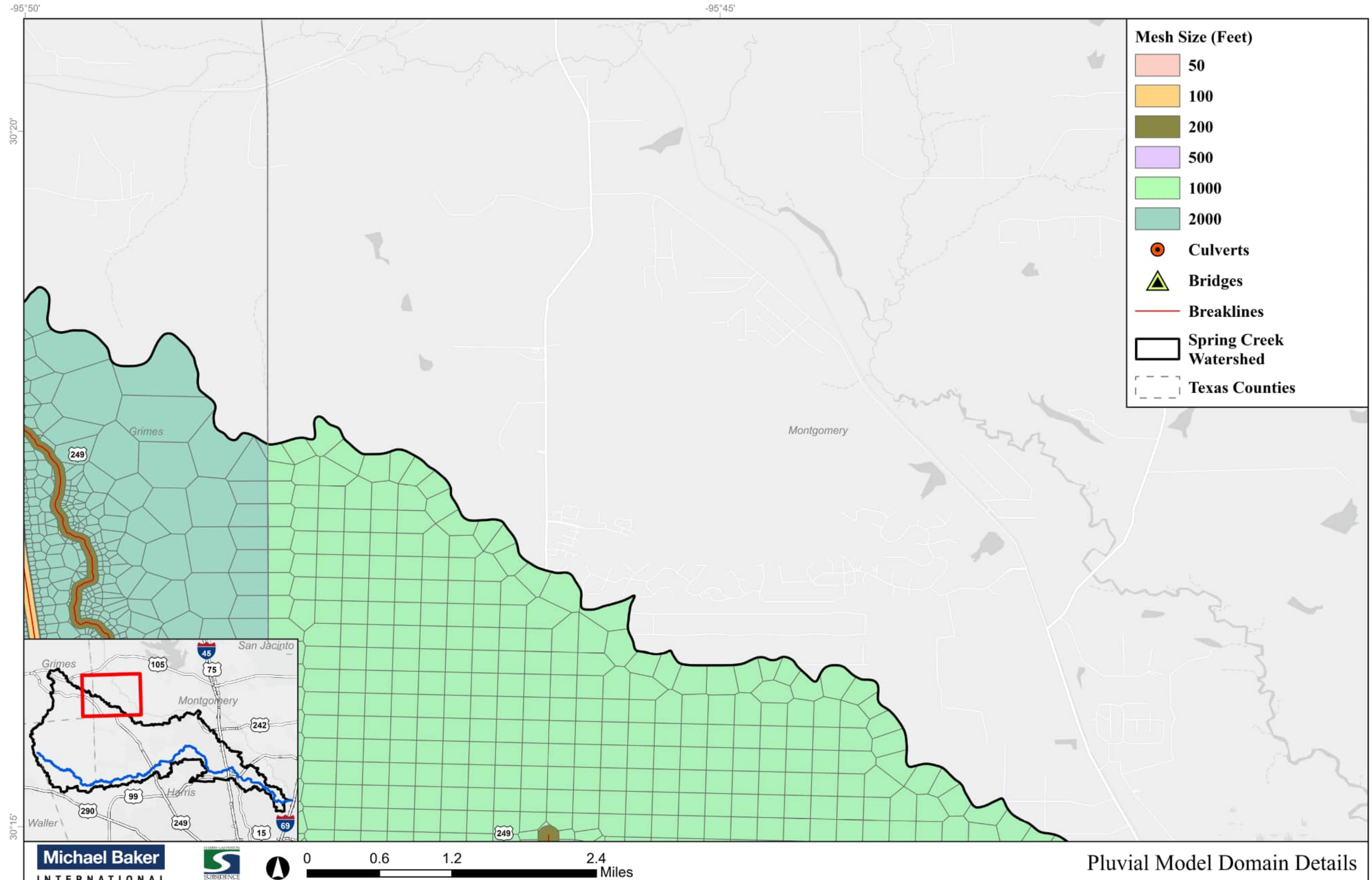

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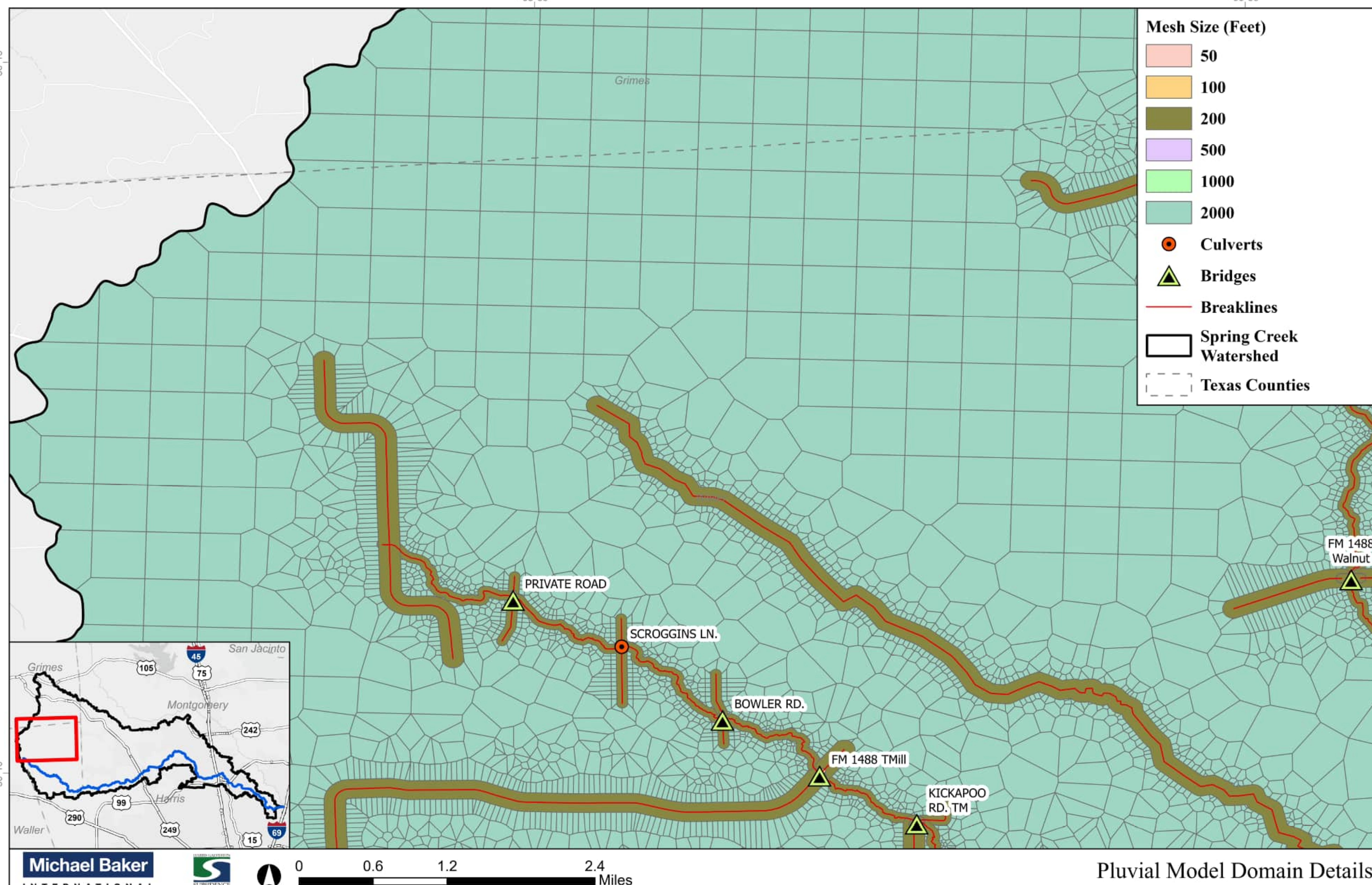

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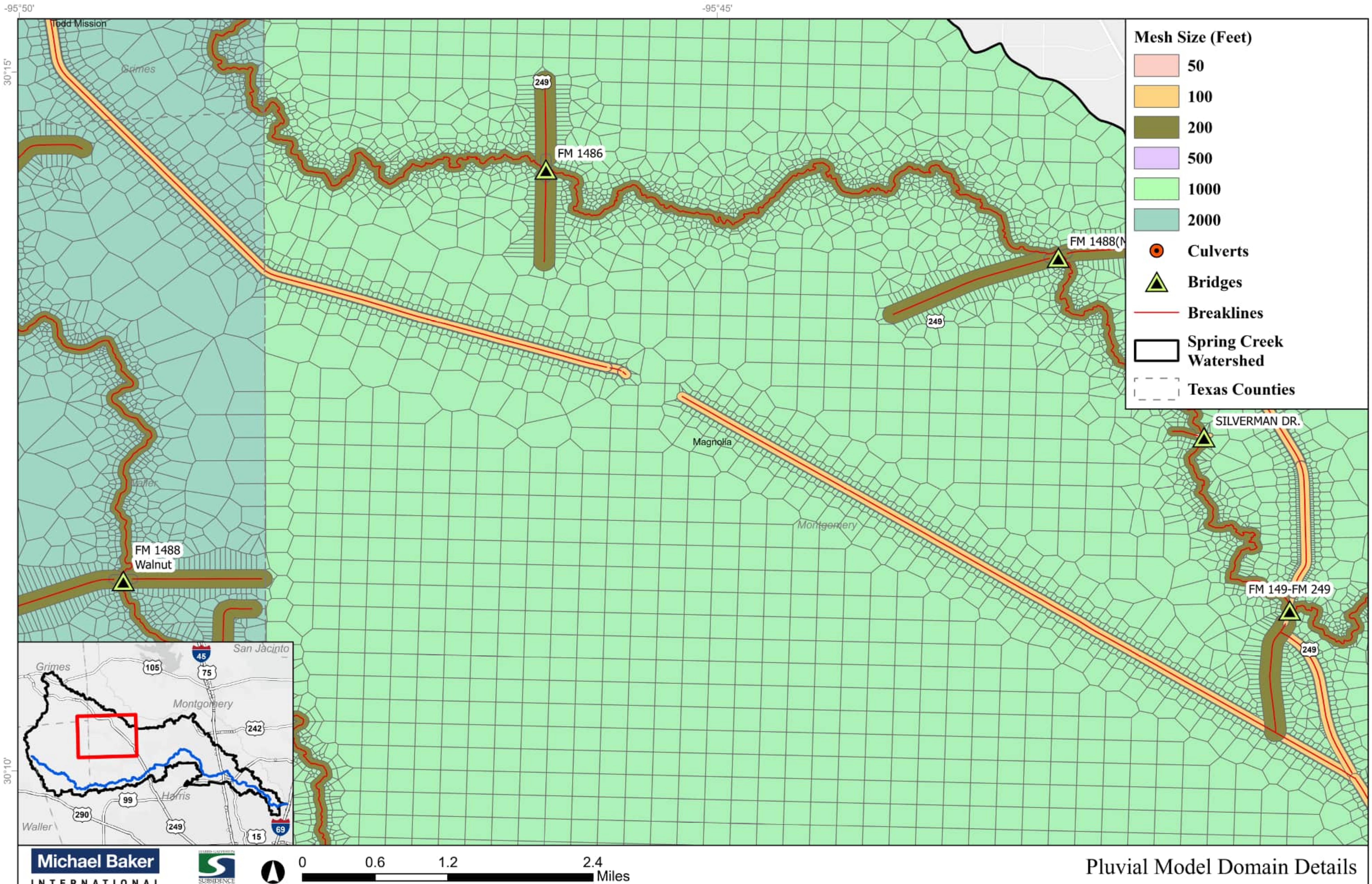
Pluvial Model Domain Details



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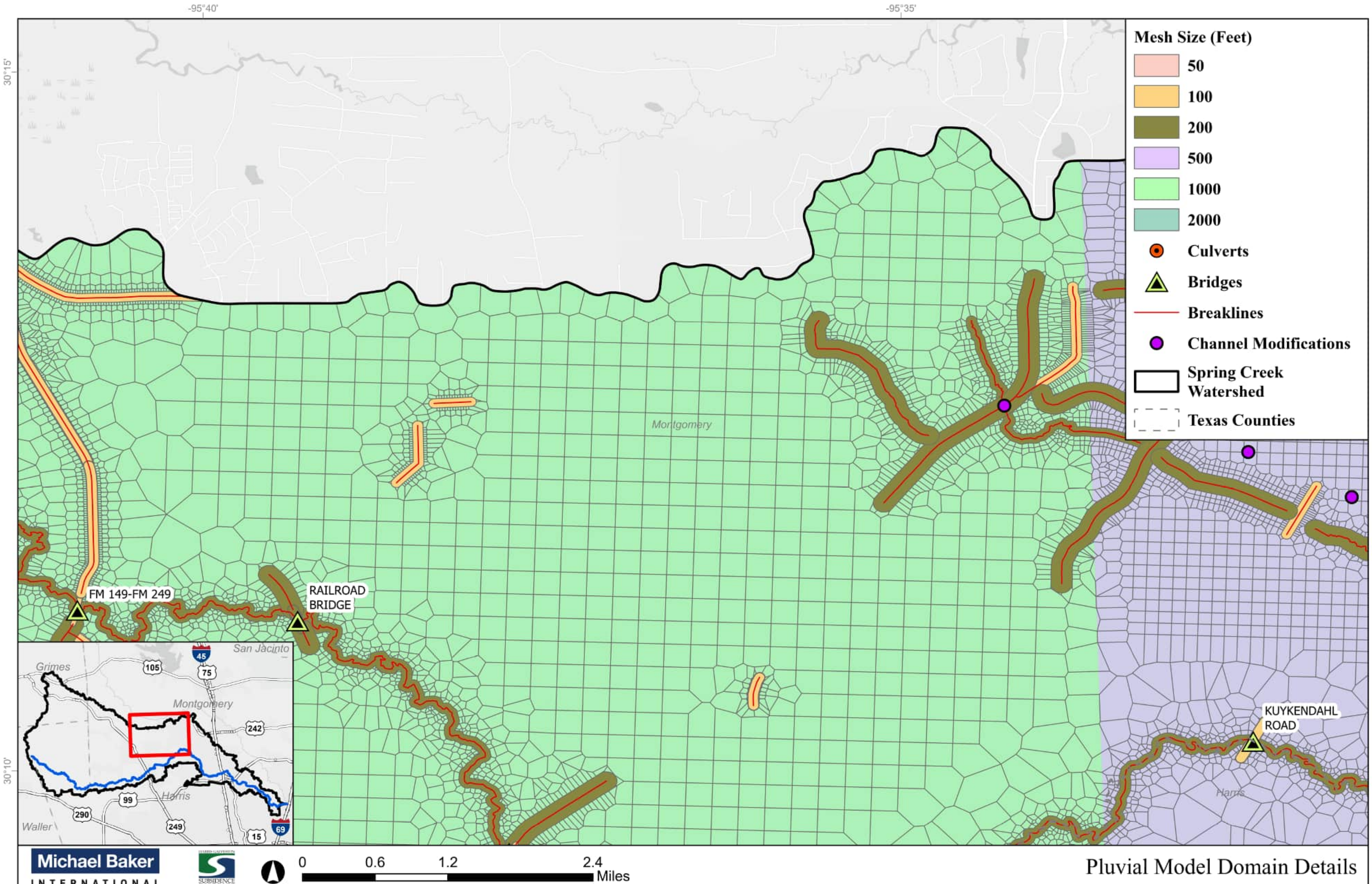
HARRIS-GALVESTON SUBSIDENCE DISTRICT

Pluvial Model Domain Details



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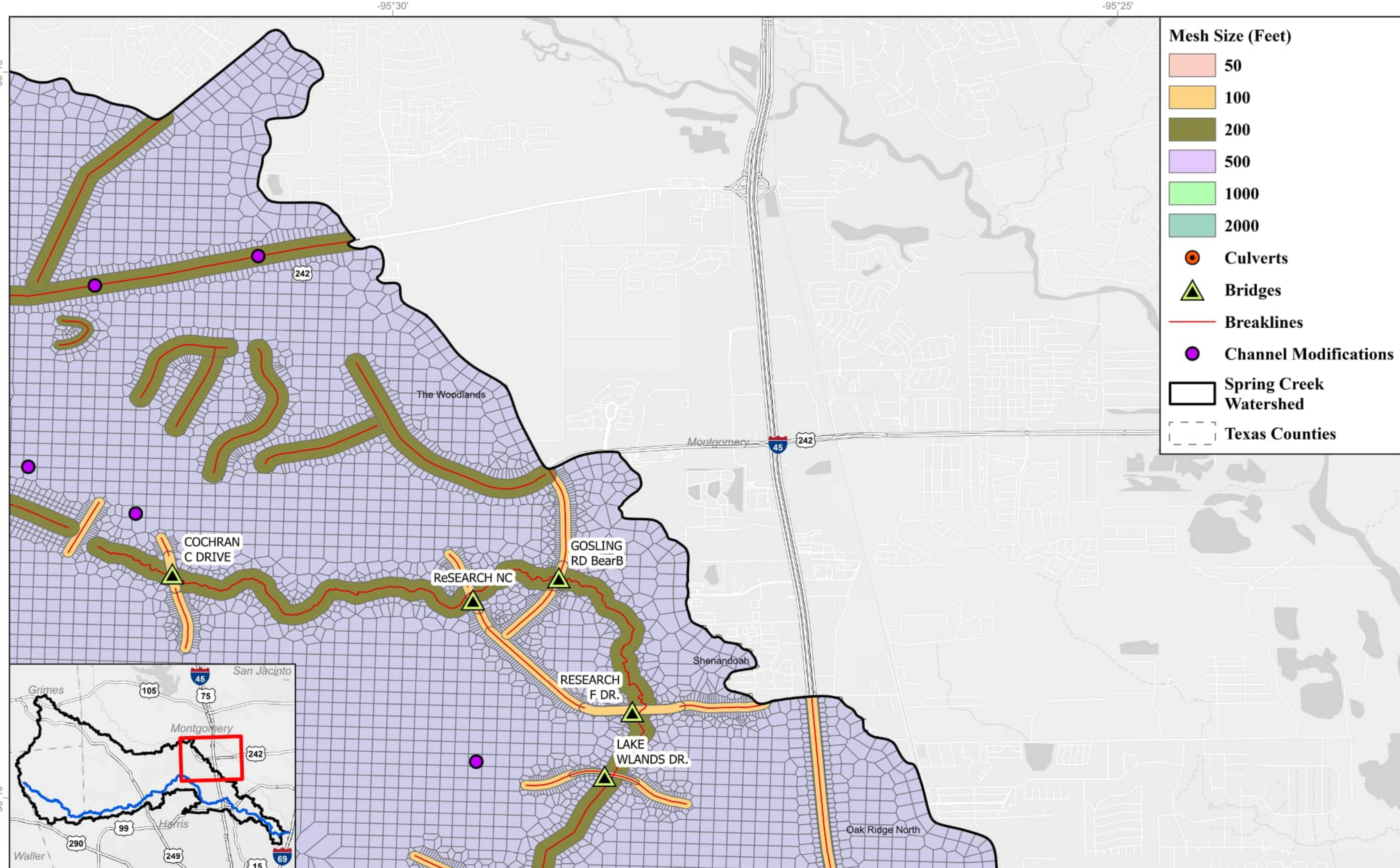

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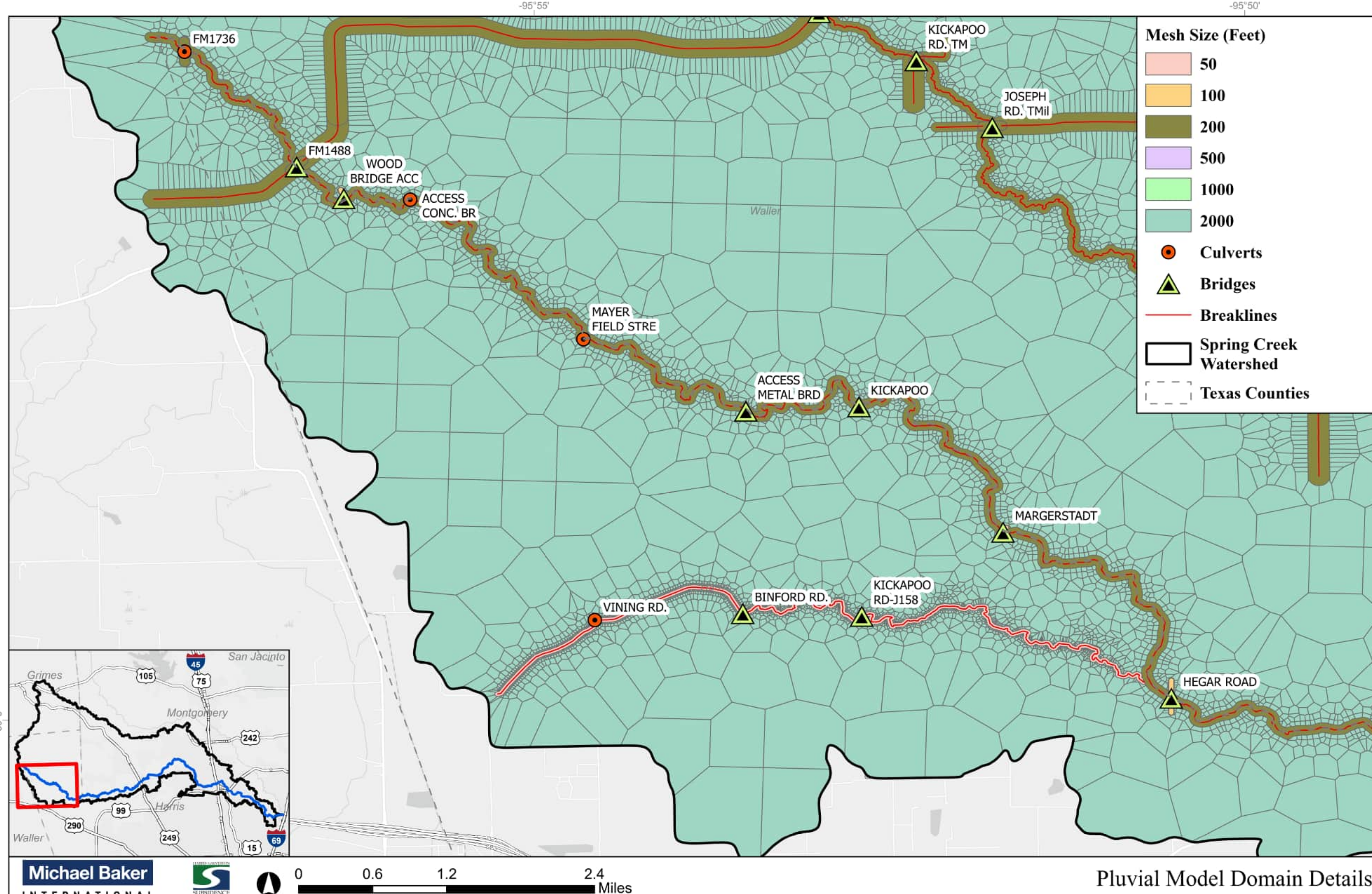
Pluvial Model Domain Details



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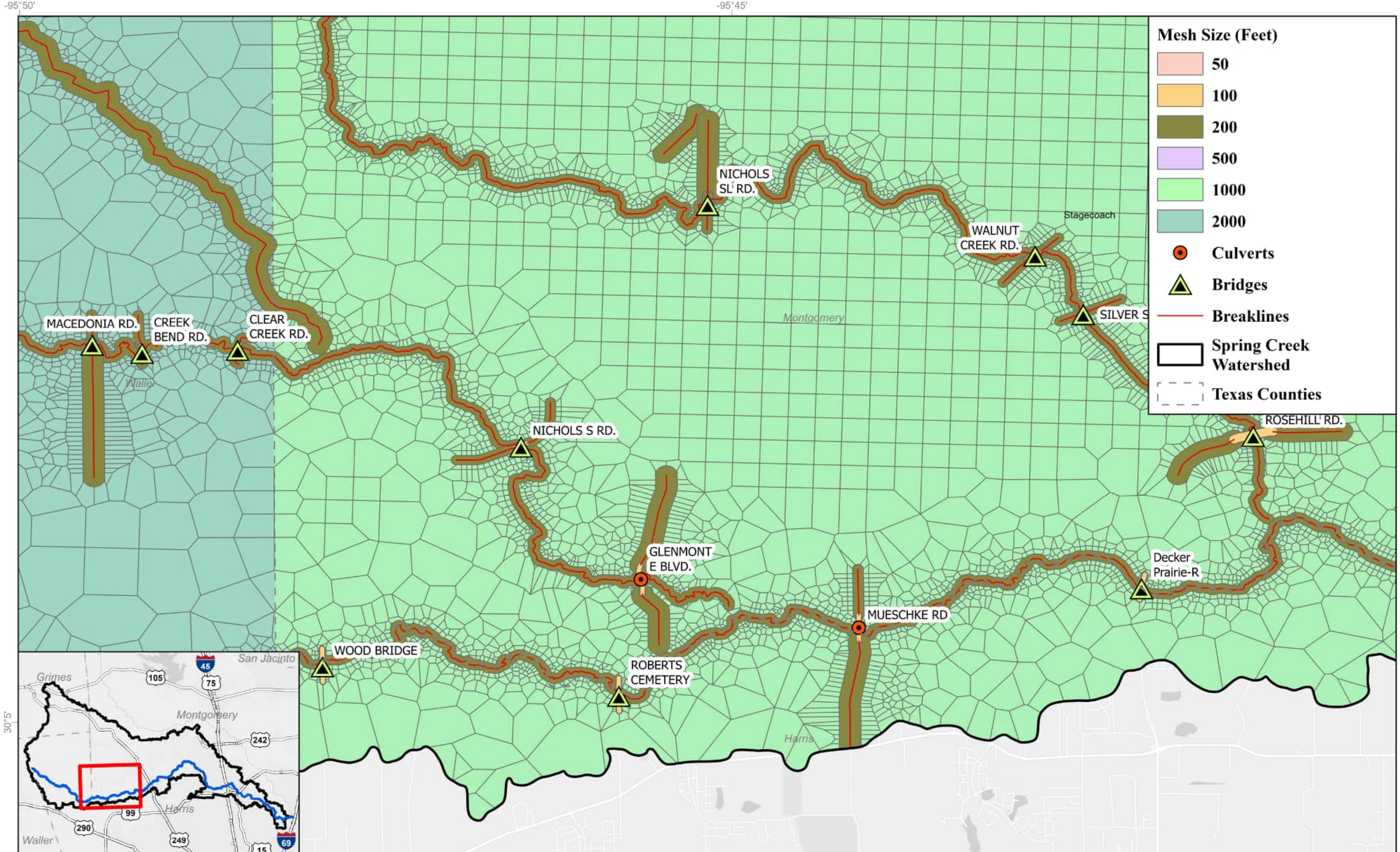
Pluvial Model Domain Details



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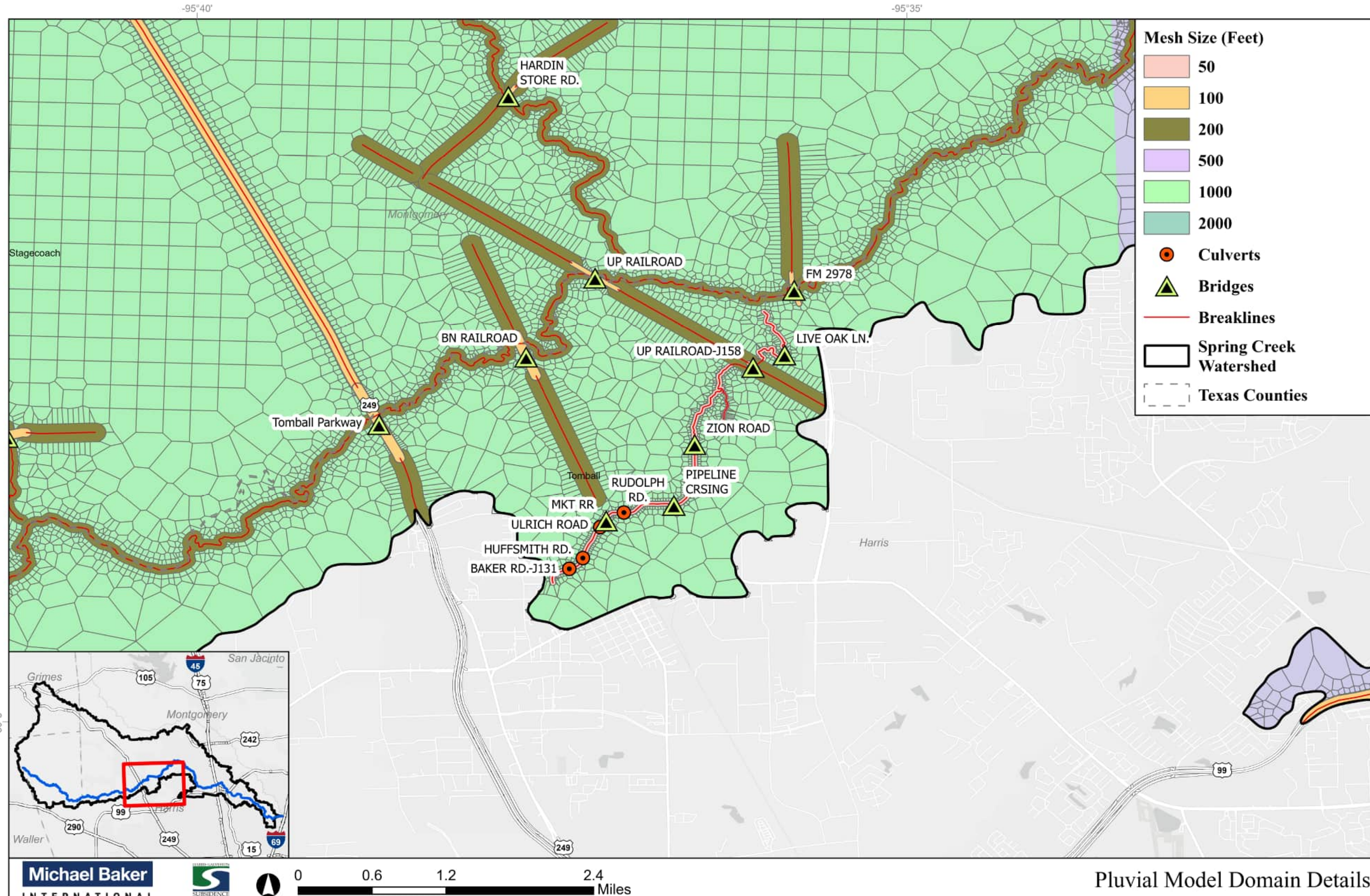
Pluvial Model Domain Details



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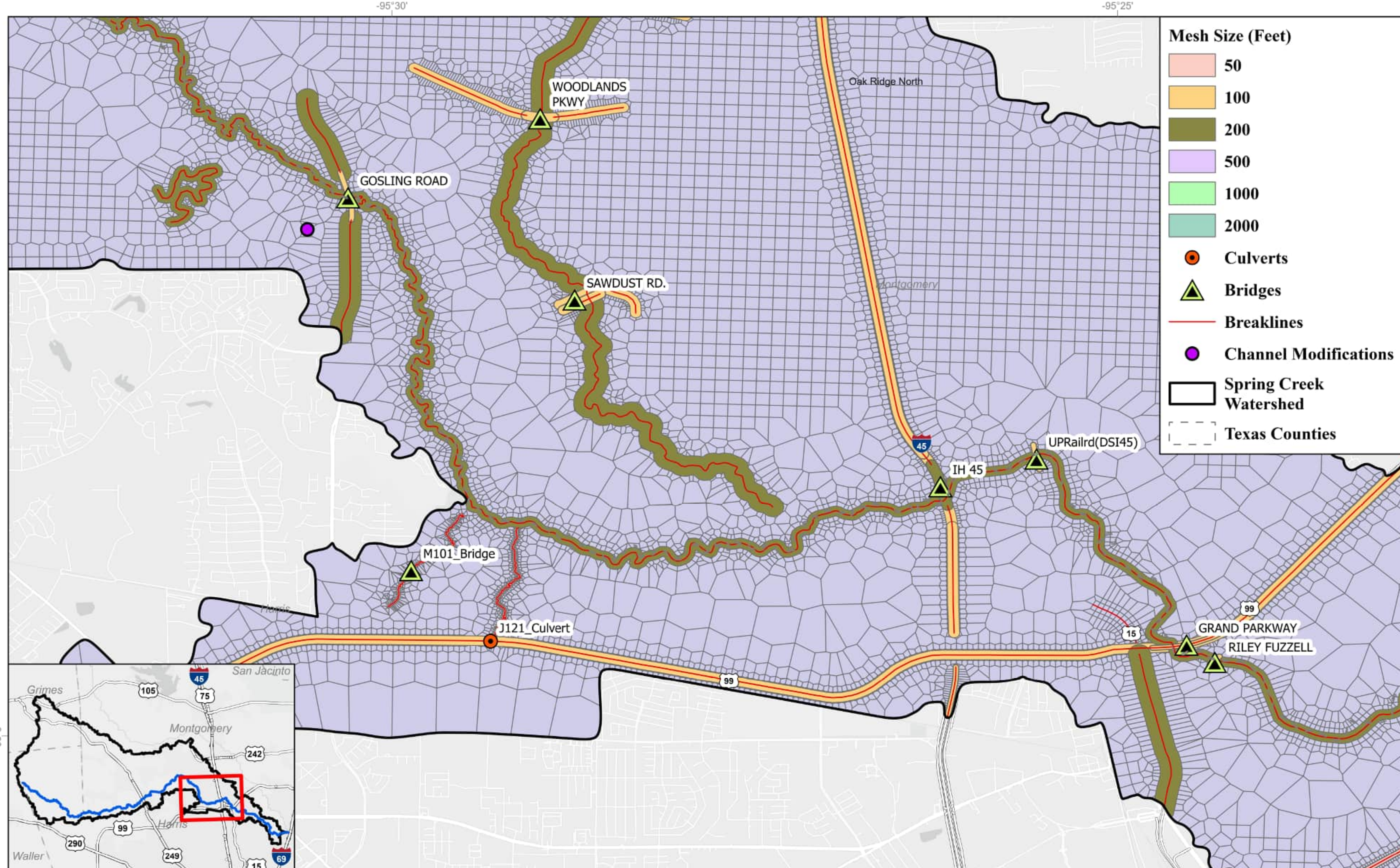

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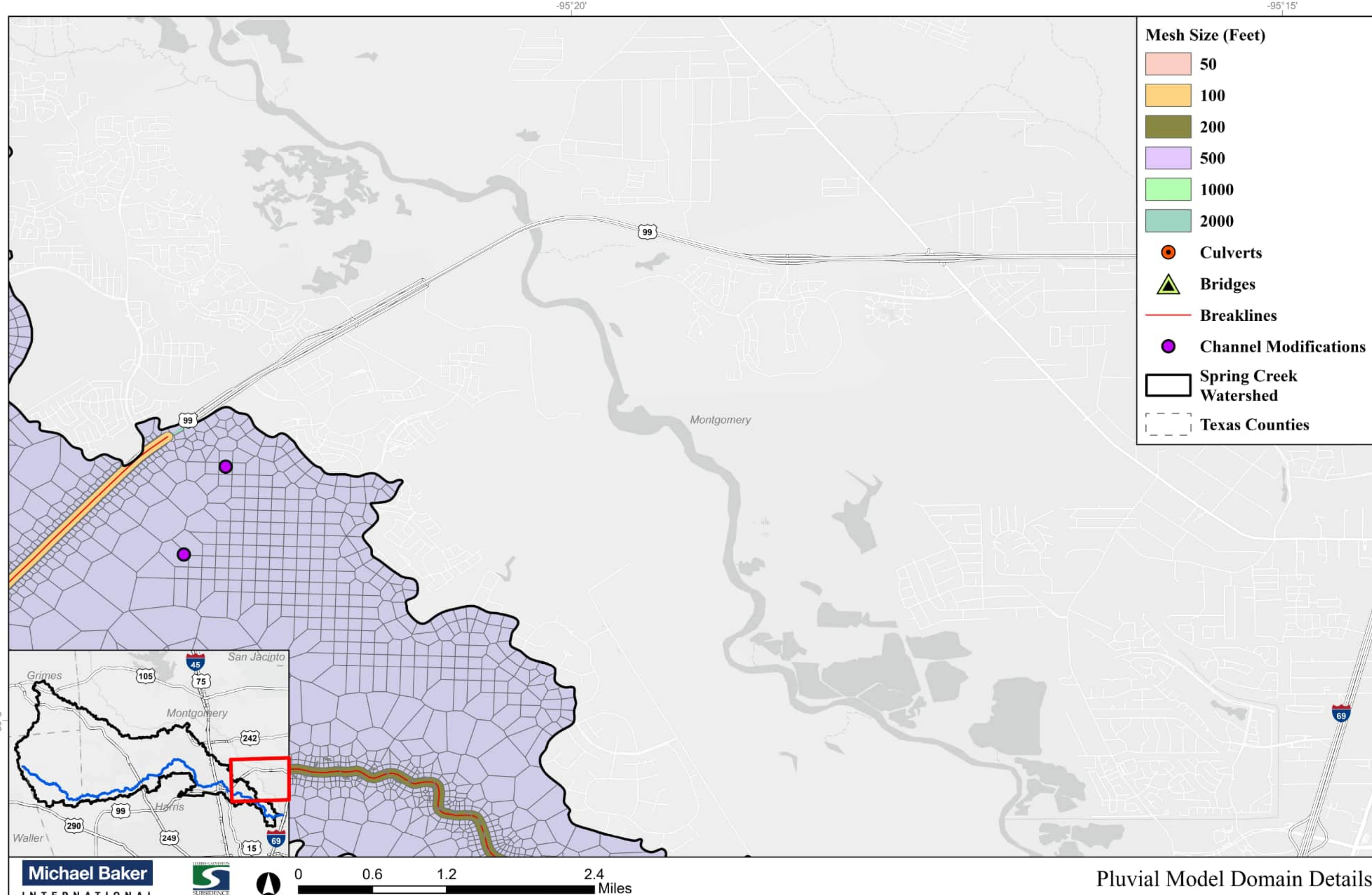
0 0.6 1.2 2.4 Miles

Pluvial Model Domain Details



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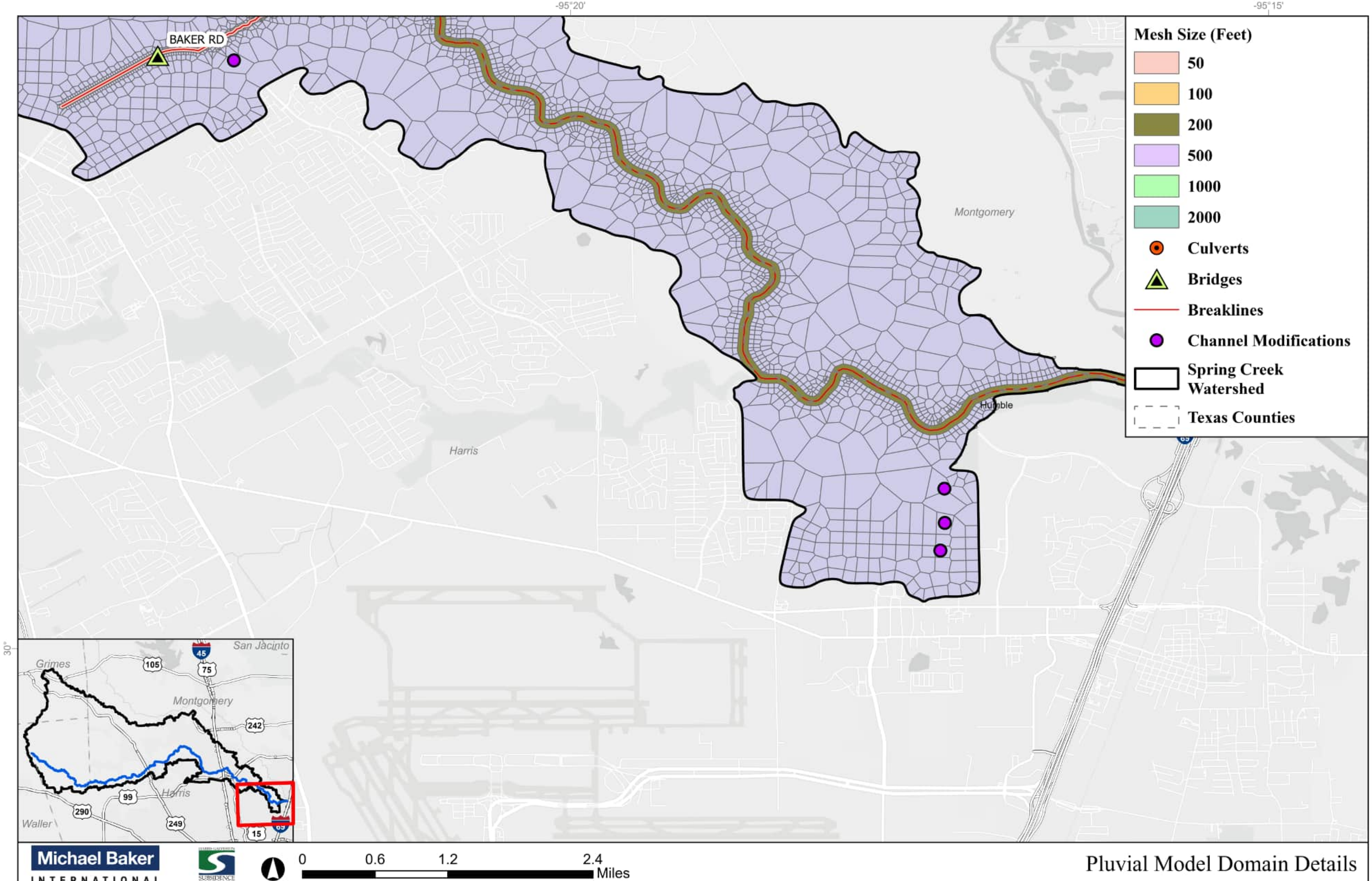
Pluvial Model Domain Details



Pluvial Model Domain Details