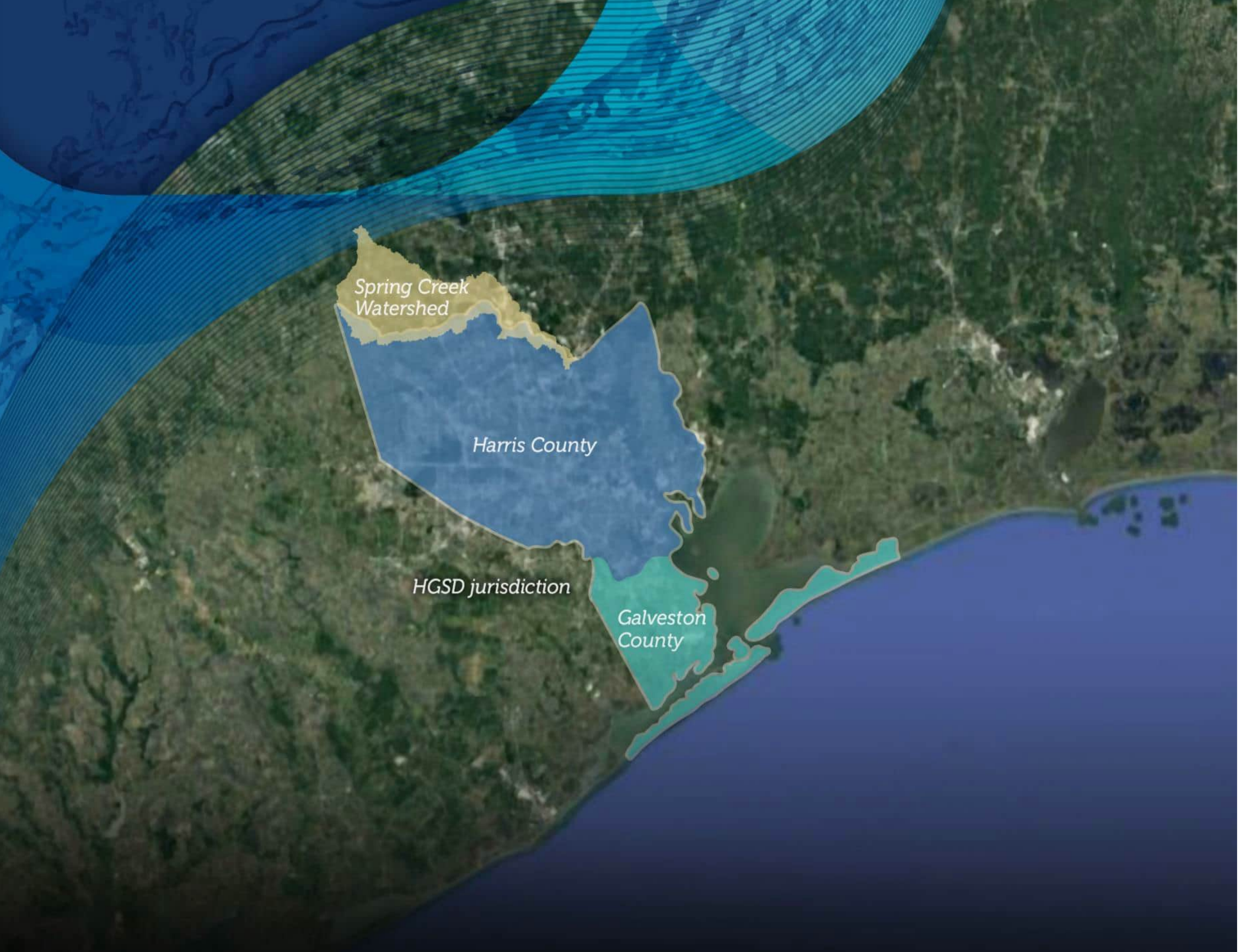
# Evaluation of Subsidence Impacts in the Spring Creek Watershed

## Technical Memorandum 3:

## Hydraulic and Economic Impact Assessment for Subsidence Scenarios



# Technical Memorandum #3:

# Hydraulic and Economic Impact Assessment for Subsidence Scenarios

# September 2025

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Michael Baker INTERNATIONAL

Under Contract No. PSA 2020-003

with Harris-Galveston Subsidence District

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**Technical Memorandum #3:**
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## Acronyms and Abbreviations

*AEL: Annualized Economic Loss*
*AEP: Annual Exceedance Probability*
*FEMA: Federal Emergency Management Agency*
*FFE: Finished Floor Elevation*
*FHWA: Federal Highway Administration*
*GIS: Geographic Information Systems*
*GLO: (The Texas) General Land Office*
*H&H: Hydrologic and Hydraulic*
*HCFCD: Harris County Flood Control District*
*HEC-FDA: Hydrologic Engineering Center - Flood Damage Reduction Analysis*
*HEC-FIA: Hydrologic Engineering Center - Flood Impact Analysis*
*HEC-HMS: Hydrologic Engineering Center - Hydrologic Modeling System*
*HEC-RAS: Hydrologic Engineering Center - River Analysis System*
*HGSD: Harris-Galveston Subsidence District*
*IH-45: Interstate 45*
*LiDAR: Light Detection and Ranging*
*MBI: Michael Baker International*
*MUD: Municipal Utility Districts*
*NSI: National Structure Inventory*
*Pe: Probability of Exceedance*
*RRC: Railroad Commission (of Texas)*
*SFD: Subsidence with Future Development*
*SI: Structural Inventory*
*SMCMUD: South Montgomery County Municipal Utility District*
*SWFD: Subsidence without Future Development*
*Tech Memo 1: Technical Memorandum #1*
*Tech Memo 2: Technical Memorandum #2*
*Tech Memo 3: Technical Memorandum #3*
*TNRIS: Texas Natural Resources Information System*
*TxDOT: Texas Department of Transportation*
*USACE: United States Army Corps of Engineers*
*USGS: United States Geological Survey*
*WSE: Water Surface Elevation*
*WW: Woodlands Water*

# 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.

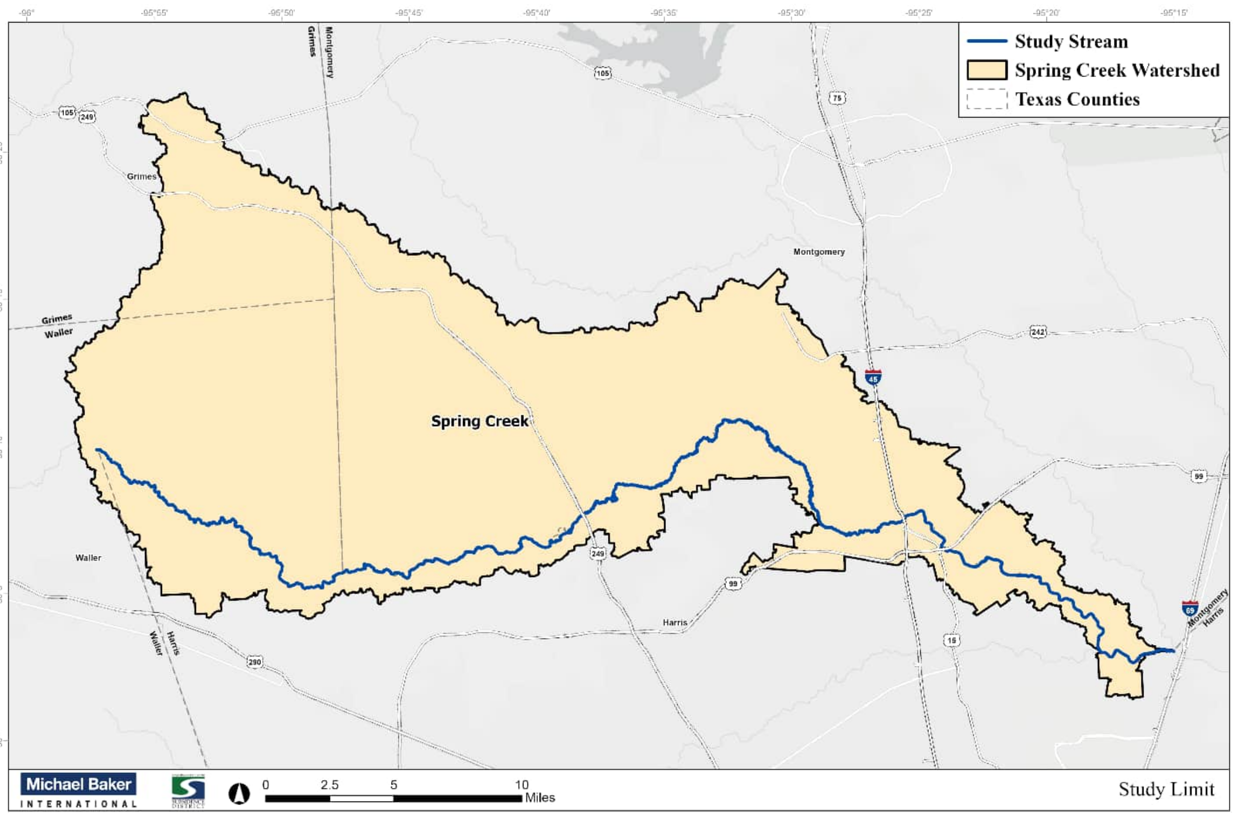



**Figure 1: Map showing the study limits - Spring Creek Watershed**

## 1.2 Summary of Technical Memorandum #1

Technical Memorandum #1 (MBI, 2024) discusses the development of the cumulative subsidence grid from 2020 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

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

1 kilometer x 1 kilometer (0.62 miles x 0.62 miles) subsidence grid to the same resolution as that of Harris County Flood Control District's (HCFCD) LiDAR resolution (3 feet x 3 feet), which was surveyed in 2018. Finally, the Kriging interpolation method was selected as the most robust method out of the four tested methods for the development of 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 2018 LiDAR. Tech Memo 1 further discussed the modification of the Hydrologic and Hydraulic (H&H) model parameters, such as hydraulic structures, building elevations, etc., for the incorporation of subsidence in the development of subsidence scenario models.

## 1.3 Summary of Technical Memorandum #2

Technical Memorandum #2 (MBI, 2024) documented the development of the hydrologic and hydraulic (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 methodology. Pluvial modeling, which is based on Rain-on-Mesh (RoM) methodology, is a new model developed for this study, which covers the entire Spring Creek watershed (**Figure 1**).

One baseline and two future scenarios: Subsidence without Future Development (SWFD) and Subsidence with Future Development (SFD) were developed using projections from 2020 to 2070 to assess flood impacts (**Figure 3**). It is unrealistic to envision a future subsidence scenario without future development; hence, this is an intermediate step to calculate the impact of subsidence. The baseline pluvial model was built from scratch and calibrated using Hurricane Harvey-2017 and validated with Hurricane Beryl-2024. It serves as the benchmark for comparing future scenarios. The SFD scenario incorporates both projected subsidence and land use changes, allowing evaluation of the individual and combined effects of subsidence with future development on flooding. The resulting flood depth differences are used to estimate economic impacts across the Spring Creek watershed

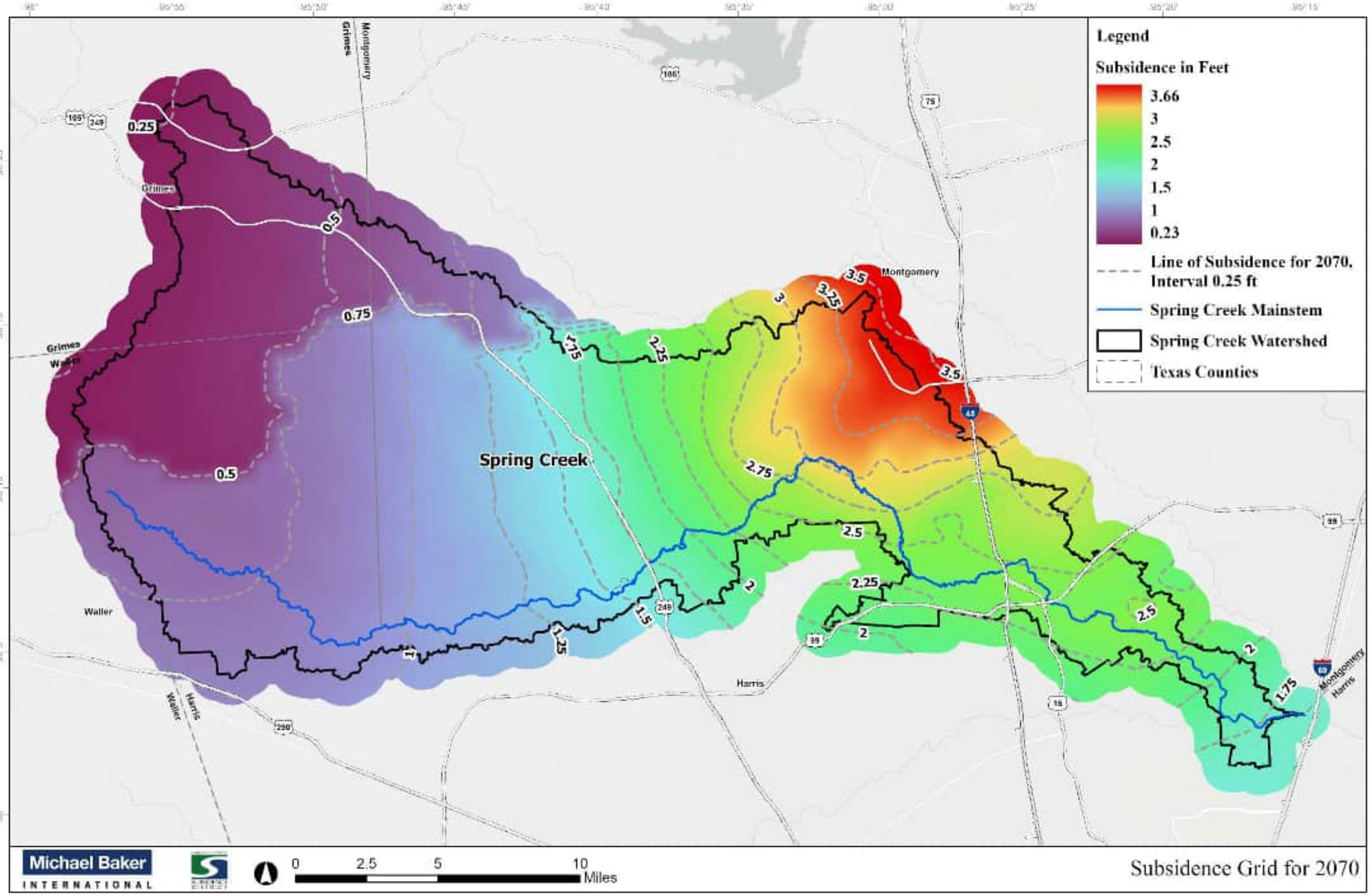



**Figure 2: Total Projected Subsidence from 2018-2070 from HGSD's Joint Regulatory Plan Review – 2023**

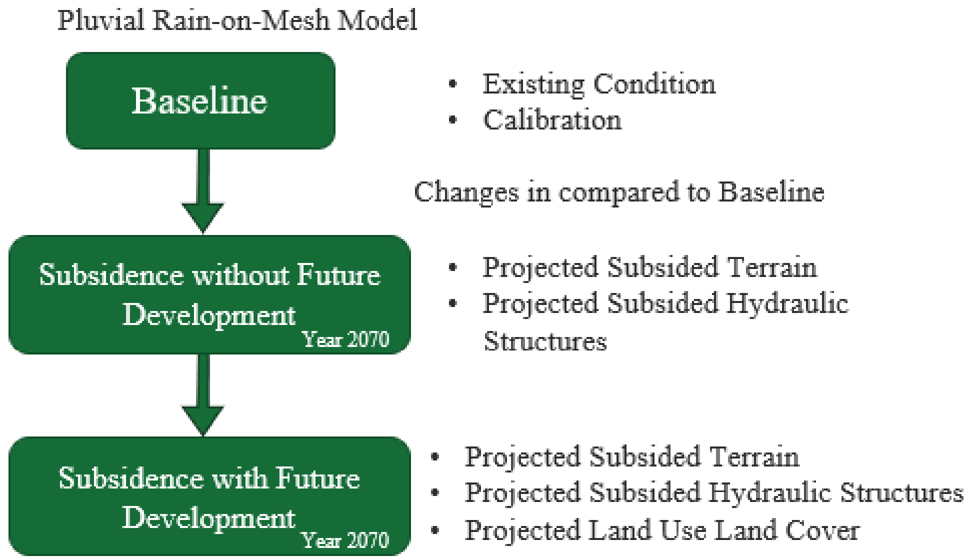



**Figure 3: Modeling Scenarios for Pluvial (Rain-on-Mesh) Model Development in Spring Creek Watershed**

## 1.4 Purpose and Scope of Technical Memorandum # 3

The purpose of this Technical Memorandum #3 (Tech Memo 3) is to document the hydraulic impacts of flooding, which may have been exacerbated due to subsidence, and assign an economic value to these increased hazards for the pluvial modeling approach. The hydraulic impacts include a summary of the model results – WSE, flooding depth, freeboard of bridges, inundation acreage, peak flow, and channel velocities – from the hydraulic model simulations. The number of flooded structures and miles of flooded roadways in the watershed were quantified and compared. These metrics were developed to provide an understanding of the effects of subsidence on structures and roadways in terms of flood damage.

The economic loss associated with the damages due to subsidence was estimated using a Go-Consequence tool for the pluvial modeling approach of 1% Annual Exceedance Probability (AEP) and 10% AEP storm events. The economic loss estimate was categorized as direct loss and indirect loss. The direct loss included damage to structures, contents of structures, and vehicles. In contrast, the indirect loss included loss of gross domestic product (GDP) and a reduction in labor incurred during flooding events. The tool estimated the direct loss using the flood depth rasters and the National Structures Inventory (NSI) data, while the indirect loss was estimated using the Economic Consequences Assessment Model (ECAM). The Annualized Economic Loss (AEL) was also estimated for the annual risk of flood losses due to subsidence over the period from 2020 to 2070 within the Spring Creek watershed.

The economic impact of the potential reactivation of the existing faults on nearby structures and infrastructures was also analyzed. The potential effects of faults on hydrology, hydraulics, and groundwater flow regimes are discussed as well. Critical infrastructure experiencing variable amounts of subsidence is also discussed. However, economic loss on these structures was outside the scope of this study and was not included in the overall economic impact. This is a potential area for future study.

### *1.4.1 **Organization of Technical Memorandum #3***

There are seven chapters in Tech Memo 3. The first chapter provides an introduction to Tech Memo 3, while chapters two, three, and four discuss hydraulic, flooding, and economic impact assessment, respectively, for the pluvial modeling approach. Similarly, chapter five provides an economic assessment of the impact of the reactivation of existing fault lines on structures and infrastructures. Chapter six discusses the limitations and lessons learned from this current study and recommendations for future studies. Chapter seven concludes Tech Memo 3.

# 2 Hydraulic Impacts Assessment

By comparing H&H modeling results between baseline, Subsidence without future development (which accounts only for the subsidence), and Subsidence with future development (which accounts for both the subsidence as well as flow changes due to future development), the model can predict the impact on hydraulics due to these changes. The changes in hydraulics are important drivers for changes in flood risk. This section discusses hydraulic results for 1% AEP design events from the pluvial HEC-RAS model.

## 2.1 Pluvial Impact Assessment

The hydraulic model primarily solves flow depth and velocity fields. The flow depth, when added to the underlying terrain elevation, becomes the water surface elevation. The velocity field is the speed and direction of flow, which can be used to calculate discharge when the flow area is considered. This section summarizes the impact on hydraulic results for pluvial modeling in terms of water level (water surface elevation, flood depth, floodplain, and freeboard) and velocity (flows).

### *2.1.1 Water Level Impact*

#### *2.1.1.1 Flood Depth*

A detailed analysis was performed using the flood depth raster from the HEC-RAS model. The net increase in flood depth was calculated by subtracting the baseline raster from the SWFD and SFD scenarios to delineate hotspots of increased flood depths. As shown in A review of **Figure 2**, the projected subsidence lowers east of Kuykendahl Road by ~3 feet, and the upstream end of the watershed subsides by only 0.5 feet (Points 'B' and 'D' in **Figure 4**). Hence, the stream gradient upstream, west of Tomball Parkway gets steeper, caused by differential subsidence, leading to increased flow velocities and reduced flood risk in the upstream portion of the watershed. Conversely, on the downstream portion (section between points "C" and "A" in **Figure 4**), the gradient decreases, along with increased flows due to future development, resulting in increased flood depth and thus flood risk.

The flood depths were also compared at cross-sections within the main reach at major crossings from Tomball Parkway Bridge to Grand Parkway Bridge from upstream (west) to downstream (east) along Spring Creek (**Figure 5**). The depths in these graphs were developed by comparing the water surface elevation in the channel to the channel thalweg elevation. At all five major crossings, the flood depth of Subsidence with future development (SFD) is higher than the baseline and subsidence without future development (SWFD) scenario. (**Figure 5**).

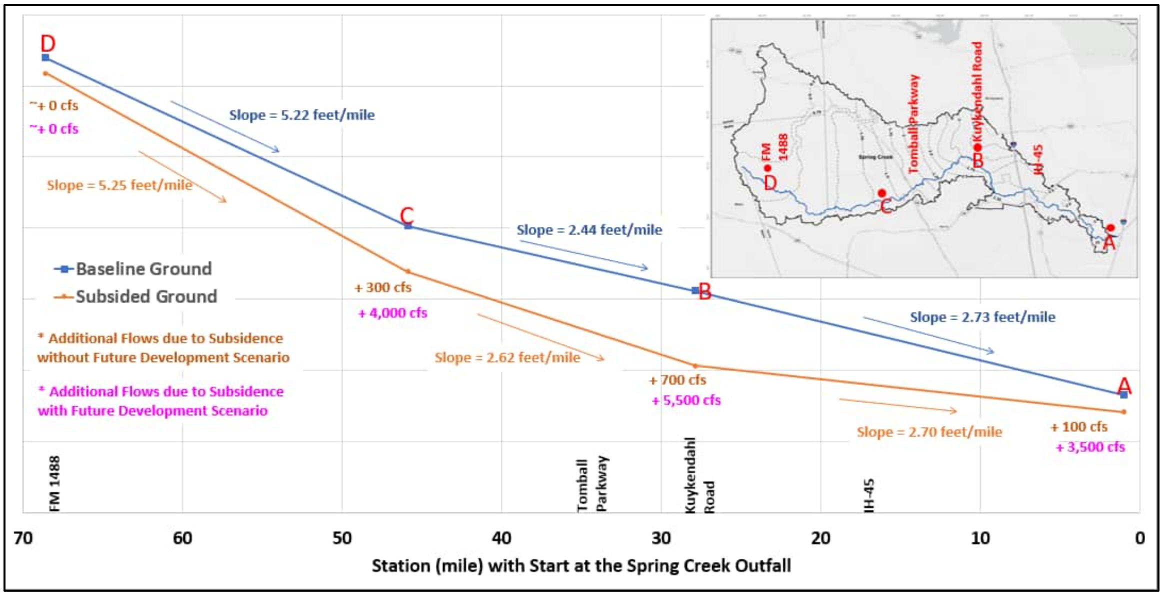



**Figure 4: Schematic Slope Comparison between Baseline and Subsidence Grounds**

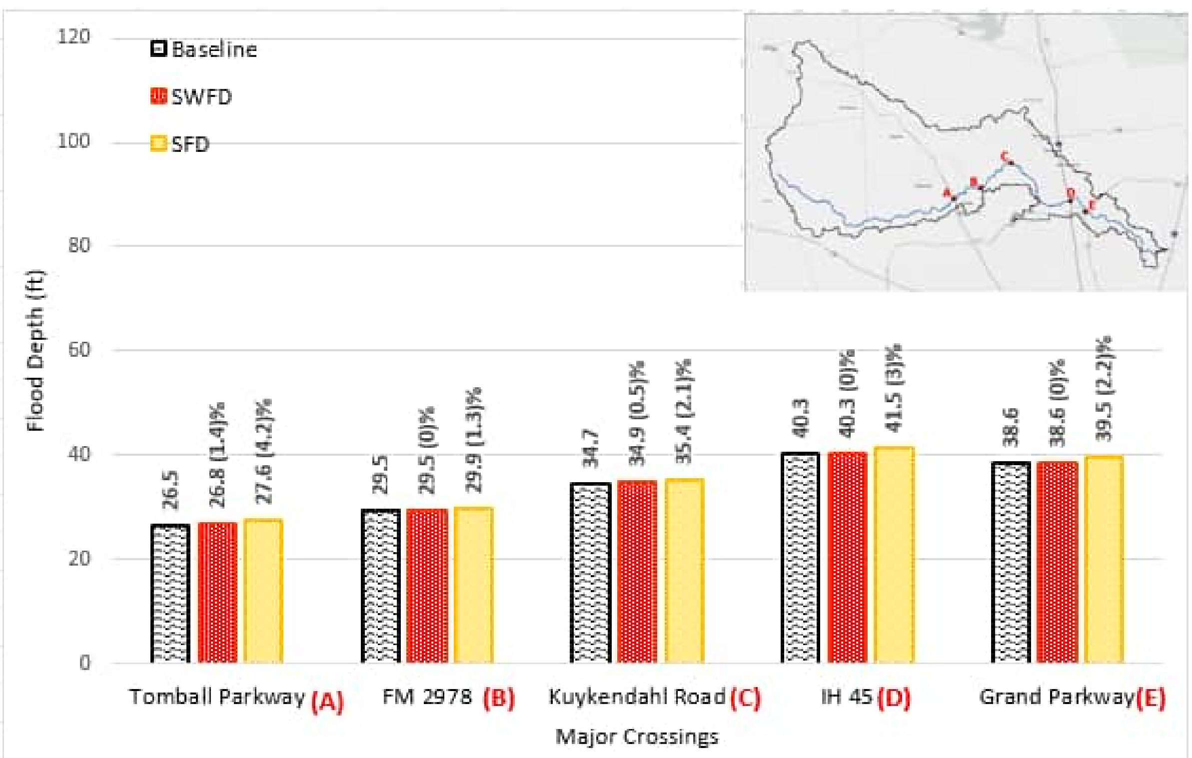



**Figure 5: Comparison of Flood Depth in Pluvial Model (1% AEP) for Baseline, Subsidence without Future Development (SWFD), and Subsidence with Future Development (SFD) at Major Crossings along Spring Creek**

**Figure 6** - **Figure 9** show the flood depth comparison between the baseline, SWFD, and SFD scenarios, respectively, for the 100-year design event for the whole watershed and east of Tomball Parkway (where the highest subsidence is projected). The SWFD scenario shows an increase in flood depth up to 0.5 feet with localized spots greater than 0.5 feet rise, while locations in the vicinity of Tomball Parkway and upstream show a reduction in flood risk. The SFD scenario shows increased flood depth just before the Tomball Parkway due to substantially increased flows (**Figure 4**) which leads to an increase in flood depth up to 1 foot, with localized spots around major crossings greater than 1 foot. Detailed maps are included in **Appendix B.**

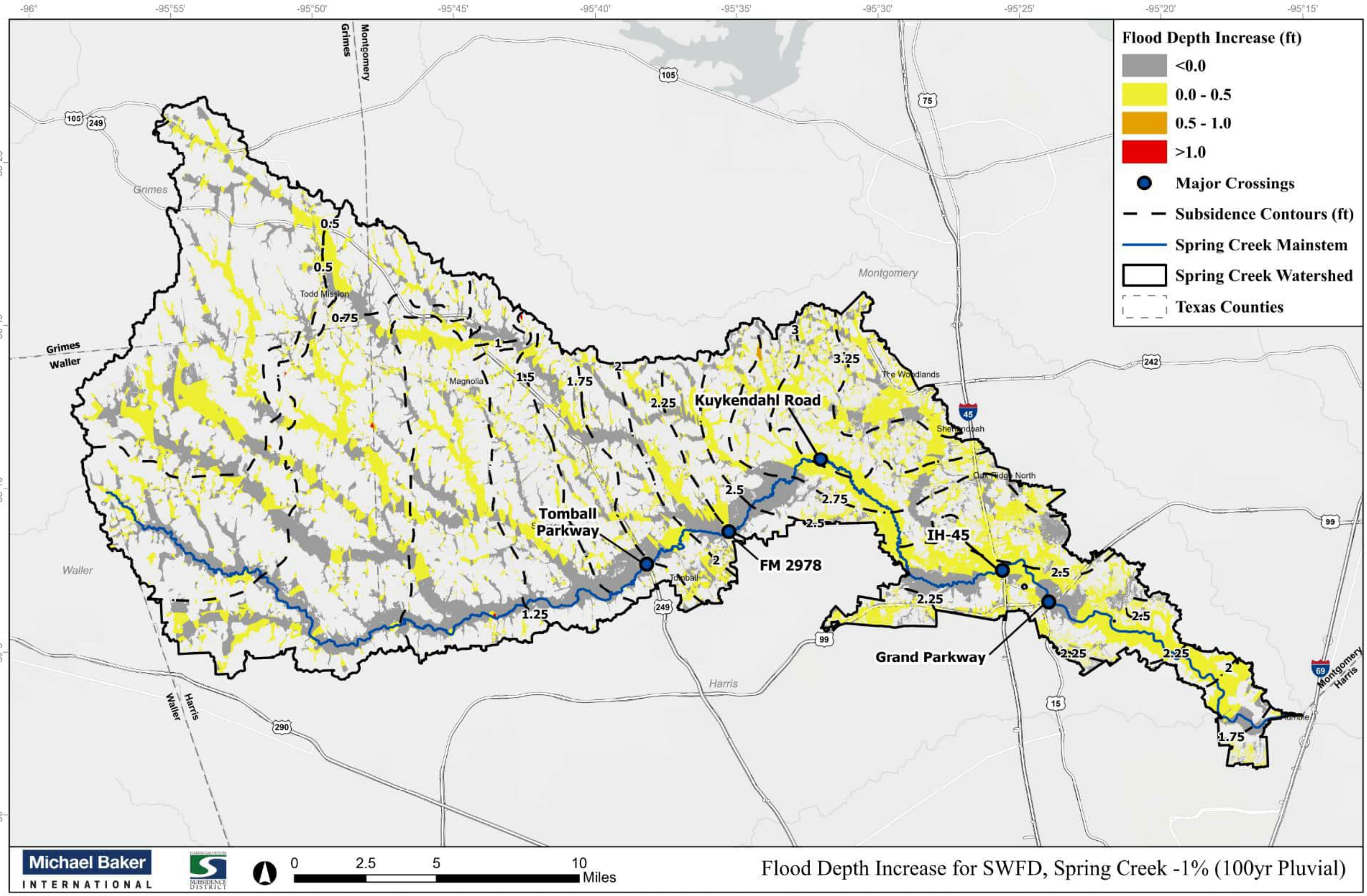



**Figure 6: Flood Depth Increase Between Baseline and SWFD Scenario for 100-Year Event (Pluvial)**

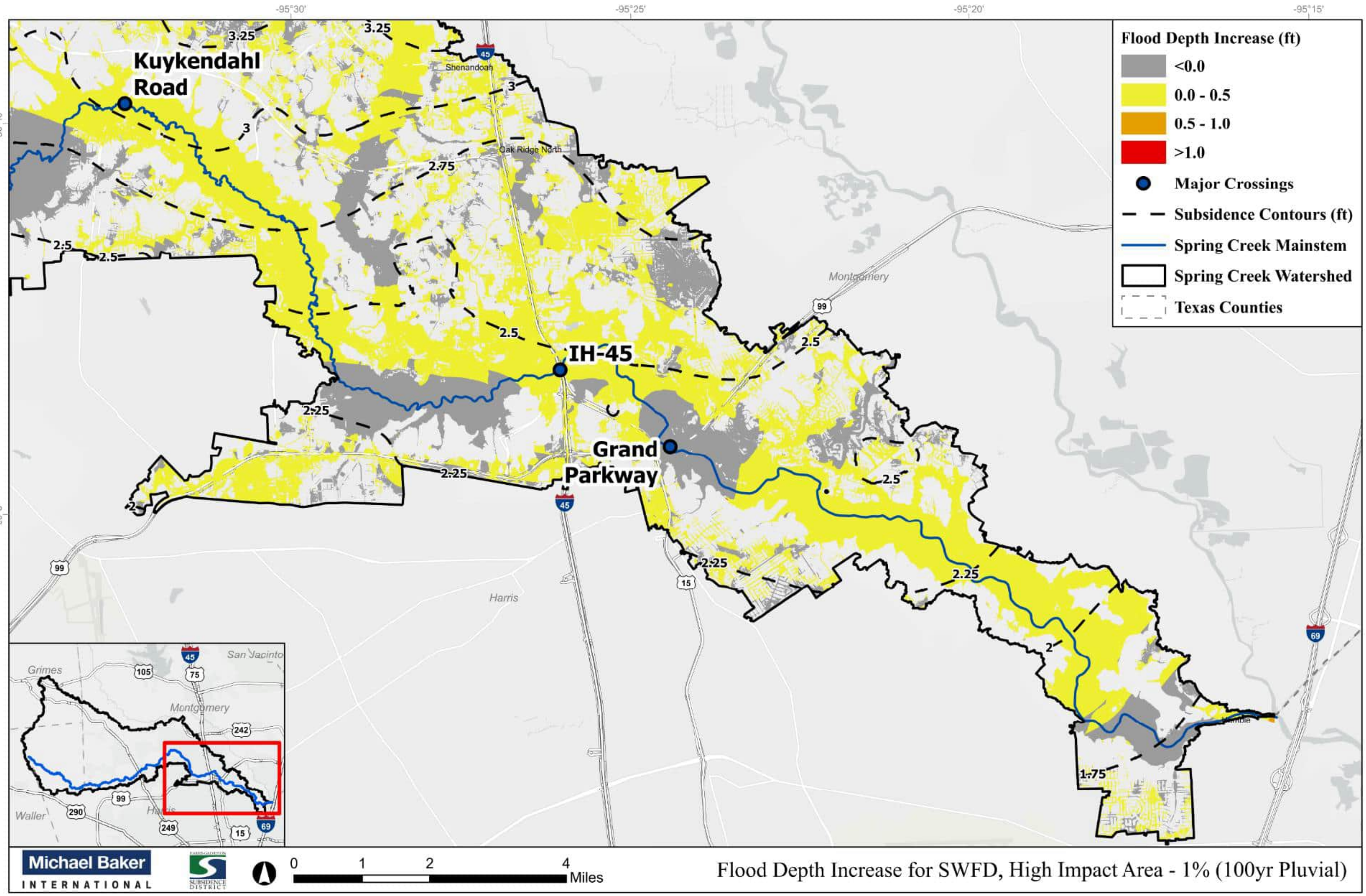



**Figure 7: Flood Depth Increase Between Baseline and SWFD Scenario for 100-Year Event (Pluvial), East of Tomball Parkway**

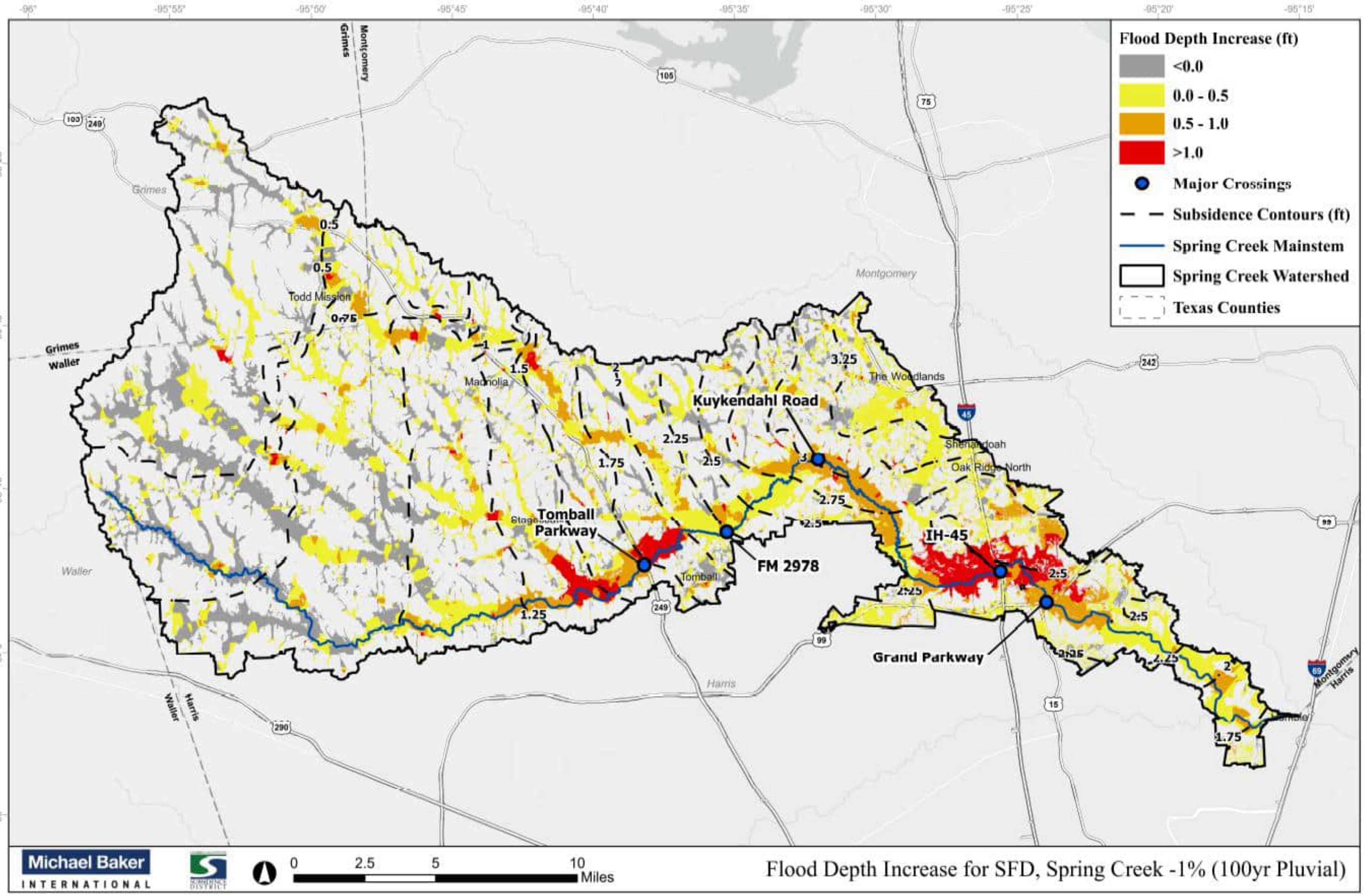



**Figure 8: Flood Depth Increase Between Baseline and Subsidence with Future Development (SFD) Scenario for 100-Year Event (Pluvial)**

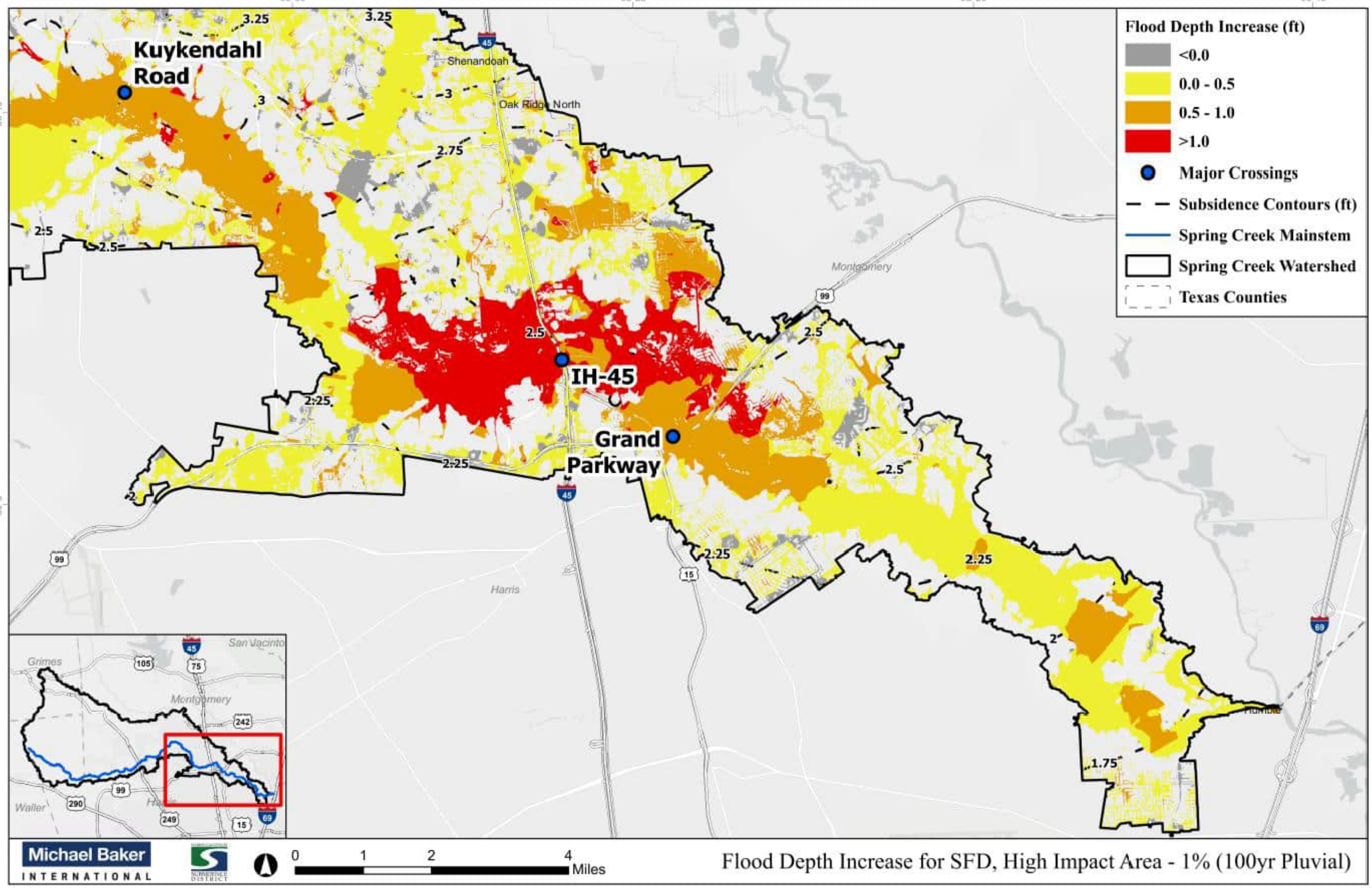



**Figure 9: Flood Depth Increase Between Baseline and Subsidence with Future Development (SFD) Scenario at 100-Year Event (Pluvial), East of Tomball Parkway**

#### *2.1.1.2 Floodplain Acreage*

Floodplain acreage is the area (in acres) that is flooded in a 1% AEP design event. Due to the dynamics of flood movement, the floodplain footprint can increase or decrease between the baseline and subsidence scenarios, as shown in **Table 1**.

**Table 1: Floodplain Acreage for Baseline, Subsidence, and Subsidence with Future Development for Pluvial Model for 100-Year Event**

| Scenarios | Total Area (acres) | Area Increased (acres) | Area Decreased (acres) | Net Change (acres) |
|---|---|---|---|---|
| Baseline | 94,363 | - | - | - |
| Subsidence without Future Development | 94,572 | 541 | 332 | +209 (+0.2%) |
| Subsidence with Future Development | 96,102 | 3,527 | 1,788 | +1,739 (+2%) |

Floodplains of SWFDe and SFD (**Figure 10**) scenarios show an approximately 0.2% to 2% increase over the baseline floodplain. Floodplain increases are noticed in the vicinity of IH-45 and Kuykendahl Road. Subsidence in this area creates a depression that increases the floodplain downstream of IH 45 and Riley Fuzzel Road. The increase in floodplain area was higher for the SFD scenario, as it encompasses a higher impervious cover. Floodplain reductions were also observed upstream of IH-45 in the SFD scenario. Please refer to **Appendix B** for detailed maps.

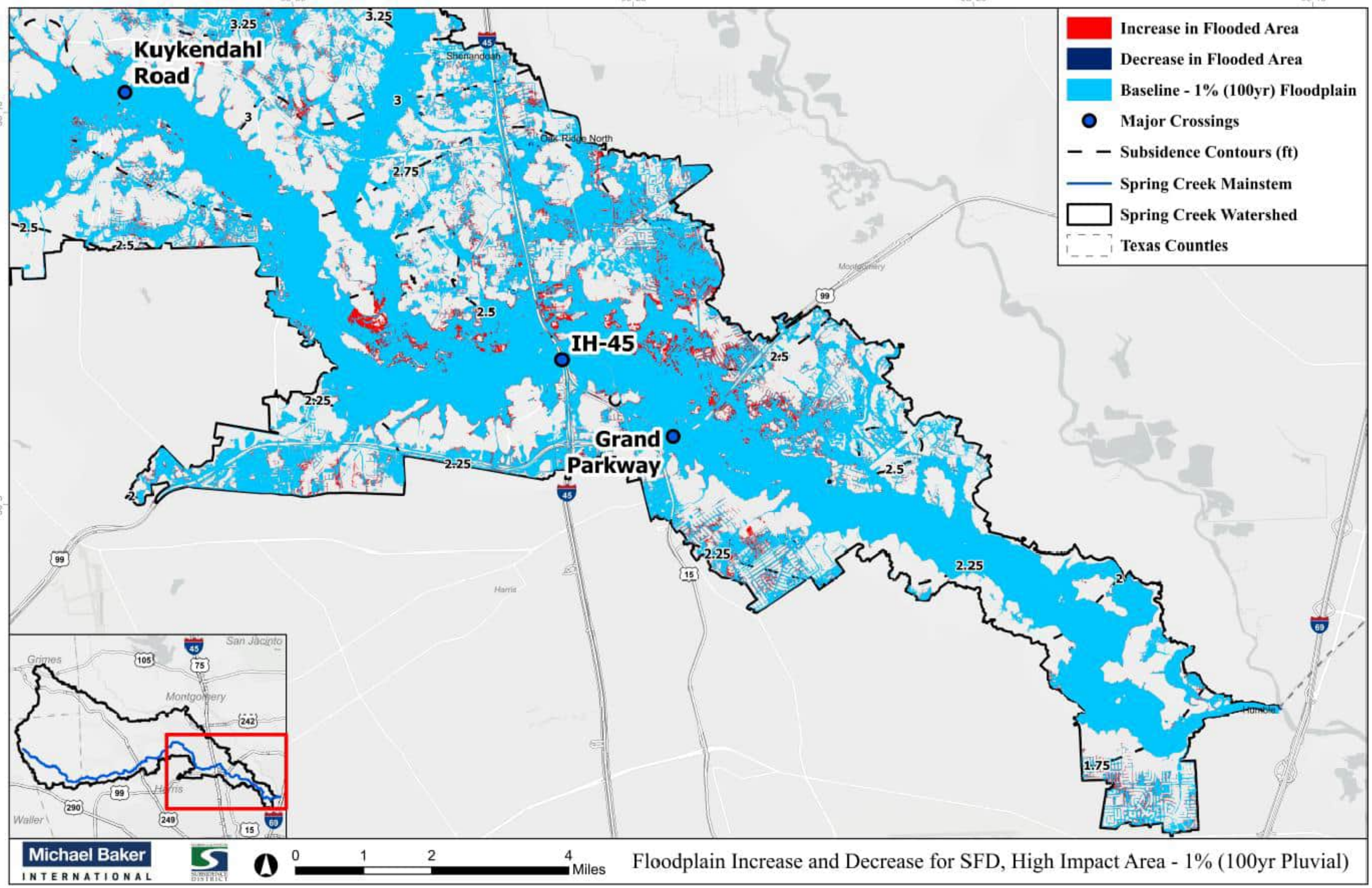



**Figure 10: Changes in 1% Floodplain in Subsidence with Future Development (SFD) Scenario Compared to Baseline Scenario, Downstream of Kuykendahl Road**

#### 2.1.1.3 Water Surface Elevations

Water Surface Elevation (WSE) comparisons are generally useful for model scenarios using the same terrain; however, the subsidence scenarios use subsided terrain, which makes comparison difficult. Since the subsidence terrain is lower than the baseline terrain, the subsidence WSE was generally lower than the baseline WSE.

A better comparison is the WSE difference (delta in WSE) between baseline and subsidence scenarios and the projected subsidence terrain. To understand the impact of WSE due to subsidence, the baseline and subsidence terrain and WSE profile at multiple major crossings were compared (**Figure 11** and **Figure 12**) for all scenarios, along with the corresponding existing terrain for Tomball Parkway and Kuykendahl Road Bridge crossings at Spring Creek. The WSE difference is the same or lower than the terrain difference between the baseline and SWFD scenarios, which is even lower for the SFD scenario. This indicates the WSE decrease is not the same as the elevation decrease due to subsidence and can vary due to hydraulics in the watershed.

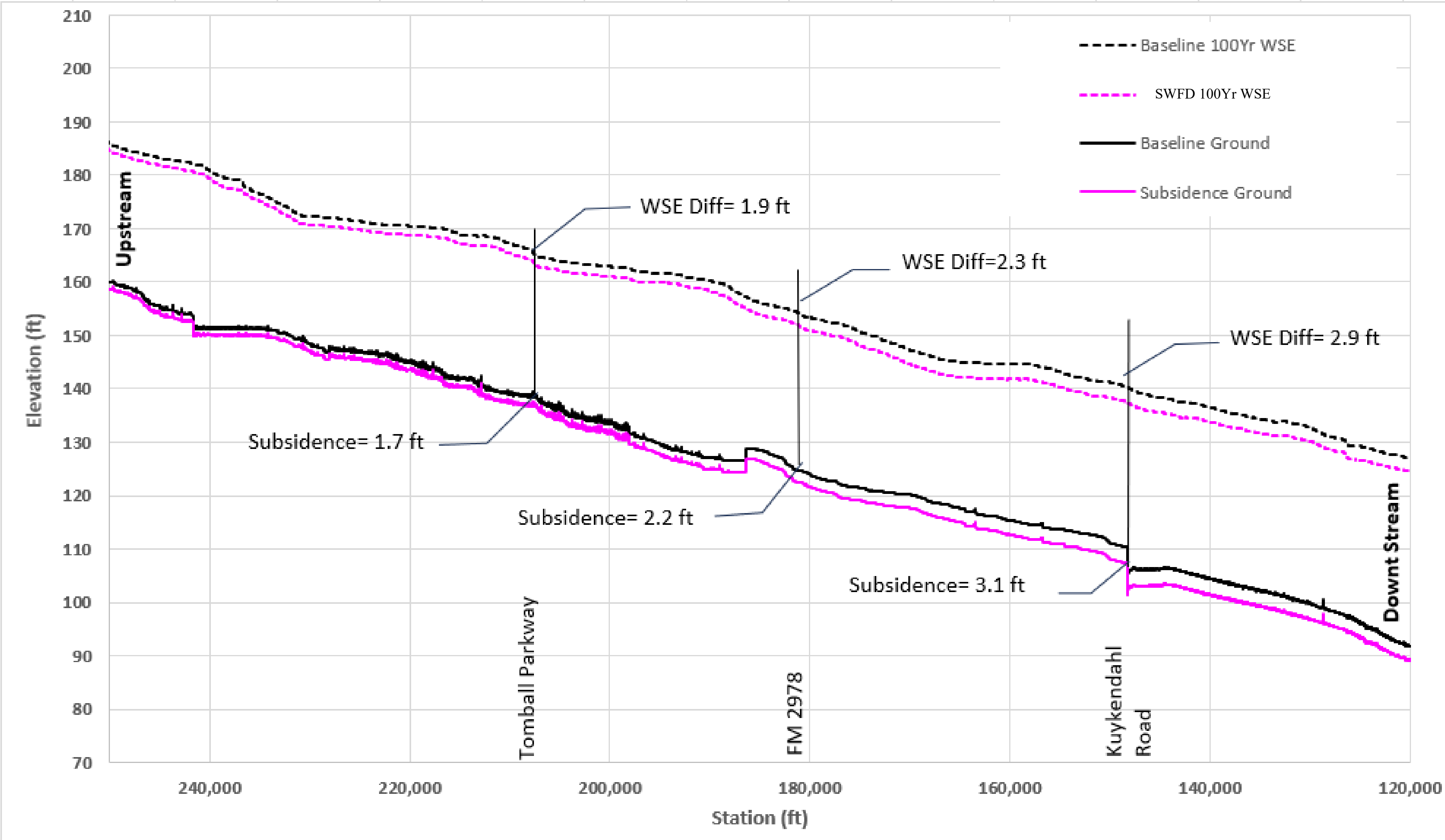



**Figure 11: Profile Comparison of Water Surface Elevation vs Projected Subsidence Depth between Baseline and Subsidence without Future Development (SWFD) Scenario (Pluvial Model) US of Kuykendahl Road**

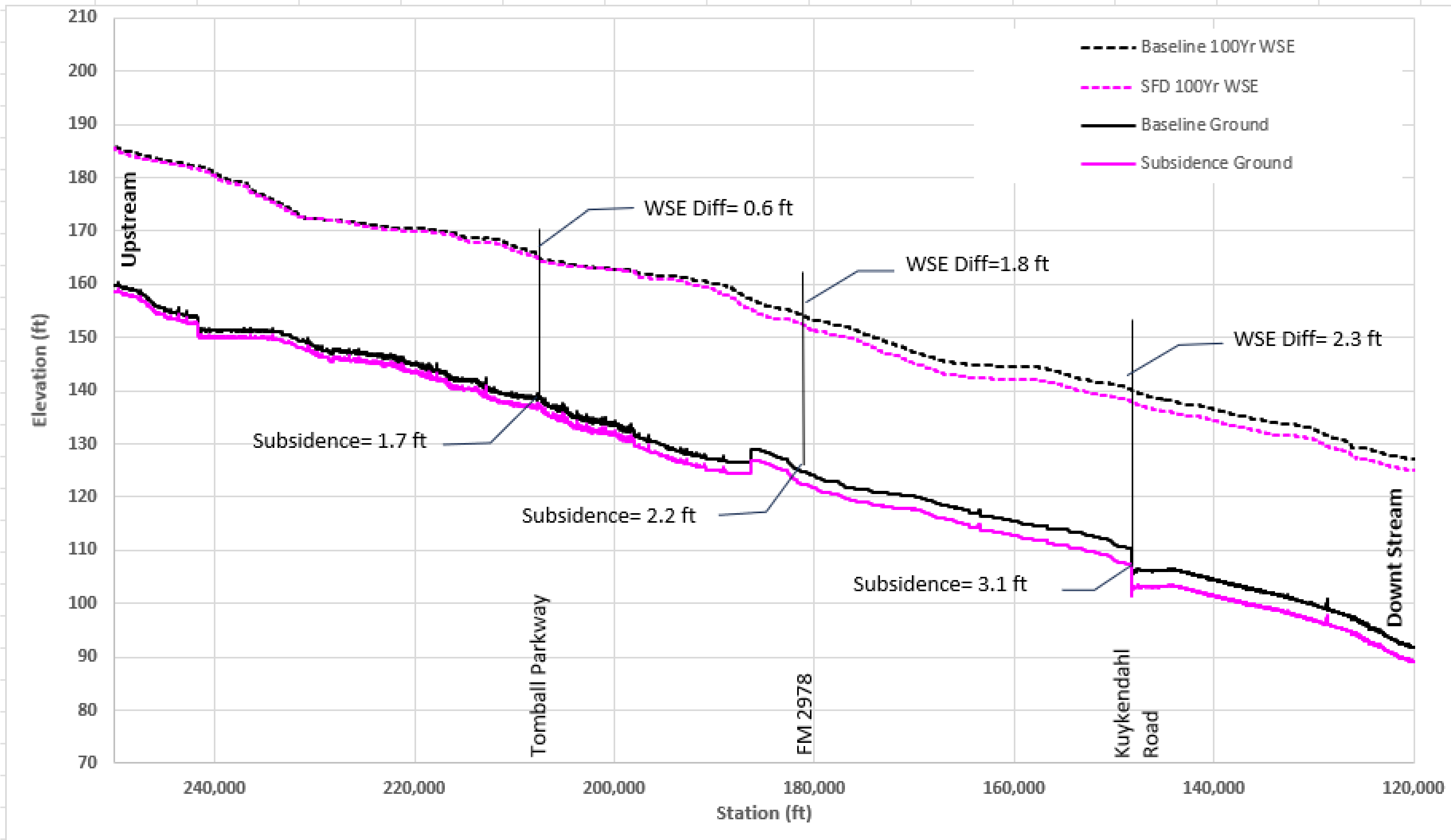



**Figure 12: Profile Comparison of Water Surface Elevation vs Projected Subsidence Depth between Baseline and Subsidence with Future Development (SFD) Scenario (Pluvial Model) US of Kuykendahl Road**

#### *2.1.1.4 Freeboard*

The freeboard of a bridge is the minimum clearance between the bottom of the bridge's girders and the highest design water level at the upstream cross-section. It's a factor of safety that helps account for unknown factors that could cause flood heights to be higher than the designed clearance. The freeboard was estimated by subtracting the computed WSE from a bridge's minimum low chord elevation. A positive value for the freeboard indicates that the flow is below the low chord of the bridge, and there is no pressure flow. A negative value indicated that the water surface for the 1% AEP impinged on the low chord of the bridge. This puts the bridge under pressure flow during that storm event. At this point, backwater flow can occur, and the velocities through the bridge opening can increase. The bridge is subjected to weir flow if the flow depth overtops the bridge.

The freeboard for five selected bridge crossings, starting at Tomball Parkway upstream to Grand Parkway downstream along the Spring Creek mainstem, is shown in **Figure 13.** The bridges between Tomball Parkway and IH 45 show no available freeboard; however, they are not overtopped. Any decision to upgrade or renovate these bridges would require detailed hydraulic and structural analysis.

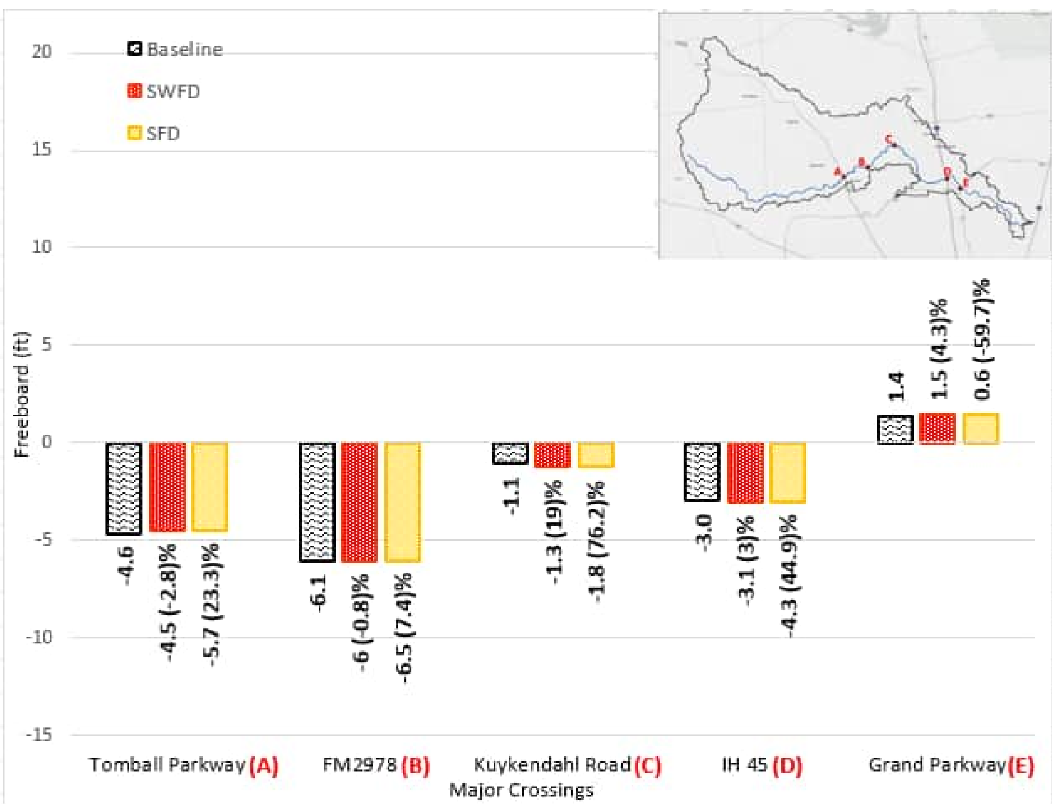



**Figure 13: Comparison of Available Freeboard for Baseline, Subsidence without Future Development (SWFD), and Subsidence with Future Development (SFD) at Major Bridge Crossings for Pluvial Model 100-year Event**

Available freeboard is generally less in the subsidence scenario and SFD scenario than in the baseline scenario. This shows that the subsidence has increased the flow depth passing under the bridge, thus reducing the available freeboard. Additionally, the SFD had less freeboard than the subsidence scenario. These trends suggest that there is a freeboard decrease as impervious cover increases, leading to increased flows.

### *2.1.2 Velocity Impact*

Maximum velocities were compared at five (5) major bridge crossings for all the scenarios for the 100-year event (**Figure 14)**. The maximum velocity for subsidence and SFD scenario was higher than the baseline scenarios at the major bridge crossing.

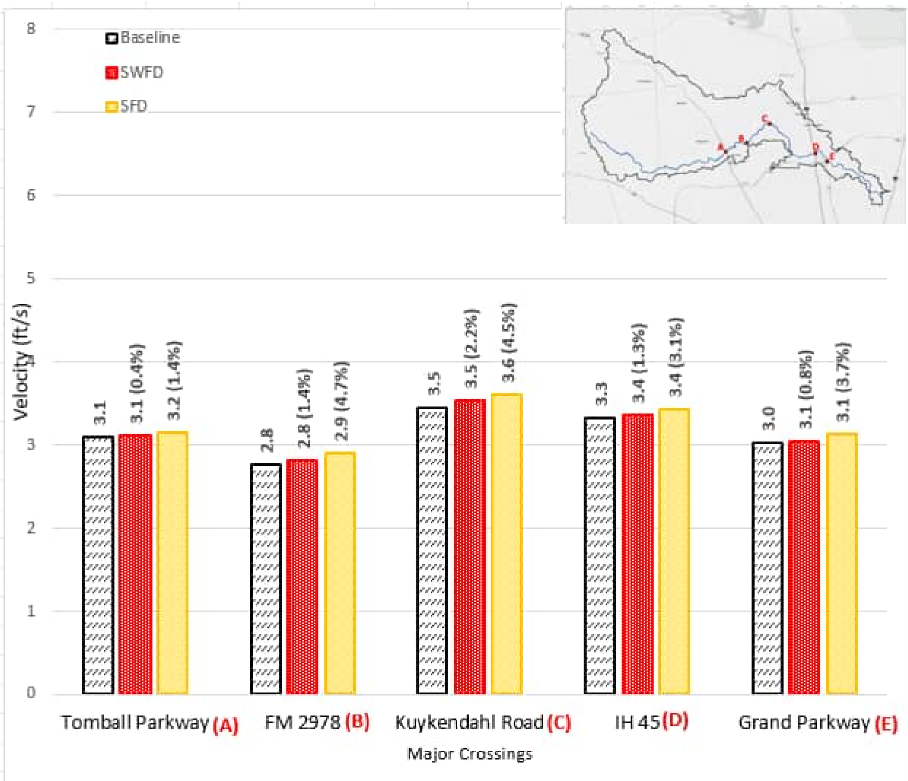



**Figure 14: Comparison of Maximum Velocity for Baseline, Subsidence without Future Development (SWFD) and Subsidence with Future Development (SFD) at Major Bridge Crossings near IH-45 for Pluvial Model**

**Figure 15** and **Figure 16** show the velocity comparison between the baseline and SWFD and SFD scenarios, respectively, for the 100-year design event. The SWFD scenario shows increased velocity west of the Kuykendahl Road bridge, while decreased velocity east. While SFD scenarios show an increase throughout the watershed, even though the increases are minimal. This is in agreement with the increase of slope west of the Kuykendahl Road bridge while decreasing slope east due to subsidence.

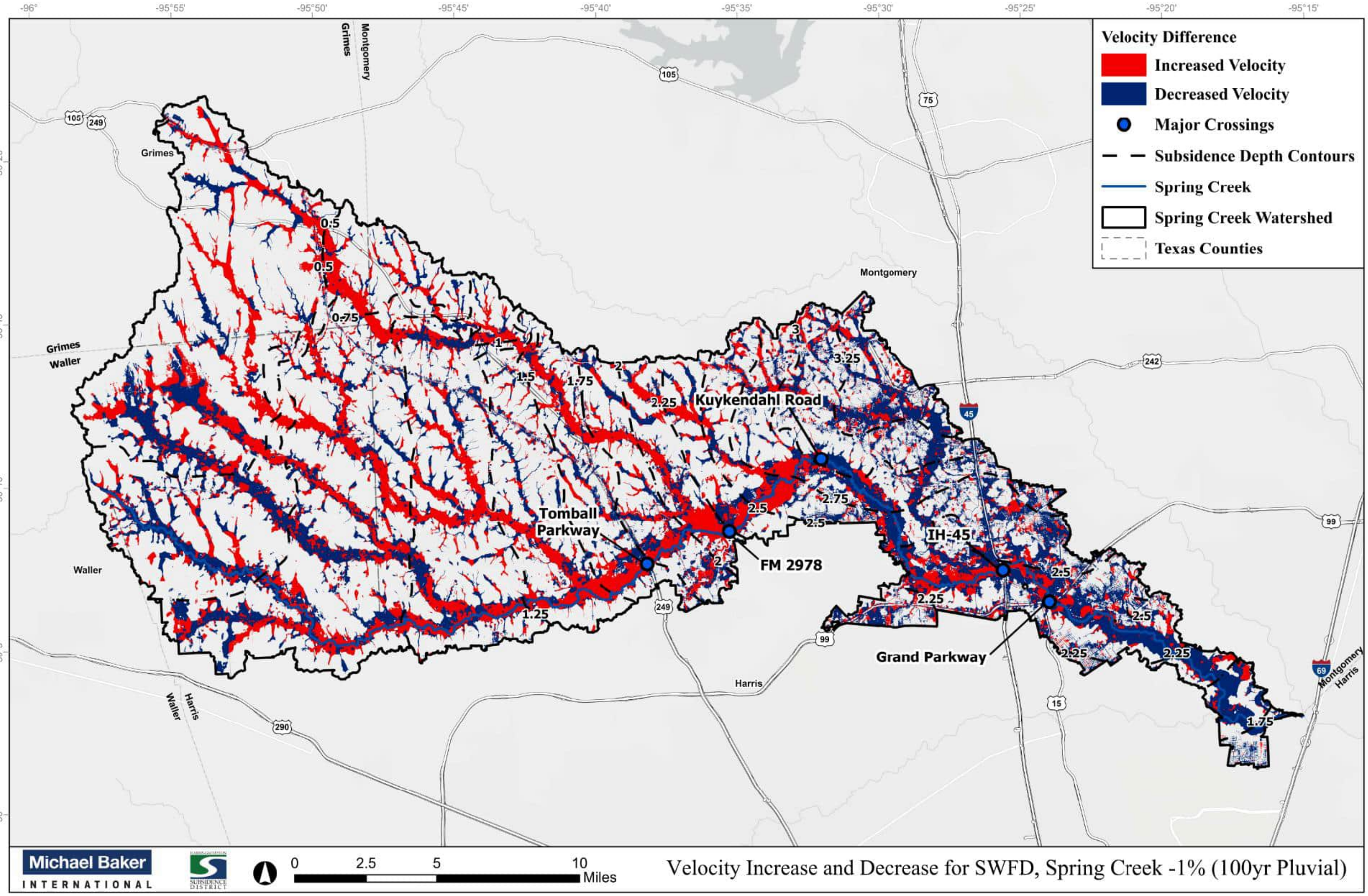



**Figure 15: Velocity Difference Between Baseline and SWFD Scenario for 100-Year Event (Pluvial) for Spring Creek**

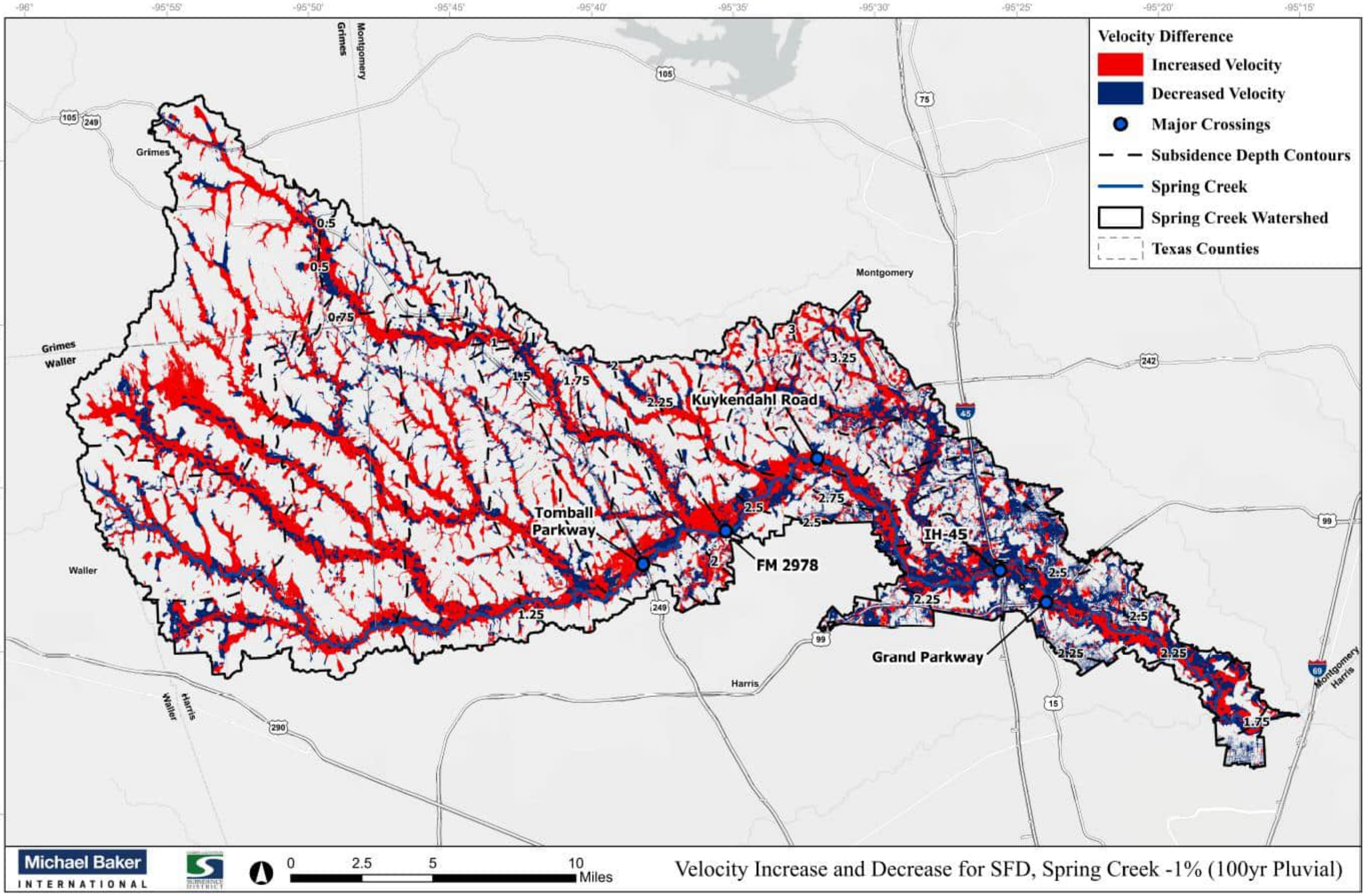



**Figure 16: Velocity Difference between Baseline and Subsidence with Future Development (SFD) for 100-Year Event (Pluvial) for Spring Creek**

#### *2.1.2.1 Changes in Peak Flow*

Peak flows were compared at major roadway crossings over Spring Creek, from the bridge at Tomball Parkway upstream to Grand Parkway downstream. Peak Flow values were compared at five major crossings for all three scenarios (**Figure 17**) for 1% AEP event. Peak flow values were extracted from the SA-2D connections at these crossing locations, which show the stage and flow hydrographs in the HEC-RAS 2D pluvial model.

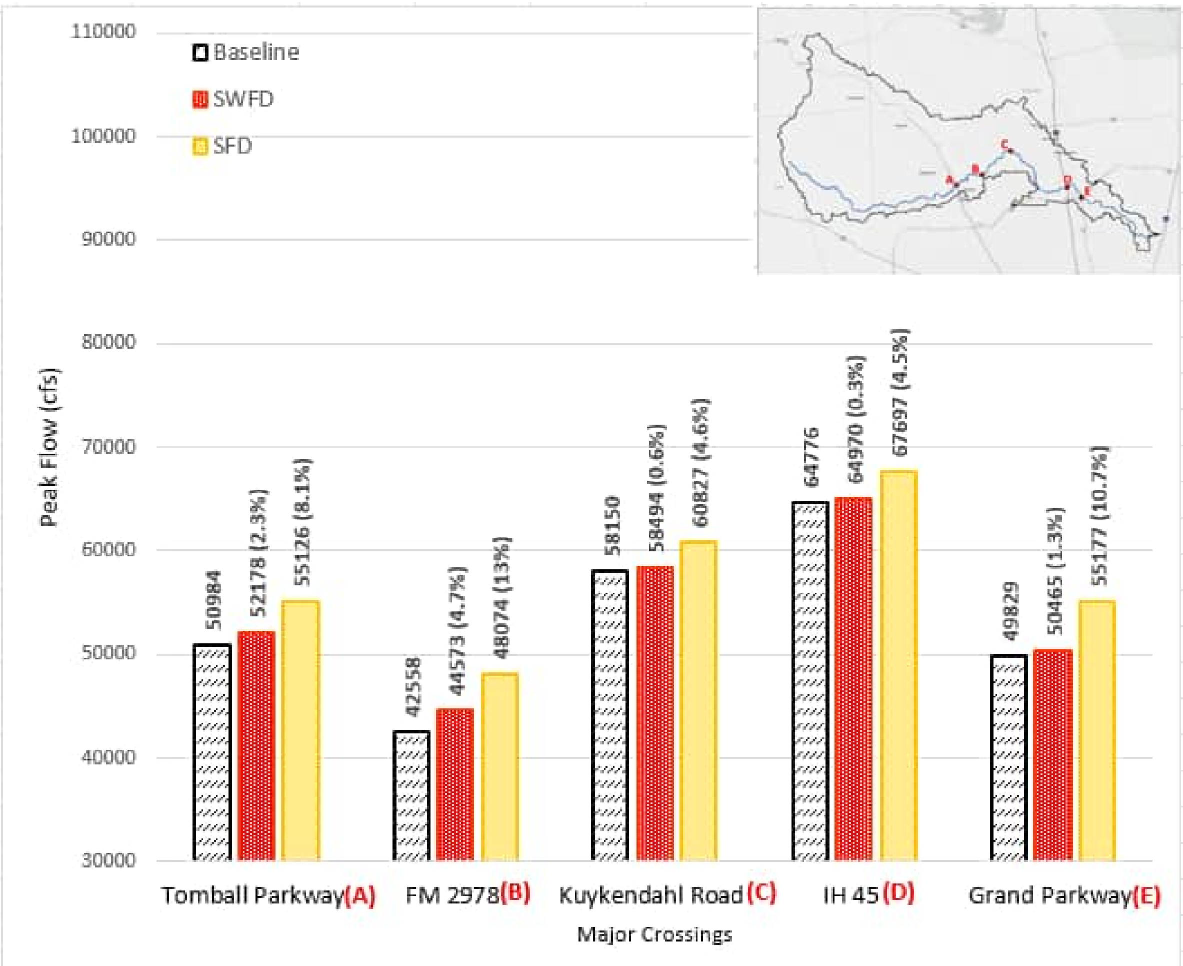



**Figure 17: Comparison of Peak Flow for Baseline, Subsidence without Future Development (SWFD) and Subsidence with Future Development (SFD) at Major Bridge Crossings near IH-45**

Peak flows at these crossings for the SWFD scenario are similar or slightly higher (0.3% to 4.7%) than the baseline, but they are substantially higher for the SFD scenario (4.5% to 13%).

# 3 Flooding Impacts Assessment

By comparing H&H modeling results between baseline, SWFD, and SFD scenarios, the model can predict how changes in subsidence and future development impact flood risk and, thus, economic impact on the Spring Creek watershed. This section discusses changes in flooding risks due to subsidence for 1% AEP design events from the pluvial HEC-RAS model.

Flooding impacts for this section are mainly focused on infrastructure - structural (buildings) and non-structural (roadways). Flooding impacts due to subsidence scenarios are quantified as the number of structures flooded as well as the total length of roadways flooded as compared to the Baseline model. The flooding impact is discussed for the pluvial modeling approach.

## 3.1 Pluvial Impact Assessment

The Pluvial impact assessment was done based on the results from the pluvial HEC-RAS model and categorized as structural and non-structural and described below.

### *3.1.1 Structural Flooding Impact*

Flooding can have devastating effects on structures, causing both immediate and long-term damage. When floodwater inundates buildings, it can weaken foundations, erode walls, and compromise the integrity of materials like wood, drywall, and insulation. Prolonged exposure to moisture can also lead to mold growth, which further deteriorates structural components and poses health risks. Additionally, flood water can also damage contents and inventory (vehicles) depreciation or loss associated with the structures. These all not only result in costly repairs but also pose significant health risks to occupants.

#### *3.1.1.1 Level of Flood Impact on Structures*

Structural flooding evaluates the flood impact associated with structures in the watershed. Flooding can have a big impact on structures, including the need for costly repairs or replacement of structural, mechanical, and electrical components, along with content and inventory loss. Even a minor flooding depth can cause significant economic loss. The common impact on a structure for different flood depths (extracted from the flood factor[ii]) is illustrated in **Figure 18**.

[ii] Greater depths of flooding cause more damage – First Street™https://help.floodfactor.com/hc/en-us/articles/360048265533-How-will-different-flood-depths-affect-my-property-

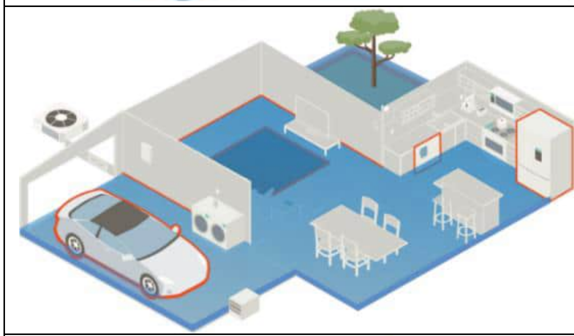
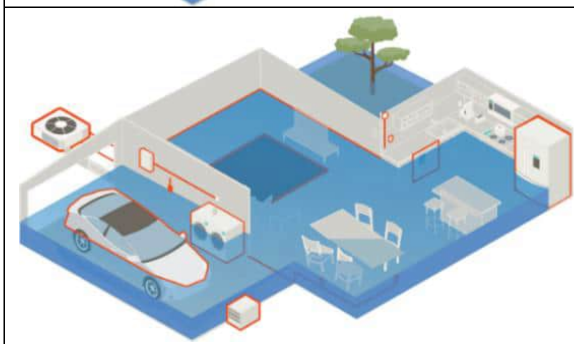
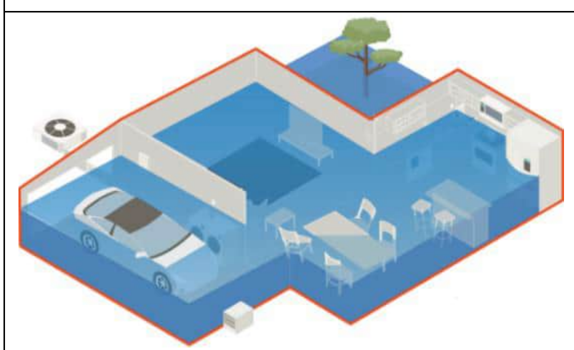
| | |
|---|---|
|  | **(I) - Flood Depth Less than six (6) inches**<br>• Drywall repair<br>• Insulation replacement<br>• Carpet and padding replacement<br>• Laminated floor replacement<br>• Warped hardwood floors |
|  | **(II) - Flood Depth Greater than six (6) inches but less than one (1) foot**<br>• Includes damages from Level one<br>• Replacement of electrical components, such as refrigerators and ovens<br>• Stalled vehicles |
|  | **(III) - Flood Depth Greater than one (1) foot but less than three (3) feet**<br>• Includes damages from Level two<br>• Electrical outlet, Heating and cooling system replacement<br>• Replacement of electrical components – washers, dryers, and dishwashers<br>• Vehicle damage |
|  | **(IV) - Flood Depth Greater than three (3) feet**<br>• Includes damages from Level three<br>• Foundation and framework damage<br>• Water supply, sewage, and plumbing system damage |

**Figure 18: Flooding Impact on a Structure (Illustration)**

*Note: Blue fill is the flooded water level, and the red outline indicates the items damaged*

Hence, structural flooding has been classified into these four (4) levels for differentiating various levels of flooding hazards and, thus, economic loss in the Spring Creek watershed.

#### *3.1.1.2 Total Number of Flooded Structures*

Due to differential subsidence and, thus, differential hydraulic impacts, the total number of flooded structures between baseline and subsidence scenarios can vary significantly. To calculate flooded structures, structure datasets were downloaded from the National Structural Inventory[iii] (NSI). The NSI dataset provides a base dataset of national coverage of structure points with attributes with consistent quality. Hence, the NSI dataset covers the entire Spring Creek watershed, which falls in four different counties.

The following relationship was implemented to determine if a structure is flooded.

$$\textit{Structural flooding depth} = \textit{Modeled flood depth at (above ground elevation)} - \textit{Foundation height of structure}$$

*where modeled flood depth for each structure (above ground elevation) was extracted from the depth raster (modeling result) of the three (3) scenarios – Baseline, Subsidence without future development, and Subsidence with future development.*
*The foundation height of the structure was obtained from the NSI shapefile.*

A positive value of the structural flooding depth indicates that the structure would be flooded. The 1% AEP flood depth at each structure was extracted from the depth raster of the baseline and subsidence scenarios. The flood depth is used to evaluate the extent of damage to the structure during a flooding event.

The total number of flooded structures in each scenario with respect to the level of flood depth (as discussed in **Section 3.1.1.1**) is shown in **Table *2*** and **Table 3.**

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iii https://nsi.sec.usace.army.mil/downloads/

**Table 2: Number of Flooded Structures in the Three (3) Scenarios of the Pluvial Model in a 100-Year Event**

| Flood Depth (ft) | Number of Flooded Structures in | | |
|---|---|---|---|
| | Baseline | Subsidence without Future Development (% change from Baseline) | Subsidence with Future Development [iv](% change from Baseline) |
| **0 – 0.5** | 3,822 | 3,895 (2%) | 4,522 (18%) |
| **0.5 – 1.0** | 2,356 | 2,407 (3%) | 3,175 (35%) |
| **1.0 – 3.0** | 3,975 | 4,041 (2%) | 5,724 (44%) |
| **> 3.0** | 2,154 | 2,175 (1%) | 2,602 (21%) |
| **Total** | **12,307** | **12,518 (2%)** | **16,023 (30%)** |

**Table 3: Number of Flooded Structures in the Three (3) Scenarios of the Pluvial Model in a 10-Year Event**

| Flood Depth (ft) | Number of Flooded Structures in | | |
|---|---|---|---|
| | Baseline | Subsidence without Future Development (% change from Baseline) | Subsidence with Future Development [v](% change from Baseline) |
| **0 – 0.5** | 1,314 | 1,338 (2%) | 1,765 (35%) |
| **0.5 – 1.0** | 783 | 790 (1%) | 920 (18%) |
| **1.0 – 3.0** | 843 | 871 (4%) | 1,112 (32%) |
| **> 3.0** | 409 | 417 (2%) | 491 (20%) |
| **Total** | **3,349** | **3,416 (2%)** | **4,289 (28%)** |

**Appendix A1** presents detailed analyses of flooded structures in each scenario, as well as newly flooded structures resulting from subsidence or roadways where subsidence increases the flooding

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[iv] *The decadal built-up area projections were obtained from the Global Human Settlement Layer (GHSL), developed by the European Commission's Joint Research Center (JRC). The built-up area projections for the Shared Socioeconomic Pathway (SSP) 2 (middle-of-the-road pathway) were selected, indicating that trends will continue on a path similar to historic patterns. The 1 km resolution built-up area layers for 2020 and 2070 were used to estimate the projected percentage increase in building footprint.* ***Results indicate a 9% increase in building footprint between 2020-2070.*** *Source - Directorate General for Regional and Urban Policy (DG REGIO) of the European Commission (2020). Projecting Global Population Grids to 2100 (BUILT-POP_PROJ_GLOBAL_SSP_R2020).*

[v] *The decadal built-up area projections were obtained from the Global Human Settlement Layer (GHSL), developed by the European Commission's Joint Research Center (JRC). The built-up area projections for the Shared Socioeconomic Pathway (SSP) 2 (middle-of-the-road pathway) were selected, indicating that trends will continue on a path similar to historic patterns. The 1 km resolution built-up area layers for 2020 and 2070 were used to estimate the projected percentage increase in building footprint.* ***Results indicate a 9% increase in building footprint between 2020-2070.*** *Source - Directorate General for Regional and Urban Policy (DG REGIO) of the European Commission (2020). Projecting Global Population Grids to 2100 (BUILT-POP_PROJ_GLOBAL_SSP_R2020).*

depth. Detailed exhibits are shown in **Appendix B**. **Section 4.2** discusses the economic loss associated with this damage**.**

### *3.1.2 Non-Structural Flooding Impact*

Non-structural flooding is limited to roadway flooding in this analysis. Non-structural (roadways) flooding causes prolonged closures, disrupting transportation and economic activities. Flooding can also hinder emergency response efforts and isolate communities, exacerbating the overall impact of flooding. Flooding on roadways can also lead to damage such as erosion of the subgrade, weakening of the base layers, dislocation of concrete slabs, surface washouts, and reduced load-bearing capacity.

The consequences include high repair costs, challenges for emergency services, and inconveniences for road users and the wider community. This disruption can also significantly impact businesses and the economy. Given the time and financial resources required for reconstruction, sustainable and long-term planning is imperative. Integrating flood risk analysis into the decision-making process is essential for effective infrastructure planning. This analysis facilitates appropriate planning for road networks and helps allocate resources for prevention, mitigation, and restoration efforts.

Flooded roadways were estimated for each scenario – baseline, SWFD, and SFD. The Geographic Information System (GIS) shapefile of roadways in the watershed was downloaded from the TxDOT website[vi]. The roadway functional classifications were consolidated for analysis, as listed in **Table 4**.

**Table 4: Roadways Classification**

| **Roadway Category** | |
|---|---|
| **Re-classified** | **Original TxDOT shapefile** |
| Highway | Interstate<br>Principal Arterial<br>Minor Arterial |
| Collector | Major Collector<br>Minor Collector |
| Local | Local Roads |

[vi] https://www.txdot.gov/data-maps/roadway-inventory.html

#### *3.1.2.1 Levels of Flood Impact on Roadways*

As little as six (6) inches of fast-moving water can cause a motorist to lose control of their vehicle. One (1) foot of floodwater on a roadway is enough to make vehicles buoyant and float away. Additionally, flood water can hydro-lock engines and severely damage them[vii]. Water ponding on roadways may potentially make them inaccessible during a flooding event. For the 1% AEP flood event of baseline, SWFD, and SFD scenarios, the roadway flooding was categorized in (a) flood depth less than or equal to one (1) foot and (b) flood depth greater than one (1) foot.

The total number of flooded roadways in each scenario, resulting from pluvial modeling for the level of flood depth, is shown in **Figure 18.** The levels and impacts of flood depth on roadways used in this analysis are discussed in the **Section 3.1.2.1**.

A detailed analysis of flooded roadways in each scenario, including newly flooded roadways due to subsidence or those where subsidence increases the flooding depth, is discussed in **Appendix A1**, with detailed exhibits provided in **Appendix B**.

**Table 5: Miles of Flooded Roadways in the Three (3) Scenarios of Pluvial Modeling for a 100-Year Event**

| Roadway Category | Baseline | | Subsidence without future development | | Subsidence with future development | |
|---|---|---|---|---|---|---|
| | Flood Depth | | | | | |
| | <= 1 foot | > 1 foot | <= 1 foot | > 1 foot | <= 1 foot | > 1 foot |
| **Highway** | 28 | 41 | 28 | 42 | 29 | 46 |
| **Collector** | 34 | 60 | 34 | 61 | 34 | 65 |
| **Local** | 165 | 351 | 163 | 356 | 154 | 389 |
| **Subtotal** | 227 | 452 | 225 | 459 | 217 | 500 |
| **Total** | 679 | | 684 | | 717 | |

### *3.1.3 Flooding Impact on Emergency Evacuation Route*

Access to the emergency evacuation route is essential to keep people safe in a hazardous event like a flood. TxDOT provides information about emergency evacuation routes within Texas. The IH-45 is the only emergency evacuation route in the spring watershed is the IH 45. This evacuation route goes through the densely populated area of Woodlands. **Figure 19** shows the 100-year floodplain near the emergency route of IH 45. Though the IH 45 bridge does not overtop, the bridge would be in pressure flow in all three scenarios. Hence, IH 45 may have to be evaluated for potential reconstruction due to a lack of freeboard in the future.

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[vii] https://www.texasattorneygeneral.gov/consumer-protection/disaster-and-emergency-scams/warning-flood-damaged-cars

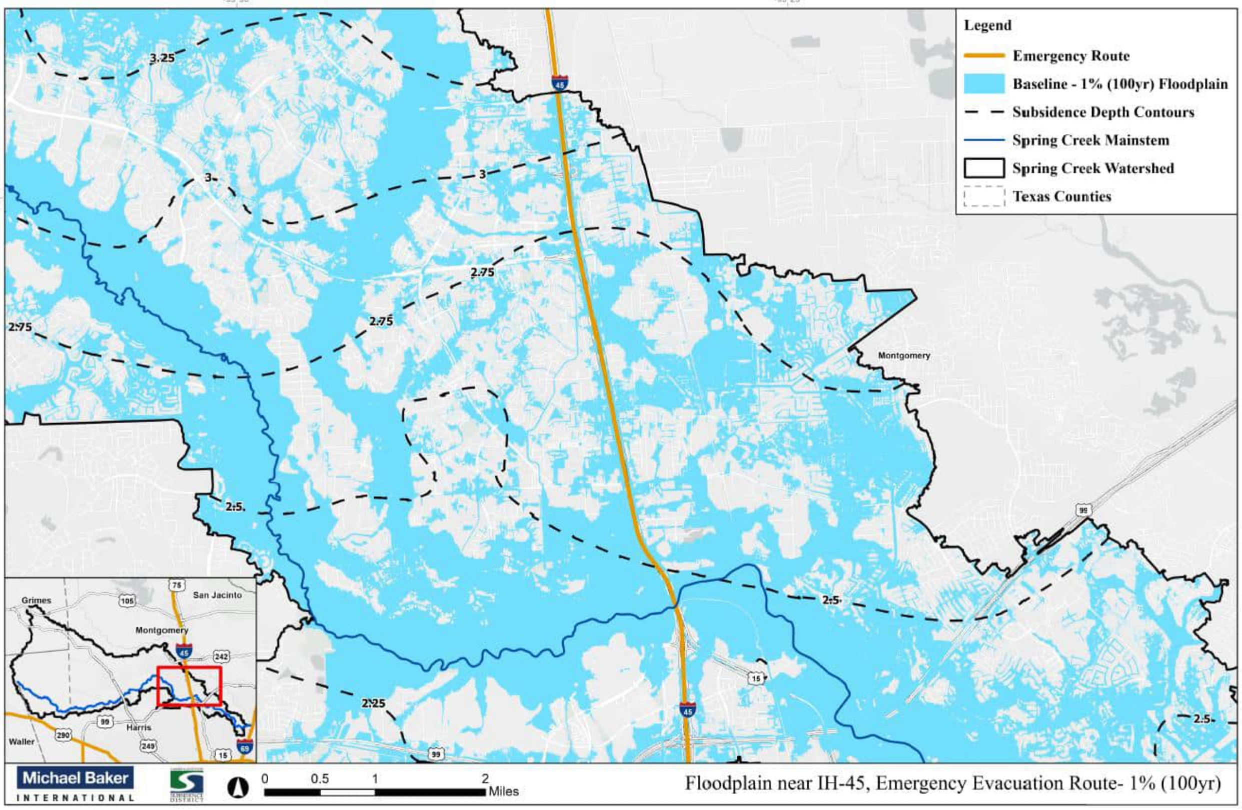


**Figure 19: Flooding near the bridge at IH-45 which is an Emergency Evacuation Route within the Spring Creek watershed**

### 3.1.4 Depth and Velocity Impact of Floodwater

The above sections discuss the impact of the depth of floodwater on structures and roadway infrastructure. However, the combination of depth (D) and velocity (V) is equally, if not more, hazardous to human life, structures, and infrastructures. Individually, these parameters represent risk – deep flows are more hazardous than shallow flows, and fast-moving floodwaters are more dangerous than slow-moving or stagnant floodwaters. Consequently, the product of these two (2) parameters is critical. The higher the product of depth and velocity (D x V) is, the greater the risk is to humans and vehicles being swept away. D x V is also an important modeling parameter to delineate boundaries for floodways. D x V value of 2.5 feet – feet/sec ($ft^2$/sec) is a critical flood hazard threshold curve (see **Figure 20)** above the shaded zone H1, above which the floodwaters start becoming hazardous for small vehicles (AEMI, 2014; Smith, Davey, & Cox, 2014). (Please note **Figure 20** is shown in metric units).

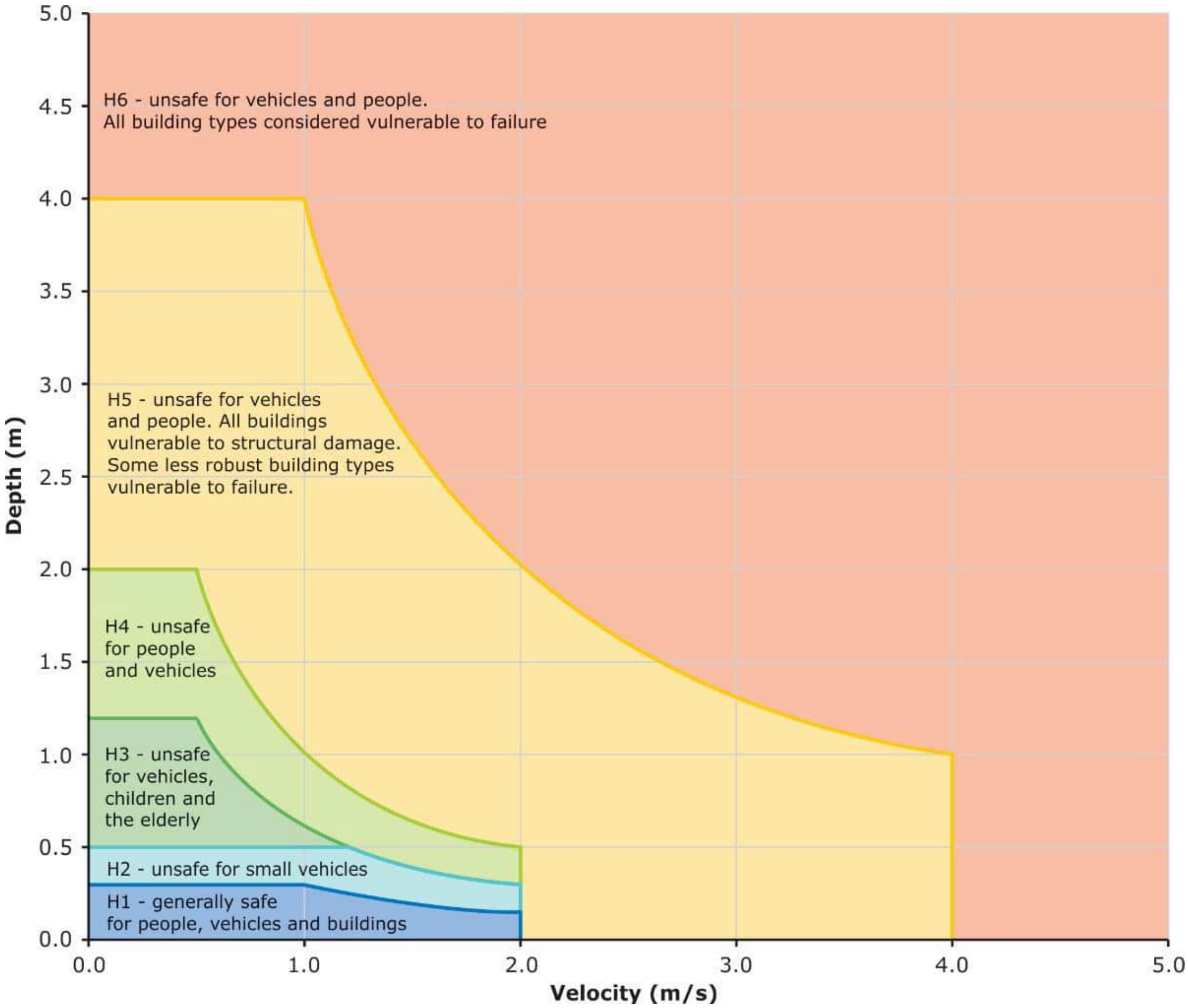


**Figure 20: Depth and Velocity Combined flood Hazard Curves (AEMI, 2014; Smith, Davey, & Cox, 2014)**

D x V raster greater than 2.5 $ft^2$/sec in the subsidence without future development scenario than the baseline scenario was calculated by subtracting the maximum D x V raster of the baseline scenario from the maximum D x V raster of the subsidence without future development scenario. The SWFD scenario shows a total of 313 acres where the D x V value is higher than 2.5 $ft^2$/sec than the baseline scenario, which is 0.34 % of the total floodplain in the SWFD scenario. The SFD scenario shows a total of 2,924 acres where the D x V value is higher than 2.5 $ft^2$/sec than the baseline scenario, which is 3.1 % of the total floodplain in the SFD scenario. Please see **Appendix B** for the detailed map.

# 4 Economic Assessment of Flooding Impact

The economic impact of subsidence has several components with interrelated losses. Subsidence in the Spring Creek watershed is linked to the withdrawal of groundwater (discussed in TM1 (MBI, 2024). Land subsidence results in significant economic losses in the form of structural damage and high maintenance costs. It affects roads and transportation networks, hydraulic infrastructure, utilities, and structural foundations. Structures in an area of subsidence can have sunken foundations, leading to cracked walls and structural instability. This can result in decreased property value during resale. Subsidence along a road can result in fractures, unevenness, and sinkholes, resulting in major disruption to the traffic, daily commute, and livelihood of the people. Municipal utilities and appurtenances subjected to subsidence can result in breakage and subsequent leakage. Higher differential subsidence along a pipeline can result in decreased hydraulic efficiency due to reverse flows. This can lead to the failure of an entire system. In the future, these infrastructures can be subjected to higher repair, replacement, or maintenance costs that can be attributed to subsidence.

Permanent inundation and increased temporary flooding are other major causes of economic losses that can be traced to subsidence. The Spring Creek watershed is prone to flooding during a 1% AEP event. Differential subsidence across a watershed can change stream gradients, thereby changing floodwater travel patterns and increasing flood depth and duration. In Harris County, extreme events have been known to cause major economic damage and loss of life. In August 2017, Hurricane Harvey created catastrophic flooding through its high-intensity rainfall and slow movement across Harris County. All 4.7 million people were impacted directly or indirectly (Lindner, 2018). About 154,170 homes were flooded, out of which 105,340 or 68% were outside the FEMA-designated 1% AEP floodplain (Lindner, 2018) which resulted in a loss of $ 125 billion statewide. Even a slight increase in flood risk in these flood-prone areas creates additional impact. Economic losses due to flooding include damage to structures (superstructure, foundation, contents, inventory), relocation of the impacted population, wage loss, rental income loss, and business interruption loss. Roadways flooded and inundated for extended durations can significantly damage roadbed structures, resulting in the repair or replacement of pavement. Flooded roadways and loss of use of critical access routes interrupt the daily economic activity of the area, which incurs more economic loss due to the associated loss of income.

## 4.1 Consequence Tool

A flood damage loss estimate is valuable for understanding and communicating the relative importance of flood risks for different severities (10% AEP, 1% AEP, or 0.2% AEP). Flood damage loss estimate is also one of the decision-support tools used to plan and prioritize the allocation of limited resources. Information from flood damage losses also helps shape the planning and regulation that can mitigate the effects of a disaster. Numerous hazard and risk assessment tools are available for quantifying the consequences of the flood hazard. Four (4) of these free public tools—HAZUS-MH, HEC-FIA, HEC-FDA, and Go Consequence were initially considered during the selection of appropriate hazard loss modeling tools, which are discussed in detail in **Appendix A2**.

To determine the suitability of each, their advantages and disadvantages were compared. The selected tool, methodology, and results are discussed in the subsequent sections.

### 4.1.1 *Summary and Selection of a Hazard Loss Modeling Tool*

A comparison of the four (4) hazard loss modeling tools was done based on the availability of data, methodology, calculation complexity, level of analysis, and output in **Table 6**. These comparisons facilitated the selection of the appropriate hazard loss modeling tool for this study.

**Table 6: Comparison of HAZUS-MH, HEC-FIA, HEC-FDA, and Go-Consequence for economic impact assessment**

| Consequence Tool | HAZUS-MH Flood Model | HEC-FIA | HEC-FDA | Go-Consequence |
|---|---|---|---|---|
| **Introduction** | 1) HAZUS Multi-Hazard<br>2) Free ArcGIS extension from FEMA | 1) HEC-Flood Impact Analysis<br>2) Free standalone software from HEC | 1) HEC-Flood Damage Reduction Analysis<br>2) Free standalone software from HEC | 1) Open source tool developed by USACE Risk Management Center<br>2) Scripts available on GitHub |

| Consequence Tool | HAZUS-MH Flood Model | HEC-FIA | HEC-FDA | Go-Consequence |
|---|---|---|---|---|
| **Analysis / Data Need** | Three (3) levels of analysis with increasing data needs for a higher level of accuracy<br>a) Level I - Only needs project area<br>b) Level II - Needs flood depth grids (additionally)<br>c) Level III - Needs structure inventory (additionally) | 1) Detailed analysis based on structure inventory data<br>2) Uses hydraulic model outputs in gridded data (ex.: depth and arrival-time grids) and/or HEC-DSS stage hydrographs (single continuous or forecasted hydrographs) as its input parameter | 1) Employs Monte Carlo simulation to estimate flood damage for multiple scenarios.<br>2) H&H data such as WSE profiles, analysis year, frequency flows, stage-discharge functions, and levee features.<br>3) Economic data such as damage categories, structure occupancy types, structure inventory data, and stage-damage functions. | 1) Computes direct losses based on the depth-damage curves and structure inventory data.<br>2) Uses the hydraulic model outputs to estimate flood depth above the finished floor elevation<br>3) Computes indirect losses including capital and labor loss using the Economic Consequences Assessment Model (ECAM) |
| **Outputs** | 1) Economic Loss<br>2) Structure and Contents Losses<br>3) Business Interruption Losses<br>4) Agricultural Losses | 1) Economic Loss<br>2) Structure and Contents Losses<br>3) Business Interruption Losses<br>4) Agricultural Losses<br>5) Life Loss (Simplified LifeSim method) | 1) Economic Loss<br>2) Physical damage to structures | 1) Direct losses to structures, contents, and vehicles<br>2) Indirect losses to production and reduction in labor workforce |

| Consequence Tool | HAZUS-MH Flood Model | HEC-FIA | HEC-FDA | Go-Consequence |
|---|---|---|---|---|
| **Advantages** | 1) Easy to use<br>2) Level-I/II can be used with depth raster from the hydraulic model output<br>3) Level-III, the detailed level analysis (similar approach as that of HEC-FIA) can be done if NSI/other data is available | 1) Easy to use with a minor learning curve<br>2) Can use the granularity of flood depth -resolution up to the structure footprint level<br>3) Considers effect of depth, velocity and arrival time to calculate<br>4) Can simulate simplified life loss | 1) Easy to use with a minor learning curve.<br>2) Can use the granularity of flood depth -resolution up to the structure footprint level.<br>3) The model performs a Monte Carlo simulation thousands of times to estimate damage and account for uncertainty.<br>4) Estimated damage can be analyzed in many different ways, for example, for a stream, analysis year, damage category and plan; results can then be used to evaluate damage over different periods in the context of flood damage reduction. | 1) Availability of scripts to automate the model for running multiple scenarios simultaneously, significantly reducing time and effort.<br>2) Availability to incorporate NSI data for detailed analysis of direct losses.<br>3) Advanced scripts to estimate indirect losses using the widely used Economic Consequences Assessment Model.<br>4) Provides outputs in easily accessible GIS data format files. |
| **Disadvantages** | 1) Level I/II only uses flood depth information up to the census block level, so high-resolution flood depth input may not be utilized to its full potential.<br>2) Only uses maximum flood depth to calculate loss; ignores the effect of velocity or duration of the flood.<br>3) No life loss module for the HAZUS-MH flood model. | 1) Cannot run any analysis without NSI or similar data.<br>2) Tedious, difficult and time-consuming to create comprehensive attributes for user-defined structures inventory if original NSI data is not accessible. | 1) Cannot run any analysis without NSI or similar data (unlike HEC-FIA).<br>2) Cannot use spatial data. Because subsidence is variable throughout the watershed, this is a limiting factor for the project scope. | 1) Does not have a user interface.<br>2) Requires some basic programming knowledge to run the tool. |

For this study, we selected the Go-Consequence tool to estimate the direct and indirect losses due to flooding. While its methodology is similar to that of HEC-FIA, it offers an open-source library capable of simultaneously estimating losses for multiple flooding scenarios, adhering to the Findable, Accessible, Interoperable, and Reproducible (FAIR) guidelines. The depth-damage curves from USACE available within the tool and the National Structures Inventory (NSI) data can be directly used to estimate the direct losses for the pluvial model. Additionally, it incorporates the Economic Consequences Assessment Model (ECAM) for estimating indirect losses, which has been widely accepted by various U.S. government agencies for indirect economic assessments across multiple hazards, including flooding.

### *4.1.2 Development of Models Go-Consequence*

The Go-Consequence tool is used to evaluate the economic consequences of the pluvial flood hazards. The Go-Consequence tool allows users to estimate flood losses from the depth of the flooding raster and the NSI data. The flood depth rasters from the HEC-RAS model were used as inputs to the Go-Consequence tool. The tool was accessed through a remote container in Visual Studio Code, and the scripts were obtained from the USACE GitHub repository. The outputs from the go-consequence tool were then analyzed in ArcPro 3.2 to obtain a summary of the economic losses for each scenario discussed in the subsequent sections.

#### *Scenario Development and Simulation*

Scenarios are user-defined simulation plans. In total, 6 simulation runs were set up for the pluvial simulations for each depth grid, as shown in **Figure 21**.

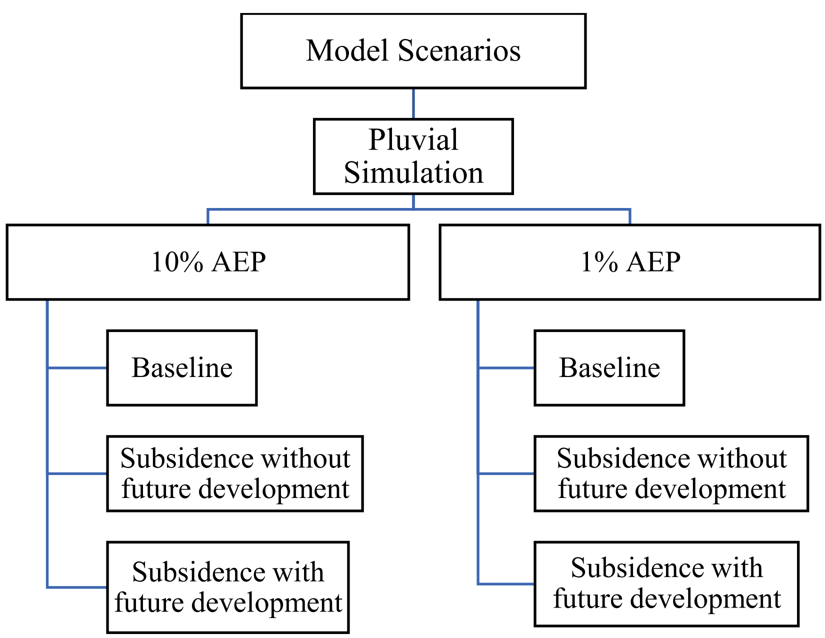


**Figure 21: Go-Consequence Loss Model Simulation Scenarios**

The scenarios were run using the Go-Consequence tool in Visual Studio Code. The results from these simulations were stored in a geodatabase. The results can be extracted as summary sheets or viewed as interactive tables within ArcPro 3.2. These results were further categorized for each inventory type and summarized to estimate the economic impact of flooding due to subsidence.

#### *4.1.3 Estimation of Loss using Go-Consequence Tool*

Flooding can cause both direct and indirect losses, each with significant impacts. The loss types and their subtypes are shown in **Table 7**. Direct losses include immediate physical damages such as the loss/depreciation of structures, personal property (contents), and inventory (vehicles). When floodwater inundates buildings, it can weaken foundations, erode walls, and compromise the integrity of materials like wood, drywall, and insulation. Prolonged exposure to moisture can lead to mold growth, which further deteriorates structural components. All of these can lead to loss and depreciation of the structure's value. Additionally, flood water can also damage contents inside the structures. During a major flooding event, vehicles such as cars and trucks (that are either parked at home or on the highway) are damaged. These are accumulating losses to a homeowner or business due to flooding. Hence, these direct losses are often quantifiable and result from the physical force of floodwater.

Indirect losses, on the other hand, are secondary effects that arise from the disruption caused by flooding. These can include a reduction in the labor workforce and a loss in Gross Domestic Product (GDP). These indirect effects of flooding can potentially incur due to business interruptions, loss of income, increased operational costs, and long-term economic impacts on communities. Indirect losses often extend beyond the immediate area of the flood, affecting supply chains, employment, and overall economic stability.

**Table 7: Types of direct and indirect losses evaluated using Go-consequence**

| Direct Loss | Indirect Loss |
|---|---|
| • Structure<br>• Contents<br>• Vehicles | • Gross Domestic Product (GDP)<br>• Labor |

The economic loss is discussed for the pluvial modeling approach in subsequent sections.

## 4.2 Economic Loss Due to Increased Flooding Due to Subsidence

The economic losses were evaluated in Go-Consequence using the flood depth rasters from the pluvial model for the six (6) previously discussed scenarios. The direct and indirect losses for baseline, SWFD, and SFD scenarios are shown in **Appendix A3**. The Go-Consequence tool was used to calculate damage based on the flood depth rasters obtained from the pluvial model for each scenario. The additional losses attributable to subsidence are discussed below.

### *4.2.1 Direct Losses Attributable to Subsidence*

The total economic loss for baseline, SWFD, and SFD conditions for 10-year and 100-year flood events, according to pluvial simulation results, is compared in **Appendix A3**. More detailed analyses were made regarding the additional losses attributable to subsidence for the SWFD and SFD, which is discussed in the subsequent sections. The additional losses that are attributable to subsidence are the losses that occurred due to subsidence scenarios, and those losses did not occur under the baseline scenario. These additional losses were categorized based on loss types and structure occupancy for both 10 and 100-year events. Moreover, the additional direct losses attributable to SFD and the increase in building footprint were estimated by multiplying the direct losses for the SFD scenario by a factor of 1.09 and subtracting them from baseline.

#### *4.2.1.1 Based on Loss Type*

As discussed in **Section 4.1.3**, there are three types of direct losses: structure, contents, and vehicles. Different types of additional direct losses attributable to subsidence for the SWFD, and SFD and increase in building footprint for 10-year and 100-year events are shown in **Table 8**. Structure losses made the largest contribution to total direct losses for most scenarios and flood events in the pluvial simulation. The highest additional direct losses for the pluvial simulation were estimated to be $445.5 million for SFD and an increase in building footprint.

**Table 8: Additional Direct Flooding Loss (attributable to subsidence) Categorized into 3 Main Types of Direct Losses – Structure, Contents, and Vehicles**

| AEP Event | Loss Type | Additional Direct Loss Attributable to Subsidence ($ million) | |
|---|---|---|---|
| | | Subsidence without Future Development | Subsidence with Future Development |
| 10-year | Structure | 5.7 | 62.2 |
| | Contents | 5.5 | 43.3 |
| | Vehicles | 0.6 | 7.3 |
| | **Total Direct Loss** | **11.8** | **112.8** |
| 100-year | Structure | 15.1 | 244.3 |
| | Contents | 17.5 | 176.5 |
| | Vehicles | 2.3 | 24.7 |
| | **Total Direct Loss** | **34.9** | **445.5** |

#### *4.2.1.2 Based on Structure Occupancy*

The direct losses were also categorized based on the occupancy type of the structure: Residential, Commercial, Public, and Industrial. Based on these types, the additional direct losses attributable to subsidence for the SFD are shown for 10 and 100-year events in **Figure 22**. In both cases, the largest contribution to direct losses can be attributed to residential areas, followed by commercial areas. Residential occupancy additional direct losses were estimated to be $255.2 million for SFD for a 100-year flood event.

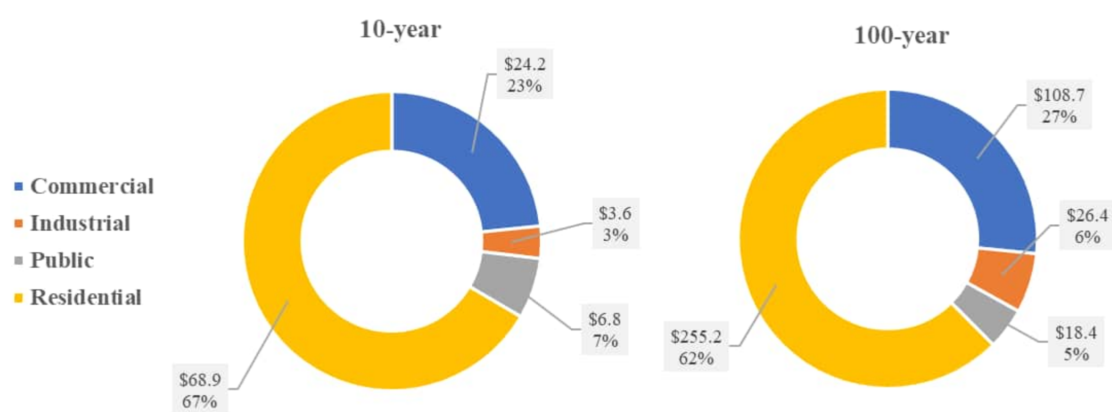


**Figure 22: Additional total direct flooding Loss ($ million; attributable to subsidence with future development) for structures, contents, and vehicles, based on structure occupancy type**

### 4.2.2 *Indirect Losses Attributable to Subsidence*

The indirect loss includes loss of gross domestic product (GDP) and reduction in labor incurred during the flooding event. The indirect losses were estimated using the Economic Consequences Assessment Model (ECAM) within the Go-Consequence tool. The event duration was set to 1-day for both the 10-year and 100-year events to estimate the indirect losses. The results of indirect losses for the baseline, subsided, and SFD are presented in **Appendix A3**. The additional indirect losses attributable to subsidence are discussed below.

#### 4.2.2.1 *Labor Loss*

The additional loss in labor workforce (persons) attributable to subsidence from the pluvial simulation for SWFD and SFD scenarios for the 10-year and 100-year flood events is compared in **Table 9**. The additional loss attributable to subsidence is the loss in labor for SWFD and SFD subtracted from the baseline. Moreover, the additional loss for SFD and the increase in the civilian labor force were estimated by multiplying the additional labor loss for the SFD scenario by a factor of 1.3. The loss in labor workforce increased with subsidence for both SWFD and SFD as compared to baseline; however, the additional loss was highest for the SFD, and an increase in the civilian labor force for both the 10-year (2,157 persons) and 100-year (3,253 persons) flood events.

**Table 9: Additional loss in labor workforce (persons) for Subsidence without future development, and Subsidence with future development and projected increase in civilian labor force**

| AEP Event | Additional labor loss attributable to subsidence (Persons) | |
|---|---|---|
| | Subsidence without future development | Subsidence with future development* |
| 10-year | 264 | 2,157 |
| 100-year | 386 | 3,253 |

*A 30% increase in the civilian labor workforce is projected for 2070 by accounting for the projected percentage increase in the Spring Creek Watershed population (47% increase) and the reduction in labor force participation rates between 2020 and 2070. https://conference.nber.org/confer/2023/SI2023/ESS/TopoleskiSlides.pdf.

#### 4.2.2.2 *Gross Domestic Product Loss*

The additional loss in GDP for SWFD and SFD with projected GDP growth for the 10-year and 100-year flooding event is compared in **Table 10.** The highest additional GDP loss was estimated to be $114 million for the SFD and a 1.5% annual projected GDP growth between 2020-2070 for the 100-year flood event.

**Table 10: Total additional loss in GDP from all sectors ($ Million) for Subsidence without future development, and Subsidence with future development and projected GDP growth**

| AEP Event | Additional GDP loss attributable to subsidence ($ million) | |
|---|---|---|
| | Subsidence without future development | Subsidence with future development and projected GDP growth |
| 10-year | 3.9 | 51.2 |
| 100-year | 8.0 | 114.0 |

*Projected GDP growth is estimated based on a 1.5% annual increase in real GDP between 2020-2070.

## 4.3 Annualized Economic Losses (AEL) – Flood Risk

Annualized economic loss (AEL) is the likelihood of loss due to a flood event (attributable to subsidence) over the years within the Spring Creek watershed. AEL annualizes the expected losses in terms of the associated flood risk by averaging them per year. AEL indicates the relative flood risk in the watershed but does not represent the total risk from flooding in any given year.

### *4.3.1 Probability of Exceedance (Pe)*

The loss from a single (1% AEP) flooding event in a year could easily exceed hundreds of millions of dollars. The estimated flow generated during a 1% AEP storm event is a statistically derived number using a probabilistic analysis of known/documented flooding events in a certain region within a certain duration. This confidence in the estimates varies depending on the availability of data representing higher frequency or larger storms and larger time durations. However, the probability of a 1% AEP flooding event happening every year from 2020 to 2070 is highly unlikely because the 1% AEP flooding event only has a 1% chance of occurring in any given year. Similarly, there could also be a potential instance where a given year could have multiple 1% AEP events. Mathematically, the probability of a 1% AEP flood occurring over a certain period of years (within the range of evaluation, 2020 – 2070) is given by the probability of exceedance ($P_e$) estimated using the empirical equation below:

$$P_e=1-[1-\frac{1}{100}]^n$$

where n is the number of years in the period. For example, the probability of a 1% AEP flood occurring over 30 30-year mortgage period (n = 30) is 26%. This means there is a 26% chance of a 1% AEP flood occurring in 30 years. This probability is also termed as the cumulative probability of a 1% AEP flood event. The probability for a 1% AEP storm event to occur in any given year increases exponentially, as seen in the curve plotted for the years from 2020 to 2070 in **Figure 23.**

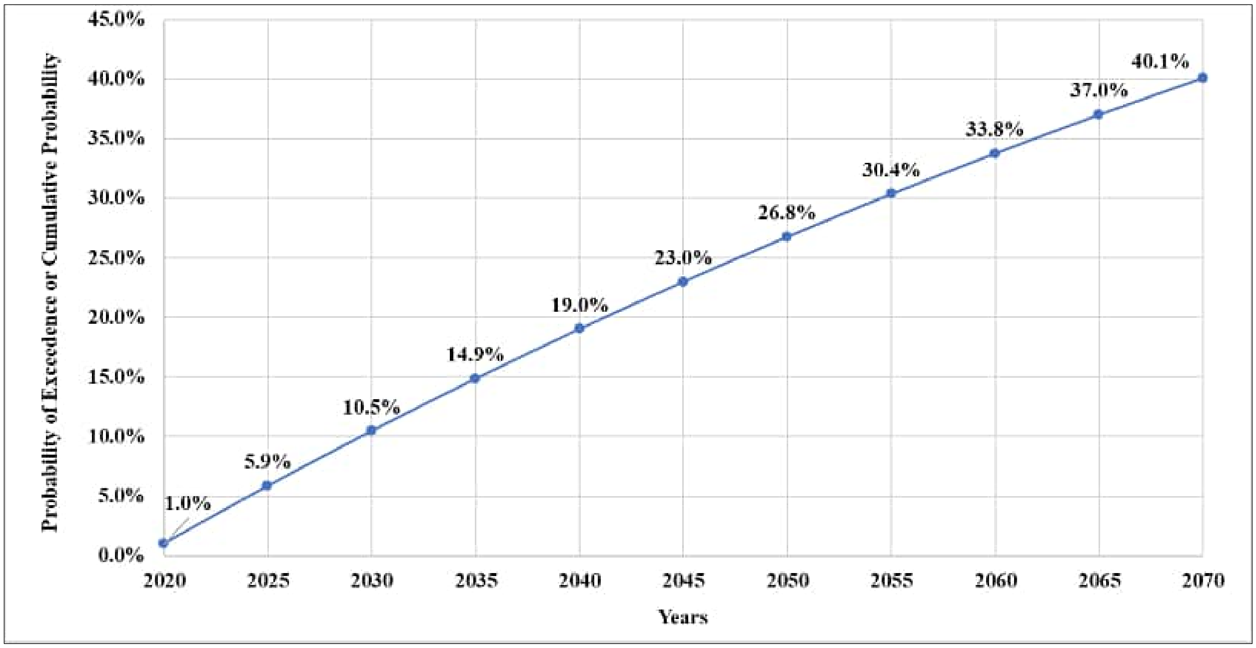


**Figure 23: The cumulative probability of a storm with a 1% Annual Exceedance Probability occurring between 2020 to 2070 is the Probability of Exceedance ($P_e$)**

**Table 11: Probability of Exceedance ($P_e$) or Cumulative Probability for every decade from 2020 to 2070**

| Range | | | $P_e$ |
|---|---|---|---|
| From | To | Number of Years | |
| 2020 | 2030 | 11 | 10.5% |
| 2020 | 2040 | 21 | 19.0% |
| 2020 | 2050 | 31 | 26.8% |
| 2020 | 2060 | 41 | 33.8% |
| 2020 | 2070 | 51 | 40.1% |

From **Table 11**, the chance of a 1% AEP flood occurring at least once over the period from 2020 to 2050 is 26.8%. From 2020 to 2070, the probability increases to 40.1%. The losses estimated from an individual flooding event were multiplied by the cumulative probability ($P_e$) to estimate the flood risk for a given year.

#### *4.3.2 Loss Attributable to Subsidence*

The economic loss of an individual flooding event occurring every year from 2020 to 2070 requires developing individual H&H models for each year, which was not within the scope of this study.

Therefore, the economic losses for each year from 2021 to 2069 were linearly interpolated between the Go-Consequence estimated loss values for the years 2020 and 2070. The total direct loss is represented by the estimated losses for structures, contents, and vehicles using Go-Consequence. GDP loss is added to the direct loss to estimate the total loss attributable to subsidence.

Interpolation of losses using a straight line/linear interpolation method was performed for the additional loss estimates attributable to subsidence between 2020 and 2070 from the pluvial model results. The linearly interpolated loss of an individual flooding event occurring every year from 2020 to 2070 is shown in **Figure 24**. Values in **Figure 23** are the additional annual flood losses attributable to subsidence if a 1% AEP occurred in a given year. For example, if a 1% AEP flooding event occurs in 2060 for the SFD scenario, the resulting flood loss can potentially amount to $372.6 million. As subsidence increases in the watershed every year, an increased deviation in losses is observed when comparing the SWFD and SFD scenario losses. In the year 2050, the additional loss attributable to SWFD is $25.7 million, and SFD is $279.4 million.

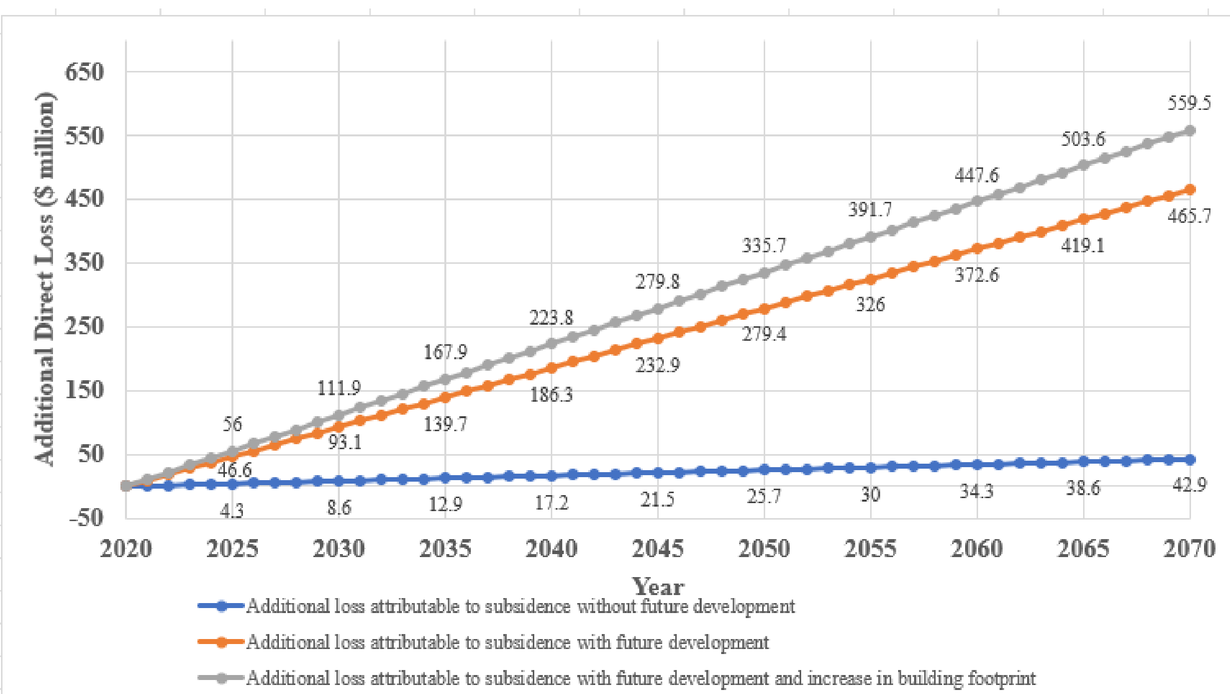


**Figure 24: Additional Loss attributable to subsidence of an individual event occurring every year from 2020 to 2070 for a 100-year pluvial flood event.**

### *4.3.3 AEL Estimation*

AEL estimates are the likelihood of loss due to flood events over the years. In other words, it is the annualized flood risk for a cumulative period. Therefore, the values in **Figure 24** do not represent AEL for a given year. The annual flood loss multiplied by the cumulative probability ($P_e$) (see **Table 11**) gives the AEL over the years, which is shown in **Figure 25** as the AEL attributable to subsidence for every year. All other factors that contribute to a flood loss were removed from the estimation. AEL from the period 2020 – 2050 was estimated to be $6.9 million for SWFD, $74.8 million for SFD, and $89.9 million for SFD and an increase in building footprint. Similarly, AEL from the period 2020 – 2070 is $17.2 million for SWFD, $186.8 million for SFD, and $224.4 million for SFD and increase in building footprint. These are annual losses associated with flood risk due to subsidence. When these losses are added to the actual flood risk, the risk faced by a property in the watershed increases. These anticipated flood risks can reduce the future value of a property, increase flood insurance, and financial hardships for the people in the watershed.

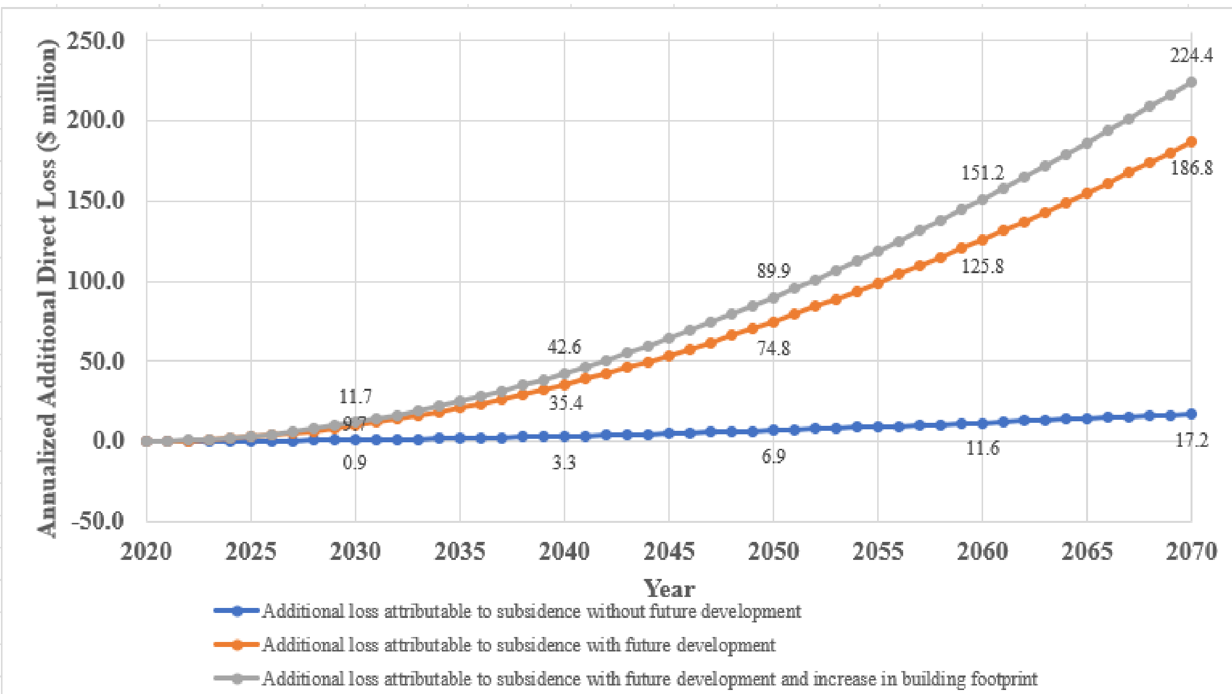


**Figure 25: Annualized Economic Losses attributable to subsidence from 2020 to 2070.**

*Note: The additional losses were multiplied by the cumulative probability of exceedance ($P_e$) for each year.*

# 5 Economic Assessment of Faultline Shifts

According to USGS (USGS, 2024), a fault is a fracture or zone of fracture between two (2) blocks of rock (**Figure 26**). Faults allow the blocks to move relative to each other. This movement may occur rapidly, in the form of an earthquake, or slowly, in the form of creep. Fortunately, most surface faulting in Harris and Montgomery counties occurs in deep, unconsolidated sediments, moving in slow creep events, and does not typically cause earthquakes. The relationship between land subsidence and fault reactivation remains complex. However, pumping of groundwater, oil, and gas has reactivated more than 300 miles of pre-existing faults in Houston in the past (Elsbury & Van Siclen, 1983), which is in the vicinity of the Spring Creek watershed.

**Figure 26: Conroe Faultline[viii]**

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[viii] *Fault lines in Montgomery County, near the corner of Sgt. Ed. Holcomb Blvd. N. and Hwy. 105 in Conroe, https://communityimpact.com/houston/conroe-montgomery/environment/2021/02/24/as-ground-sinks-debate-ensues-over-montgomery-countys-groundwater/, Eva Vigh, Community Impact Newspaper*

## 5.1 Faults in Spring Creek Watershed

As detailed in the report titled 'Faults Study in Spring Creek' by Dr. Shuhab Khan, SK Geosciences (please refer to **Appendix A** of TM1 (MBI, 2024) for details), there are seven (7) different faults near the Spring Creek watershed, namely Hockley, Hufsmith, Panther Branch, Big Barn, Egypt, Conroe and Other faults (**Figure 27**). A few unnamed faults are also shown beneath other faults. Out of these seven (7) faults, four (4) faults (Big Barn, Egypt, Hufsmith, and others) fall within the Spring Creek watershed (**Figure 27** and **Table 12**). The subsidence depth contour (Figure 27) indicates Big Barn and Egypt faults are located in high subsidence areas whereas Hufsmith and Others faults are located in relatively low subsidence areas. Most of these are normal faults and generally trend in a southwest-northeast direction and dip towards the southeast at around 70º (Norman C. E., 1991). The rate of movement for these faults varies from 0.2 to 1.2 inches per year (Norman & Howe, 2011; Worrall & Snelson, 1989). The rates of movement reported for each of these faults from previous studies, along with the reported period of record, are also shown in **Table 12**. Please refer to **Appendix A1** of the Data Collection Memo (MBI, 2024) for more details on the faults.

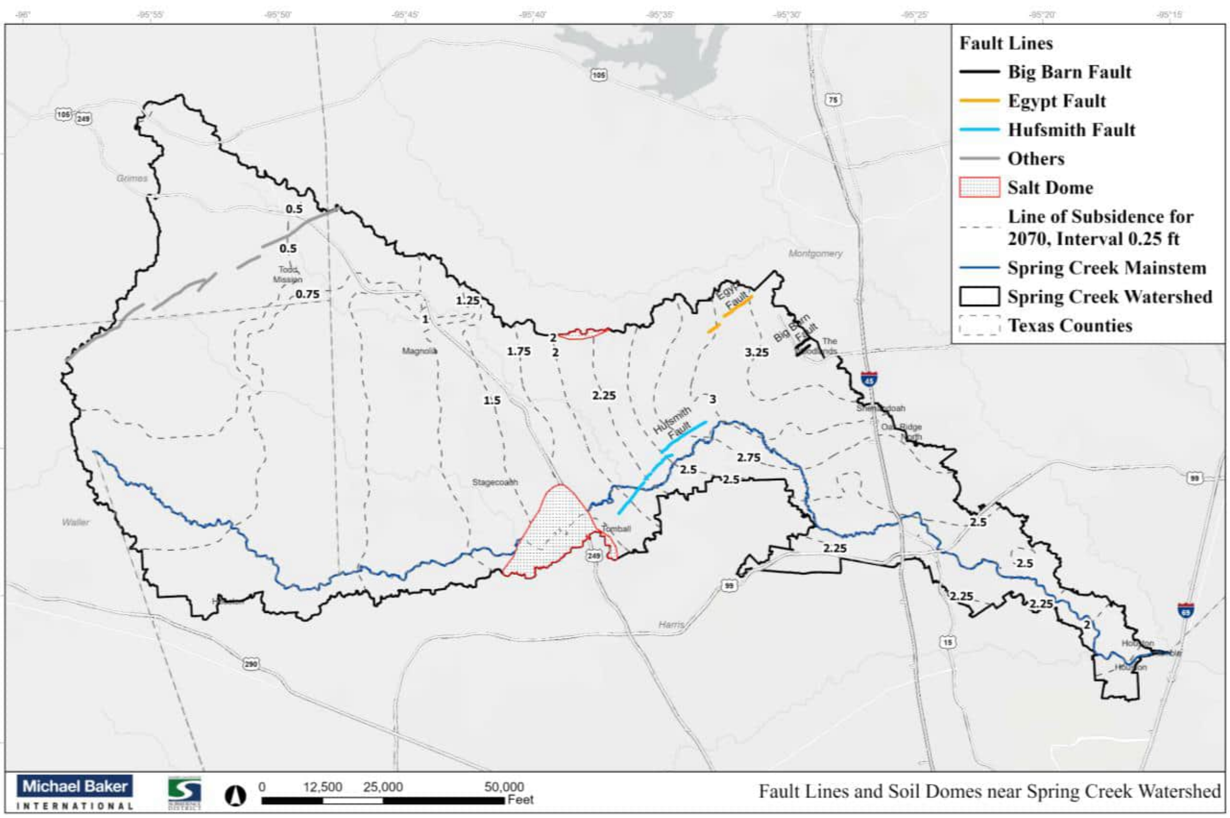


**Figure 27: Faults and Salt Domes near Spring Creek Watershed along with Subsidence Depth Contours**

**Table 12: Faults in Spring Creek Watershed**

| Fault Name | Down throw n Side | Total Length (mile) | Length within Spring Creek Watershed (mile) | Rate of Movement (inch/year) | Period of Record for Rate of Movement | Reference |
|---|---|---|---|---|---|---|
| **Big Barn Fault** | SE | 5.8 | 1.3 | 0.00 | 08/1985-09/1986 | Minteer, 2018 |
| | | | | 0.64 | 02/1987-09/1987 | Minteer, 2018 |
| **Egypt Fault** | SE | 1.9 | 1.9 | 0.50 | 1966-present | Qu et. al. 2019 |
| **Hufsmith Fault** | SE | 5.0 | 5.0 | 0.50 | 1966-present | Qu et. al. 2019 |
| **Other** | SE | 19.3 | 11.4 | 0.50 | 1966-present | Qu et. al. 2019 |

### 5.1.1 *Big Barn Fault*

The Big Barn fault, located northeast of the Spring Creek watershed in Montgomery County, intersects IH-45 near Guinn Road, about 20 miles north of Houston, Texas. Formed during the Jurassic Age, it remained largely inactive until the past 20 years, when it caused significant deformation near IH-45 (Minteer, 2018). Big Barn fault showed negligible movement during 1985-1986 with considerable movement measured during 1987 (Minteer, 2018) (see Table 12). There are at least five (5) segments of the Big Barn fault identified with a total length of 5.8 miles. However, only two (2) segments of this fault lie within the study area. Big Barn is a normal fault with downthrown towards the southeast.

### 5.1.2 *Egypt Fault*

The Egypt fault lies just west of the Big Barn fault on the northeast side of the Spring Creek watershed in Montgomery County. It intersects FM 1488 near Bear Branch Lane, about 20 miles north of Houston. Since 1966, it has shown intermittent activity, averaging 0.5 inches of movement per year (Qu, Lu, Kim, & Zheng, 2019).

### 5.1.3 *Hufsmith Fault*

The Hufsmith fault, a normal fault with a southeast downthrown side, is located southeast of the Spring Creek watershed, extending from Harris to Montgomery counties and crossing Spring Creek west of FM 2978. It consists of at least five segments, with only one in Harris County. Since 1966, it has shown intermittent activity, averaging 0.5 inches of movement per year. (Qu, Lu, Kim, & Zheng, 2019).

### 5.1.4 *Other Fault*

An additional fault without an identified name is described as Other Fault in this study. This fault is located in the southwest portion of the Spring Creek watershed, mostly in Grimes County, but it also extends slightly to Waller and Montgomery counties. This fault crosses FM 1774 and Highway 249 in Grimes County. The fault has at least five (5) segments with a downthrown side towards the southeast. Movement along this fault has been relatively intermittent throughout any given year with an average rate of 0.5 inches per year from 1966 to the present (Qu, Lu, Kim, & Zheng, 2019).

## 5.2 Potential Hazard to Structures and Infrastructures due to Faultline Shifts

Surface faultline shift poses hazards to structures and infrastructure because one side of the fault displaces relative to the other which can severely damage structures and infrastructures. In the most severe cases, the structure or infrastructure can collapse (**Figure 28**), potentially resulting in injuries or loss of life and property. In less severe instances, structural damage may render the structure uninhabitable and require costly repairs. Similarly, moderate to less damage to infrastructures like roads (**Figure 29**), rails, bridges, utilities (water lines, gas, optic cables, etc.), and other pipelines (oil, other liquids, and gases) may interrupt service or completely halt it, potentially impacting the safety, health, and property of the impacted population.

**Figure 28: Impacts of surface fault on a house. The house shown on the left collapsed due to extreme damage and the house shown on the right suffered moderate damage resulting in costly repairs. Red arrows show the relative trend of horizontal movement. (CADC, CGS, 2018)**

Structures and infrastructure that lie in proximity to the faults are more susceptible to damage. These zones are called fault hazard bands (**Figure 30**) (where the risk of significant fault-induced differential movement is greater than average (Elsbury & Van Siclen, 1983). A fault hazard band has three (3) parts (Elsbury & Van Siclen, 1983): surface deformation, zone of uncertainty, and zone of clearance. All of these components are site-dependent and vary substantially for the same fault within a short distance. However, based on the approximations provided in the previous study done in Houston (Elsbury & Van Siclen, 1983), a fault hazard band of 200 feet (~50 feet for surface deformation, ~50 feet on each side of the zone of uncertainty, and ~25 feet on each side of the zone of clearance) was assumed. This fault hazard band was used to qualitatively assess the number of structures and infrastructure that lie within this zone, as presented in **Table 13.**


**Figure 29: Impacts of Long Point surface fault on a road.**[ix]

[ix] *Image courtesy of Richard G. Howe, PG, CPG*

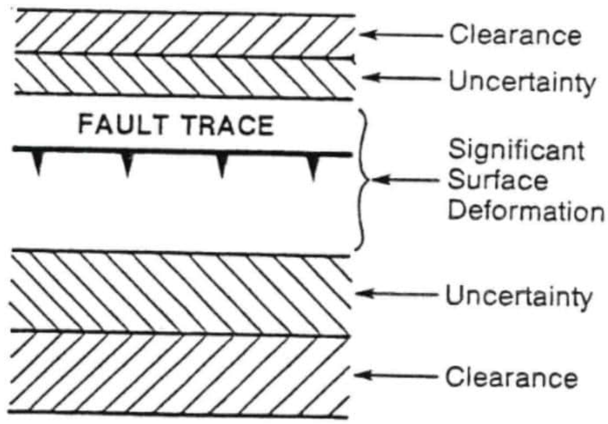


**Figure 30: Parts of a Fault Hazard Band (Elsbury & Van Siclen, 1983)**

### *5.2.1 Potential Hazard to Structures*

Structures are in danger of cracked foundations, walls, or even collapse due to the potential reactivation of the fault. Hence, the number of structures was assessed within 100 feet of the buffer on both sides (fault hazard band of 200 feet) within the boundary of the Spring Creek watershed (**Table 13**). The structure footprint data are accessed from the National Structural Inventory[x] (NSI). The parcel data with a market value assessment for the year 2024 was downloaded from the Texas Natural Resources Information System (TNRIS)[xi]. It is to be noted that there are uncertainties in the structure's footprint data, parcel data, and market value assessment and may not be the current representation of actual values. The market values presented in **Table 13** do not represent potential economic losses from a fault shift, but rather the total estimated market value of the property within the fault hazard band. This study makes no inference that a total or certain percentage of property loss will result from potential fault movement. Similarly, there are structures with missing market assessment values in the TNRIS dataset. This study did not include the market value for those structures. The values presented are for qualitative inference only.

As shown in **Table 13**, 56 structures are within 200 feet of the fault hazard band. The total market value (2024 parcel appraisal) of these structures, along with the parcel, can be as high as ~$38 million within 200 feet of the fault hazard band. However, this table does not make an inference that a 100% loss will occur in each of these structures. This value merely represents the total asset within the hazard zone and not the damage amount. The values presented in **Table 13** are also not included in the total economic assessment presented in previous chapters.

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[x] *https://nsi.sec.usace.army.mil/downloads/*
[xi] https://data.tnris.org/collection/?c=d0f7da13-ab09-4994-a16f-d52589e2476e

**Table 13: Structures in the Vicinity of the Faults in Spring Creek Watershed**[xii]

| Fault Name | Structures within 200 feet of Fault Hazard Band | |
|---|---|---|
| | Number | Total Market Value (millions USD) |
| **Big Barn Fault** | 1 | 7.0 |
| **Egypt Fault** | 10 | 9.7 |
| **Hufsmith Fault** | 17 | 10.5 |
| **Other** | 28 | 11.1 |
| **Total** | **56** | **38.3** |

### 5.2.2 *Potential Hazard to Infrastructure*

#### *5.2.2.1 Roadways*

Roadways are subject to crack development or even collapse from the potential reactivation of the fault. Roadways within 200 feet of the fault hazard band of each fault in the Spring Creek watershed are tabulated in **Table 14**. If a road falls within the intersection of this buffer zone (100 feet on each side of the fault), 200 feet of the roadway section is assumed to be damaged and must be repaired by reconstruction. It is to be noted that the level of potential damage and the section of the roadway affected by fault movement depends upon an assortment of variables like fault movement, strike, dip, type of roadway, angle of intersection, etc. The value of 200 feet of roadway section damage is an approximation that can significantly differ depending upon all these aforementioned variables. The roadway inventory was downloaded from the TxDOT website[xiii]. To simplify the different functional classifications attributed to the TxDOT roadway inventory, the functional classification is consolidated as roadway categories, as shown in **Table 4.**

The Federal Highway Administration (FHWA) has developed a typical cost per mile per lane for different types of roadway improvements (Please see **Appendix A4** ). **Table 15** shows a summary of the information from **Appendix A4**. Using the appropriate geography (urban or rural) and functional roadway category, the total reconstruction cost of each linear foot of the existing road is calculated. The drainage infrastructure construction cost for each functional class of road is assumed to be included in the cost estimate. For example, the Big Barn fault intersects a major urban road with two (2) lanes for a total of 600 linear feet. The roadway is classified as "Minor

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[xii] *The data and any related materials contained herein are provided without warranty of any kind, either express or implied, including, but not limited to, the implied warranties of merchantability, or fitness for a particular purpose. The data cannot be used in litigation of any kind. The entire risk of use of the data shall be with the user and is provided "as is," for research purposes only.*
[xiii] https://www.txdot.gov/data-maps/roadway-inventory.html

Arterial." The reconstruction cost for the existing lane for Minor Arterial is $4.0 (in millions of 2014 Dollars per lane mile) (**Table 15**). Using the Consumer Price Index Inflation Calculator from the Bureau of Labor Statistics[xiv], a 35% inflation is added to convert the 2014 costs to 2024 dollars. Hence, the total cost for 600 feet of existing road reconstruction is estimated as

$$\$4.0 * 1000000 * 2 * 1.35 * (600 / 5280) = \sim \$1{,}200{,}000.$$

As shown in **Table 14** , there are 43 road segments within the 200 feet of fault hazard band with a total reconstruction cost of approximately $11 million. It is noted that the economic, social, and health impacts of temporary road closures due to potential damage caused by fault movement are not included in this study. This study does not capture costs to repair future proposed roadway construction that occurs within 200 feet of the fault lines.

**Table 14: Roadways in the Vicinity of the Faults in Spring Creek Watershed**

| Fault Name | Roadway within Fault Hazard Band of 200 feet | | | | | |
|---|---|---|---|---|---|---|
| | Number of Road Segments | Roadway Class (Linear Feet) | | | | Cost Estimate of Reconstruction |
| | | Highways | Collector | Highways | Total | |
| **Big Barn Fault** | 3 | 600 | | | 600 | 1.2 |
| **Egypt Fault** | 7 | 400 | | 1,600 | 2,000 | 2.1 |
| **Hufsmith Fault** | 10 | | 300 | 1,900 | 2,200 | 2.1 |
| **Other** | 23 | 400 | 500 | 4,800 | 5,700 | 5.9 |
| **Total** | **43** | **1,400** | **800** | **8,300** | **10,500** | **11.3** |

**Table 15: Typical Costs per Lane Mile Assumed in Highway Economic Requirements System by Type of Improvement**

| Reclassify | TxDOT Road Class | Typical Costs of Reconstructing Existing Lane (per Lane Mile) | |
|---|---|---|---|
| | | Millions (2014, Dollars) | Millions (202, Dollars) |
| Highway | Principal Arterial Other | 5.9 | 8.0 |
| | Minor Arterial | 4.0 | 5.4 |
| Collector | Major Collector | 4.0 | 5.4 |
| | Minor Collector | 5.9 | 8.0 |
| Local | Local Roads | 4.0 | 5.4 |

*Note: Please refer to* ***Appendix A4*** *for a complete version of this table*

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[xiv] https://data.bls.gov/cgi-bin/cpicalc.pl?cost1=1.00&year1=201401&year2=202410

### *5.2.2.2 Railways*

The Spring Creek watershed is served by approximately 51 miles of railroad (according to data downloaded from the Railroad Commission of Texas (RRC)[xv]). The majority are from the Union Pacific Railroads, Burlington Northern Railroads, and others. Railroads can be deformed or severed by the potential reactivation of a fault. Railroads within the 200 feet of fault hazard band of each fault in the Spring Creek watershed are tabulated in Table 16. If a rail falls within the intersection of this buffer zone (100 feet on each side of the fault), 200 feet of the rail section is assumed to be damaged and must be repaired by reconstruction. It is to be noted that the level of potential damage and the section of the railroad affected by fault movement depends upon an assortment of variables like fault movement, strike, dip, railway alignment and angle of intersection, etc. 200 feet of railway section damage is an approximation which can significantly differ depending upon all these aforementioned variables.

**Table 17** presents typical railway construction from Eno's Transit Capital Construction Database[xvi] (**Appendix A5**). The cost per mile (in 2022 US dollars) for railway construction from these four (4) projects is averaged and is used for the cost estimation for railway reconstruction. Using the Consumer Price Index Inflation Calculator from the Bureau of Labor Statistics[xiv], a 9% inflation is added to convert 2022 dollars to 2024 dollars. Hence, the average cost per mile for railway construction is 172*1.09 =~$188 million (2024 dollars). As shown in **Table 16** , two (2) railway segments are within 200 feet of the fault hazard band of the four (4) faults, with a total reconstruction cost of approximately $14 million.

**Table 16: Railways in the Vicinity of the Faults in Spring Creek Watershed**

| Fault Name | Railway within 200 feet of Fault Hazard Band | | |
|---|---|---|---|
| | Number of Railway Segment | Railway Linear Feet | Cost Estimate of Reconstruction (million USD-2024) |
| Big Barn Fault | - | - | - |
| Egypt Fault | - | - | - |
| Hufsmith Fault | 1 | 200 | 7.1 |
| Other | 1 | 200 | 7.1 |

xv *https://www.rrc.texas.gov/resource-center/research/gis-viewer/*
xvi *https://projectdelivery.enotrans.org/transitcostsexplorer/*

| Total | 2 | 400 | 14.2 |
|---|---|---|---|

**Table 17: Typical Construction for Railway Projects in Houston, Texas**

| Railway Project | Project Type | Length (mile) | Cost per Mile (Million USD-2022) | Cost per Mile (Million USD-2024) |
|---|---|---|---|---|
| Metro Purple Line, Light Rail, Houston, TX (2009-2015) | New | 6.7 | 165 | 180 |
| Metro Green Line, Light Rail, Houston, TX (2009-2015) | New | 3.2 | 247 | 269 |
| Metro Red Line Extension, Light Rail, Houston, TX (2009-2013) | Extension | 5.3 | 197 | 214 |
| Metro Red Line (Original), Light Rail, Houston, TX (2001-2004) | New | 7.5 | 81 | 88 |
| **Average** | | | **172** | **188** |

*Note: Please refer to **Appendix A5**[xvi] for a complete version of this table*

#### *5.2.2.3 Storm Sewer*

As discussed in detail in the data collection report (MBI, 2024), the municipal utilities in the watershed such as storm sewer, sanitary sewers, and water supply pipeline were collected from the following agencies:

(i) Woodlands Water (WW)

(ii) South Montgomery County Municipal Utility District (SMCMUD)

(iii) Montgomery County Municipal Utility District 119 (MUD 119)

These data sets were reviewed in conjunction with the fault lines to better understand how future fault reactivation may impact them.

The WW GIS data were only relevant for a few faults. The data from SMCMUD were not located near any previously identified faults. Please see the **Data Collection memo** (MBI, 2024) for details on these datasets. WW GIS data included information on the material, diameter, upstream-downstream flowline elevations, and length for several, but not all, pipeline datasets. The missing attributes (material and diameter) that are needed for estimating costs were assumed from the nearest sections of pipelines. The unit cost for storm sewer construction was inferred from the TxDOT average low-bid unit price list[xvii]. However, apart from datasets available from WW, a large portion of the watershed does not have these utility datasets readily available. Because most of the data are available for the Woodlands area only, the length of storm sewer outside the Woodlands (and the associated cost of replacement) for faults without data are inferred proportionally from the length of storm sewer of the fault near Woodlands. This was done by correlating the population density of cities near faults (without data) with the population density of Woodlands to create a high-level estimate.

**Figure 31** shows cities and planned communities near Spring Creek watershed. Woodlands is not a city, but a planned community located on 27,000 acres of forestland in an unincorporated area of Montgomery County, Texas. It is shown as an urban area together as a Conroe-Woodlands community. The population density (2020) of the communities and cities in the vicinity of the watershed is shown in **Table 18**. The population (data provided by HGSD) and the area of each community/city within the watershed near the fault were used to calculate the population density of each community/city. Municipal infrastructure data were only available for the area of Woodlands near the Big Barn fault. The other three (3) faults did not have storm sewer data available.

To predict the length of storm sewer in the vicinity of each fault, a multiplier factor was computed by comparing the population density of Conroe-Woodlands with other cities. For example, the

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[xvii] *https://www.dot.state.tx.us/insdtdot/orgchart/cmd/cserve/bidprice/s_0401.htm*

population density of Tomball (near the Hufsmith faults) is 1,290; hence, the multiplier is 1,290/2,499=0.52 as compared to the Woodlands-Conroe community (Big Barn fault).

For this high-level estimate, and due to the unavailability of data, if 100 feet (arbitrary example) of storm sewer is located in the vicinity of Big Barn fault, Tomball (near Hockley fault), would be assumed to have 52 feet (52% of 100 feet) of storm sewer which has a population density of 52% of the Woodlands-Conroe community. The cost of reconstruction will be inferred using the same proportionality. The level of potential damage and the section of storm sewer affected by fault movement depend upon an assortment of variables like fault movement, strike, dip, storm sewer alignment, and angle of intersection. Pipe material, diameter, depth, and age can also significantly affect the level and quantity of storm sewer damage.

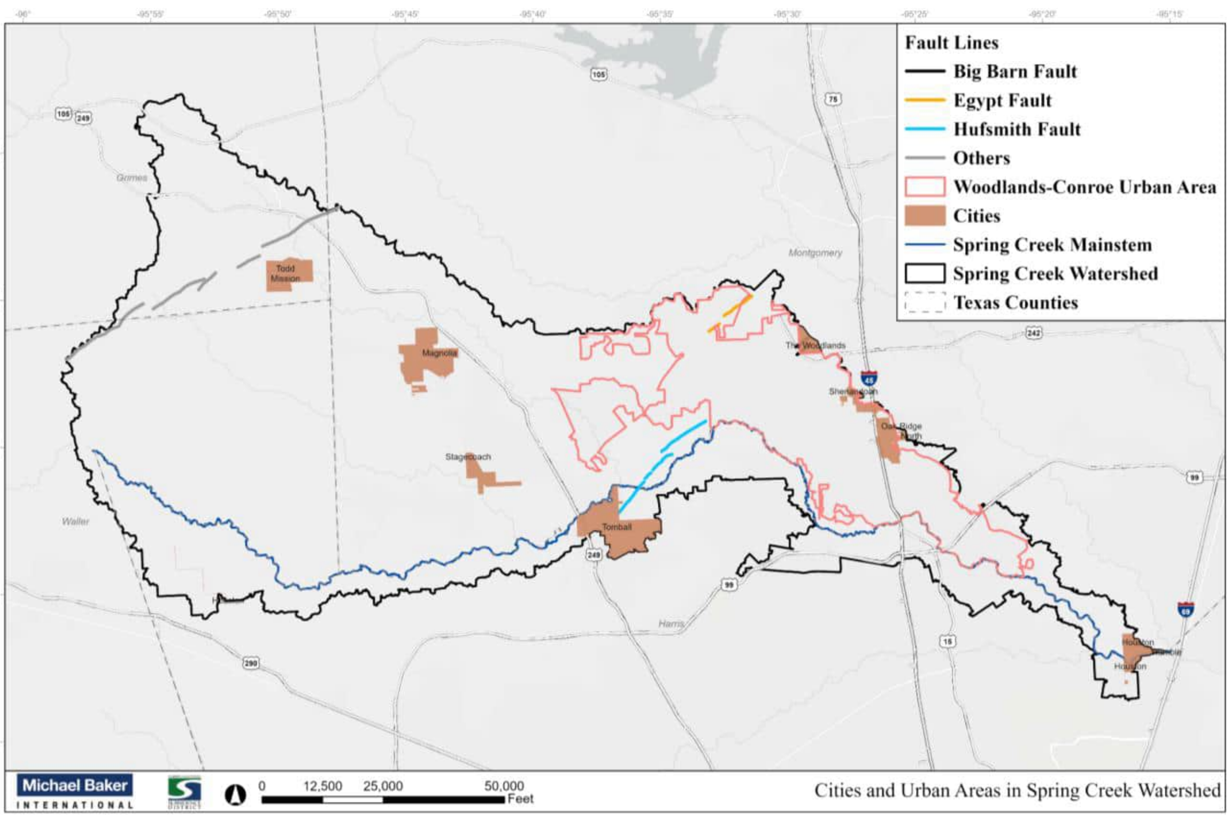


**Figure 31: Cities and Urban Areas in Spring Watershed**

**Table 18: Population Density of the Cities in the Vicinity of the Faults in Spring Creek Watershed**

| City/Urban Area | Area (square miles) | Population (2020) | Population Density (2020) (people/sq mile) | Multiplier | Nearest Fault Name |
|---|---|---|---|---|---|
| Conroe-Woodlands | 63.4* | 158,434 | 2,499 | 1 | Big Barn Fault |
| | | | | | Egypt Fault |
| Tomball | 4.7 | 6,063 | 1,290 | 0.52 | Hufsmith Fault |
| Todd Mission | 2.0 | 211 | 106 | 0.04 | Other |

*Note:*

**The total area of the Conroe-Woodlands community is 134.2 square miles, out of which only 63.4 square miles fall within the watershed. The population density is calculated using the area and population within the watersheds.*

Storm sewers within the 200 feet of fault hazard band of each fault in the Spring Creek watershed are tabulated in **Table 19**. However, as mentioned earlier, only the storm sewer data near Big Barn Fault was available and it was used to correlate the number of storm sewer segments, linear feet, and cost estimate of replacement using the multiplier shown in **Table 18**.

As shown in **Table 19**, 11 storm sewer segments overlapped by these four (4) faults with a total of approximately 5,580 linear feet (~1 mile) and a reconstruction cost estimate of approximately $0.5 million). The potential flooding and relative economic, social, and health impacts due to fault-damaged storm sewers till they are fixed or reconstructed are not included in this study.

**Table 19: Storm Sewer in the Vicinity of the Faults in Spring Creek Watershed**

| Fault Name | Storm sewer within Fault Hazard Band of 200 feet | | |
|---|---|---|---|
| | Number of Segments | Storm sewer Linear Feet | Cost Estimate of Replacement ($) |
| Big Barn Fault | 4 | 2,180 | 0.2 |
| Egypt Fault | 4 | 2,180 | 0.2 |
| Hufsmith Fault | 2 | 1,130 | 0.1 |
| Other | 1 | 90 | 0..01 |
| **Total** | **11** | **5,580** | 0.51 |

#### *5.2.2.4 Water Supply Pipelines*

Similar to storm sewer data, water supply pipeline data were also only available for Woodlands. As discussed in detail in the storm sewer section, a similar methodology using population density correlation was used to predict water supply pipelines near faults with missing data. Waterlines like any other pipeline can also be deformed, cracked, or severed due to reactivation of the fault. Hence, water supply pipelines in the vicinity of each fault in the Spring Creek watershed are tabulated in **Table 20** which shows the waterline segments within the 200 feet of fault hazard band. However, as mentioned earlier, only the water supply pipeline data near the Big Barn fault were available and they were used to correlate the number of water supply pipeline segments, linear feet, and cost estimate of replacement using the multiplier shown in **Table 18**. As shown in **Table 20, f**ive (5) waterline segments overlap these three (3) faults with a total of approximately 500 linear feet and a reconstruction cost estimate of approximately $13,000 within the fault hazard band of 200 feet. The potential social and health impacts due to fault-damaged water supply pipelines till they are fixed or reconstructed are not included in this study.

**Table 20: Water Supply Pipelines in the Vicinity of the Faults in Spring Creek Watershed**

| Fault Name | Waterlines within Fault Hazard Band of 200 feet | | |
|---|---|---|---|
| | **Number of Segment** | **Waterlines Linear Feet** | **Cost Estimate of Replacement** |
| Big Barn Fault | 2 | 200 | 5,200 |
| Egypt Fault | 2 | 200 | 5,200 |
| Hufsmith Fault | 1 | 100 | 2,600 |
| Other | - | - | - |
| **Total** | **5** | **500** | **13,000** |

#### *5.2.2.5 Sanitary Sewer*

Similar to storm sewer data, sanitary sewer data were also only available for Woodlands. As discussed in detail in the storm sewer section, a similar methodology using population density correlation was used to predict sanitary sewers near faults with missing data. Sanitary sewers, like any other pipeline, can also be deformed, cracked, or severed due to reactivation of the fault. Hence, sanitary sewers in the vicinity of each fault in the Spring Creek watershed are tabulated in **Table 21** which shows the sanitary sewer segment within 200 feet of fault hazard band. However, as mentioned earlier, only the sanitary sewer data near the Big Barn fault were available and they were used to correlate the number of sanitary sewer segments, linear feet, and cost estimate of replacement using the multiplier shown in **Table 18**. As shown in **Table 21**, there are five (5) sanitary sewer segments overlapped by three (3) faults with approximately 38 total linear feet and a reconstruction cost estimate of approximately $2,000 within the fault hazard band of 200 feet. The potential social and health impacts of the fault-damaged sanitary sewers till they are fixed or reconstructed are not included in this study.

**Table 21: Sanitary Sewer in the Vicinity of the Faults in Spring Creek Watershed**

| Fault Name | Sanitary sewer within Fault Hazard Band of 200 feet | | |
|---|---|---|---|
| | Number of Segment | Sanitary Sewer Linear Feet | Cost Estimate of Replacement |
| Big Barn Fault | 2 | 15 | 800 |
| Egypt Fault | 2 | 15 | 800 |
| Hufsmith Fault | 1 | 8 | 400 |
| Other | - | - | - |
| **Total** | **5** | **38** | **2,000** |

#### *5.2.2.6 Transmission (Gas and Liquid) Pipelines*

Excluding utilities, other buried pipelines that transport liquids and gas like crude oil, refined oil, natural gas, and other highly volatile liquids, can also be deformed, cracked, or severed due to reactivation of the fault. The gas and liquid pipelines discussed here are limited to those available from RRC[xv] and there may be other gas and liquid pipelines not included in RRC datasets.

Pipelines within 200 feet of the fault hazard band of each fault in the Spring Creek watershed are tabulated in **Table 22**. If a pipeline falls within the intersection of this buffer zone (100 feet on each side of the fault), 200 feet of the pipeline segment is assumed to be damaged on each side and must be repaired by reconstruction. The level of potential damage and sections of the pipeline affected by fault movement depends upon an assortment of variables like fault movement, strike, dip, pipeline material, diameter alignment, angle of intersection, etc. 200 feet of pipeline segment damage on both sides of a fault is an approximation which can significantly differ depending upon all these aforementioned variables. A detailed analysis of pipeline rupture due to a fault was outside the scope of this study.

The cost estimate of the replacement of each pipeline is calculated based on the American Petroleum Institute report (API, 2017). The API estimated average U.S. pipeline costs of $178,000 per inch-mile for 2016 (in nominal dollars) for large gas transmission pipelines. Based on this, using the Consumer Price Index Inflation Calculator from the Bureau of Labor Statistics[xiv], a 1.31 inflation multiplier is added to determine 2024 dollars from 2016 and a 0.74 regional cost multiplier is added for Texas (Southwest Region)[xviii]. The API cost estimate for transmission pipeline construction is $151,000 per inch-mile where the diameter of the pipeline is in inches. If a fault intersects multiple pipelines with different diameters, the mean diameter is used for the cost estimation. Please refer to **Appendix A6** for details on pipeline construction costs.

As shown in **Table 22**, 21 pipeline segments are within 200 feet of fault hazard band with a total segment length of 4,900 feet (~0.9 miles) and a reconstruction cost of approximately $6.3 million.

**Table 22: Pipelines in the Vicinity of the Faults in Spring Creek Watershed**

| **Fault Name** | **Pipeline within Fault Hazard Band of 200 feet** | | | |
|---|---|---|---|---|
| | **Number of Pipelines** | **Total Length (feet)** | **Diameter (inches)** | **Cost Estimate of Repair (million USD)** |
| Big Barn Fault | 2 | 400 | 16", 20" | 0.2 |
| Egypt Fault | - | - | - | - |
| Hufsmith Fault | 7 | 1,700 | 6.6"-20" | 0.7 |
| Other | 12 | 2,800 | 4.5"-36" | 1.8 |
| **Total** | **21** | **4,900** | **-** | **2.6** |

#### *5.2.2.7 Other Infrastructure*

Other infrastructure like fiber optic cables, underground power lines, power poles, manholes, hydrants, valves, outfalls, pumps, etc. in the vicinity of the fault zone can also potentially be affected by fault movement. However, some datasets, like fiber optic cables, were not readily available and a detailed analysis of their interaction with the fault movement is not included in this study. Manholes, hydrants, valves, and outfalls were available for a limited area of the watershed. Hence, cost estimates of these infrastructures were not included in this study.

### *5.2.3 Estimate of Potential Hazard to Structures and Infrastructures due to Fault Movement*

**Table 23** summarize the cost estimates of total assets of structures and infrastructure within 200 feet of the fault hazard band of the four (4) faults within the Spring Creek watershed, as discussed

[xviii] *https://www.gem.wiki/Oil_and_Gas_Pipeline_Construction_Costs#cite_ref-6*

in **Section 5.2**. As tabulated in **Table 23** , the total assets of structures overlapped by these four (4) faults are approximately $38 million. The total infrastructure reconstruction cost estimate if potentially damaged by the reactivated faults is approximately $32 million. Summing both structure and infrastructure assets brings the total to approximately $70 million. Many assumptions were necessary to calculate this approximate estimate which is discussed in **Section 5.2**.

It is important to note one of the limitations in **Table 23** is that this approximate cost estimate is based on the present-day infrastructure. This study does not predict future changes in density and reconstruction cost of this infrastructure for future subsidence scenarios.

**Table 23: Economic Loss Potential of Structures and Infrastructures within the Fault Hazard Band of 200 feet in Spring Creek Watershed**

| Fault Name | Within Fault Hazard Band of 200 feet | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Structures | Roadways | Railways | Transmission Pipelines | Storm Sewer | Water Supply Pipelines | Sanitary Sewer | Total Infrastructure | Total (Structure+Infrasture) Cost |
| Big Barn Fault | 7 | 1.2 | - | 0.6 | 0.2 | 0.0052 | 0.0008 | 2.0 | 9.0 |
| Egypt Fault | 9.7 | 2.1 | - | - | 0.2 | 0.0052 | 0.0008 | 2.3 | 12.0 |
| Hufsmith Fault | 10.5 | 2.1 | 7.1 | 1.5 | 0.1 | 0.0026 | 0.0004 | 10.8 | 21.3 |
| Other | 11.1 | 5.9 | 7.1 | 4.2 | 0..01 | - | - | 17.2 | 28.3 |
| **Total** | **38.3** | **11.3** | **14.2** | **6.3** | **0.5** | **0.013** | **0.002** | **32.3** | **70.6** |

**Table 24** summarizes the potential impact within a 200-foot hazard band of these four faults. A total of 56 structures fall within this zone, with a combined market value of approximately $38 million. Estimated infrastructure reconstruction costs (including roadways, utilities, and pipelines) reach $32 million, bringing the total potential impact to around $70 million if these faults were to reactivate. **Table 24** shows that the longest fault segment ("Other fault") has the highest total economic impact, as expected. However, when normalized per mile, the Big Barn and Egypt faults pose greater economic hazards if reactivated due to differential subsidence. Average subsidence values within 200 feet of each fault segment are color-coded from red (highest) to green (lowest).

As previously discussed, fault hazard bands vary significantly over short distances, highlighting the need for detailed, site-specific studies in future assessments.

**Table 24: Potential Economic Impact due to Faultline Shift per Mile within Fault Hazard Band of 200 feet in Spring Creek Watershed**

| Fault Name | Length within Study Area[1] (mile) | Total Economic Impact[2] (million $) | Economic Impact per Mile[3] (million $/ mile) | Average Subsidence Depth[4] (feet) |
|---|---|---|---|---|
| Big Barn Fault | 1.3 | 9 | 7 | 3.1 (2.9-3.3) |
| Egypt Fault | 1.9 | 12 | 6 | 3.4 (3.4-3.5) |
| Hufsmith Fault | 5.0 | 21 | 4 | 2.4 (1.9-2.9) |
| Other | 11.4 | 28 | 3 | 0.4 (0.3-1.9) |

*Notes:*
[1]*Study Area = Spring Creek watershed*
[2]*Total Economic Impact = Total structure asset cost and total repair cost for damaged infrastructure that falls within the fault hazard band of 200 feet. This table does infer that a certain percentage of damage will occur in structures and the structure cost shown is the total asset of structures appraised (2024) for that parcel.*
[3]*Economic Impact per Mile = Total economic impact as described above per mile of the fault within the fault hazard band of 200 feet.*
[4]*Average Subsidence Depth = Average values from subsidence depth raster extracted within the fault hazard band of 200 feet for each fault segment. The values in parentheses are the range of these raster values.*
*The color gradient shows the economic impact per mile with the highest economic impact per mile in red color and the lowest economic impact in green color.*

### *5.2.4 Potential Effect on Hydrology and Hydraulics*

As discussed in the previous section, the Hufsmith fault crosses Spring Creek just west of FM 2978. As faults slip past each other due to potential reactivation, Spring Creek banks can potentially steepen as the downthrown side of the Hufsmith fault is on the southeast side. An increase in gradient will result in the rapid flow of water with decreased lag time. This, in turn will result in higher discharge, potential erosion, and increased flood risk with increased health and economic impacts. A more drastic effect can make a stream break its original course and flow into a new path (Dascher-Cousineau, Finneganand, & Brodsky, 2021). This diversion, if it occurs rapidly, can lead to unexpected and destructive flooding in nearby communities. All these aforementioned effects on hydrology and hydraulics, and the resulting impact on flood risk, were outside the scope of this project, and are not part of the current study.

### *5.2.5 Potential Effect on Groundwater Flow Regime*

Depending upon the geometrical dislocations of geologic units caused by fault shifts, depth below the surface, and material in the fault zone, faults can potentially affect the regional groundwater flow regime (Faunt, 1997). Faults can act as either preferential conduits or barriers to flow, depending on whether faults are in relative tension, compression, or shear. Any changes to the regional groundwater flow regime will have wide implications on groundwater availability. Surface contaminants can also potentially be transported to the aquifer, damaging its pristine quality. Surface wells in the vicinity of faults can also be impacted. However, these impacts were outside the scope of this project and are not part of the current study. Similarly, faults can also be a potential site of livestock or wildlife injury or even death. A larger and deeper fault can also be fatal to humans if one is not careful in its vicinity.

## 5.3 Potential Effect on Critical Structures due to Subsidence Topography

Land subsidence can significantly damage critical infrastructures through the differential settlement of the foundation. This is a separate impact from increased flood risk. Even uniform settlement can cause structural instability due to changes in topographic gradient or surface rupture, increased risk of flooding, or saltwater intrusion in coastal areas. This can result in substantial damage and a significant impact on the property values of the infrastructure. A qualitative discussion on critical structures exposed to varying levels of subsidence in 2070 is discussed in **Appendix A7**, however economic impact on these critical infrastructures due to subsidence topography is outside the scope of the study.

# 6 Lessons Learned and Recommendations for Future Studies

TM2 (MBI, 2024) discussed the recommendations for future studies that involve modeling components that were not modified and were not within the scope of the study. In this section, we discuss the lessons learned and recommendations for future studies that involve the economic impact (as well as social and health impact) of subsidence.

1. **Data Inadequacy**: Similar to most studies, the availability of good and relevant data always increases the accuracy of the model and estimates. This study is no exception. The subsidence grid was projected in a 1 km x 1km grid, which was used to interpolate 3 feet by 3 feet (LiDAR resolution) for the H&H modeling. The large coarse resolution of the projected subsidence grid does not capture the differential subsidence on a scale that is relevant for H&H modeling, hence the resulting 3 feet by 3 feet subsidence raster is a smooth interpolation of the coarser grid (1 km). Hence, the subsidence grid may not capture the differential subsidence that is more relevant for H&H modeling and thus provide a better flood risk.

   Due to data limitations, flood and subsidence-related economic impacts on utilities (storm sewer, sanitary sewer, and water supply) were not fully estimated. Available utility data from WW and SMCMUD were limited in coverage. Fault-related utility impacts were projected using WW data and population density, as no datasets existed within fault hazard zones. Future studies should aim to collect comprehensive watershed-wide utility data. Additionally, inundation, damage, and cost estimates are based on subsidence and population projections, along with the HCFCD baseline model. Any updates to these inputs could significantly alter the results.

2. **Future Precipitation Change:** No change in precipitation is assumed for 2070. Any significant change in future precipitation will cause a change in the hydraulic model and thus the inundation. Change in inundation will cause a significant difference in the cost estimate of flooded properties. It should be noted that the economic consequence only considers 1% or 10% events happening once in 2070; however, due to the impact of continued impact of warming in the future, the 100-year flood event is likely to increase by 809% to an 11-year event[xix]. This is an area for future study that could reveal increased flow and thus increased cost estimates of flooding in the watershed for the year 2070.

3. **Inflation Projection for 2070:** All the cost estimates presented in this study (unless specifically mentioned) are in 2024 US dollar values, and no inflation is assumed for 2070,

[xix] PR_The-Precipitation-Problem.pdf NOAA's 1-in-100-Year Flooding Events Now Expected Every 8 Years

even though the subsidence scenarios and population density are projected for the year 2070. Even though a general progressive increase in the price of materials and services is expected to occur in the future, the prediction of inflation is outside the scope of this study.

4. **Future Land-Use Change:** Future land cover and land-use changes in the Spring Creek watershed are expected to increase urbanization, leading to more impervious surfaces and reduced infiltration. This will likely shorten the time of concentration and increase flash flood discharge. Growth in structures and infrastructure will also raise the risk of inundation and associated costs. However, due to limited future projection data and the scope of this study, further analysis was not conducted. To account for the increased losses to structures due to the increase in building footprint, we utilized the global decadal built-up area projections by the European Commission's Joint Research Center (JRC) and identified a 9% increase in building footprint in the Spring Creek Watershed by 2070[iv]. However, due to the coarse spatial resolution of the projections (1-kilometer grid), it was not possible to conduct a detailed evaluation of flood depths and projected damage to individual structures. Therefore, the economic losses for the SFD were directly multiplied by a factor of 1.09 to estimate additional losses due to an increase in building footprint. A future study detailing the projections of these structures and infrastructure at a finer resolution is recommended for a detailed economic impact assessment.

5. **Flood Risk Mitigation Projects and Policy Changes:** Most of these assumptions discuss the potential adverse impact of subsidence and flooding. However, there are several flood risk mitigation projects proposed in the watershed as a part of HCFCD's 2018 flood control bond program. Changes in policy by federal and local authorities can alter groundwater pumping and use, which will have a direct impact on subsidence. However, changes in future policy cannot be predicted. These changes, if they occur, will alter subsidence, area of inundation, and the number and cost estimate of structures and infrastructure significantly more than those approximated in this study.

6. **Agricultural Impact:** Subsidence changes the hydraulic gradient, which can adversely impact drainage along with the irrigated lands, ditches, and natural streams (Bhattacharya & Singh, 1985). Subsidence cracks can increase hydraulic conductivity, leading to increased infiltration, decreased evapotranspiration, and higher base flows in some streams (Hobba, 1993) and lower base flows in others. This also changes the natural ecosystem of the area. The economic impact of subsidence on agriculture, livestock, and wildlife was not studied in this project. Even though a small percentage of the area is agricultural in the vicinity of the watershed, even less of it is affected by 1% AEP pluvial inundation (**Figure 32**). However, future land-use changes, subsidence, and flooding will also have a significant impact on agriculture in the future (2070).

A detailed impact and economic assessment of agricultural areas are recommended for future studies.

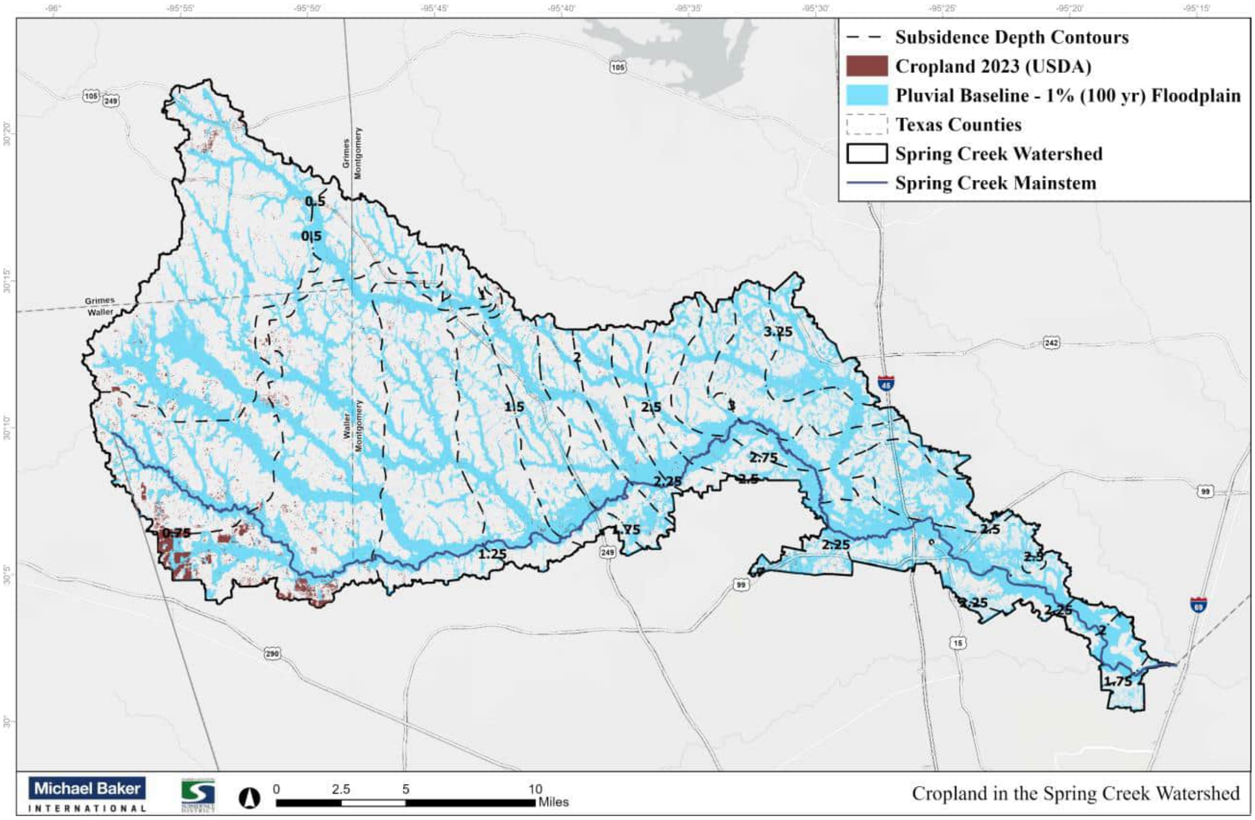


**Figure 32: Cropland area in the Spring Creek Watershed**

7. **Wetlands Impact:** A review of the National Wetlands Inventory dataset on the US Fish and Wildlife Services Wetlands Mapper website[xx]. There are approximately 14 square miles of wetlands, including freshwater ponds and lakes in the Spring Creek Watershed (**Figure 33**). Wetlands provide significant economic and ecological value, supporting wildlife, infrastructure, navigation, and recreation, while also offering flood protection by acting as a sponge to soak up and store extra runoff and then releasing it slowly after the event recedes. Subsidence can harm wetlands by altering slopes or reducing sediment supply, potentially converting them to open water. While Spring Creek lacks estuarine wetlands, it does contain freshwater wetlands, some of which, especially near The Woodlands, show signs of subsidence (**Figure 33**). However, this study did not assess the detailed impacts or economic implications, which are recommended for future research.

[xx] https://www.fws.gov/wetlands/data/mapper.html

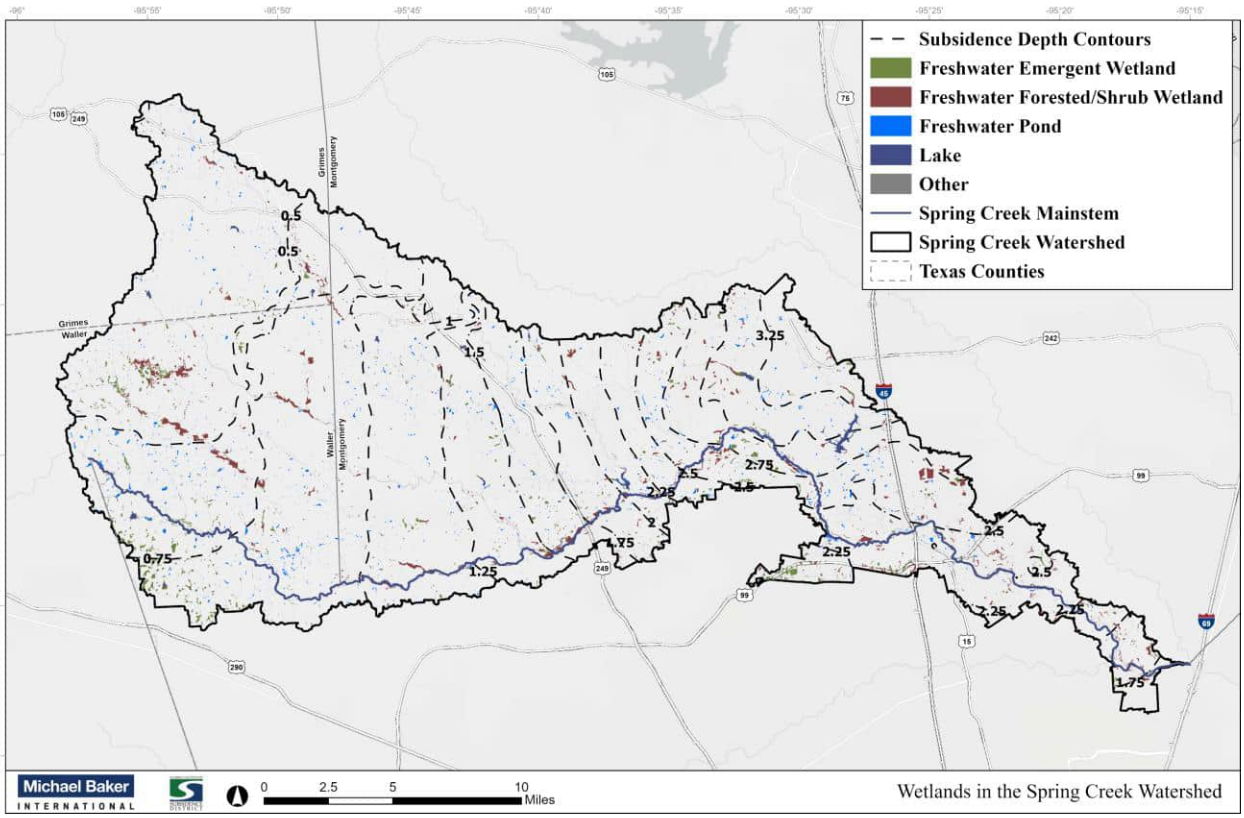


**Figure 33: Wetlands in the Spring Creek Watershed (National Wetlands Inventory)**

8. **Environmental Impact:** Subsidence can potentially change the natural retention of the aquifer, thereby changing the flow path and velocity of the aquifer. Subsidence-induced fissuring and fracturing in overlying and neighboring aquifers can contaminate the groundwater. Contamination of groundwater has a serious impact, including poor drinking water quality, loss of water supply, high cleanup costs, high costs for alternative water supplies, and/or potential health problems. The cost implication of this environmental impact due to subsidence was not studied and is recommended for future use.

9. **Loss Estimates and Risk Modeling:** As discussed in **Section 4.1.1**, Go-Consequence was selected for the economic impact assessment. The Go-Consequence tool uses the NSI data to estimate the direct and indirect losses due to a flood hazard. However, as the NSI data was last updated in 2022, the current as well as future market value of the structures and inventory are not represented, which may underestimate the losses. Also, the Go-Consequence tool measures labor loss by the number of employed individuals displaced or removed from the workforce, without assigning a monetary value to this loss. Converting labor loss into a monetary value

for each sector could enhance the assessment of total losses resulting from a flood hazard but was outside the scope of the current study.

Additionally, a straight-line interpolation used for estimation of AEL for years 2021 to 2069 due to the absence of additional data points reduces the loss estimation accuracy. Additional data points between 2020 and 2070 (which require the development of individual H&H models for each year) would have better represented the AEL.

10. **Fault Reactivation Potential:** A detailed analysis of the reactivation potential of faultlines and their relationship to subsidence is not within the scope of this study. The potential economic impact of the reactivation of the faults was estimated based on the neighborhood of the present-day studied fault. A fault hazard band of 200 feet was assumed where the risk of significant fault-induced differential movement is greater than average, and the economic cost estimate is based on this approximation. Potential effects on hydrology and hydraulics and groundwater flow regime were discussed but not quantified in **Sections 5.2.4** and **5.2.5**. A detailed study of faults and their hazard bands is recommended for future studies which will be site-dependent and may vary substantially for the same fault within a short distance.

11. **Salt Domes:** Shallow Gulf Coast salt domes are commonly associated with subsidence, sinkholes, and piping features (Looff & Looff, 2000). The salt domes shown in **Figure 34** are generally deep (please see **Appendix A1** in the **Data Collection Memo** (MBI, 2024)). However, several factors, including human activity, can induce or accelerate movement in these salt domes, which in turn can lead to sinkhole development, subsidence, and piping. The relationship of subsidence projection to these salt domes, and thus the economic impact, is not studied. Similarly, the effect of faults and their potential reactivation to these salt domes and their economic impact were not studied in this project and are recommended for future study.

12. **Long-term Impact on Structures:** Severe subsidence can also have a long-term impact on a locality, city, county, or even on a larger regional extent. Frequent inundation of the subsidence land parcel and structures can cause a loss of property value. Frequent flooding can deteriorate structural material and their contents, leading to expensive repair costs. Frequent inundation also hinders the development of new communities. All of these can lead to increased migration away from the subsidence terrain. Significant migration of population away from an impacted community can result in short-term as well as long-term impacts on the economy. These can include loss of tax revenue for the local, state, and national governments. One of the dramatic examples of severe subsidence in the Brownwood subdivision of Baytown (**Figure 34**), part of the greater Houston area, which was once a bustling coastal community but was completely abandoned due to severe subsidence. Brownwood was 10 feet above sea level in the 1930s but

had subsided more than 6 feet by 1978. Hurricane Alicia in 1983[xxi] caused disastrous flooding, after which all the homes in the subdivision were abandoned (Ingebritsen & Galloway, 2014).

**December 1952** **December 1977**

**Figure 34: Google Earth Imagery showing Sinking of Land due to Subsidence between 1952 and 1977 in Brownwood Subdivision of Baytown**

13. **Critical infrastructures:** Land subsidence can significantly damage critical infrastructures through the differential settlement of the foundation. However, the economic impact from subsidence topography on these critical infrastructures was outside the scope of this study and was not included in the overall economic impact.

14. **Long-term Impact on Roads:** Frequent flooding of infrastructure, especially roads, can hinder commutes to hospitals, businesses, and education centers and can impact business. The various economic aspects of the population in the impacted community can also be adversely affected. Long-term ponding can spread pollutants and create a breeding ground for mosquitoes, leading to an increase in diseases. Moreover, frequent flooding can deteriorate pavement material leading to initiation or acceleration of road cracks. This will increase the

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[xxi] *https://houstonhistorymagazine.org/2019/03/brownwood-from-neighborhood-to-nature-center/*

maintenance or reconstruction cost of the roadways. The economic impact of this increased maintenance or reconstruction cost was not studied in this project.

15. **Elevation Change Impact to Hydraulic Structures and Vertical Datums:** Hydraulic structures that are designed to work under certain elevations (gravity dams, pumps, etc.) will need to be raised or reconstructed if subsidence impacts the head difference of the designed stage. The economic impact of this increased maintenance or reconstruction cost was not studied in this project. Similarly, vertical datums, which are established known heights above or below reference (usually mean sea level) may be affected due to subsidence (**Figure 35**). This impact in vertical reference can affect the accuracy of surveys, which can impact many critical data and services, the economic impact of which is beyond the scope of this project.

**Figure 35: Impacted Vertical Survey Marker (in Louisiana) due to Subsidence of the Surrounding Area**[xxii]

16. **Evaluation of Future Development as a Baseline Model:** The combined impact of future development and subsidence has shown a compounding effect. To better isolate the influence of subsidence, a hydraulic modeling scenario using future development as the baseline, compared to one that includes both future development and subsidence, may offer clearer insights. However, it's important to note that excluding future development from future scenarios may lead to unrealistic assumptions and an underestimation of flood risk and associated economic impacts.

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[xxii] *https://oceanservice.noaa.gov/education/tutorial_geodesy/geo06_vert.html*

# 7 Conclusion

Subsidence in the Spring Creek watershed is projected to range from 0.2 to 3.7 feet by 2070, averaging 1.44 feet over 50 years. Around upstream, subsidence steepens the upstream gradient, increasing flow velocities and reducing depths, while downstream areas near IH-45 experience slower flows and deeper water. This shift contributes to increased flooding and infrastructure damage. The impact on WSE is nonlinear and further intensified by future development. SFD scenarios showed a rise in floodplain acreage by 2%, inundating more than ~3,400 structures as compared to the baseline (if a 100-year event were to occur). This hazard increases to more than ~3,700 flooded structures when the future increase in building footprint is assumed. The increased flooding of the structures was seen in a notable number near the IH 45 and downstream of Kuykendahl Road in both SWFD and SFD scenarios

Roadway flooding is substantial, with over 40 miles affected in the SFD scenario compared to the baseline. This highlights the major disruption potential to transportation infrastructure from combined subsidence and development impacts. Subsidence also increases structural vulnerability. Bridge freeboard decreases in subsidence scenarios, raising overtopping risks. Peak flows rise up to 13% at major crossings due to future development, further exacerbating flood hazards.

Economic losses were estimated using the Go-Consequence tool for 100- and 10-year flood events. Direct losses (structures, contents, vehicles) and indirect losses (labor and production) were calculated across scenarios (**Table 25**). A 1% AEP flood event in 2070 could result in an additional $43 million in losses due to subsidence alone. When future development and increased impervious cover are considered, this impact rises to $466 million. These findings show that future development significantly compounds flood-related losses. A caveat to the future development H&H modeling scenario is that it does not consider future development in structures and infrastructure densities, even though the model considers the future increase in flows due to changes land cover. To partially account for this issue, a 9% increase was applied to losses in the SFD scenario. Including these factors, the total projected loss climbs to $560 million. On average, each inch of watershed-wide subsidence could lead to $2.5 million in losses from subsidence alone, $27 million when factoring in future development flows, and $32 million when also accounting for increased buildings and population. Similarly, labor force reductions exceed 2,500 people (~3,300 people for the SFD scenario), though not included in the total dollar loss estimate.

Due to watershed hydraulics, areas experiencing the greatest increase in flood risk may not coincide with locations of significant subsidence caused by groundwater pumping. For example, while subsidence in the Conroe-Woodlands community is projected to rise substantially, the most notable increase in flood risk is observed downstream, near the IH-45 corridor.

Differential subsidence may trigger faultline shifts, though the link between subsidence and fault reactivation remains complex. This study identifies four faults; Big Barn, Egypt, Hufsmith, and Others, within the Spring Creek watershed, assessing their economic impact within a 200-foot hazard band. A total of 56 structures fall within this zone, valued at approximately $38 million (2024 market value). Infrastructure repair costs (roads, utilities, pipelines) are estimated at $32 million, bringing the total potential impact to $70 million if faults reactivate. Given the variability of fault hazard bands over short distances, detailed site-specific studies are recommended.

**Table 25: Economic Impact (Additional Loss) Due to Increased Flood Hazard (Pluvial) Due to Subsidence in Spring Creek Watershed**

| Flood Event | Flood Economic Loss | Subsidence without future development ($ million) | Subsidence with future development GDP ($ million) |
|---|---|---|---|
| **10-year** | Direct Loss | 12 | 113 |
| | Indirect Loss | 4 | 51 |
| | **Total Loss** | **16** | **164** |
| **100-year** | Direct Loss | 35 | 446 |
| | Indirect Loss | 8 | 114 |
| | **Total Loss** | **43** | **560** |

*Notes:*

1. *The dollar value shown here is the 2024 USD value; no inflation of the dollar value is projected.*
2. *For SFD scenario, a 9% increase in building footprint between 2020-2070 was obtained from the Global Human Settlement Layer, developed by the European Commission's Joint Research Center*
3. *For SFD scenario, a 30% increase in the civilian labor workforce is projected between 2020 and 2070 by accounting for the projected percentage increase in the Spring Creek Watershed population (47% increase) and the reduction in labor force participation rates.*
4. *For SFD scenario, the projected GDP growth is estimated based on a 1.5% annual increase in real GDP between 2020-2070 (Daly & Gedminas, 2022)*
5. *The economic consequence only considers 1% or 10% events happening once in 2070; however, due to the impact of continued impact of warming in the future, the 100-year flood event is likely to increase by 809% to an 11-year event*[xxiii]

The study confirms that subsidence significantly amplifies flood damage and associated economic losses, both direct (infrastructure damage) and indirect (business and labor disruption). These also lead to structural failures, utility disruptions, property devaluation, and increased insurance costs. Additional risks include stream instability, soil erosion, and faultline shifts triggered by differential subsidence. Changes in topography can also damage infrastructure independently of flooding. These risks threaten future development and strain the local economy, especially as urbanization and population growth heighten vulnerability. The combined effect of subsidence and future development is far greater than either alone, with flood losses rising exponentially with subsidence

[xxiii] PR_The-Precipitation-Problem.pdf NOAA's 1-in-100-Year Flooding Events Now Expected Every 8 Years

depth. Spatial variability in subsidence across the watershed results in uneven flood impacts. Hence, subsidence can potentially cause widespread impact, and some of those are discussed in this memorandum.

Summarizing, subsidence in the Spring Creek watershed is projected to range from 0.2 to 3.7 feet by 2070, averaging 1.44 feet over 50 years, with a potential economic consequence estimated to cross $560 million (2024 USD) for a 100-year flood event. On average, each inch of watershed-wide subsidence could result in $2.5 million in losses from subsidence alone, or $32 million, when future development due to increased population, GDP, and buildings are included for a 100-year event. To mitigate these risks, comprehensive planning is essential. A groundwater sustainability strategy that limits extraction and includes regular subsidence monitoring across the watershed is strongly recommended.

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# Appendix A: Supporting Document and References

# Appendix A1: Additional Hydraulic and Flooding Impact Details

# Appendix A1: Additional Hydraulic and Flooding Impact Details

## 1 Flooding Impacts Assessment- Details

By comparing H&H modeling results between Baseline, Subsidence without future development, and Subsidence with future development scenarios, the model can predict how changes in future subsidence and future development impact flood risk and thus economic impact on the Spring Creek watershed. This section discusses changes in flooding risks due to subsidence for 1% AEP design events from the pluvial HEC-RAS models.

Flooding impacts for this section are mainly focused on infrastructure - structural (buildings) and non-structural (roadways). Flooding impacts due to Subsidence scenarios are quantified as the number of structures flooded, as well as the total length of roadways flooded, as compared to the Baseline model. The flooding impact is discussed for the pluvial modeling approach.

### 1.1 Pluvial Impact Assessment

Results from the pluvial HEC-RAS model were used for this assessment. The flood impact assessment was categorized as structural and non-structural and is described below.

#### 1.1.1 Structural Flooding Impact

Flooding can have devastating effects on structures, causing both immediate and long-term damage. When floodwater inundates buildings, it can weaken foundations, erode walls, and compromise the integrity of materials like wood, drywall, and insulation. Prolonged exposure to moisture can also lead to mold growth, which further deteriorates structural components and poses health risks. Additionally, flood water can also damage contents and inventory (vehicles), depreciation or loss associated with the structures. These all not only result in costly repairs but also pose significant health risks to occupants.

##### *1.1.1.1 Level of Flood Impact on Structures*

Structural flooding evaluates the flood impact associated with structures in the watershed. Flooding can have a big impact on structures, including the need for costly repairs or replacement of structural, mechanical, and electrical components, along with content and inventory loss. Even a minor flooding depth can cause significant economic loss. The common impact on a structure for different flood depths (extracted from the flood factor[i]) is illustrated in **Figure 1**.

[i] https://help.floodfactor.com/hc/en-us/articles/360048265533-How-will-different-flood-depths-affect-my-property-

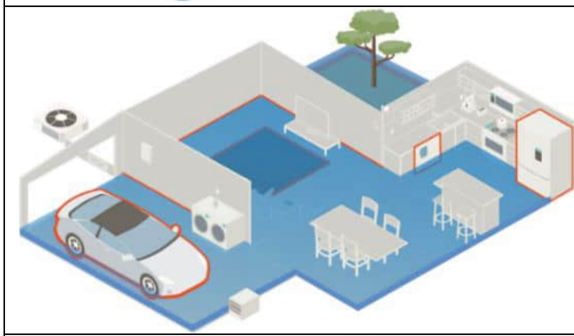
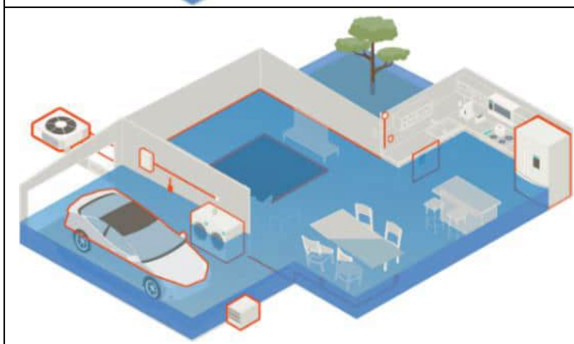
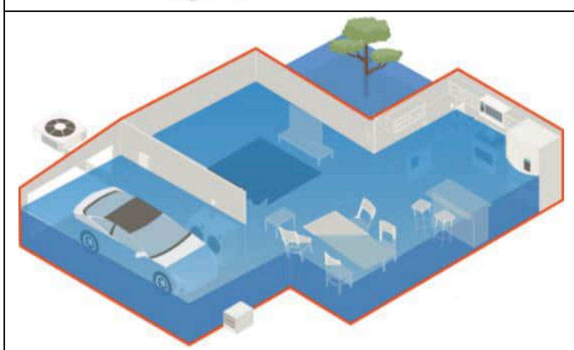
| | |
|---|---|
|  | **(I) - Flood Depth Less than six (6) inches**<br>• Drywall repair<br>• Insulation replacement<br>• Carpet and padding replacement<br>• Laminated floor replacement<br>• Warped hardwood floors |
|  | **(II) - Flood Depth Greater than six (6) inches but less than one (1) foot**<br>• Includes damages from Level-1<br>• Replacement of electrical components, such as refrigerators and ovens<br>• Stalled vehicles |
|  | **(III) - Flood Depth Greater than one (1) foot but less than three (3) feet**<br>• Includes damages from Level-2<br>• Electrical outlet, Heating and cooling system replacement<br>• Replacement of electrical components – washers, dryers, and dishwashers<br>• Vehicle damage |
|  | **(IV) - Flood Depth Greater than three (3) feet**<br>• Includes damages from Level-3<br>• Foundation and framework damage<br>• Water supply, sewage, and plumbing system damage |

**Figure 1: Flooding Impact on a Structure (Illustration)**

*Note: Blue fill is the flooded water level, and the red outline indicates the items damaged*

Hence, structural flooding has been classified into these four (4) levels for differentiating various levels of flooding hazard and thus economic loss in the Spring Creek watershed.

#### *1.1.1.2 Total Number of Flooded Structures*

Due to differential subsidence and thus differential hydraulic impacts, the total number of flooded structures between the Baseline and Subsidence scenarios can vary significantly. To calculate flooded structures, structure datasets were downloaded from the National Structural Inventory[ii] (NSI). The NSI dataset provides a base dataset of national coverage of structure points with attributes with consistent quality. Hence, the NSI dataset covers the entire Spring Creek watershed, which falls in four different counties.

The following relationship was implemented to determine whether a structure would be flooded or not.

$$\begin{matrix} \textit{Structural} \\ \textit{flooding depth} \end{matrix} = \begin{matrix} \textit{Modeled flood depth at} \\ \textit{(above ground elevation)} \end{matrix} - \begin{matrix} \textit{Foundation height} \\ \textit{of structure} \end{matrix}$$

*where the modeled flood depth for each structure (above ground elevation) was extracted from the depth raster (modeling result) of the three (3) scenarios – Baseline, Subsidence without future development, and Subsidence with future development.*
*The foundation height of the structure was obtained from the NSI shapefile*.

A positive value of the structural flooding depth indicates that the structure would be flooded. The 1% AEP flood depth at each structure was extracted from the depth raster of the Baseline and Subsidence scenarios. The flood depth is used to evaluate the extent of damage to the structure during a flooding event.

The total number of flooded structures in each scenario for five ranges of flood depth is shown in **Table 1.** The levels and impacts of flood depth on structures used in this analysis are discussed in **Section 1.1.1.1.** The structures flooded in the Subsidence without future development scenario are discussed in **Section 1.1.1.3**. The structures flooded in Subsidence with future development scenarios are discussed in **Section 1.1.1.4.**

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[ii] https://nsi.sec.usace.army.mil/downloads/

**Table 1: Number of Flooded Structures in the three (3) Scenarios of the pluvial model in a 100-year event**

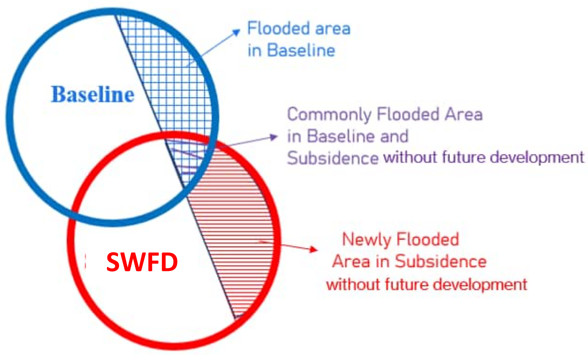
| Flood Depth (ft) | Number of Flooded Structures in | | |
|---|---|---|---|
| | **Baseline** | **Subsidence without Future Development (% change from Baseline)** | **Subsidence with Future Development [iii](% change from Baseline)** |
| **0 – 0.5** | 3,822 | 3,895 (2%) | 4,522 (18%) |
| **0.5 – 1.0** | 2,356 | 2,407 (3%) | 3,175 (35%) |
| **1.0 – 3.0** | 3,975 | 4,041 (2%) | 5,724 (44%) |
| **> 3.0** | 2,154 | 2,175 (1%) | 2,602 (21%) |
| **Total** | **12,307** | **12,518 (2%)** | **16,023 (30%)** |

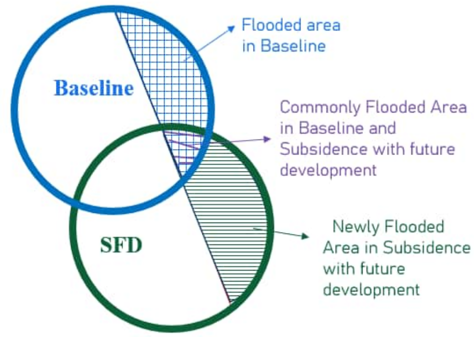
#### *1.1.1.3 Flooded Structures in Subsidence without Future Development Scenario*

A total of 12,518 structures are flooded in the 1% AEP floodplain of the SWFD scenario, as indicated in **Table 1**. The depth raster of the Baseline was subtracted from that of the SWFD scenario to quantify the increased flood depth at each flooded structure due to subsidence. This identified, among the 12,518 flooded structures, 365 structures are newly flooded structures due to the floodplain increase in the Subsidence without future development scenario, and 7,754 structures were commonly flooded in the Baseline scenario but inundated with higher flood depth in the Subsidence without future development scenario. The comparison and quantification of results to understand the flood risk and damage associated with subsidence in the newly and commonly flooded structures are described in the following sections.

***Figure 2*** **(a)** shows in a simplified manner using a Venn diagram, the area that represents the newly flooded area as well as the area that represents the commonly flooded area between Baseline and Subsidence Scenario. Similarly, ***Figure 2*** **(b)** the area that represents the newly flooded area as well as the area that represents the commonly flooded area between Baseline and Subsidence with the future development Scenario.

[iii] *The decadal built-up area projections were obtained from the Global Human Settlement Layer (GHSL), developed by the European Commission's Joint Research Center (JRC). The built-up area projections for the Shared Socioeconomic Pathway (SSP) 2 (middle-of-the-road pathway) were selected, indicating that trends will continue on a path similar to historic patterns. The 1 km resolution built-up area layers for 2020 and 2070 were used to estimate the projected percentage increase in building footprint.* ***Results indicate a 9% increase in building footprint between 2020-2070.*** *Source - Directorate General for Regional and Urban Policy (DG REGIO) of the European Commission (2020). Projecting Global Population Grids to 2100 (BUILT-POP_PROJ_GLOBAL_SSP_R2020).*






**(a)** **(b)**

**Figure 2: Venn Diagram showing newly flooded and commonly flooded areas between (a) the Baseline and Subsidence without future development (SWFD) scenario, (b) the Baseline and Subsidence with future development (SFD) scenario**

### 1.1.1.3.1 Newly Flooded Structures

Newly flooded structures refer to structures with flood depth above their finished floor elevation in areas inundated only in the SWFD scenario due to subsidence terrain. These structures were not flooded in the Baseline scenario. To understand the impact of flooding due to subsidence, the 365 newly flooded structures were further categorized into different flood depth ranges, as shown in **Figure 3.**

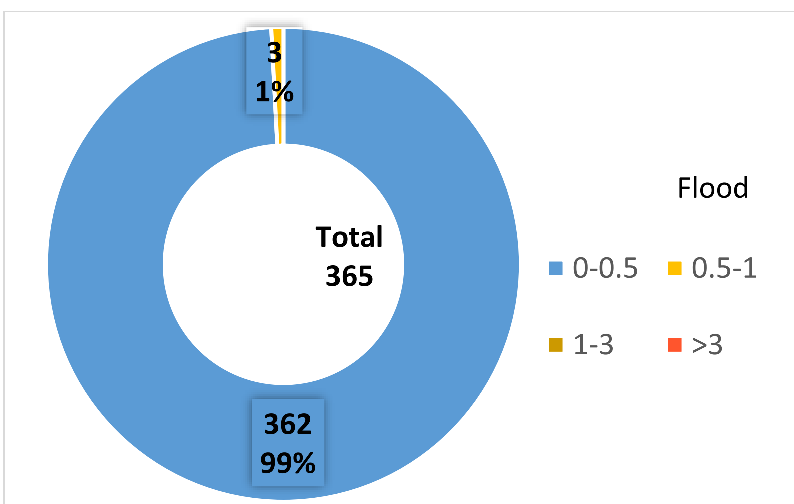



**Figure 3: Distribution of Newly Flooded Structures in SWFD Scenario**

**Figure 3** shows, for each flood depth level, the number and percentage distribution of the newly flooded structures in the 1% AEP floodplain of the SWFD scenario.

These indicate that the flood depths in the structures, as a result of subsidence, fall into Level One and Level Two flood impacts as described in **Section 1.1.1.1**. These levels of flooding could cause substantial losses to the structures by requiring repairs/replacement of drywall, insulation, floor carpet, laminated floor, refrigerators, ovens, heating and cooling systems, electrical outlets, and parked vehicles (illustrated in **Figure 1**). No newly flooded structures were subject to flooding higher than one (1) foot in the SWFD scenario.

A large number of newly flooded structures occurred downstream of Kuykendahl Rd and IH-45. These were observed in areas with increased subsidence between 2.5 ft and 3 ft and predominantly located along the north bank of Spring Creek in Montgomery County, as compared to those located on the south bank in Harris County. See **Figure 4** for the location of newly flooded structures downstream of Kuykendahl Rd and IH-45. A detailed map series including selected areas along Spring Creek is shown in **Appendix B**. The economic loss associated with this damage is discussed in **Section 4** of Tech Memo 3.

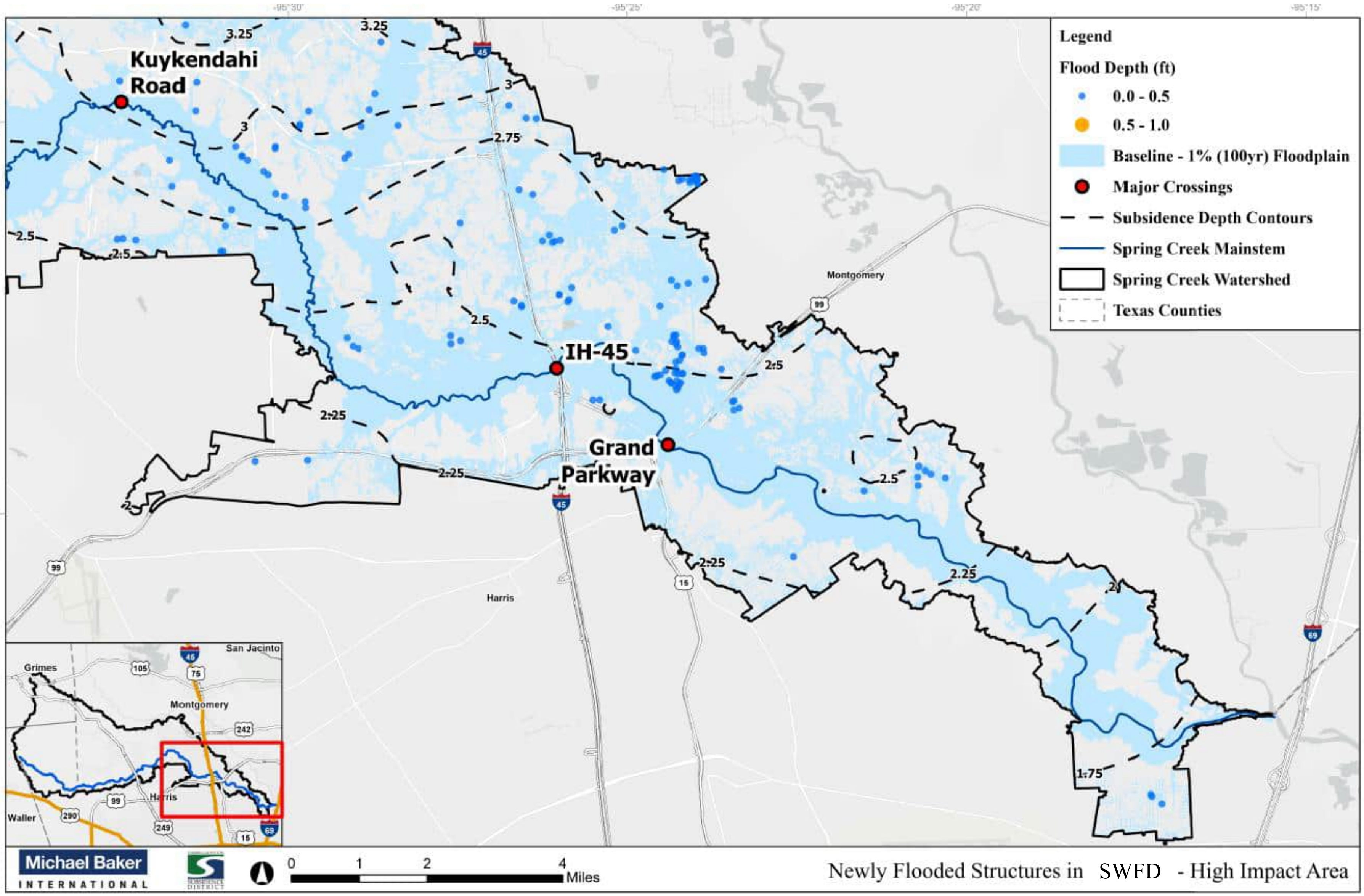



**Figure 4: Location of Newly Flooded Structures in SWFD Scenario but not flooded in Baseline, downstream of Kuykendahl Road**

### 1.1.1.3.2 Commonly Flooded Structures

Commonly flooded structures refer to the structures that were already flooded in the Baseline scenario and were subject to greater flood depths in the SWFD scenario. To understand the impact of the flood depths due to subsidence, the 7,754 commonly flooded structures were further categorized into different flood depth ranges as shown in **Figure 5**.

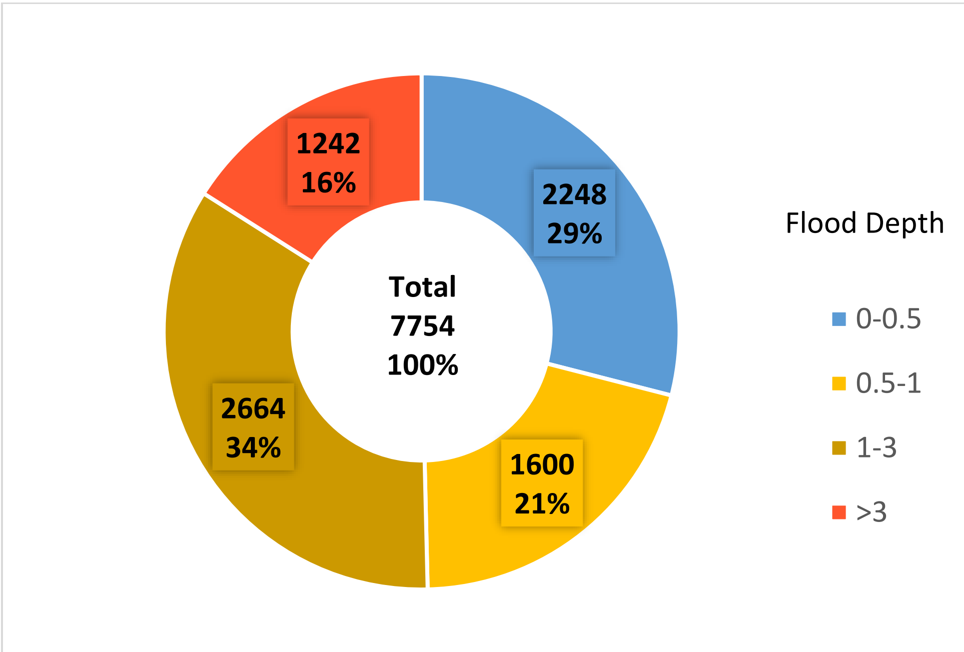



**Figure 5: Distribution of Commonly Flooded Structures Subject to Higher Flood Depth in SWFD Scenario**

**Figure 5** shows, for each flood depth level, the number and percentage distribution of the commonly flooded structures that were subject to higher flood depth in the 1% AEP floodplain of the SWFD scenario. The impact of different flood depth levels is described in the Section **1.1.1.1.**

**Figure 6** shows the largest concentration of these structures that were flooded in both Baseline and SWFD scenarios near Kuykendahl Road and near the IH 45 area. There are a large number of structures with a flood depth of more than three (3) feet just downstream of the IH 45 bridge crossing. A detailed map series of the Spring Creek watershed with commonly flooded structures is shown in **Appendix B**.

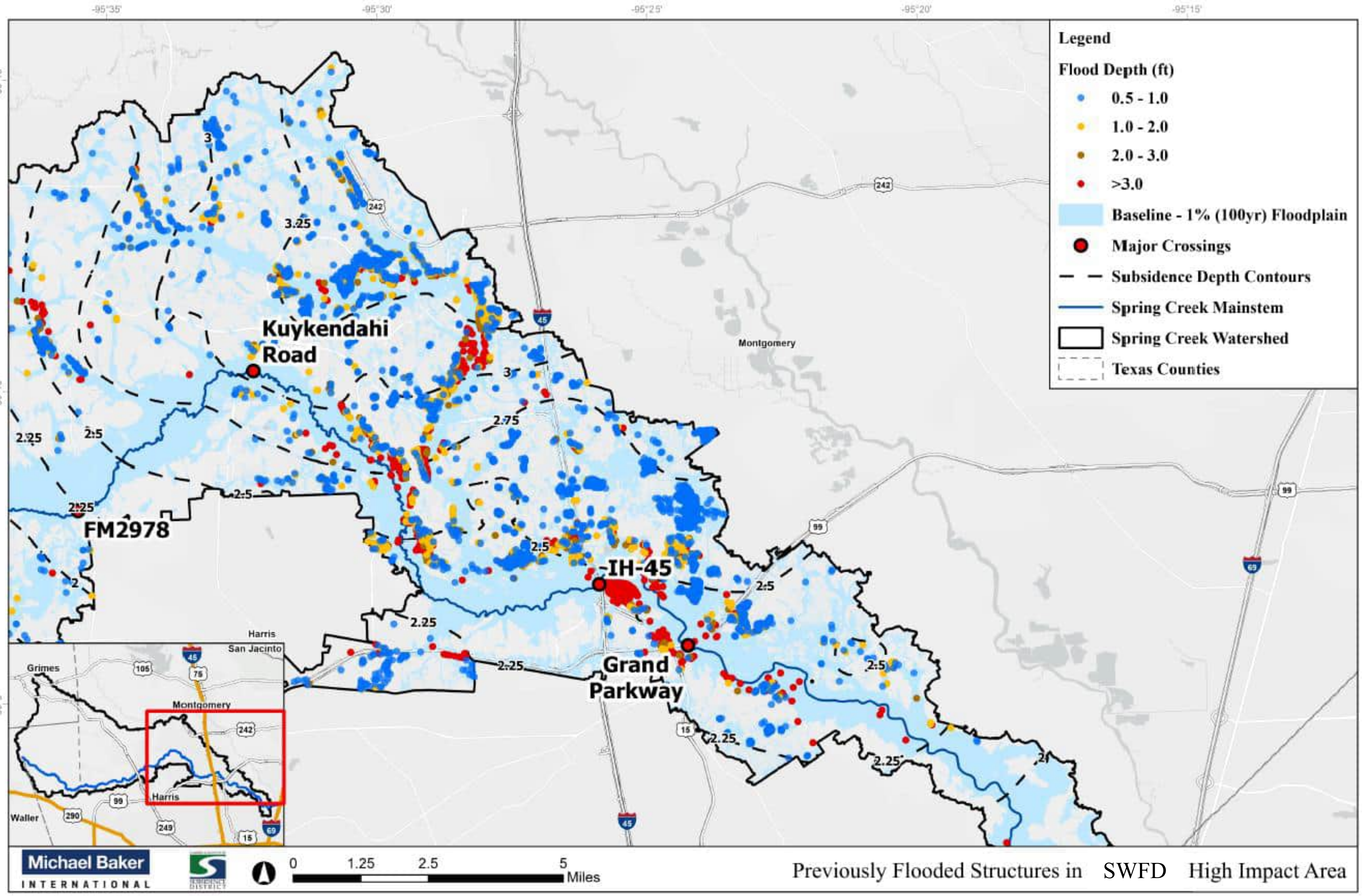



**Figure 6: Location of Commonly Flooded Structures Subject to Higher Flood Depth in SWFD Scenario, downstream of Kuykendahl Road**

Further to understand the flood impact in the commonly flooded structures, the amount of increase in flood depth due to subsidence was estimated by subtracting the flood depth in the Baseline scenario from the flood depth in the SWFD scenario. **Figure** *7* categorizes the number and percentage distributions of the commonly flooded structures based on the amount of increase in flood depth.

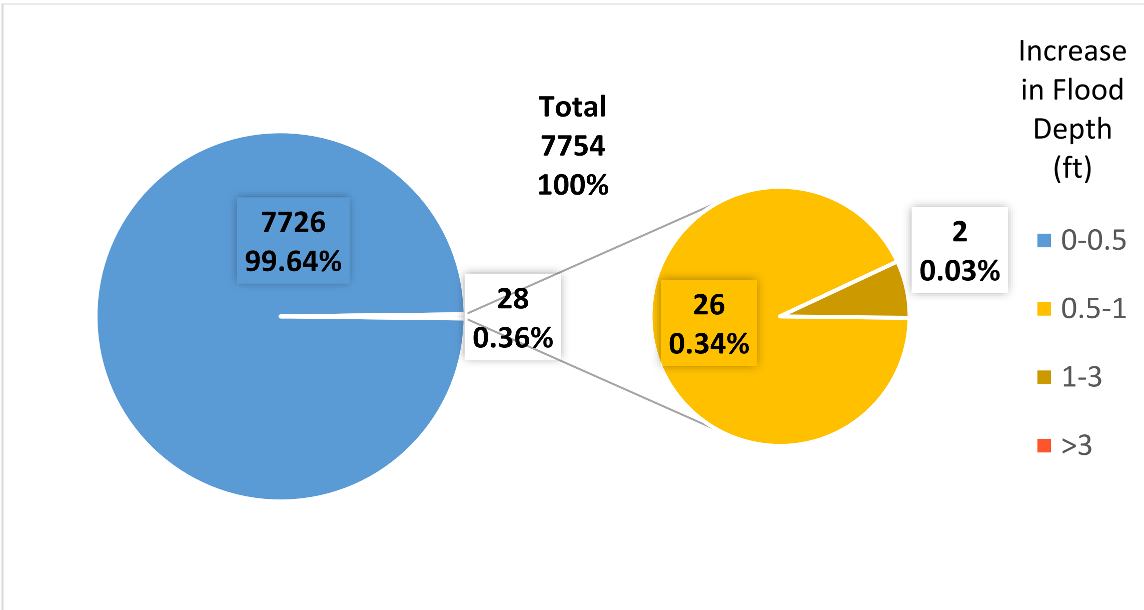



**Figure 7: Distribution of Increase in Flood Depth of Commonly Flooded Structures in SWFD Scenario**

**Figure** *7* shows that most of the structures that were flooded in Baseline have an increased risk of flooding up to six (6) inches due to subsidence. These structures would see an increase in flood insurance costs and depreciation of their property values due to their increased risk of flooding.

#### *1.1.1.4 Flooded Structures in Subsidence with Future Development Scenario*

A total of 15,715 structures are flooded in the 1% AEP floodplain of Subsidence with future development scenario, as indicated in **Table 1**. The depth raster of the Baseline was subtracted from that of the Subsidence with the future development scenario to quantify the increased flood depth at each flooded structure due to subsidence. This identified, among the 15,715 flooded structures, 3,807 structures are newly flooded structures due to the floodplain increase in the Subsidence with future development scenario, and 9,733 structures were commonly flooded in the Baseline scenario but inundated with higher flood depth in the Subsidence with future development scenario. The comparison and quantification of results to understand the flood risk and damage associated with subsidence, coupled with future development in the newly and commonly flooded structures, are described in the following sections.

#### 1.1.1.4.1 Newly Flooded Structures

Newly flooded structures refer to those with flood depths above their finished floor elevation in areas inundated in only the Subsidence with future development scenario as a result of subsidence terrain. These structures were not flooded in the Baseline scenario. To understand the impact of flooding due to subsidence with future development, the 3,807 newly flooded structures were further categorized into different flood depth ranges as shown in **Figure 8**.

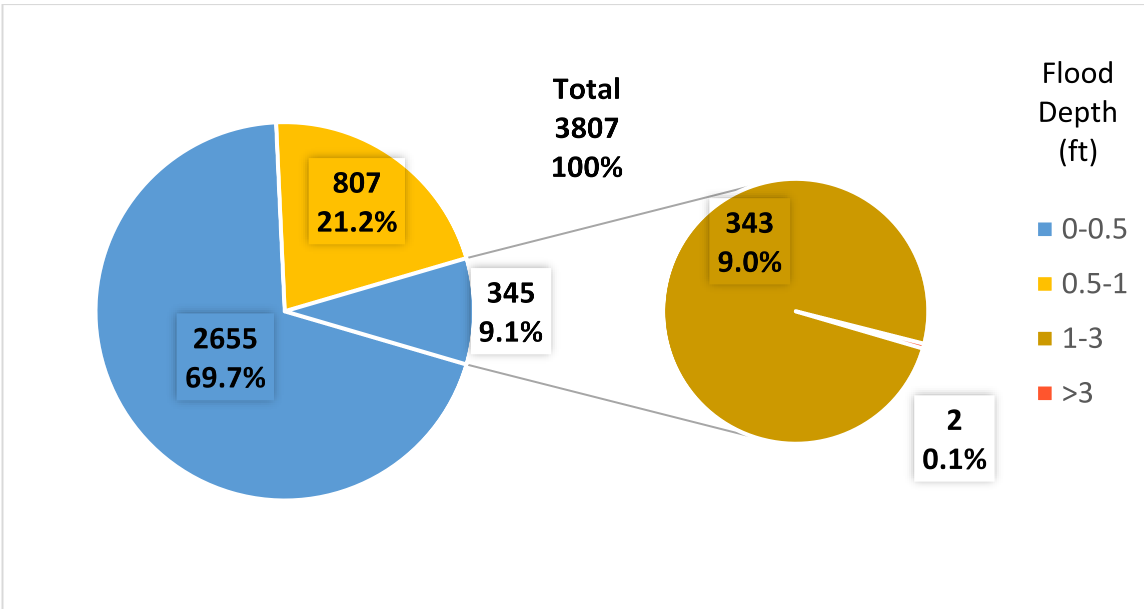



**Figure 8: Distribution of Newly Flooded Structures in Subsidence with Future Development Scenario**

**Figure 8** shows, for each flood depth level, the number and percentage distributions of the newly flooded structures in the 1% AEP floodplain of the Subsidence with future development scenario. These indicate that the flood depths in most of the structures, as a result of subsidence, fall into Level One and Level Two flood impacts as described in Section **1.1.1.1**. These levels of flooding could cause substantial losses to the structures by requiring repairs/replacement of drywall, insulation, floor carpet, laminated floor, refrigerators, ovens, heating and cooling systems, electrical outlets, and parked vehicles (illustrated in **1.1.1.1**). The higher level of flooding causes a lot of substantial damage, which was discussed in the Section **1.1.1.1** thus having a high cost.

**Figure 9** shows that a notable number of newly flooded structures are near the IH 45 area and downstream of Kuykendahl Road for the Subsidence with future development scenario. Detailed map series including selected areas along Spring Creek are shown in **Appendix B**. The economic loss associated with this damage is discussed in **Section 4** of the Tech Memo 3.

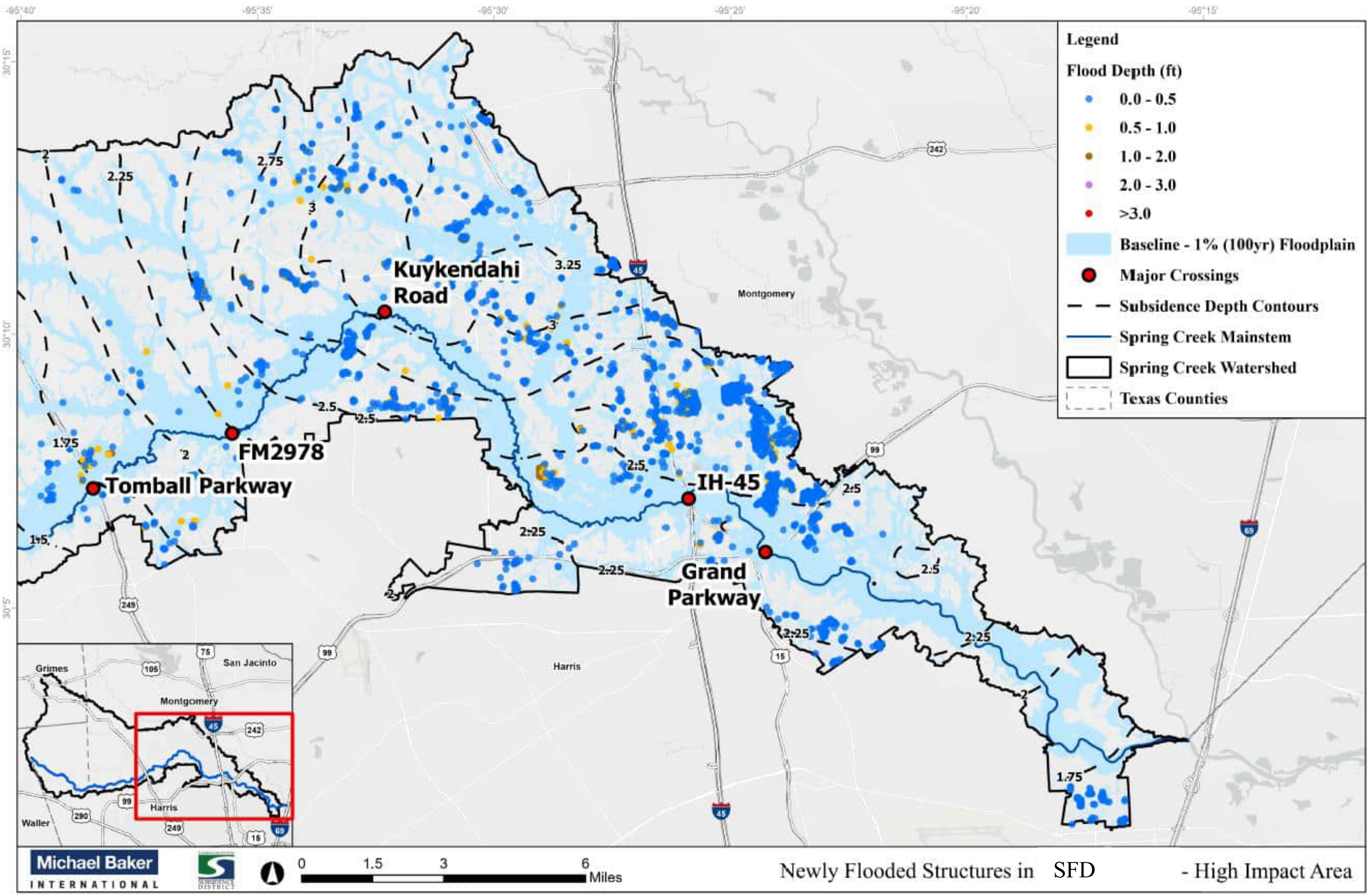



**Figure 9: Location of Newly Flooded Structures in Subsidence with Future Development Scenario, but not Flooded in Baseline, Downstream of Kuykendahl Road**

#### 1.1.1.4.2 Commonly Flooded Structures

Commonly flooded structures refer to the structures that were already at flood risk due to flooding in the Baseline scenario and were subject to greater flood depths in the Subsidence with future development scenario. To understand the impact of the flood depths due to subsidence, the 9,733 commonly flooded structures were further categorized into different flood depth ranges as shown in **Figure 10**.

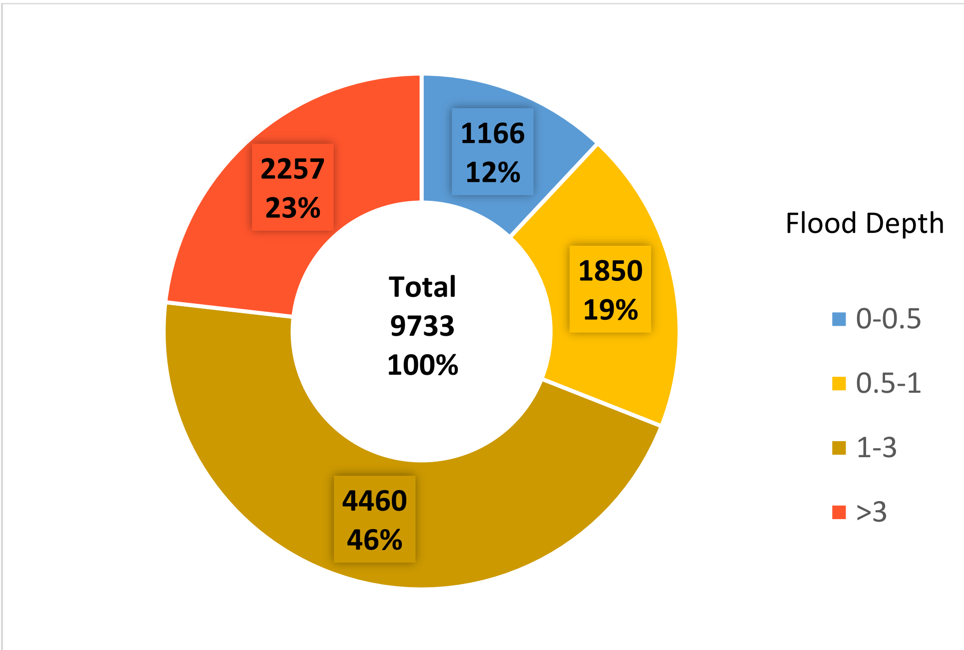



**Figure 10: Distribution of Commonly Flooded Structures Subject to Higher Flood Depth in Subsidence with Future Development Scenario**

**Figure 10** shows, for each flood depth level, the number and percentage distributions of the commonly flooded structures that were subject to higher flood depth in 1% AEP floodplain of Subsidence with future development scenario. The impact of different flood depth levels is described in Section **1.1.1.1**.

A large number of commonly flooded structures occurred in the vicinity of FM 2978 and downstream of IH-45. Both of these areas show a significant number of structures with higher flood depth of more than one (1) feet. See **Figure 11** for the location of commonly flooded structures vicinity of Kuykendahl Rd and downstream IH-45. Detailed map series of the Spring Creek watershed with commonly flooded structures are shown in **Appendix B**.

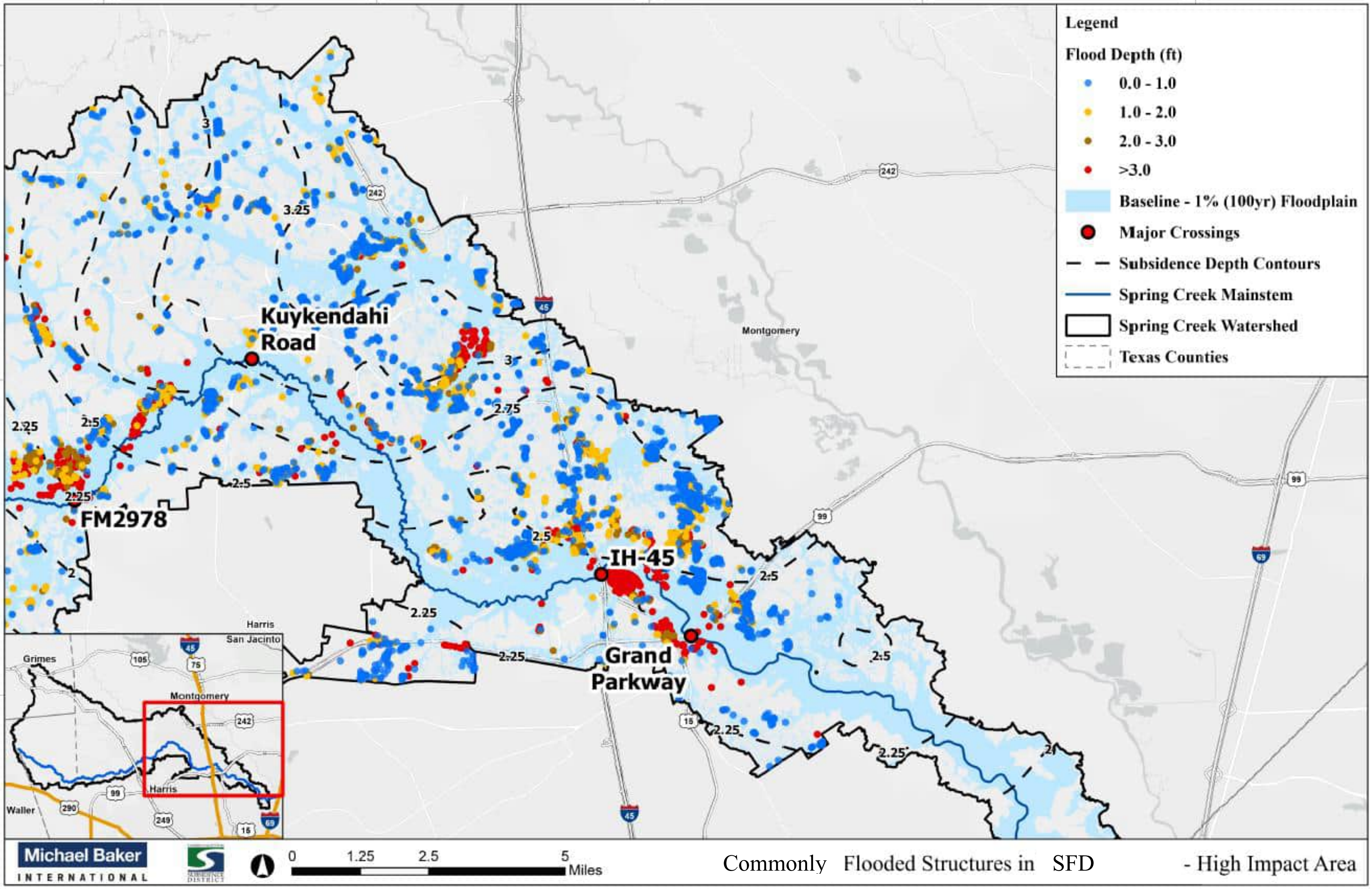



**Figure 11: Location of Commonly Flooded Structures Subject to Higher Flood Depth in Subsidence with Future Development Scenario, vicinity of Kuykendahl Road**

Further to understand the flood impact in the commonly flooding structures, the amount of increase in flood depth due to subsidence with future development was estimated by subtracting the flood depth in the Baseline scenario from the flood depth in the Subsidence with future development scenario. **Figure 12** categorizes the number and percentage distributions of the commonly flooded structures based on the amount of increase in flood depth.

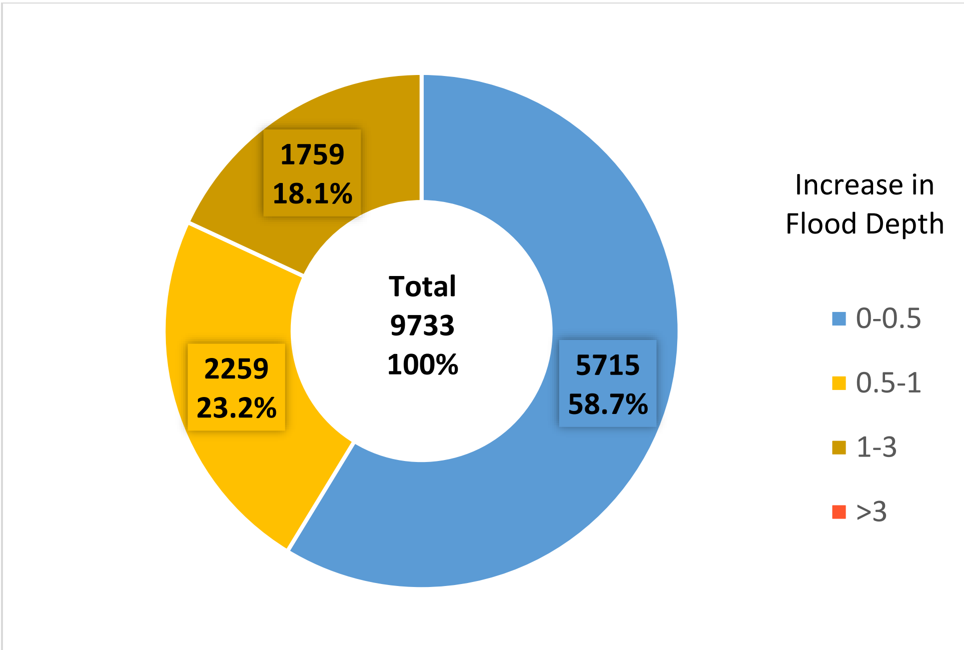



**Figure 12 : Distribution of Commonly Flooded Structures Subject to Higher Flood Depth in Subsidence with Future Development Scenario**

**Figure 12** shows that most of the structures in Subsidence with future development scenario have increased up to two (2) foot in flooded depth, with a very small number of structures with an increase of flooded depth between two (2) to three (3) feet when compared with the Baseline. These structures would see an increase in flood insurance costs and depreciation of their property values due to their increased risk of flooding.

### 1.1.2 Non-Structural Flooding Impact

Non-structural flooding is limited to roadway flooding in this analysis. Non-structural (roadways) flooding causes prolonged closures, disrupting transportation and economic activities. Flooding can also hinder emergency response efforts, and isolate communities, exacerbating the overall impact of flooding. Flooding on roadways can also lead to damage such as erosion of the subgrade, weakening of the base layers, dislocation of concrete slabs, surface washouts, and reduced load-bearing capacity.

Flooded roadways were estimated for each scenario – Baseline, Subsidence without future development, and Subsidence with future development. The Geographic Information System

(GIS) shapefile of roadways in the watershed was downloaded from the TxDOT website[4]. The roadway functional classifications were consolidated for analysis as listed in Table 2.

**Table 2: Roadways Classification**

| Roadway Category | |
|---|---|
| **Re-classified** | **Original TxDOT shapefile** |
| Highway | Interstate<br>Principal Arterial<br>Minor Arterial |
| Collector | Major Collector<br>Minor Collector |
| Local | Local Roads |

### *1.1.2.1 Levels of Flood Impact on Roadways*

As little as six (6) inches of fast-moving water can cause motorists to lose control of their vehicles. One (1) foot of floodwater on a roadway is enough to make vehicles buoyant and float away. Additionally, floodwater can hydro-lock engines and severely damage them[5]. Water ponding on roadways may potentially make them untravellable during a flooding event. For the 1% AEP flood event of Baseline, Subsidence without future development, and Subsidence with future development scenarios, the roadway flooding was categorized in (a) flood depth less than or equal to one (1) foot and (b) flood depth greater than one (1) foot.

The total number of flooded roadways in each scenario, resulting from pluvial modeling for the level of flood depth, is shown in **Table 3.** The levels and impacts of flood depth on roadways used in this analysis are discussed in Section **1.1.2.1**. The roadways flooded in the Subsidence without future development scenario are discussed in Section 1.1.2.2. The roadways flooded in Subsidence with future development scenarios are discussed in Section **1.1.2.3.**

**Table 3: Miles of Flooded Roadways in the three (3) Scenarios of Pluvial Modeling**

| **Roadway Category** | **Baseline** | | **Subsidence without future development** | | **Subsidence with future development** | |
|---|---|---|---|---|---|---|
| | **Flood Depth** | | | | | |
| | **<= 1ft** | **> 1ft** | **<= 1ft** | **> 1ft** | **<= 1ft** | **> 1ft** |
| **Highway** | 28 | 41 | 28 | 42 | 29 | 46 |
| **Collector** | 34 | 60 | 34 | 61 | 34 | 65 |
| **Local** | 165 | 351 | 163 | 356 | 154 | 389 |
| **Subtotal** | 227 | 452 | 225 | 459 | 217 | 500 |
| **Total** | 679 | | 684 | | 717 | |

[4] https://www.txdot.gov/data-maps/roadway-inventory.html
[5] https://www.texasattorneygeneral.gov/consumer-protection/disaster-and-emergency-scams/warning-flood-damaged-cars

#### *1.1.2.2 Flooded Roadways in Subsidence without Future Development Scenario*

651.5 miles of roadways are flooded in 1% AEP floodplain of the Subsidence without future development scenario, as indicated in **Table *3***. To understand the impact of the subsidence on the flooded roadways, the flooded roadways are sorted into newly flooded roadways and commonly flooded roadways. To quantify the miles of roadways in these two groups, the depth raster of the SWFD and Baseline scenarios was converted to depth polygons at flood depth of less than or equal to one (1) foot and greater than one (1) foot and intersected to the roadway shapefile. This identified, among the 651.5 miles of flooded roadways, 7.9 miles of roadways are newly flooded roadways due to the floodplain increase in the SWFD scenario. Another 646.4 miles of roadways flooded in the SWFD scenario were commonly flooded in the Baseline scenario. The comparison and quantification of results to understand the flood risk and damage associated with subsidence in the newly and commonly flooded roadways are described in the following sections.

##### 1.1.2.2.1 Newly Flooded Roadways

Newly flooded roadways refer to roadways with flood depth above their surface elevation in areas inundated only in the SWFD scenario due to subsidence terrain. These roadways were not flooded in the Baseline scenario. To understand the impact of flooding due to subsidence, the 7.9 miles of newly flooded roadways were further categorized into three roadway categories which are – highway, collector, and local as well as by flood depth of below and above one (1) foot. Flood depths of greater than one (1) foot is considered untravellable. The miles of the newly flooded roadways and the associated flood depth level are provided in **Figure 13.**

It is noted that 0.17 miles (2%) of local roadways are untraversable roadways with flood depths of greater than one (1) foot. No highway and collector had a flood depth of greater than one (1) foot only in the SWFD scenario. Most of the newly flooded roads in the SWFD scenario are in the vicinity of Kuykendahl Road and the IH 45 area. Please find detailed maps of newly flooded roads in the SWFD scenario in **Appendix B**.

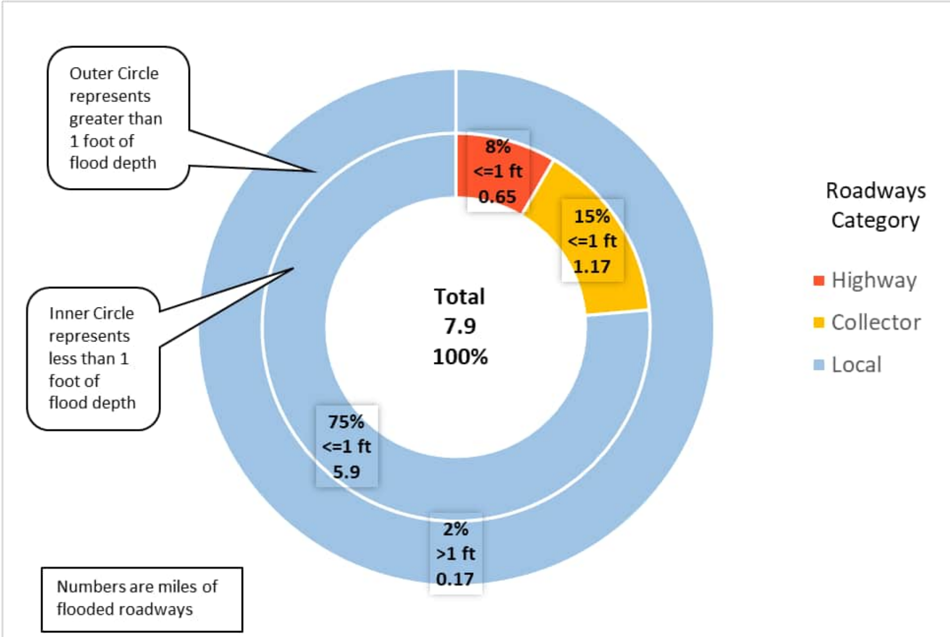



**Figure 13: Miles of Newly Flooded Roadways in SWFD Scenario**

#### 1.1.2.2.2 Commonly Flooded Roadways

Commonly flooded roadways refer to the roadways that were not only already flooded in the Baseline scenario but also flooded in the SWFD scenario. To understand the impact of flooding due to subsidence, the 646.4 miles of commonly flooded roadways, are further categorized into three roadway categories which are – highway, collector, and local as well as by flood depth of below and above one (1) foot. Flood depths of greater than one (1) foot is considered untravellable. Then miles of these flooded roadway categories were compared to the miles of flooded roadway categories in the Baseline scenario to quantify the impact of the flooding due to subsidence. The miles of the commonly flooded roadways in the SWFD scenario and the associated flood depth level are provided in **Figure 14**. The miles of the commonly flooded roadways in the Baseline scenario and the associated flood depth level are provided in **Figure 15.**

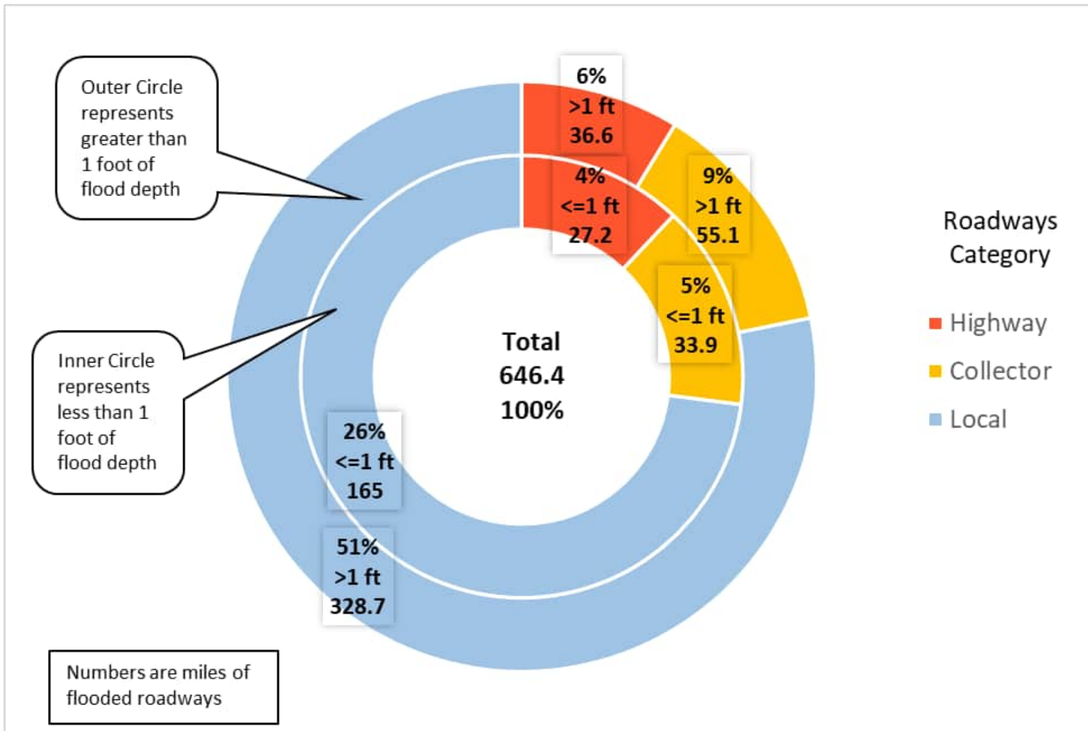



**Figure 14: Miles of Commonly Flooded Roadways in SWFD Scenario according to pluvial model results**

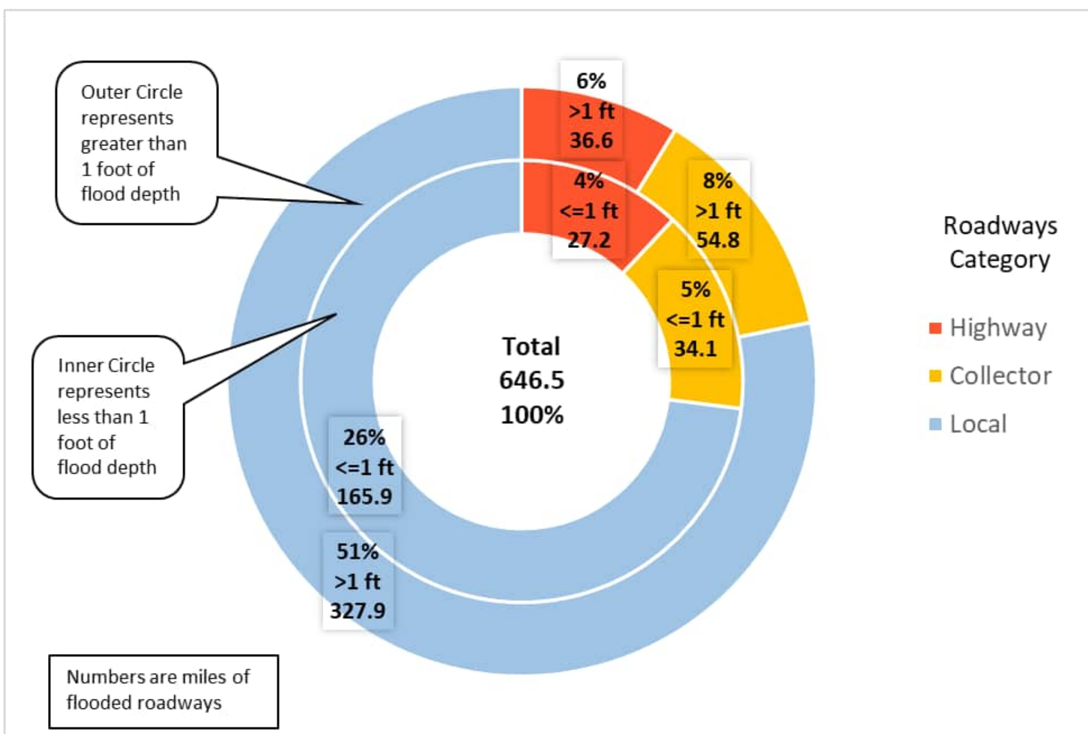



**Figure 15: Miles of Commonly Flooded Roadways in Baseline Scenario according to pluvial model results**

**Figure 16** shows the increase in the number of roads that were commonly flooded in the SWFD scenario from the Baseline scenario for each category, and the total number of highways that were flooded did not change. It is noted that an increase in untravellable roads (more than one foot flooded) is equal to the decrease in miles of roads that were flooded less than one foot. Please find detailed maps of commonly flooded roads in the SWFD scenario in **Appendix B**.

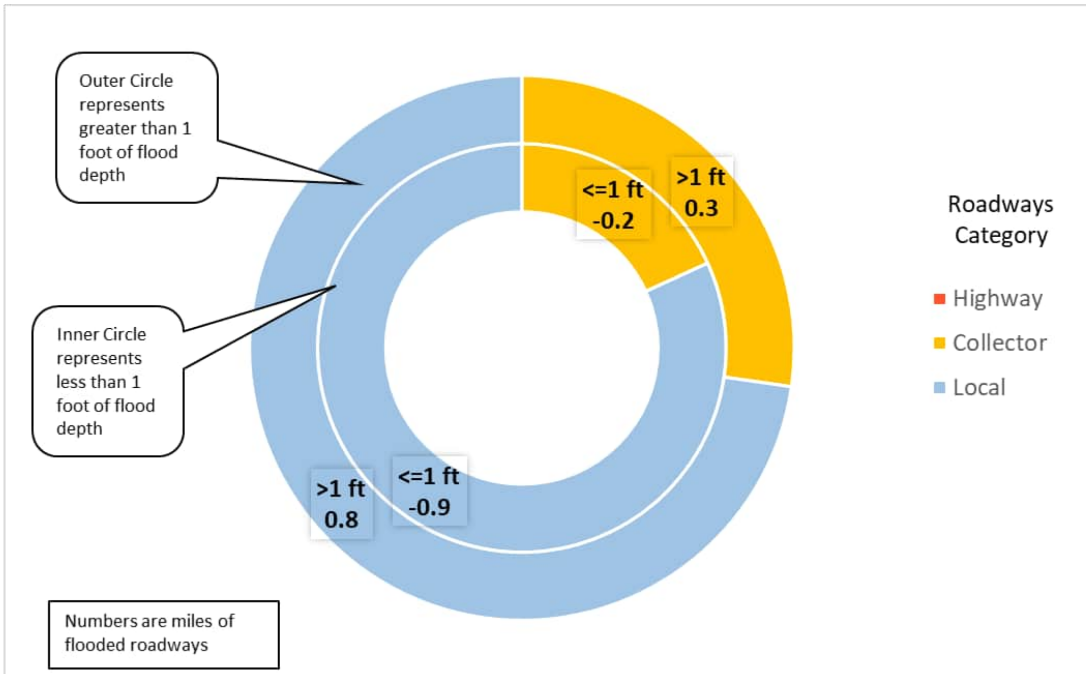



**Figure 16: Increase in Miles of Commonly Flooded Roadways in SWFD Scenario**

### *1.1.2.3 Flooded Roadways in Subsidence with Future Development Scenario*

689.6 miles of roadways are flooded in 1% AEP floodplain of Subsidence with future development scenario as indicated in ***Table 3***. Similar to the flooded structures (discussed in Section above) , to understand the impact of the subsidence on the flooded roadways,

the flooded roadways are sorted into newly flooded roadways and commonly flooded roadways. To quantify the miles of roadways in these two groups, the flood depth raster of the Subsidence with future development and Baseline scenarios were converted to depth polygons at flood depth of less than or equal to one (1) foot and greater than one (1) foot and interest to the roadway shapefile. This identified, among the 689.6 miles of flooded roadways, 58.4 miles of roadways are newly flooded roadways due to the floodplain increase in Subsidence with future development scenario. Another 630.6 miles of roadways flooded in Subsidence with future development scenario are commonly flooded in the Baseline scenario. The comparison and quantification of results to understand the flood risk and damage associated with subsidence coupled with future development in the newly and commonly flooded roadways are described in the following sections.

### 1.1.2.3.1 Newly Flooded Roadways

Newly flooded roadways refer to the roadways that have flood depth above their surface elevation in areas inundated in only the Subsidence with future development scenario as a result of subsidence terrain. These roadways were not flooded in the Baseline scenario. To understand the impact of flooding due to subsidence, the 58.4 miles of newly flooded roadways were further categorized into three roadway categories which are – highway, collector, and local as well as by flood depth of below and above one (1) foot. Flood depths of greater than one (1) foot is considered untravellable. The miles of the newly flooded roadways and associated flood depth levels are provided in **Figure 17**.

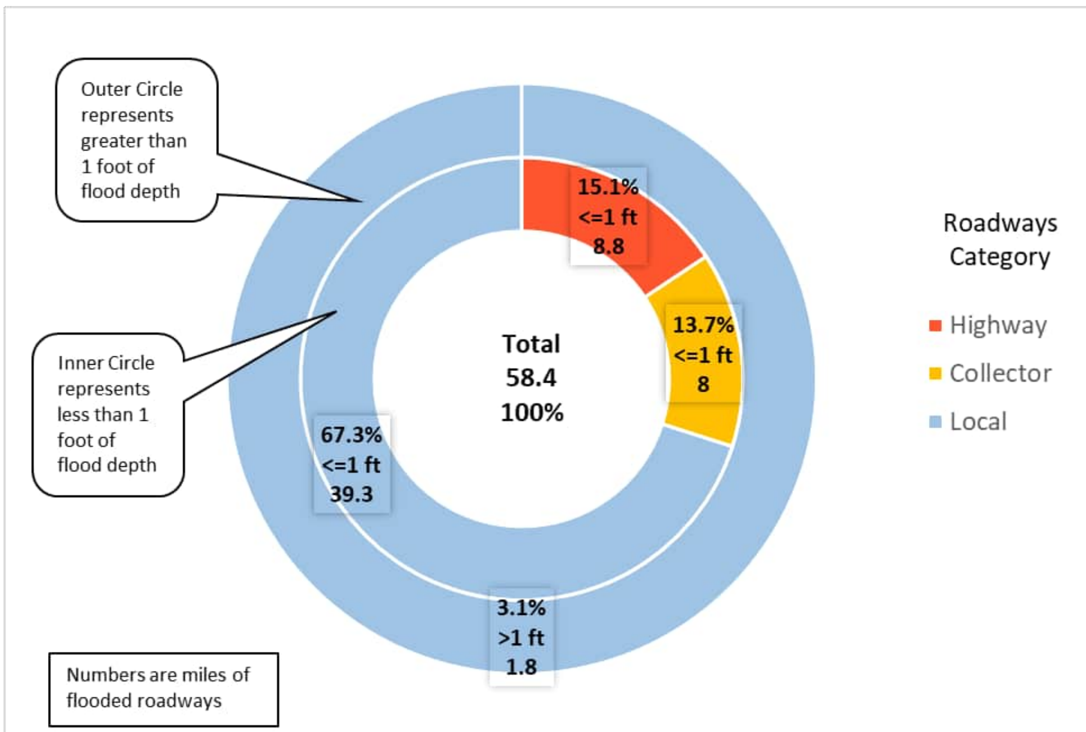



**Figure 17: Miles of Newly Flooded Roadways in Subsidence with Future Development Scenario**

It is noted that 1.8 miles (3.1%) of local roadways are untravellable roadways with flood depth of greater than one (1) foot. No highway and collector had a flood depth of greater than one (1) foot only in the Subsidence with future development scenario. Most of the newly flooded roads in the Subsidence with future development scenario are in the vicinity of Kuykendahl Road and the IH 45 area. Please find detailed maps of newly flooded roads in the Subsidence with future development scenario in **Appendix B**.

### 1.1.2.3.2 Commonly Flooded Roadways

Commonly flooded roadways refer to the roadways that were not only already flooded in the Baseline scenario but also flooded in the Subsidence scenario with future development. To understand the impact of flooding due to subsidence, the 630.6 miles of commonly flooded roadways, are further categorized into three roadway categories which are – highway, collector, and local as well as by flood depth of below and above one (1) foot. Flood depth of greater than one (1) foot is considered untravellable. Then miles of these flooded roadway categories were compared to the miles of flooded roadway categories in the Baseline scenario to quantify the impact of the flooding due to subsidence. The miles of the commonly flooded roadways in the Subsidence with future development scenario and the associated flood depth level are provided in **Figure 18**. The miles of the commonly flooded roadways in the Baseline scenario and the associated flood depth level are provided in **Figure 19**.

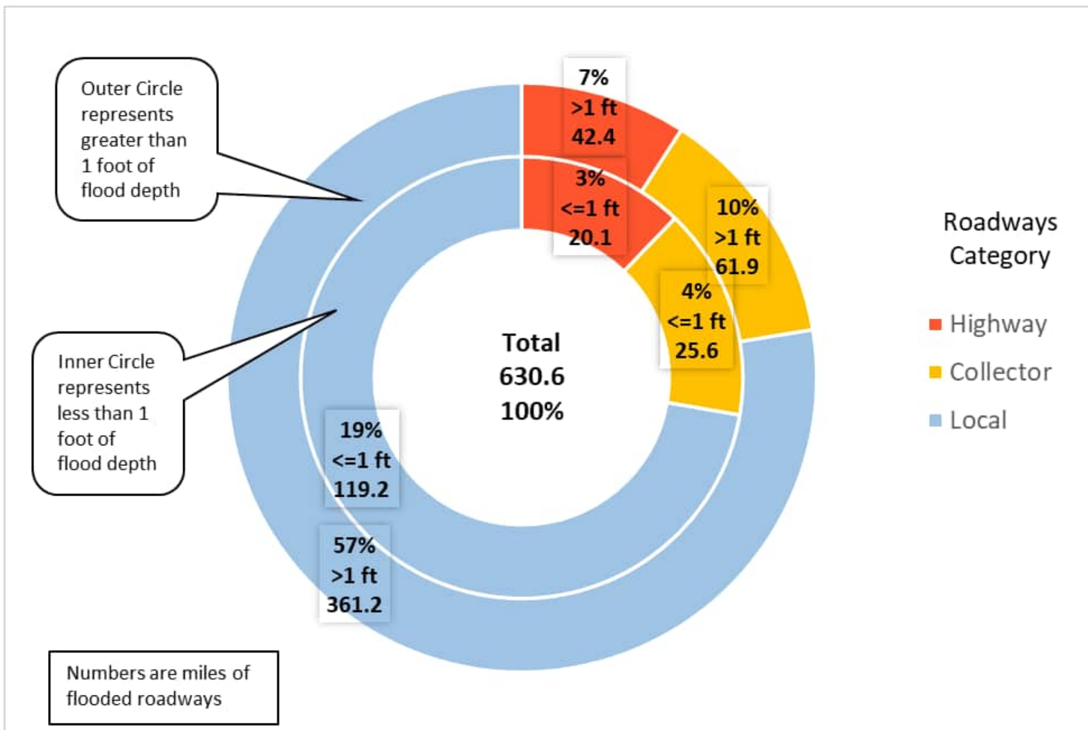



**Figure 18: Miles of Commonly Flooded Roadways in Subsidence with Future Development Scenario**

**Figure 20** shows the increase in the number of roads that were commonly flooded in the Subsidence with future development scenarios from the Baseline scenario for each category. It is noted that an increase in untravellable roads (more than one foot flooded) is equal to the decrease in miles of roads that were flooded less than one foot. Please find the detailed maps of commonly flooded roads in the Subsidence with future development scenarios in **Appendix B.**

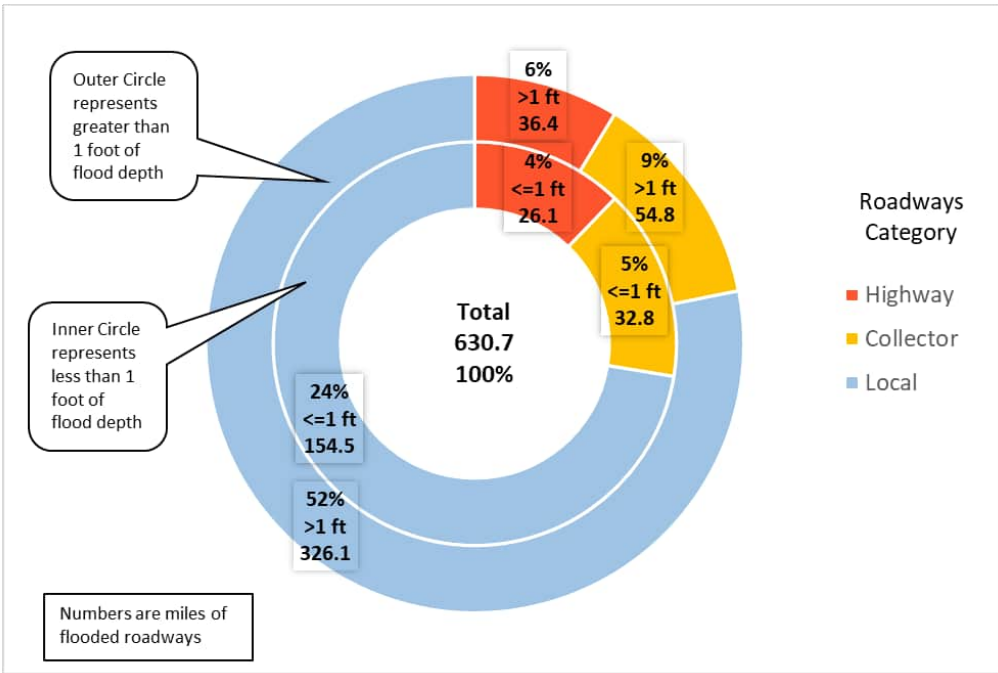



**Figure 19: Miles of Commonly Flooded Roadways in Baseline Scenario**

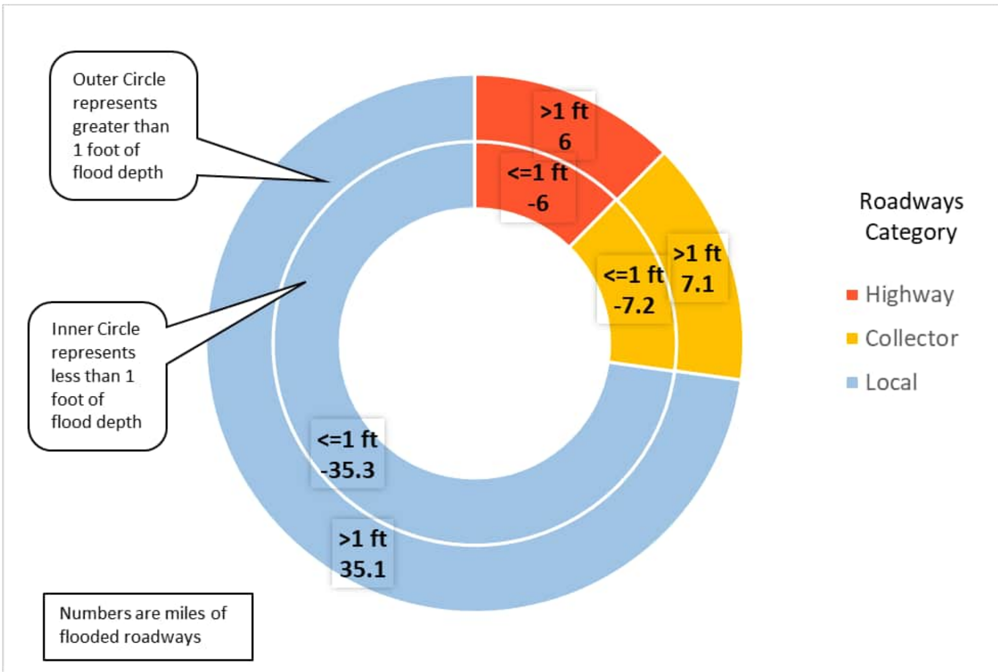



**Figure 20: Increase in Miles of Commonly Flooded Roadways in Subsidence with future development Scenario**

# Appendix A2: Flood Hazard Economic Consequence Tools Comparison

# Appendix A2

# Flood Hazard Economic Consequence Estimation Tools

As a part of economic consequence analysis, four different tools were considered, among which Go-Consequence was chosen. The details of each tool are discussed in below.

## 1 HAZUS

Hazards U.S. Multi-Hazard (HAZUS-MH)[1] is a useful risk assessment software program for analyzing potential losses from floods, hurricane winds, tsunami, and earthquakes. HAZUS-MH uses ESRI® ArcMap software to run its calculations and is a free extension for ArcGIS® Desktop. HAZUS-MH was developed by FEMA under contract with the National Institute of Building Sciences.

The Flood Model of the HAZUS is an integrated system for identifying and quantifying flood risks using national elevation and other hydrologic and hydraulic datasets.

Physical damage analysis defines the hazard and calculates damage to residential and commercial buildings, schools, critical facilities, and infrastructure. Economic loss analysis calculates the lost jobs, business interruptions, and repair and reconstruction costs. And the social impact analysis identifies casualties, shelter requirements, and medical aid using data from the physical damage analysis. HAZUS loss estimation comprises of following damage estimates:

- Damage to General Building Stock
- Damage to Essential Facilities
- Damage to Lifeline Systems
- Damage to Vehicles
- Damage and Loss to Agriculture (Crop)
- Debris Generation
- Direct Economic Losses
- Other Direct Losses
- Social Losses and Induced Damage (Shelter Needs)
- Indirect Economic Losses

There are three levels of HAZUS-MH usage. Level 1 uses the default data that is embedded in HAZUS-MH and does a basic analysis. In Level 2, additional, detailed local data can be imported to the HAZUS-MH environment, and the analysis could run using this higher-quality data. Experts and engineers can change some of the values that HAZUS-MH suggests and use HAZUS-MH in Level 3 with higher accuracy for their specific study region. As can be seen in the figure below, as

[1] https://www.fema.gov/flood-maps/products-tools/hazus

the level of analysis moves from Level 1 (basic level) to Level 3 (advanced level), the effort needed by the user, and input data increases while providing a greater level of detailed outputs.

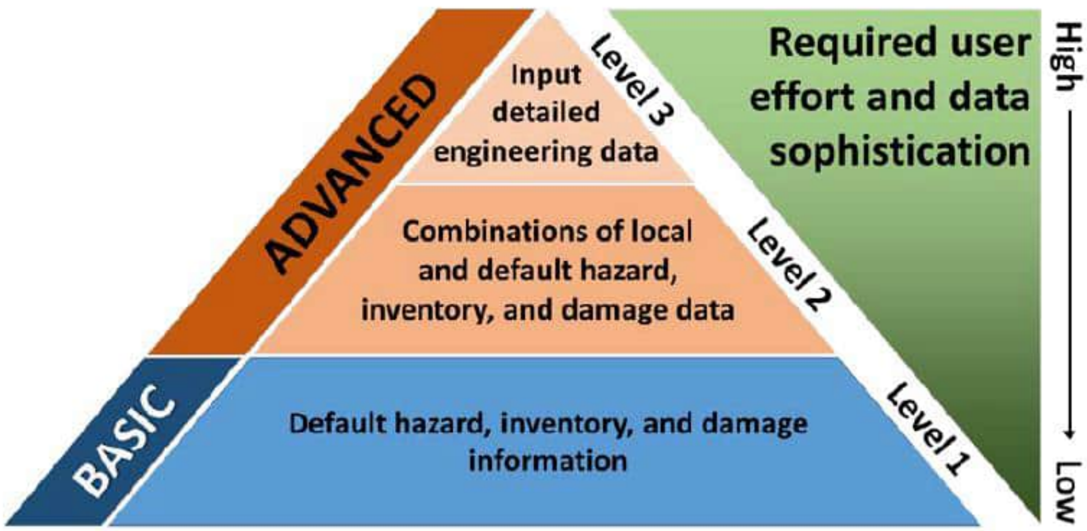



**Figure 1: HAZUS Level of Analysis[2]**

## 1.1 Direct Damage

The HAZUS Flood Model uses estimates of flood depth along with depth-damage functions to compute the possible damage to buildings and infrastructure that may result from flooding. Two inputs to the damage module are required to estimate building damage: (1) the building occupancy type and first-floor elevation, which typically includes design levels (pre-or post-FIRM); and (2) the depth of flooding, at the building or area weighted throughout the census block where the building is located. The model building type may not be known for each building, but it can be estimated from the default inventory using a relationship between the building type and occupancy. The depth of flooding is determined using the FIT for a Level 2 study or the Level 1 methodology contained in the Flood Model. Flood Information Tool ("FIT" tool) is used to preprocess site-specific flood hazard data and facilitate its import into the Flood Model for further analysis of damage and loss. The outputs of the damage module are area-weighted estimates of damage as a percent of replacement cost, at the census block or for a given building. These are used as inputs to the induced physical damage and direct economic and social loss modules.

## 1.2 Depth-Damage Functions

The HAZUS Flood Model uses the Federal Insurance Administration's "credibility weighted" depth-damage curves and selected curves developed by various districts of the USACE for

[2] *https://www.fema.gov/sites/default/files/documents/fema_using-hazus-mitigation-planning_2018.pdf*

estimating damage to the general building stock. For essential facilities, such as hospitals, schools, and fire stations, the damage is estimated by applying a default depth-damage curve, which is then editable by the user to create a specific function for the facility. Damage is estimated for lifeline systems with a separate set of damage functions that define the potential damage to components of the systems that are either uniquely vulnerable to inundation or are expensive to repair or replace. Various components are grouped based on similar vulnerabilities and expected losses.

# 2 HEC-FIA

Hydrologic Engineering Center's (HEC) Flood Impact Analysis (HEC-FIA) is free standalone software from HEC which utilizes geospatial datasets to build structure inventories, assign values and population per structure. Using the structure inventory, with geospatially and externally derived flood depth grids, HEC-FIA can estimate direct and indirect economic, agricultural, and life loss consequences for flood hazards. HEC-FIA computes the result for a single event in either deterministic or uncertainty mode which utilizes a Monte Carlo approach. The user can define the uncertainties about any structure in the floodplain in many ways, and each has various impacts on the different consequence calculations. HEC-FIA can also be linked into HEC-WAT (Watershed Analysis Tool) with the FRA (Flood Risk Analysis) compute option to randomize the events being evaluated in HEC-FIA so that economic uncertainties along with hydrologic, hydraulic, and geotechnical uncertainties can all be evaluated by alternative. This capability allows users to evaluate current and future risks in a changing[3] environment. This paper describes how HEC-FIA can be utilized to help evaluate the consequences for various alternatives within a floodplain.

## 2.1 Direct-Damage Calculations

HEC-FIA calculates the direct losses for structures in the form of structure damage, content damage, and vehicle damage. These damages are calculated in the traditional methods as described in ER 1105-2-100 (USACE, 2000) using relationships such as those described in EGM 01-03 (EGM, 2003). HEC-FIA evaluates the direct damages of an event, except that structure survivorship which is based on depth and velocity thresholds is now a part of the direct damage estimate. In HEC-FIA damages are described by unique occupancy types and damage categories which allows the user to organize direct damage estimates by damage categories and occupancy types which map to sectors and subsectors of the economy. Examples of damage categories would be: Residential, Industrial, Commercial, and Public; and examples of occupancy types might be: Ind1, Ind2, Ind3 which may represent light industrial, heavy industrial, etc. The resulting damage calculations would be on a per structure basis, representing the dollar damage for contents, structure, and vehicles organized by sector and subsector of the economy.

Additionally, HEC-FIA calculates the loss of life and human impacts from flooding events. This impact is described on a structure-by-structure level which includes the distinction between labor in industrial and commercial structures or residential population as well as differentiating between those over and under the age of sixty-five. HEC-FIA calculates those who evacuated, keeping track

*3 https://www.hec.usace.army.mil/confluence/fiadocs/fiaum/v.3.1* of how long they were evacuated, and how many people lost their lives. The resulting population displaced or harmed would be able to be aggregated by area, damage category, and occupancy type.

The resulting magnitude of the direct economic should be characterized as a function dependent upon the nature and timing of the event. Based on the above description of direct loss calculations, the magnitude of the loss of workers, buildings, and infrastructure estimated by the direct economic modeling will be determined by the nature of the hazard through utilizing depth, duration, and depth times velocity. These damage driving parameters incorporate the nature and timing of the hydraulic event and can be changed through the hydraulic model to represent structural alternatives throughout the floodplain.

## 2.2 Indirect-Damage Calculations

To evaluate indirect economic impacts HEC-FIA links to a variant of ECAM which is a computable general equilibrium model with separate datasets for each county in the United States. Although this model is specifically set up for data in the United States, the requirement for data outside of the United States can be addressed as well. This section describes the basic concepts underlying the ECAM modeling framework. Some further references are available for the interested reader. While direct economic impact estimation is tied directly to the hydraulic event, the approach described below for indirect economic impacts is tied to the reduction in labor and capital rather than the hydraulic event itself. As discussed above, the reductions in labor and capital are a function of the hydraulic event and represent a condition that is predicated on the nature of the event and how it changes due to alternatives and future conditions.

The indirect economic ramifications are determined mainly by the population living in the area, and by the severity of the direct economic impact. To estimate the complete economic impact of flooding logically and consistently across multiple counties, numerous potential direct impact characteristics are usually boiled down into a few major parameters, which are then inserted into the economic model. Therefore, it typically does not matter whether the flood is a wall of water that destroys everything downstream, or is simply a rising tide, that eventually inundates several buildings, the effect from an indirect economic standpoint is a loss of workers, buildings, and infrastructure that are necessary inputs used to produce goods and services, which are direct outputs from the direct economic calculation.

The approach to indirect impact experiments is often called a "counterfactual experiment", which begins with a recent picture of the study area in focus (the factual). The counterfactual is what the economy would have been in the state of the world was changed based on some hazard or shock. The changes considered in the experiments at hand are reductions to physical (productive) capital and reductions to available labor. This provides a before and after picture of the economy. The changes are usually depicted using a percentage change, which is then converted to a total dollar amount. Please refer to the HEC-FIA user manual for more information.

## 3 HEC-FDA

Hydrologic Engineering Center's (HEC) Flood Damage Reduction Analysis (HEC-FDA)[4] is free standalone software from HEC which is risk-based and employs Monte Carlo simulation to estimate flood damages for multiple scenarios. As such, the model is used to formulate and evaluate flood damage reduction plans. To estimate flood damages, the model first randomly chooses an exceedance value and then relates the value to a discharge. Discharge is subsequently related to stage using a stage-discharge relationship. The model estimates damages to a building or structure due to water surface elevation by subtracting the first floor or ground elevation from the water surface elevation, and then multiplying the value by the structure value. Content value is determined using a content-to-structure value ratio. The model performs a Monte Carlo simulation thousands of times to estimate damages and to account for uncertainty. Estimated damages can be analyzed in many different ways, for example, for a stream, analysis year, damage category, and plan, and results can then be used to evaluate damages over different periods in the context of flood damage reduction.

The capabilities of HEC-FDA are as follows:

- Quantifies the uncertainty in discharge-frequency, stage-discharge, geotechnical levee failure, stage-damage functions
- Incorporates these uncertainties into economic and performance analyses of alternative flood damage reduction plans.
- Evaluate plans by expected annual damage associated with a given analysis year or the equivalent annual damage over the project life of the plan.
- Provides Information on the flood risk performance in the results.
- Provides output tables and selected graphics of information by plan, analysis year, stream, and damage reach for the plan.
- Compares results of the various plans

Please refer to the HEC-FDA user manual for more information.

## 4 Go-Consequence

Go-Consequence[5] is an economic consequence tool developed by the US Army Corps of Engineers (USACE) Risk Management Center (RMC) to support the evaluation of economic risk posed by several natural hazards including flooding. The go-consequence library, developed in Go and available on GitHub, offers an open-source platform for simultaneously running multiple scenarios for evaluating the economic impacts of flooding events. Unlike HEC-FIA, the Go-Consequence tool has no user interface and can be accessed by setting up a remote container in Visual Studio Code to automate model runs for numerous scenarios. The tool uses structures and population

[4] https://www.hec.usace.army.mil/software/hec-fda/

[5] https://github.com/USACE/go-consequences

information, flooding depths, and depth-damage curves to estimate the economic impacts of flooding.

The go-consequence tool categorizes the economic impact of flooding into two major types of losses: Direct, and Indirect loss. The direct loss includes damage to building structures, damage to contents, and damage to vehicles. The indirect loss includes a reduction in the labor workforce due to flooding, and the monetary loss in production of goods and services. A detailed explanation of the direct and indirect loss calculations in the go-consequence tool is discussed below.

### 4.1 Direct-Loss Calculations

The approach for calculating direct losses in the Go-Consequence tool is similar to the HEC-FIA model discussed in Section 2 based on the guidelines established by ER 1105-2-100 and EGM 01-03. The estimated direct losses include damage to structures (such as load bearings, architectural elements, and electrical components), contents (such as furniture and supplies), and vehicles. The tool uses the depth-damage curves provided by the USACE for both residential and non-residential building types to estimate direct losses from a flood event.

The depth of flooding at each structure is extracted from the HEC-RAS model. Then, the percentage of damage corresponding to the flood depth above the finished floor elevation of each structure is determined using the depth-damage curve.

The National Structures Inventory (NSI) dataset is used to obtain the values of structures, contents, and vehicles (in US dollars). The percentage of damage from the depth-damage function, specific to the loss and occupancy type for each structure, is multiplied by the actual value to estimate the economic loss (in US dollars) from a flooding event.

### 4.2 Indirect-Loss Calculations

The go-consequence tool uses the Economic Consequences Assessment Model (ECAM) to estimate the indirect losses due to a flooding event. The indirect losses include loss of capital (US dollars), and loss of labor due to displacement of employed individuals or their removal from workforce (number of persons).

The tool uses computable general equilibrium (CGE) modeling to evaluate the effects of an external shock (such as floods) to the economy. The severity of the shock leading to a constraint on production is determined based on the direct loss estimates. The go-consequence tool calculates the capital and labor loss ratios based on the damage to non-residential structures estimated while calculating direct losses, which are then used as inputs for the ECAM model. The post-shock economy is then rebalanced through optimization, and a new equilibrium is reached that incorporates the cascading effects of the shock. The resulting change in production and employment is reported in the model output.

# Appendix A3: Go-Consequence Detailed Loss Tables

# Appendix A3: Go Consequence Detailed Loss Tables

The total estimated economic consequences of the pluvial flood hazards were estimated using the flood depth rasters for each scenario obtained from HEC-RAS and the Go-Consequence tool. The total direct losses (in $ million) to structures, contents, and vehicles estimated for the baseline, Subsidence without future development, and Subsidence with future development scenarios are shown in **Table 1** for the 10% AEP (10-year) event and in **Table 2** for the 1% AEP (100-year) event. The additional direct losses due to subsidence without future development and subsidence with future development were estimated by subtracting the total direct losses for these scenarios from the baseline.

**Table 1: Total direct loss for Baseline, Subsidence without future development, and Subsidence with future development for a 10-year pluvial simulation**

| Type of Loss | Total Direct Loss (in million $) | | |
|---|---|---|---|
| | Baseline | Subsidence without future development | Subsidence with future development |
| Structure | 194.9 | 200.6 | 252 |
| Contents | 188.3 | 193.8 | 228 |
| Vehicles | 35.3 | 35.9 | 42 |
| **Total Direct Loss** | **418.5** | **430.3** | **522** |

**Table 2: Total direct loss for Baseline, Subsidence without future development, and Subsidence with future development for a 100-year pluvial simulation**

| Type of Loss | Total Direct Loss (in million $) | | |
|---|---|---|---|
| | Baseline | Subsidence without future development | Subsidence with future development |
| Structure | 847.9 | 863 | 1072 |
| Contents | 711.1 | 728.6 | 873 |
| Vehicles | 103.5 | 105.8 | 126.2 |
| **Total Direct Loss** | **1662.5** | **1697.4** | **2071.2** |

The indirect economic consequences estimated using Go-Consequence include the loss in labor workforce and the loss in GDP. These losses are calculated based on the USACE's Economic Consequences Assessment Model (ECAM) by the Go-Consequence tool. The total losses in the labor workforce in the baseline, Subsidence without future development, and Subsidence with future development are shown in **Table 3**, and the total losses in GDP are shown in **Table 4**.

**Table 3: Decrease in labor workforce (person) for the Baseline, Subsidence without future development, and Subsidence with future development scenarios**

| Model | Event | Baseline | Subsidence without future development | Subsidence with future development |
|---|---|---|---|---|
| **Pluvial** | **10-year** | 10,740 | 11,004 | 12,399 |
| | **100-year** | 22,329 | 22,715 | 24,831 |

**Table 4: Decrease in GDP ($ million) for the Baseline, Subsidence without future development and Subsidence with future development scenarios**

| Model | Event | Baseline | Subsidence without future development | Subsidence with future development |
|---|---|---|---|---|
| **Pluvial** | **10-year** | 164.4 | 168.3 | 190 |
| | **100-year** | 400.0 | 408.0 | 457.0 |

The total indirect losses shown above are the total sum of indirect losses reported in each individual sector by the ECAM model. While most of the sectors show a decrease in labor workforce and GDP due to a flooding event, a few sectors such as Electric power generation and supply, show an increase in both labor workforce and GDP due to the heightened demand for power restoration and infrastructure repair. The losses in labor for each sector are shown in **Table 5** for 10% AEP (10-year) event and **Table 6** for 1% AEP (100-year) event. Similarly, the individual sector wise losses in GDP are shown in **Table 7** for 10% AEP (10-year) event and **Table 8** for 1% AEP (100-year) event.

**Table 5: Decrease in labor (persons) by sector for 10-year pluvial simulation**

| Sector | Decrease in Labor (persons) | | |
|---|---|---|---|
| | Baseline | Subsidence without future development | Subsidence with Future Development |
| Agriculture | 107 | 108 | 115 |
| All other services | 4,720 | 4,838 | 5,477 |
| Chemical processing and refining | 20 | 21 | 26 |
| Construction | 418 | 428 | 484 |
| Electronic instruments | 261 | 268 | 303 |
| Food processing | 75 | 77 | 84 |
| Forestry | 12 | 13 | 15 |
| Furniture manufacturing | 21 | 22 | 24 |
| General manufacturing | 1,761 | 1,805 | 2,035 |
| Information processing and publication | 59 | 61 | 68 |
| Livestock and ranching | 27 | 28 | 27 |
| Minerals mining | 26 | 27 | 31 |
| Natural gas distribution | 5 | 5 | 6 |
| Non-government associations | 322 | 330 | 371 |
| Oil gas and coal Extraction | 49 | 50 | 57 |
| Paper printing and publishing | 108 | 110 | 126 |
| Post and communications | 6 | 6 | 6 |
| Recreation activities | 604 | 618 | 689 |
| State and federal government | 1,017 | 1,042 | 1,185 |
| Textiles and wearing apparel | 21 | 21 | 22 |
| Transportation equipment manufacturing | 50 | 51 | 57 |
| Transportation services | 517 | 530 | 595 |
| Water sewage and other systems | 17 | 17 | 21 |
| Wholesale and retail distribution | 473 | 483 | 524 |
| Wood manufacturing | 44 | 45 | 51 |
| **Total** | **10,740** | **11,004** | **12,399** |

**Table 6: Decrease in labor (persons) by sector for 100-year pluvial simulation**

| Sector | Decrease in Labor (persons) | | |
|---|---|---|---|
| | Baseline | Subsidence without future development | Subsidence with Future Development |
| Agriculture | 227 | 229 | 243 |
| All other services | 9,946 | 10,121 | 11,114 |
| Chemical processing and refining | 96 | 99 | 129 |
| Construction | 875 | 891 | 977 |
| Electronic instruments | 566 | 577 | 640 |
| Food processing | 142 | 144 | 154 |
| Forestry | 30 | 30 | 34 |
| Furniture manufacturing | 37 | 37 | 39 |
| General manufacturing | 3,785 | 3,852 | 4,242 |
| Information processing and publication | 118 | 120 | 130 |
| Livestock and ranching | 61 | 61 | 54 |
| Minerals mining | 70 | 72 | 84 |
| Natural gas distribution | 12 | 12 | 14 |
| Non-government associations | 644 | 654 | 709 |
| Oil gas and coal Extraction | 109 | 110 | 118 |
| Paper printing and publishing | 239 | 243 | 269 |
| Post and communications | 4 | 4 | 2 |
| Recreation activities | 1,123 | 1,142 | 1,217 |
| State and federal government | 2,219 | 2,261 | 2,499 |
| Textiles and wearing apparel | 32 | 32 | 31 |
| Transportation equipment manufacturing | 109 | 111 | 121 |
| Transportation services | 1,061 | 1,079 | 1,175 |
| Water sewage and other systems | 42 | 43 | 48 |
| Wholesale and retail distribution | 679 | 687 | 671 |
| Wood manufacturing | 103 | 104 | 117 |
| **Total** | **22,329** | **22,715** | **24,831** |

**Table 7: Decrease in Gross Domestic Product (GDP, in $ million) by sector for 10-year pluvial simulation**

| Sector | Decrease in GDP ($ million) | | |
|---|---|---|---|
| | Baseline | Subsidence without future development | Subsidence with Future Development |
| Agriculture | 10.6 | 10.8 | 11.7 |
| All other services | 4.3 | 4.4 | 4.9 |
| Construction | 0.7 | 0.7 | 0.8 |
| Electronic instruments | 12.0 | 12.3 | 14.1 |
| Food processing | 5.4 | 5.5 | 6.2 |
| Forestry | 16.6 | 17.0 | 19.3 |
| Furniture manufacturing | 20.6 | 21.1 | 23.8 |
| General manufacturing | 15.1 | 15.5 | 17.4 |
| Information processing and publication | 2.8 | 2.8 | 3.1 |
| Inventory valuation adjustment | 4.2 | 4.3 | 4.8 |
| Minerals mining | 6.5 | 6.7 | 7.7 |
| Natural gas distribution | 1.4 | 1.4 | 2.0 |
| Non-government associations | 5.9 | 6.0 | 6.7 |
| Paper printing and publishing | 17.6 | 18.1 | 20.5 |
| Recreation activities | 1.1 | 1.1 | 1.2 |
| State and federal government | 2.8 | 2.8 | 3.2 |
| Transportation equipment manufacturing | 10.0 | 10.2 | 11.3 |
| Transportation services | 5.6 | 5.7 | 6.4 |
| Water sewage and other systems | 3.1 | 3.2 | 3.6 |
| Wood manufacturing | 18.2 | 18.7 | 21.2 |
| **Total** | **164.4** | **168.3** | **189.7** |

**Table 8: Decrease in Gross Domestic Product (GDP, in $ million) by sector for 100-year pluvial simulation**

| Sector | Decrease in GDP ($ million) | | |
|---|---|---|---|
| | Baseline | Subsidence without future development | Subsidence with Future Development |
| Agriculture | 24.4 | 24.7 | 26.9 |
| All other services | 9.8 | 10.0 | 11.0 |
| Construction | 1.6 | 1.6 | 1.8 |
| Electronic instruments | 29.4 | 30.0 | 34.1 |
| Food processing | 11.8 | 12.0 | 13.3 |
| Forestry | 41.4 | 42.2 | 47.4 |
| Furniture manufacturing | 48.9 | 49.9 | 55.5 |
| General manufacturing | 36.1 | 36.8 | 41.2 |
| Information processing and publication | 6.4 | 6.5 | 7.2 |
| Inventory valuation adjustment | 9.6 | 9.8 | 10.9 |
| Minerals mining | 18.9 | 19.3 | 22.4 |
| Natural gas distribution | 4.7 | 4.9 | 6.2 |
| Non-government associations | 13.1 | 13.3 | 14.7 |
| Paper printing and publishing | 43.0 | 43.8 | 49.0 |
| Recreation activities | 1.9 | 1.9 | 2.0 |
| State and federal government | 6.4 | 6.5 | 7.2 |
| Transportation equipment manufacturing | 25.7 | 26.2 | 29.6 |
| Transportation services | 13.3 | 13.6 | 15.1 |
| Water sewage and other systems | 7.5 | 7.6 | 8.5 |
| Wood manufacturing | 46.0 | 46.9 | 53.1 |
| **Total** | **400.0** | **407.6** | **457.2** |

# Appendix A4: Highways Reconstruction Cost - Highway Investment Analysis Methodology-2014

U.S. Department of Transportation
**Federal Highway Administration**
1200 New Jersey Avenue, SE
Washington, DC 20590
202-366-4000



# Appendix A: Highway Investment Analysis Methodology



Investments in highway resurfacing and reconstruction and in highway and bridge capacity expansion are modeled using the Highway Economic Requirements System (HERS), which has been used since the publication of the 1995 C&P Report. This appendix describes the basic HERS methodology and approach, and details the model features that have changed significantly from those used for the 2015 C&P Report.

# Highway Economic Requirements System

HERS begins the investment analysis process by evaluating the current state of the highway system using information on pavements, geometry, traffic volumes, vehicle mix, and other characteristics from the Highway Performance Monitoring System (HPMS) sample dataset. Using section-specific traffic growth projections, HERS forecasts future conditions and performance across several funding periods. As used in this report, the future analysis covers four consecutive 5-year periods. At the end of each period, the model checks for deficiencies in eight highway section characteristics: pavement condition, surface type, volume/service flow (V/SF) ratio (a measure of congestion), lane width, right shoulder width, shoulder type, horizontal alignment (curves), and vertical alignment (grades).

After HERS determines that a section's pavement or capacity is deficient, it identifies potential improvements to correct some or all of the section's deficient characteristics. The HERS model evaluates seven kinds of improvements: resurfacing, resurfacing with shoulder improvements, resurfacing with widened lanes (i.e., minor widening), resurfacing with added lanes (i.e., major widening), reconstruction, reconstruction with widened lanes, and reconstruction with added lanes. For reconstruction projects, the model allows for upgrades of low-grade surface types when warranted by sufficient traffic volumes. For improvements that add travel lanes, HERS further distinguishes between two capacity additions: those that can be made at "normal cost" and those on sections where obstacles to widening are present, making capacity additions feasible only at "high cost." HERS might also evaluate alignment adjustments to improve curves, grades, or both.

When evaluating which potential improvement, if any, should be implemented on a particular highway section, HERS employs incremental benefit-cost analysis. This analysis compares the benefits and costs of a candidate improvement with those of a less aggressive alternative—for example, reconstructing and adding lanes to a section could be compared with reconstruction alone. HERS defines benefits as reductions in direct highway user costs, agency costs, and societal costs. Highway user benefits include reductions in travel time costs, crash costs, and vehicle operating costs (e.g., fuel, oil, and maintenance costs); agency benefits include reduced routine maintenance costs (plus the residual value of projects with longer expected service lives than the alternative); societal benefits include reduced vehicle emissions. Increases in any of these costs resulting from a highway improvement (such as higher emissions rates at high speeds or the increased delay associated with a work zone) would be factored into the analysis as a negative benefit ("disbenefit").

Dividing these improvement benefits by the capital costs associated with implementing the improvement results in a benefit-cost ratio (BCR) that is used to rank potential projects on different highway sections. HERS implements improvements in order of BCR, with the improvement having the highest BCR implemented first. Thus, as each additional project is implemented, the marginal BCR declines, resulting in a decline in the average BCR for all implemented projects. However, total net benefits continue to increase as additional projects are implemented, until the point at which the marginal BCR falls below 1.0 (i.e., costs exceed benefits). Investment beyond this point is not economically justified because a decline in total net benefits would result.

Because HERS analyzes each highway section independently rather than the entire transportation system, it cannot fully evaluate the network effects of individual highway improvements. Although efforts have been made to account indirectly for some network effects, HERS is fundamentally reliant on its primary data source—the national sample of independent highway sections contained in HPMS. Fully recognizing all network effects would require developing significant new data sources and analytical techniques.

# HERS Improvement Costs

For the 2004 C&P Report, significant changes were made to the structure of the HERS improvement cost matrix, the assumed unit costs in that matrix, and the manner in which those values were applied. The improved cost updates reflected in the 2004 C&P Report were based on highway project data from six States. The 2004 update disaggregated the improvement cost values in urban areas by functional class and by urbanized area size. Three population groupings were used: small urban (populations of 5,000 to 49,999), small urbanized (populations of 50,000 to 200,000), and large urbanized (populations of more than 200,000).

For the 2006 C&P Report, additional project cost data were collected for large urbanized areas, rural mountainous regions, and high-cost capacity improvements. These data were used to update the HERS improvement cost matrix, which was also modified to include a new category for major urbanized areas with populations of more than 1 million. The HERS improvement cost matrix was adjusted further for the 2008 C&P Report based on additional analysis of the data previously collected.

*Exhibit A-1* identifies the costs per lane mile assumed by HERS for different types of capital improvements. For rural areas, separate cost values are applied by terrain type and functional class, while costs are broken down for urban areas by population area size and type of highway. These costs are intended to reflect the typical values for these types of projects in 2014, and thus do not reflect the large variation in cost among projects of the same type, even in a given year. Such variation, which is evident in the project-level data on which these typical values are based, is attributable to several location-specific factors. For example, the costs assumed for highway widening projects are predicated on each section's having several bridges typical for the section's length, but in reality some sections will have more bridges than other sections of equal length, which adds to costs. Among other factors that could make costs unusually high are complicated interchanges, major environmental issues, and other extreme engineering issues.

The values shown in *Exhibit A-1* for adding a lane at "normal cost" reflect costs of projects for which sufficient right-of-way is available or readily obtained to accommodate additional lanes. The values for adding lane equivalents at "high cost" are intended to reflect situations in which conventional widening is infeasible and alternative approaches are required to add capacity to a given corridor. Such alternatives include the construction of parallel facilities, double decking, tunneling, or the purchase of extremely expensive right-of-way. HERS models these lane equivalents as though they are part of existing highways, but some of this capacity could be from new highways or other modes of transportation.

Exhibit A-1: Typical Costs per Lane Mile Assumed in HERS by Type of Improvement

| Category | Typical Costs (Thousands of 2014 Dollars per Lane Mile) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Reconstruct and Widen Lane | Reconstruct Existing Lane | Resurface and Widen Lane | Resurface Existing Lane | Improve Shoulder | Add Lane, Normal Cost | Add Lane, Equivalent High Cost | New Alignment, Normal | New Alignment, High |
| **Rural** | | | | | | | | | |
| **Interstate** | | | | | | | | | |
| **Flat** | $1,993 | $1,302 | $1,128 | $462 | $86 | $2,561 | $3,551 | $3,551 | $3,551 |
| **Rolling** | $2,234 | $1,335 | $1,298 | $492 | $142 | $2,777 | $4,493 | $4,493 | $4,493 |
| **Mountainous** | $4,235 | $2,924 | $2,151 | $728 | $297 | $8,646 | $10,121 | $10,121 | $10,121 |
| **Other Principal Arterial** | | | | | | | | | |
| **Flat** | $1,556 | $1,042 | $941 | $371 | $57 | $2,052 | $2,937 | $2,937 | $2,937 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Rolling** | $1,757 | $1,071 | $1,069 | $413 | $96 | $2,197 | $3,546 | $3,546 | $3,546 |
| **Mountainous** | $3,412 | $2,411 | $2,072 | $583 | $126 | $7,756 | $8,931 | $8,931 | $8,931 |
| **Minor Arterial** | | | | | | | | | |
| **Flat** | $1,423 | $915 | $877 | $329 | $54 | $1,865 | $2,618 | $2,618 | $2,618 |
| **Rolling** | $1,718 | $1,013 | $1,091 | $354 | $99 | $2,138 | $3,372 | $3,372 | $3,372 |
| **Mountainous** | $2,854 | $1,871 | $2,072 | $486 | $224 | $6,547 | $7,857 | $7,857 | $7,857 |
| **Major Collector** | | | | | | | | | |
| **Flat** | $1,499 | $969 | $905 | $336 | $69 | $1,937 | $2,617 | $2,617 | $2,617 |
| **Rolling** | $1,640 | $985 | $1,018 | $356 | $93 | $1,979 | $3,220 | $3,220 | $3,220 |
| **Mountainous** | $2,489 | $1,541 | $1,482 | $486 | $143 | $4,191 | $5,474 | $5,474 | $5,474 |
| **Urban** | | | | | | | | | |
| **Freeway/Expressway/Interstate** | | | | | | | | | |
| **Small Urban** | $3,356 | $2,324 | $2,645 | $564 | $103 | $4,211 | $13,784 | $5,675 | $19,373 |
| **Small Urbanized** | $3,608 | $2,344 | $2,736 | $667 | $137 | $4,601 | $15,117 | $7,649 | $26,114 |
| **Large Urbanized** | $5,754 | $3,837 | $4,238 | $895 | $517 | $7,700 | $25,826 | $11,220 | $38,303 |
| **Major Urbanized** | $11,509 | $7,675 | $8,224 | $1,483 | $1,034 | $15,400 | $64,219 | $22,440 | $85,845 |
| **Other Principal Arterial** | | | | | | | | | |
| **Small Urban** | $2,925 | $1,974 | $2,420 | $473 | $105 | $3,579 | $11,691 | $4,474 | $15,270 |
| **Small Urbanized** | $3,130 | $1,998 | $2,530 | $559 | $140 | $3,878 | $12,715 | $5,520 | $18,841 |
| **Large Urbanized** | $4,471 | $2,929 | $3,702 | $703 | $451 | $5,675 | $18,961 | $7,577 | $25,864 |
| **Major Urbanized** | $8,942 | $5,857 | $7,405 | $1,135 | $902 | $11,350 | $43,997 | $15,154 | $65,597 |
| **Minor Arterial/Collector** | | | | | | | | | |
| **Small Urban** | $2,155 | $1,491 | $1,831 | $346 | $76 | $2,643 | $8,562 | $3,228 | $11,019 |
| **Small Urbanized** | $2,258 | $1,508 | $1,848 | $394 | $93 | $2,785 | $9,050 | $3,961 | $13,520 |
| **Large Urbanized** | $3,040 | $2,017 | $2,527 | $483 | $253 | $3,861 | $12,820 | $5,155 | $17,594 |
| **Major Urbanized** | $6,080 | $4,033 | $3,822 | $804 | $507 | $7,722 | $43,997 | $10,310 | $54,445 |

Source: Highway Economic Requirements System.

# Pavement Condition Modeling

The version of HERS used for this report incorporates a revision to the modeled relationship between pavement roughness and average speed. In the previous model, pavement roughness causes drivers to slow down only when it reaches a level of roughness found extremely rarely on U.S. highways (International Roughness Index (IRI) > ~380 in/mi). This relationship, taken from the World Bank's HDM-4 model, was based mainly on studies from low-income countries that are dated and for which documentation is unavailable in some cases. Yu and Lu (2014) observed that relevant data on the roughness-speed relationship that could be generalized to the United States is scant[1]. In their own study using data from California highways, they found that the average free-flow speed decreases 0.0083 mph with every 1 in/mi increase in roughness. In incorporating this finding into HERS, it has been assumed that pavement roughness has no impact on speed at roughness levels below IRI values of 157 in/mi. This threshold value is taken from the economic evaluation manual of the New Zealand Transport Agency, which advises users to assume zero impacts of pavement roughness on vehicle running costs and rider comfort for roughness levels below 2.5 m/km (=157 in/mi).[2]

## Valuation of Travel Time Savings

As indicated in Appendix A of the 2015 C&P Report, the values of travel time used in HERS were comprehensively updated to support the economic analyses of alternative highway investment levels presented in the main chapters of that report. The primary objectives of that update were to:

- Identify reliable, recent sources of information on major components of the values of travel time, including hourly values of vehicle drivers' and other occupants' time, vehicle occupancy, and the distribution of vehicle use by travel purpose.
- Expand HERS' previous estimates of the hourly value and amount of work-related business travel using light-duty passenger vehicles (automobiles and light trucks), which previously included only work-related travel in household vehicles, including corporate and government fleets, rental vehicles, emergency vehicles (police and fire), and taxi service.
- Distinguish between hourly values of travel time for buses and those for three- or four-axle single-unit trucks, which were previously combined into a single vehicle class in HERS.
- Ensure that the values of travel time for vehicle occupants used in HERS were consistent with DOT's official guidance on valuing travel time savings.

No important sources of new information on these issues since the previous C&P Report could be identified, so the adjustments to the values of travel time reported in this edition were limited to minor changes and technical corrections to the previous values. In addition, the values used in the current (23rd) edition of the C&P Report were converted from constant 2012 dollars, which were used in the previous report, to constant 2014 dollars, to make them consistent with other economic values used in the analyses described previously in this report.

Changes to key inputs used to construct the values of time reported in *Exhibit A-2*, corrections to the calculations used to construct the table entries, and their effects on the entries in the table include the following:

- A small fraction of use of rental cars (HERS VT1 and VT2) and light-duty trucks (VT3) was reassigned from personal to business travel to reflect households' use of rental vehicles. Previously, all household use of rental vehicles was assumed to be for personal travel; this revision assumes instead that household use of rental vehicles is divided between business and personal travel in the same proportion as is use of household-owned vehicles. Because business travel is assumed to be valued at a higher hourly rate than personal travel, this change slightly increases the average values of travel time per vehicle hour for HERS VT1, VT2, and VT3.
- Travel using light-duty trucks—including vans, pickups, and SUVs—owned by businesses but stored at the private residences of business owners or employees, as reported in the 2002 Vehicle Inventory and Use Survey, was accounted for separately. Use of these vehicles was previously assumed to be included in travel by household members reported in 2009 National Household Travel Survey (NHTS), but the extent to which this assumption was correct was unknown. The model has been updated to allow for the presence of additional passengers when

these vehicles are used for business travel. This change increases the estimated average occupancy of HERS VT3 (4-tire trucks) slightly, which increases the value of travel time per vehicle hour for HERS VT3 slightly.

- Business travel using urban public transit and intercity bus services, as reported in the 2009 NHTS, was accounted for and valued separately. Previously, all passengers traveling on public transit and intercity buses were assumed to be engaged in personal travel. Because business travel is assumed to be valued at a higher hourly rate than personal travel, this change slightly increases the average values of travel time per vehicle hour for HERS VT5a (3-4 Axle Single-Unit Trucks) and 5b (Buses).

*Exhibit A-2* shows components of the hourly value of travel time for each HERS vehicle type, reports the overall average values of time per vehicle hour in 2014 dollars, and compares these with the 2012 values used in the 2015 C&P Report.

Exhibit A-2: Estimated 2014 Values of Travel Time by Vehicle Type

| 2014 Travel Time Cost Element | VT1 Small Auto | VT2 Medium Auto | VT3 4-Tire Truck | VT4 6-Tire Truck | VT5a 3–4 Axle Truck | VT5b Bus | VT6 4-Axle Combination | VT7 5+-Axle Combination |
|---|---|---|---|---|---|---|---|---|
| **Business Travel** | | | | | | | | |
| **Value of Time per Person Hour** | $32.30 | $31.74 | $30.90 | $27.40 | $28.13 | $25.73 | $28.53 | $28.53 |
| **Average Vehicle Occupancy** | 1.33 | 1.33 | 1.36 | 1.38 | 1.14 | 1.50 | 1.02 | 1.02 |
| **Total Hourly Value of Occupants' Time** | $42.98 | $42.11 | $42.17 | $37.79 | $32.18 | $38.59 | $28.99 | $28.99 |
| **Vehicle Capital Cost per Vehicle** | N/A | N/A | N/A | $12.38 | $19.71 | $7.80 | $15.62 | $12.95 |
| **Inventory Value of Cargo** | N/A | N/A | N/A | N/A | N/A | N/A | $0.10 | $0.17 |
| **Value of Time per Vehicle Hour** | $42.98 | $42.11 | $42.17 | $50.17 | $51.89 | $46.40 | $44.72 | $42.11 |
| **Personal Travel** | | | | | | | | |
| **Value of Time per Person Hour** | $12.53 | $12.53 | $12.53 | N/A | N/A | $12.53 | N/A | N/A |
| **Average Vehicle Occupancy** | 1.57 | 1.76 | 1.64 | N/A | N/A | 12.64 | N/A | N/A |
| **Value of Time per Vehicle Hour** | $19.74 | $22.00 | $20.55 | N/A | N/A | $158.44 | N/A | N/A |
| **Share of Vehicle Use for Personal Travel** | 88.96% | 90.32% | 78.14% | N/A | N/A | 89.90% | N/A | N/A |
| **Average Values per Vehicle Hour** | | | | | | | | |
| **2014** | $22.31 | $23.95 | $25.27 | $50.17 | $51.89 | $204.84 | $44.72 | $42.11 |
| **2012 (from 2015 C&P Report)** | $21.43 | $23.06 | $24.58 | $53.15 | $54.34 | $180.51 | $44.37 | $41.75 |

Source: DOT Revised Guidance on the Value of Travel Time in Economic Analysis (Revision 2 – 2015 Update) and internal DOT estimates.

# Highway Operational Strategies

One of the key modifications to HERS, introduced in the 2004 C&P Report, was the ability to consider the impact of highway management and operational strategies, including Intelligent Transportation Systems (ITS), on highway system performance. This feature has been substantially updated in this report following review of literature on ITS impacts. Current and future investments in operations are modeled outside of HERS, but the impacts of these deployments affect the model's internal calculations, and thus also affect the capital improvements considered and implemented in HERS.

Among the many operational strategies available to highway agencies, HERS considers only certain types based on the availability of suitable data and empirical impact relationships. These strategies have been revised from the 2015 C&P Report after a literature review to update the impacts of operations strategies and to remove others. The 2015 C&P Report operations strategies that have changes in the method of application are:

- Ramp Metering is now modeled as an 8-percent increase in freeway base capacity; this value feeds directly into the freeway delay function. Compared to the previous method, the positive impact of ramp meters is now more modest.
- Integrated Corridor Management is now modeled as a 25-percent decrease in freeway base delay. This delay decrease is higher than the factor previously used, resulting in larger delay decrease.
- Traveler information and emergency vehicle signal preemption were removed from consideration due to questionable impact relationships from the literature.

The impacts of all other operations strategies remain the same. *Exhibit A-3* details the operational strategies deployed and the estimates of their impacts, which are based primarily on a review of the DOT ITS Benefits Database (https://www.itsbenefits.its.dot.gov/its/benecost.nsf/ByLink/BenefitsAbout).

Exhibit A-3: Impacts of Operations Strategies in HERS

| Operations Strategy | Impact Category | Impact |
|---|---|---|
| **Arterial Management** | | |
| **Adaptive Signal Control** | **Delay** | -25% |
| | **Travel time** | -12% |
| **Automated Enforcement; Speed and Red Light Cameras** | Total Crashes | -15% |
| **Signal Timing Coordination** | **Delay** | -20% |
| | **Travel time** | -10% |
| **Freeway Management** | | |
| **Ramp Metering** | **Mainline Capacity** | 6% |
| | **Total Crashes** | -30% |
| **Road Weather Systems** | | |
| **Anti-icing Technology** | Total Crashes | -70% |
| **RWIS and Other Weather Information** | Total Crashes | -15% |
| **Incident Management (Freeways Only)** | | |
| **Incident Detection with Service Patrols** | Incident Duration | -55% |
| **Active Transportation and Demand Management Systems** | | |
| **Dynamic Ramp Metering** | Capacity | 8% |

| **Integrated Corridor Management Systems** | | |
|---|---|---|
| **Smart Corridors Solutions (ASC, TSP, HOT/HOV Lanes, Ramp Metering)** | **Travel Time** | -15% |
| | **Total Crashes** | -20% |
| | **Total Delay** | -25% |

Source: Highway Economic Requirements System.

# Examples of HERS Impact Estimates

HERS calculates the impacts of investments on speeds, operating costs, crash costs, and emissions. These calculations use a set of lookup tables and equations that vary by vehicle type and other variables, and are generally drawn from other published sources such as the Highway Capacity Manual and Highway Safety Manual. More detailed information is available in the HERS Technical Report, which is currently being updated and will be made available online at (https://www.fhwa.dot.gov/policy/otps/).

## Vehicle Operating Costs

*Exhibit A-4* demonstrates the effects of pavement roughness on vehicle operating costs in the HERS model. Vehicle operating costs include fuel, oil, tires, maintenance and repair, and vehicle depreciation. For simplicity, figures are shown for only two vehicle types (small automobile and combination truck) over a range of speeds (20-70 mph), for three different pavement conditions (IRI 50, 95, 170) on level, straight pavement. As discussed in Chapter 6, ride quality changes from “good” to “fair” as IRI rises above 95 and then to “poor” for IRI above 170. HERS currently resets the IRI to 50 following a full reconstruction project.)

As *Exhibit A-4* shows, improvements to pavement condition reduce vehicle operating costs but the size of the impact varies. For example, for a small automobile traveling at 50 miles per hour on a level, straight road, estimated operating cost is 17 percent lower at an IRI of 50 rather than 170 (per-VMT cost of $0.291 vs. $0.351). For a combination truck under the same conditions, the estimated reduction in operating costs would be 16 percent. (Note that these results would differ for roads with curves or grades.)

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Exhibit A-4: Example of Vehicle Operating Costs per VMT

| International Roughness Index (IRI) | Vehicle Speed (miles per hour) | | | | | |
|---|---|---|---|---|---|---|
| | 20 | 30 | 40 | 50 | 60 | 70 |
| **Small Automobiles** | | | | | | |
| **50** | $0.366 | $0.305 | $0.284 | $0.291 | $0.320 | $0.365 |
| **95** | $0.383 | $0.322 | $0.302 | $0.311 | $0.341 | $0.390 |
| **170** | $0.417 | $0.357 | $0.339 | $0.351 | $0.387 | $0.442 |
| **Combination Trucks** | | | | | | |
| **50** | $1.220 | $0.989 | $0.884 | $0.888 | $0.990 | $1.175 |
| **95** | $1.258 | $1.029 | $0.929 | $0.940 | $1.050 | $1.244 |
| **170** | $1.341 | $1.119 | $1.030 | $1.055 | $1.184 | $1.401 |

Source: Highway Economic Requirements System.

## Emissions

Emissions are estimated using emission rates per VMT for three vehicle classes (four-tire autos and trucks; single-unit trucks; and combination trucks) and four highway types (rural highway with unrestricted access, rural highway with restricted access, urban highway with unrestricted access, and urban highway with restricted access). Highway improvement projects are modeled as affecting emissions through their influence on travel volumes and speeds. Emission costs are then monetized using data from EPA's MOVES model.

*Exhibit A-5* provides an example of HERS' estimates of air pollution damage costs. It shows average air pollution costs per VMT at 5 mph intervals for each of HERS' three vehicle classes operating on rural highway sections with restricted access. The figures are an overall total for four types of emissions: CO, $SO_X$, $NO_X$, and PM. As shown, emission costs per VMT vary by vehicle type and speed but are substantially higher when vehicles are traveling at low speeds, such as during extreme congestion. For example, for four-tire vehicles, a decrease in speed from the 13-17 mph range to 3-7 mph increases the estimated emission cost by 91 percent (per VMT, from $0.0167 to $0.0319). For a combination truck making the same change in operating speeds, the increase in emission cost would be 70 percent. At any speed, the emissions cost per VMT is substantially higher for single-unit trucks than for four-tire vehicles, and still higher for combination trucks.

Exhibit A-5: Example of Emission Damage Costs ($ per Vehicle-Mile)

| Speed | Four-Tire Vehicles | Single-Unit Trucks | Combination Trucks |
|---|---|---|---|
| < 3 | $0.0515 | $1.0493 | $2.4214 |
| 3—7 | $0.0319 | $0.5331 | $1.2262 |
| 8—12 | $0.0214 | $0.2958 | $0.7699 |
| 13—17 | $0.0167 | $0.2271 | $0.7215 |
| 18—22 | $0.0140 | $0.1924 | $0.6659 |
| 23—27 | $0.0135 | $0.1693 | $0.6262 |
| 28—32 | $0.0139 | $0.1605 | $0.6098 |
| 33—37 | $0.0156 | $0.1437 | $0.4813 |
| 38—42 | $0.0169 | $0.1372 | $0.4603 |
| 43—47 | $0.0177 | $0.1316 | $0.4438 |
| 48—52 | $0.0177 | $0.1257 | $0.4045 |
| 53—57 | $0.0169 | $0.1201 | $0.3580 |
| 58—62 | $0.0164 | $0.1119 | $0.3385 |
| 63—67 | $0.0166 | $0.1086 | $0.3528 |
| 68—72 | $0.0172 | $0.1060 | $0.3640 |
| >= 73 | $0.0183 | $0.1020 | $0.3527 |

Source: Highway Economic Requirements System.

## Safety

Crash rates are estimated in HERS using a set of empirically derived equations for six different types of roads: urban/rural freeways, urban/rural multi-lane roads, and urban/rural two-lane roads. Improvement projects modeled in HERS can affect estimated crashes through their influence on traffic volumes and other crash model parameters, such as grade, curvature, and the presence and dimensions of shoulders and medians.

*Exhibit A-6* shows the calculations for rural multi-lane roads, which are based on a modified version of an equation developed by Wang, Hughes, and Stewart. (Jun Wang, Warren Hughes and Richard Stewart, *Safety Effects of Cross-Section Design of Rural Four-Lane Highways*, FHWA Report FHWA-RD-98-071, May 1998, Equation 6.)

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Exhibit A-6: Safety Equation for Rural Multi-Lane Roads

$$\mathbf{CRASH = CRC \times AADT^{0.073} \times exp(0.131 \times RHRRML - 0.151 \times AC + 0.034 \times DDRML + 0.078 \times INTSPM - 0.572 \times RPA - 0.094 \times SHLDW - 0.003 \times MEDW + 0.429 \times PDEVEL)}$$

**where:**

| | |
|---|---|
| **CRASH** | crash rate per 100 million VMT |
| **AADT** | annual average daily traffic |
| **CRC** | crash rate coefficient for rural multilane roads (=165.5 in this case) |
| **RHRRML** | roadside hazard rating for rural multilane roads (=2.45) |
| **AC** | 1 for sections with (full or partial) access control, 0 for other sections |
| **DDRML** | driveway density (per mile) for rural multilane roads (0.94 used for the 23rd C&P Report) |
| **INTSPM** | intersections per mile (maximum =10) |
| **RPA** | 1 for rural principal arterials and rural Interstate, 0 for lower functional systems |
| **SHLDW** | right shoulder width, in feet (maximum = 12 feet) |
| **MEDW** | 50 if positive barrier median, median width, in feet, otherwise (maximum = 50) |
| **PDEVEL** | probability that road is in area of dense development (=31% for undivided multi-lane and 9% for divided multi-lane) |

Source: Highway Economic Requirements System.

# Unquantified Costs and Benefits

## Planning and Miscellaneous Agency Costs

The HERS model omits the costs that highway projects entail in public consultation and outreach. Also omitted are possible effects of highway projects on certain types of agency costs, such as those for overhead and highway law enforcement and safety; these effects defy quantitative generalizations, being quite context-specific. Even the direction of these effects could vary. For example, adding capacity to some highway corridors could reduce the incidence of aggressive driving, which can be engendered by frustration with stop-and-go traffic, which in turn could reduce the need for highway patrol presence. On other highway corridors, however, adding capacity could *increase* the need for highway patrol presence by making speeding more possible. For many items of overhead expense, one would expect the types of projects that HERS models to have only marginal impact if any: for example, simple resurfacing of pavement would generally not affect materially the costs of traffic control center operations.

## Environmental Effects

Apart from changes to emissions of pollutants, HERS does not capture the environmental impacts of highway projects such as changes in noise levels, ecosystem disruption, or water runoff. The HPMS database on which HERS relies lacks the information that would be needed to model these effects, which do not readily lend themselves to quantitative, or even qualitative, generalizations. Projects often include elements to mitigate or remediate harm to the environment, such as noise walls; these are reflected in the HERS estimates of typical improvement costs.

Although negative effects can remain, positive effects are also possible. For example, while increases in freeway traffic volume and speed may increase traffic noise levels, adding capacity to a severely congested urban arterial might reduce noise levels from congestion-related horn honking. Moreover, even with reasonable estimates of environmental impacts, translating these measures into impacts on well-being and monetary costs or benefits is generally quite challenging. How would an analyst value, for example, the loss of aesthetics from a row of trees being cut down to carve out additional lanes? The contingent valuation approach is standard for addressing such questions, but its validity is widely debated. For these various reasons, HERS limits its modeling of environmental impacts to the changes in pollution emissions.

### Economic Effects

The savings in transportation costs that result from highways improvements produce a variety of economic adaptations that entail increased highway use (“induced travel”). Popular examples include changes to freight logistics, such as more frequent shipments to economize on inventory. As a generic allowance for the net benefits from such adaptations, HERS measures an “incremental consumer surplus,” which could also be termed an induced travel benefit. Relative to the other user benefits that HERS measures—the savings in time and vehicle operating costs for existing travel—the induced travel benefit is quite small. However, it does not capture all the benefits from economic adaptations to highway improvements. Potential additional benefits can result from market catchment areas expanding after highways improve; this can increase both productivity (by facilitating competition) and the variety of goods and services that are available. FHWA continues to monitor and evaluate the growing body of research on these hard-to-measure benefits for possible future treatment within HERS.

### Other Effects

HERS evaluates projects independently for a geographically scattered national sample of highway sections. Its assessment of national needs for highway investment will thus not capture benefits for which a network model would be required, such as the option value of additional alternative routes or travel routes becoming less circuitous. HERS also does not consider the effects of modeled highway improvements on non-motorized transportation. For motor vehicles, a possibly significant effect it does not capture is the increase in traveler comfort resulting from pavement improvements. Although research into how much travelers value this benefit is scant, this value could conceivably be significant compared to savings in vehicle operating costs from pavement improvements, which HERS does measure.

## Future HERS Enhancements Currently Underway

As part of an ongoing program of model revisions and improvements, the matrix of typical costs per mile for the various types of highway capital improvements modeled in HERS, as reflected in *Exhibit A-1*, is currently being updated. As part of this effort, the matrix will be expanded to capture differences in costs associated with “typical reconstruction” versus “total reconstruction,” which would involve complete reconstruction of the roadway starting at the subgrade. The current distinction between “normal cost” capacity expansion and “high cost” capacity expansion will be broadened to consider the impact on expansion costs resulting from different types of obstacles to widening that are now coded by the States in HPMS. Other aspects of this research effort include developing procedures for adjusting the cost matrix to remove costs associated with culverts and bridge replacements in conjunction with highway widening projects, in anticipation that future enhancements to the National Bridge Investment Analysis System will allow it to compute such needs more accurately than HERS can. Procedures also will be developed to facilitate analysis of the variable costs associated with different overlay depths.

Work is also underway to refine and update the new pavement performance equations recently introduced into HERS. These equations were based on an early version of the American Association of State Highway and Transportation Officials (AASHTO) Mechanistic-Empirical Pavement Design Guide algorithms, some of which have subsequently been revised. This research is also intended to address certain anomalies encountered in translating the simplified mechanistic-empirical equations into the HERS framework.

FHWA has initiated a major effort to update the equations for predicting vehicle fuel economy and other vehicle operating costs currently included in HERS and in several other public and private-sector tools for highway benefit-cost analysis. The current HERS procedures are based on a 1982 study and are not considered adequately reflective of current vehicle technology and driving patterns. The new study builds on the Strategic Highway Research Program 2 Naturalistic Driving Study and the Road Information Database to develop driving cycles that will be used to model the relationship between vehicle speed and fuel consumption. The impacts of road curvature and pavement roughness on fuel consumption also will be explored. This project includes modeling the relationships among pavement roughness, speed, roadway characteristics, and vehicle operating costs such as repair and maintenance, tire wear, mileage-related vehicle depreciation, and oil consumption.

FHWA is engaged in research to update and refine the HERS valuation of travel time savings. The proliferation of tolled express lanes on U.S. highways has provided valuable new data for studies of motorist willingness to pay for travel time savings, and the evidence from these and other studies is being examined.

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[1] Yu, B, and Lu, Q. 2014, Empirical model of roughness effect on speed. International Journal of Pavement Engineering, vol. 15, no. 4, pp. 345-351. [Return to Section]

[2] New Zealand Transport Agency 2016, Economic Evaluation Manual, First Edition, Amendment 1. Available at: http://www.nzta.govt.nz/assets/resources/economic-evaluation-manual/economic-evaluation-manual/docs/eem-manual-2016.pdf. [Return to Section]

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# Appendix A5: Railways Construction Cost - Eno Transit Construction Cost Database - December 2022

| Project_ID | Country | US State | Region | Agency | Project | Project_Type | Mode | GroundBreaking_Month | GroundBreaking_Year | Month_Opened | Year_Opened | GB | Opening | Time to Construct (months) | Time to Construct (years) | Length (km) | Length (mi) | Percent_Tunnel | Tunnel_Length | Percent_Elevated | Elevated_Length | Percent_At_Grade | At_Grade_Length | Stations |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1213 | US | AZ | Phoenix | Valley Metro | Central Mesa Extension | Extension | Light Rail | June | 2012 | August | 2015 | June 2012 | August 2015 | [illegible] | [illegible] | 5.0 | 3.09 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4 |
| 1214 | US | AZ | Phoenix | Valley Metro | Northwest Extension Phase 1 | Extension | Light Rail | January | 2013 | March | 2016 | January 2013 | March 2016 | [illegible] | [illegible] | 5.2 | 3.19 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 3 |
| 1215 | US | AZ | Phoenix | Valley Metro | Gilbert Road Extension | Extension | Light Rail | October | 2016 | May | 2019 | October 2016 | May 2019 | [illegible] | [illegible] | 3.1 | 1.90 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2 |
| 1216 | US | CA | Los Angeles | LA Metro | Blue Line | Initial and Extension | Light Rail | October | 1985 | July | 1990 | October 1985 | July 1990 | [illegible] | [illegible] | 35.4 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 22 |
| 1217 | US | CA | Los Angeles | LA Metro | Green Line | Initial and Extension | Light Rail | January | 1991 | August | 1995 | January 1991 | August 1995 | [illegible] | [illegible] | 31.4 | 19.48 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 14 |
| 1218 | US | CA | Los Angeles | LA Metro | Red (B) Line Phase 2A and 2B | Extension | Heavy Rail | January | 1989 | June | 1999 | January 1989 | June 1999 | [illegible] | [illegible] | 10.7 | 6.63 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 8 |
| 1219 | US | CA | Los Angeles | LA Metro | Red (B) Line Phase 3 | Extension | Heavy Rail | May | 1994 | June | 2000 | May 1994 | June 2000 | [illegible] | [illegible] | 10.4 | 6.45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 3 |
| 1220 | US | CA | Los Angeles | LA Metro | Expo Line Phase 1 | New | Light Rail | September | 2006 | April | 2012 | September 2006 | April 2012 | [illegible] | [illegible] | 13.8 | 8.58 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 1221 | US | CA | Los Angeles | LA Metro | Expo Line Phase 2 | Extension | Light Rail | September | 2011 | May | 2016 | September 2011 | May 2016 | [illegible] | [illegible] | 10.6 | 6.58 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 7 |
| 1222 | US | CA | Los Angeles | LA Metro | Gold Line - LA to Pasadena | New | Light Rail | June | 2000 | July | 2003 | June 2000 | July 2003 | [illegible] | [illegible] | 22.1 | 13.67 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13 |
| 1223 | US | CA | Los Angeles | LA Metro | Gold Line - Eastside Extension | Extension | Light Rail | July | 2004 | November | 2009 | July 2004 | November 2009 | [illegible] | [illegible] | 9.7 | 5.99 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 8 |
| 1224 | US | CA | Los Angeles | LA Metro | Gold Line Foothill Extension Phase 2A | Extension | Light Rail | June | 2010 | March | 2016 | June 2010 | March 2016 | [illegible] | [illegible] | 18.5 | 11.48 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 6 |
| 1225 | US | CA | Sacramento | Sacramento Regional | Blue Line Extension: South Corridor Phase 1 | Extension | Light Rail | | 1999 | September | 2003 | 1999 | September 2003 | [illegible] | [illegible] | 10.1 | 6.29 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 7 |
| 1226 | US | CA | Sacramento | Sacramento Regional | Gold Line Extension Folsom Corridor | Extension | Light Rail | | 1999 | October | 2005 | 1999 | October 2005 | [illegible] | [illegible] | 20.6 | 12.87 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 10 |
| 1227 | US | CA | Sacramento | Sacramento Regional | Green Line | New | Light Rail | October | 2009 | June | 2012 | October 2009 | June 2012 | [illegible] | [illegible] | 1.6 | 1.00 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2 |
| 1228 | US | CA | Sacramento | Sacramento Regional | Blue Line Extension - South Corridor Phase 2 | Extension | Light Rail | November | 2011 | August | 2015 | November 2011 | August 2015 | [illegible] | [illegible] | 6.9 | 4.29 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4 |
| 1229 | US | CA | San Francisco | BART | BART - SFO Extension | Extension | Heavy Rail | November | 1997 | June | 2003 | November 1997 | June 2003 | [illegible] | [illegible] | 13.9 | 8.59 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4 |
| 1230 | US | CA | San Francisco | BART | Coliseum-Oakland International Airport Line | New | Heavy Rail | October | 2010 | November | 2014 | October 2010 | November 2014 | [illegible] | [illegible] | 5.2 | 3.19 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2 |
| 1231 | US | CA | San Francisco | BART | BART Warm Springs | Extension | Heavy Rail | September | 2009 | March | 2017 | September 2009 | March 2017 | [illegible] | [illegible] | 8.7 | 5.39 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 |
| 1232 | US | CA | San Francisco | BART | eBART | Extension | Commuter Rail | October | 2010 | May | 2018 | October 2010 | May 2018 | [illegible] | [illegible] | 16.1 | 10.08 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 |
| 1233 | US | CA | San Francisco | SFMTA | Central Subway | New | Light Rail | February | 2010 | November | 2022 | February 2010 | November 2022 | [illegible] | [illegible] | 3.4 | 2.10 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4 |
| 1234 | US | CO | Denver | RTD | W Line | New | Light Rail | May | 2007 | April | 2013 | May 2007 | April 2013 | [illegible] | [illegible] | 19.5 | 12.08 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 12 |
| 1235 | US | CO | Denver | RTD | A Line | New | Commuter Rail | August | 2010 | April | 2016 | August 2010 | April 2016 | [illegible] | [illegible] | 37.8 | 23.46 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 7 |
| 1236 | US | CO | Denver | RTD | B Line | New | Commuter Rail | March | 2013 | February | 2017 | March 2013 | February 2017 | [illegible] | [illegible] | 16.8 | 10.46 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 8 |
| 1237 | US | CO | Denver | RTD | Gold G Line | New | Commuter Rail | August | 2011 | April | 2019 | August 2011 | April 2019 | [illegible] | [illegible] | 18.0 | 11.16 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 7 |
| 1238 | US | CO | Denver | RTD | Southeast Extension | Extension | Light Rail | May | 2016 | May | 2019 | May 2016 | May 2019 | [illegible] | [illegible] | 3.7 | 2.30 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 3 |
| 1239 | US | DC | Washington, DC | WMATA | Red Line Wheaton to Glenmont | Extension | Heavy Rail | August | 1993 | July | 1998 | August 1993 | July 1998 | [illegible] | [illegible] | 2.5 | 1.57 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 |
| 1240 | US | DC | Washington, DC | WMATA | Green Line Mid-City Segment (U Street to Fort Totten) | Extension | Heavy Rail | May | 1993 | September | 1999 | May 1993 | September 1999 | [illegible] | [illegible] | 4.7 | 2.91 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2 |
| 1241 | US | DC | Washington, DC | WMATA | Green Line from Anacostia to Branche Avenue | Extension | Heavy Rail | January | 1995 | January | 2001 | January 1995 | January 2001 | [illegible] | [illegible] | 10.7 | 6.66 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 5 |
| 1242 | US | DC | Washington, DC | WMATA | Silver Line phase 1 | New | Heavy Rail | March | 2009 | July | 2014 | March 2009 | July 2014 | [illegible] | [illegible] | 18.8 | 11.67 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 5 |
| 1243 | US | DC | Washington, DC | WMATA | Silver Line phase 2 | Extension | Heavy Rail | September | 2014 | November | 2022 | September 2014 | November 2022 | [illegible] | [illegible] | 18.3 | 11.37 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 6 |
| 1244 | US | FL | Miami | Miami-Dade Transit | AirportLink metrorail | Extension | Heavy Rail | May | 2009 | July | 2012 | May 2009 | July 2012 | [illegible] | [illegible] | 3.8 | 2.36 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 |
| 1245 | US | MA | Boston | MBTA | Green Line Extension | Extension | Light Rail | June | 2018 | December | 2022 | June 2018 | December 2022 | [illegible] | [illegible] | 6.9 | 4.28 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 6 |
| 1246 | US | MN | Minneapolis | Metro Transit | Metro Blue Line (light rail) | New | Light Rail | January | 2001 | June | 2004 | January 2001 | June 2004 | [illegible] | [illegible] | 19.1 | 11.87 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 19 |
| 1247 | US | MN | Minneapolis | Metro Transit | Metro Green Line (light rail) | New | Light Rail | November | 2010 | June | 2014 | November 2010 | June 2014 | [illegible] | [illegible] | 15.8 | 9.78 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 23 |
| 1248 | US | NC | Charlotte | CATS | Blue Line | New | Light Rail | February | 2005 | November | 2007 | February 2005 | November 2007 | [illegible] | [illegible] | 15.5 | 9.58 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 15 |
| 1249 | US | NC | Charlotte | CATS | Blue Line Extension | Extension | Light Rail | September | 2013 | March | 2018 | September 2013 | March 2018 | [illegible] | [illegible] | 15.0 | 9.28 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 11 |
| 1250 | US | NJ | Hudson County | New Jersey Transit | Hudson-Bergen light rail | New | Light Rail | April | 1997 | January | 2011 | April 1997 | January 2011 | [illegible] | [illegible] | 27.4 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 24 |
| 1251 | US | NJ | Trenton | New Jersey Transit | Southern NJ Light Rail Transit System | New | Light Rail | May | 2000 | March | 2004 | May 2000 | March 2004 | [illegible] | [illegible] | 45.1 | 27.96 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 21 |
| 1252 | US | NY | New York | MTA | 7 extension | Extension | Heavy Rail | December | 2007 | September | 2015 | December 2007 | September 2015 | [illegible] | [illegible] | 1.6 | 0.99 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 |
| 1253 | US | NY | New York | MTA | Second Avenue Phase 1 | Extension | Heavy Rail | April | 2007 | January | 2017 | April 2007 | January 2017 | [illegible] | [illegible] | 2.7 | 1.67 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 3 |
| 1254 | US | OR | Portland | TriMet | Westside/Hillsboro MAX | Extension | Light Rail | July | 1993 | September | 1998 | July 1993 | September 1998 | [illegible] | [illegible] | 28.5 | 17.70 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 20 |
| 1255 | US | OR | Portland | TriMet | Airport MAX Red Line | Extension | Light Rail | May | 1999 | September | 2001 | May 1999 | September 2001 | [illegible] | [illegible] | 8.8 | 5.48 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4 |
| 1256 | US | OR | Portland | TriMet | Interstate MAX | [illegible] | Light Rail | November | 2000 | May | 2004 | November 2000 | May 2004 | [illegible] | [illegible] | 9.3 | 5.74 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 10 |
| 1257 | US | OR | Portland | TriMet | Green Line light rail | [illegible] | Light Rail | February | 2007 | September | 2009 | February 2007 | September 2009 | [illegible] | [illegible] | 6.5 | 4.03 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 8 |
| 1258 | US | OR | Portland | TriMet | South Corridor/Portland Mall MAX | Extension | Light Rail | February | 2007 | September | 2009 | February 2007 | September 2009 | [illegible] | [illegible] | 13.5 | 8.36 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 20 |
| 1259 | US | OR | Portland | TriMet | Orange Line light rail | [illegible] | Light Rail | [illegible] | 2011 | September | 2015 | [illegible] | September 2015 | [illegible] | [illegible] | 11.7 | 7.28 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 10 |
| 1260 | US | PA | Pittsburgh | Port Authority of Allegheny County | North Shore Connector | Extension | Light Rail | [illegible] | 2006 | March | 2012 | [illegible] | March 2012 | [illegible] | [illegible] | 1.9 | 1.20 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 3 |
| 1261 | US | TX | Dallas | DART | DART Green Line Extensions to Buckner and Carrollton | Extension | Light Rail | December | 2007 | December | 2010 | December 2007 | December 2010 | [illegible] | [illegible] | 45.9 | 28.46 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 16 |
| 1262 | US | TX | Dallas | DART | Blue Line Extension to Rowlett | Extension | Light Rail | [illegible] | 2008 | December | 2012 | [illegible] | December 2012 | [illegible] | [illegible] | 7.4 | 4.59 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 |
| 1263 | US | TX | Dallas | DART | Orange Line Phase 1 to Irving | New | Light Rail | June | 2009 | July | 2012 | June 2009 | July 2012 | [illegible] | [illegible] | 8.7 | 5.39 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 3 |
| 1264 | US | TX | Dallas | DART | Orange Line Phase 2 to Belt Line | Extension | Light Rail | June | 2009 | December | 2012 | June 2009 | December 2012 | [illegible] | [illegible] | 6.3 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2 |
| 1265 | US | TX | Dallas | DART | Orange Line Phase 3 to DFW | Extension | Light Rail | April | 2012 | August | 2014 | April 2012 | August 2014 | [illegible] | [illegible] | 7.5 | 4.69 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 |
| 1266 | US | TX | Dallas | DART | South Oak Cliff (SOC-3) Blue Line Extension | Extension | Light Rail | October | 2014 | October | 2016 | October 2014 | October 2016 | [illegible] | [illegible] | 4.2 | 2.60 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2 |
| 1267 | US | TX | Houston | Metro | Red Line (Original) | New | Light Rail | March | 2001 | January | 2004 | March 2001 | January 2004 | [illegible] | [illegible] | 12.1 | 7.48 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 16 |
| 1268 | US | TX | Houston | Metro | Red Line Extension | Extension | Light Rail | [illegible] | 2009 | December | 2013 | [illegible] | December 2013 | [illegible] | [illegible] | [illegible] | 5.28 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 8 |
| 1269 | US | TX | Houston | Metro | Green Line | New | Light Rail | July | 2009 | May | 2015 | July 2009 | May 2015 | [illegible] | [illegible] | 5.2 | 3.19 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 7 |
| 1270 | US | TX | Houston | Metro | Purple Line | New | Light Rail | July | 2009 | May | 2015 | July 2009 | May 2015 | [illegible] | [illegible] | 10.8 | 6.68 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 11 |
| 1271 | US | UT | Salt Lake City | UTA | Blue Line (Original) | New | Light Rail | April | 1997 | December | 1999 | April 1997 | December 1999 | [illegible] | [illegible] | 24.2 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 16 |
| 1272 | US | UT | Salt Lake City | UTA | Red Line (Original) | New | Light Rail | August | 2000 | December | 2001 | August 2000 | December 2001 | [illegible] | [illegible] | 3.7 | 2.30 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 1273 | US | UT | Salt Lake City | UTA | Green Line (West Valley Extension) | Extension | Light Rail | June | 2008 | August | 2011 | June 2008 | August 2011 | [illegible] | [illegible] | 8.2 | 5.09 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4 |
| 1274 | US | UT | Salt Lake City | UTA | Red Line (Mid-Jordan Extension) | Extension | Light Rail | May | 2008 | August | 2011 | May 2008 | August 2011 | [illegible] | [illegible] | 17.1 | 10.58 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 9 |
| 1275 | US | UT | Salt Lake City | UTA | Blue Line Draper Extension | Extension | Light Rail | [illegible] | 2011 | August | 2013 | [illegible] | August 2013 | [illegible] | [illegible] | 6.1 | 3.78 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 3 |
| 1276 | US | UT | Salt Lake City | UTA | Green Line (Airport Extension) | Extension | Light Rail | [illegible] | 2008 | April | 2013 | [illegible] | April 2013 | [illegible] | [illegible] | 9.7 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 6 |
| 1277 | US | VA | Norfolk | Hampton Roads Transit | Hampton Roads Tide Light Rail | New | Light Rail | December | 2007 | August | 2011 | December 2007 | August 2011 | [illegible] | [illegible] | 11.9 | 7.38 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 11 |
| 1278 | US | WA | Seattle | Sound Transit | 1 Line - Initial Segment | New | Light Rail | November | 2003 | July | 2009 | November 2003 | July 2009 | [illegible] | [illegible] | 25.1 | 15.57 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 14 |
| 1279 | US | WA | Seattle | Sound Transit | Angle Lake Extension | Extension | Light Rail | [illegible] | 2013 | September | 2016 | [illegible] | September 2016 | [illegible] | [illegible] | 2.6 | 1.60 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 |
| 1280 | US | WA | Seattle | Sound Transit | U Link | Extension | Light Rail | March | 2009 | March | 2016 | March 2009 | March 2016 | [illegible] | [illegible] | 5.1 | 3.16 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2 |
| 1281 | ZA | | Gauteng Province | Gautrain Management Agency | Gautrain | New | Commuter Rail | [illegible] | 2006 | June | 2012 | [illegible] | June 2012 | [illegible] | [illegible] | 80.0 | 49.60 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 9 |
| 1282 | GB | | London | TfL | Elizabeth Line (Central and Southeast Sections) | New | Heavy Rail | May | 2009 | May | 2022 | May 2009 | May 2022 | [illegible] | [illegible] | 23.3 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 1283 | US | LA | Los Angeles | LA Metro | K Line (Crenshaw/LAX Project) | New | Light Rail | January | 2014 | October | 2022 | January 2014 | October 2022 | [illegible] | [illegible] | 13.5 | 8.41 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

| Project_ID | Average Station Spacing (mi) | Midpoint | Lookup Year | PPP_Lookup | Inflation_Lookup | PPP_Conversion | Inflation_Conversion | Currency | Unadjusted_Reported_Cost | PPP Adjusted Cost | Inflation Adjusted Cost | Final Cost (excl. vehicles and support facilities where possible - see cost note) | Cost_per_KM | Cost_per_Mile |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1213 | 0.77 | 2014 | 2014 | N/A | US2014 | 1.00000 | 1.27 | USD | 197 | 197 | 251 | 251 | 50 | 81 |
| 1214 | 1.06 | 2015 | 2015 | N/A | US2015 | 1.00000 | 1.24 | USD | 327 | 327 | 407 | 407 | 79 | 127 |
| 1215 | 0.95 | 2018 | 2018 | N/A | US2018 | 1.00000 | 1.13 | USD | 184 | 184 | 208 | 208 | 68 | 109 |
| 1216 | 1.05 | 1988 | 1988 | N/A | US1988 | 1.00000 | 2.76 | USD | 877 | 877 | 2422 | 2422 | 68 | 110 |
| 1217 | 1.50 | 1993 | 1993 | N/A | US1993 | 1.00000 | 2.40 | USD | 718 | 718 | 1720 | 1720 | 55 | 88 |
| 1218 | 0.83 | 1994 | 1994 | N/A | US1994 | 1.00000 | 2.31 | USD | 1687 | 1687 | 3894 | 3777 | 353 | 569 |
| 1219 | 2.15 | 1997 | 1997 | N/A | US1997 | 1.00000 | 2.14 | USD | 1240 | 1240 | 2657 | 2524 | 243 | 391 |
| 1220 | 0.95 | 2009 | 2009 | N/A | US2009 | 1.00000 | 1.46 | USD | 960 | 960 | 1398 | 1398 | 101 | 163 |
| 1221 | 0.94 | 2014 | 2014 | N/A | US2014 | 1.00000 | 1.27 | USD | 1288 | 1288 | 1639 | 1639 | 154 | 249 |
| 1222 | 1.14 | 2002 | 2002 | N/A | US2002 | 1.00000 | 1.91 | USD | 721 | 721 | 1376 | 1376 | 62 | 101 |
| 1223 | 0.75 | 2007 | 2007 | N/A | US2007 | 1.00000 | 1.57 | USD | 887 | 887 | 1389 | 1389 | 144 | 232 |
| 1224 | 1.91 | 2013 | 2013 | N/A | US2013 | 1.00000 | 1.31 | USD | 714 | 714 | 934 | 934 | 50 | 81 |
| 1225 | 0.90 | 2001 | 2001 | N/A | US2001 | 1.00000 | 1.97 | USD | 224 | 224 | 441 | 322 | 32 | 51 |
| 1226 | 1.29 | 2002 | 2002 | N/A | US2002 | 1.00000 | 1.91 | USD | 268 | 268 | 512 | 430 | 21 | 33 |
| 1227 | 0.50 | 2011 | 2011 | N/A | US2011 | 1.00000 | 1.38 | USD | 44 | 44 | 61 | 61 | 38 | 61 |
| 1228 | 1.07 | 2013 | 2013 | N/A | US2013 | 1.00000 | 1.31 | USD | 270 | 270 | 353 | 353 | 51 | 82 |
| 1229 | 2.15 | 2000 | 2000 | N/A | US2000 | 1.00000 | 2.01 | USD | 1530 | 1530 | 3069 | 2916 | 210 | 339 |
| 1230 | 1.60 | 2012 | 2012 | N/A | US2012 | 1.00000 | 1.34 | USD | 484 | 484 | 649 | 649 | 126 | 203 |
| 1231 | 5.39 | 2013 | 2013 | N/A | US2013 | 1.00000 | 1.31 | USD | 750 | 750 | 981 | 981 | 113 | 182 |
| 1232 | 10.08 | 2014 | 2014 | N/A | US2014 | 1.00000 | 1.27 | USD | 525 | 525 | 668 | 668 | 41 | 66 |
| 1233 | 0.52 | 2016 | 2016 | N/A | US2016 | 1.00000 | 1.21 | USD | 1950 | 1931 | 2333 | 2308 | 683 | 1101 |
| 1234 | 1.01 | 2010 | 2010 | N/A | US2010 | 1.00000 | 1.42 | USD | 735 | 735 | 1042 | 938 | 48 | 78 |
| 1235 | 3.35 | 2013 | 2013 | N/A | US2013 | 1.00000 | 1.31 | USD | 1403 | 1403 | 1834 | 1610 | 43 | 69 |
| 1236 | 1.31 | 2015 | 2015 | N/A | US2015 | 1.00000 | 1.24 | USD | 654 | 654 | 814 | 736 | 44 | 70 |
| 1237 | 1.60 | 2015 | 2015 | N/A | US2015 | 1.00000 | 1.24 | USD | 505 | 505 | 628 | 566 | 31 | 51 |
| 1238 | 0.77 | 2018 | 2018 | N/A | US2018 | 1.00000 | 1.13 | USD | 209 | 209 | 236 | 206 | 56 | 90 |
| 1239 | 1.57 | 1996 | 1996 | N/A | US1996 | 1.00000 | 2.22 | USD | 244 | 244 | 541 | 466 | 184 | 296 |
| 1240 | 1.45 | 1996 | 1996 | N/A | US1996 | 1.00000 | 2.22 | USD | 596 | 596 | 1323 | 1323 | 282 | 455 |
| 1241 | 1.33 | 1998 | 1998 | N/A | US1998 | 1.00000 | 2.11 | USD | 850 | 850 | 1793 | 1596 | 149 | 240 |
| 1242 | 2.33 | 2012 | 2012 | N/A | US2012 | 1.00000 | 1.34 | USD | 2982 | 2982 | 3999 | 3605 | 191 | 309 |
| 1243 | 1.90 | 2018 | 2018 | N/A | US2018 | 1.00000 | 1.13 | USD | 3028 | 3028 | 3417 | 2892 | 158 | 254 |
| 1244 | 2.36 | 2011 | 2011 | N/A | US2011 | 1.00000 | 1.38 | USD | 506 | 506 | 696 | 696 | 183 | 296 |
| 1245 | 0.71 | 2018 | 2018 | N/A | US2018 | 1.00000 | 1.13 | USD | 2300 | 2300 | 2595 | 2595 | 376 | 607 |
| 1246 | 0.63 | 2003 | 2003 | N/A | US2003 | 1.00000 | 1.86 | USD | 672 | 672 | 1253 | 1052 | 55 | 88 |
| 1247 | 0.43 | 2012 | 2012 | N/A | US2012 | 1.00000 | 1.34 | USD | 957 | 957 | 1283 | 1283 | 81 | 131 |
| 1248 | 0.64 | 2006 | 2006 | N/A | US2006 | 1.00000 | 1.61 | USD | 463 | 463 | 746 | 746 | 48 | 78 |
| 1249 | 0.84 | 2016 | 2016 | N/A | US2016 | 1.00000 | 1.21 | USD | 1200 | 1200 | 1450 | 1450 | 97 | 156 |
| 1250 | 0.71 | 2004 | 2004 | N/A | US2004 | 1.00000 | 1.75 | USD | 2300 | 2300 | 4035 | 4035 | 147 | 238 |
| 1251 | 1.33 | 2002 | 2002 | N/A | US2002 | 1.00000 | 1.91 | USD | 699 | 699 | 1334 | 1081 | 24 | 39 |
| 1252 | 0.99 | 2011 | 2011 | N/A | US2011 | 1.00000 | 1.38 | USD | 2420 | 2420 | 3330 | 3330 | 2081 | 3357 |
| 1253 | 0.56 | 2012 | 2012 | N/A | US2012 | 1.00000 | 1.34 | USD | 4900 | 4900 | 6571 | 6571 | 2434 | 3925 |
| 1254 | 0.88 | 1996 | 1996 | N/A | US1996 | 1.00000 | 2.22 | USD | 969 | 969 | 2152 | 1851 | 65 | 105 |
| 1255 | 1.37 | 2000 | 2000 | N/A | US2000 | 2.00000 | 2.01 | USD | 125 | 250 | 502 | 502 | 57 | 91 |
| 1256 | 0.57 | 2002 | 2002 | N/A | US2002 | 1.00000 | 1.91 | USD | 343 | 343 | 655 | 491 | 53 | 86 |
| 1257 | 0.50 | 2008 | 2008 | N/A | US2008 | 1.00000 | 1.50 | USD | 388 | 388 | 583 | 583 | 90 | 145 |
| 1258 | 0.42 | 2008 | 2008 | N/A | US2008 | 1.00000 | 1.50 | USD | 559 | 559 | 840 | 714 | 53 | 85 |
| 1259 | 0.73 | 2013 | 2013 | N/A | US2013 | 1.00000 | 1.31 | USD | 1495 | 1495 | 1955 | 1955 | 166 | 269 |
| 1260 | 0.40 | 2009 | 2009 | N/A | US2009 | 1.00000 | 1.46 | USD | 510 | 510 | 743 | 743 | 384 | 620 |
| 1261 | 1.78 | 2009 | 2009 | N/A | US2009 | 1.00000 | 1.46 | USD | 1800 | 1800 | 2622 | 2622 | 57 | 92 |
| 1262 | 4.59 | 2011 | 2011 | N/A | US2011 | 1.00000 | 1.38 | USD | 310 | 310 | 427 | 427 | 58 | 93 |
| 1263 | 1.80 | 2011 | 2011 | N/A | US2011 | 1.00000 | 1.38 | USD | 500 | 500 | 688 | 688 | 79 | 128 |
| 1264 | 1.95 | 2011 | 2011 | N/A | US2011 | 1.00000 | 1.38 | USD | 400 | 400 | 550 | 550 | 88 | 141 |
| 1265 | 4.69 | 2013 | 2013 | N/A | US2013 | 1.00000 | 1.31 | USD | 397 | 397 | 519 | 519 | 69 | 111 |
| 1266 | 1.30 | 2015 | 2015 | N/A | US2015 | 1.00000 | 1.24 | USD | 195 | 195 | 243 | 243 | 58 | 93 |
| 1267 | 0.47 | 2003 | 2003 | N/A | US2003 | 1.00000 | 1.86 | USD | 324 | 324 | 604 | 604 | 50 | 81 |
| 1268 | 0.66 | 2011 | 2011 | N/A | US2011 | 1.00000 | 1.38 | USD | 756 | 756 | 1040 | 1040 | 122 | 197 |
| 1269 | 0.46 | 2012 | 2012 | N/A | US2012 | 1.00000 | 1.34 | USD | 587 | 587 | 787 | 787 | 153 | 247 |
| 1270 | 0.61 | 2012 | 2012 | N/A | US2012 | 1.00000 | 1.34 | USD | 823 | 823 | 1104 | 1104 | 102 | 165 |
| 1271 | 0.94 | 1998 | 1998 | N/A | US1998 | 1.00000 | 2.11 | USD | 295 | 295 | 622 | 466 | 19 | 31 |
| 1272 | 0.29 | 2001 | 2001 | N/A | US2001 | 1.00000 | 1.97 | USD | 94 | 94 | 185 | 185 | 50 | 81 |
| 1273 | 1.27 | 2010 | 2010 | N/A | US2010 | 1.00000 | 1.42 | USD | 370 | 370 | 525 | 525 | 64 | 103 |
| 1274 | 1.18 | 2010 | 2010 | N/A | US2010 | 1.00000 | 1.42 | USD | 481 | 481 | 682 | 512 | 30 | 48 |
| 1275 | 1.26 | 2012 | 2012 | N/A | US2012 | 1.00000 | 1.34 | USD | 143 | 143 | 192 | 192 | 31 | 51 |
| 1276 | 1.00 | 2011 | 2011 | N/A | US2011 | 1.00000 | 1.38 | USD | 350 | 350 | 482 | 482 | 50 | 80 |
| 1277 | 0.67 | 2009 | 2009 | N/A | US2009 | 1.00000 | 1.46 | USD | 279 | 279 | 406 | 406 | 34 | 55 |
| 1278 | 1.11 | 2006 | 2006 | N/A | US2006 | 1.00000 | 1.61 | USD | 2558 | 2558 | 4120 | 4120 | 164 | 265 |
| 1279 | 1.60 | 2015 | 2015 | N/A | US2015 | 1.00000 | 1.24 | USD | 331 | 331 | 412 | 412 | 160 | 258 |
| 1280 | 1.58 | 2013 | 2013 | N/A | US2013 | 1.00000 | 1.31 | USD | 1756 | 1756 | 2296 | 2111 | 414 | 668 |
| 1281 | 5.51 | 2009 | 2009 | ZA2009 | US2009 | 0.22705 | 1.46 | Rand | 25400 | 5767 | 8399 | 8399 | 105 | 169 |
| 1282 | 1.62 | 2016 | 2016 | GB2016 | US2016 | 1.00000 | 1.21 | GBP | 15800 | 15800 | 19089 | 19089 | 819 | 1182 |
| 1283 | 1.05 | 2018 | 2018 | N/A | US2018 | 1.00000 | 1.13 | USD | 2329 | 2429 | 2741 | 2543 | 188 | 302 |

| Project_ID | Guideway | Stations Share | Support Facilities | Sitework | Systems | ROW and Land Acquisition | Vehicles | Professional Services | Contigency/Finance Charge/Other | Cost_Reference | Cost_Note |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1213 | | | | | | | | | | https://www.transit.do | FTA Before and After Study - 2019 - excl. rolling stock |
| 1214 | | | | | | | | | | https://www.valleymet | Valley Metro Project Report Card - 2016 |
| 1215 | | | | | | | | | | https://www.azcentral. | news reporting - 2019 |
| 1216 | | | | | | | | | | https://www.metro.net | Total cost for entire line via LA Metro homepage, no date |
| 1217 | | | | | | | | | | https://www.metro.net | Total cost for entire line via LA Metro homepage, no date |
| 1218 | 11% | 39% | 0% | 3% | 5% | 5% | 3% | 33% | 1% | https://www.transit.do | FTA Capital Cost Database - excl rolling stock |
| 1219 | 25% | 20% | 0% | 3% | 5% | 6% | 5% | 36% | 0% | https://www.transit.do | FTA Capital Cost Database - excl. rolling stock |
| 1220 | | | | | | | | | | https://media.metro.ne | Major Construction Program Summary - Quarter Ending March 2019 (LA Metro) |
| 1221 | | | | | | | | | | https://media.metro.ne | Major Construction Program Summary - Quarter Ending March 2019 (LA Metro) |
| 1222 | | | | | | | | | | https://media.metro.ne | Major Construction Program Summary - Quarter Ending March 2019 (LA Metro) |
| 1223 | | | | | | | | | | https://media.metro.ne | Major Construction Program Summary - Quarter Ending March 2019 (LA Metro) |
| 1224 | | | | | | | | | | https://media.metro.ne | Major Construction Program Summary - Quarter Ending March 2019 (LA Metro) |
| 1225 | 22% | 10% | 0% | 4% | 12% | 9% | 27% | 17% | 0% | https://www.transit.do | FTA Capital Cost Database - excl rolling stock |
| 1226 | 24% | 8% | 3% | 7% | 23% | 3% | 13% | 19% | 0% | https://www.transit.do | FTA Capital Cost Database - excl rolling stock |
| 1227 | | | | | | | | | | https://www.sacrt.com | Agency document - 2012 |
| 1228 | | | | | | | | | | https://www.transit.do | FTA Before and After - 2013 |
| 1229 | 29% | 21% | 5% | 1% | 11% | 15% | 0% | 19% | 0% | https://www.transit.do | FTA Capital Cost Database - excl rolling stock |
| 1230 | | | | | | | | | | https://www.railway-te | Reporting |
| 1231 | | | | | | | | | | https://www.bart.gov/a | From BART website - 2019 |
| 1232 | | | | | | | | | | https://www.bart.gov/a | Reporting + BART website - 2018 |
| 1233 | 18% | 34% | 0% | 17% | 6% | 2% | 1% | 21% | 0% | https://www.sfmta.com | Current figure from June 2022 Progress report, excl. rolling stock |
| 1234 | 16% | 6% | 0% | 29% | 9% | 10% | 10% | 12% | 8% | FOIA - "FasTracks Pr | FOIA'd costs from RTD - excludes rolling stock |
| 1235 | 14% | 1% | 0% | 23% | 8% | 13% | 12% | 13% | 16% | FOIA - "FasTracks Pr | FOIA'd costs from RTD - excludes rolling stock |
| 1236 | 17% | 4% | 0% | 27% | 15% | 11% | 10% | 17% | 0% | FOIA - "FasTracks Pr | FOIA'd costs from RTD - excludes rolling stock |
| 1237 | 11% | 4% | 0% | 19% | 11% | 18% | 10% | 13% | 15% | FOIA - "FasTracks Pr | FOIA'd costs from RTD - excludes rolling stock |
| 1238 | 15% | 15% | 0% | 22% | 12% | 3% | 13% | 18% | 3% | FOIA - "FasTracks Pr | FOIA'd costs from RTD - excludes rolling stock |
| 1239 | 32% | 15% | 14% | 3% | 7% | 1% | 0% | 29% | 0% | https://www.transit.do | FTA Capital Cost Database - excl rolling stock |
| 1240 | 39% | 20% | 0% | 9% | 4% | 3% | 0% | 25% | 0% | https://www.transit.do | FTA Capital Cost Database - excl rolling stock |
| 1241 | 30% | 18% | 11% | 5% | 7% | 4% | 0% | 25% | 0% | https://www.transit.do | FTA Capital Cost Database - excl rolling stock |
| 1242 | 23% | 13% | 3% | 9% | 11% | 2% | 7% | 31% | 0% | http://www.dullesmetr | MWAA - excl. rolling stock (obtained via monthly progress report https://www.tra |
| 1243 | 7% | 9% | 9% | 27% | 8% | 2% | 7% | 24% | 7% | http://www.dullesmetr | MWAA - excl. rolling stock and railyard (obtained via monthly progress report htt |
| 1244 | | | | | | | | | | https://www.miamidad | Miami-Dade official reported cost - 2019 |
| 1245 | | | | | | | | | | https://www.mbta.com | Current budget |
| 1246 | 42% | 6% | 5% | 2% | 15% | 7% | 11% | 10% | 2% | https://www.transit.do | FTA Capital Cost Database - excl rolling stock |
| 1247 | | | | | | | | | | https://metrocouncil.or | MetroTransit |
| 1248 | | | | | | | | | | https://www.transit.do | FTA Before and After Study - 2011 |
| 1249 | | | | | | | | | | https://www.transporta | DOT + Reporting |
| 1250 | | | | | | | | | | https://www.fhwa.dot. | FHWA/NJT |
| 1251 | 27% | 4% | 8% | 10% | 7% | 12% | 11% | 22% | 0% | https://www.transit.do | FTA Capital Cost Database - excl rolling stock |
| 1252 | | | | | | | | | | https://rpa.org/uploads | FTA Reporting via RPA Report, 2019 |
| 1253 | | | | | | | | | | https://rpa.org/uploads | FTA Reporting via RPA Report, 2019 |
| 1254 | 37% | 7% | 2% | 4% | 8% | 7% | 12% | 23% | 0% | https://www.transit.do | FTA Capital Cost Database - excl rolling stock |
| 1255 | | | | | | | | | | | |
| 1256 | 36% | 3% | 4% | 10% | 10% | 2% | 21% | 12% | 2% | https://www.transit.do | FTA Capital Cost Database - excl rolling stock |
| 1257 | | | | | | | | | | https://www.transit.do | FTA Before and After Study - 2014; excludes existing ROW, rolling stock, and re |
| 1258 | 13% | 6% | 1% | 31% | 13% | 4% | 14% | 18% | 0% | https://www.transit.do | FTA Capital Cost Database - excl rolling stock |
| 1259 | | | | | | | | | | https://trimet.org/histo | Trimet Website |
| 1260 | 29% | 23% | 0% | 13% | 8% | 2% | 0% | 25% | 0% | https://www.transit.do | FTA Before and After Study - 2016 |
| 1261 | | | | | | | | | | https://www.dart.org/a | DART reference book - 2019 |
| 1262 | | | | | | | | | | https://www.dart.org/a | DART reference book - 2019 |
| 1263 | | | | | | | | | | https://www.fhwa.dot. | Estimate from The Transport Politic (phase 1 + 2 cost $900M, individual breakdo |
| 1264 | | | | | | | | | | https://www.fhwa.dot. | Estimate from The Transport Politic (phase 1 + 2 cost $900M, individual breakdo |
| 1265 | | | | | | | | | | https://www.fhwa.dot. | FHWA |
| 1266 | | | | | | | | | | https://www.dart.org/a | DART reference book - 2019 |
| 1267 | | | | | | | | | | https://www.ridemetro | Metro Website - 2014 |
| 1268 | | | | | | | | | | https://web.archive.org | Reporting - 2013 |
| 1269 | | | | | | | | | | https://webcache.goog | Reporting - 2015 |
| 1270 | | | | | | | | | | https://webcache.goog | Reporting - 2015 |
| 1271 | 31% | 5% | 5% | 2% | 11% | 12% | 20% | 14% | 0% | https://www.transit.do | FTA Capital Cost Database - excl rolling stock |
| 1272 | | | | | | | | | | https://www.metro-ma | Reporting from 2001, excludes rolling stock |
| 1273 | | | | | | | | | | https://www.deseret.c | Reporting - 2013 |
| 1274 | 10% | 3% | 3% | 26% | 15% | 12% | 22% | 10% | 0% | https://www.transit.do | FTA Before and After - 2016, excl. rolling stock |
| 1275 | | | | | | | | | | https://www.deseret.c | Reporting - 2013 |
| 1276 | | | | | | | | | | https://www.deseret.c | Reporting - 2013 |
| 1277 | | | | | | | | | | https://www.transit.do | FTA Before and After Study - 2015, excl. rolling stock |
| 1278 | | | | | | | | | | https://www.transit.do | FTA Before and After Study - 2013 |
| 1279 | 30% | 13% | 0% | 17% | 6% | 11% | 0% | 23% | 0% | FOIA - "Cost Summar | Amount committed to date via Sound Transit FOIA |
| 1280 | 30% | 23% | 2% | 4% | 7% | 8% | 6% | 20% | 1% | FOIA - "Cost Summar | Working authorized allocation via Sound Transit FOIA, excl. rolling stock |
| 1281 | | | | | | | | | | https://www.railway-technology.com/projects/gautrain/ | |
| 1282 | | | | | | | | | | https://www.london.go | Only Central and SE sections (Paddington to Abbey Wood and to Tunnel Entrance SW |
| 1283 | | | | | | | | | | https://www.dropbox.c | Final cost in FY23 budget minus SW maintenence Yard and Pre-revenue service (see p |

Source: https://docs.google.com/spreadsheets/d/1vswm6N0KWt3HS6o2OpOnTUr0JcUzKkjy/edit?gid=1308280872#gid=1308280872

| | Description |
|---|---|
| Country | Country where project is located |
| State | State where project is located (US + CA only) |
| City | City/region where project is located |
| Agency | Agency overseeing construction/operation |
| Project | Project name |
| Type | Whether a project is a new stand-alone line or an extension of an existing service |
| Mode | Whether project is light rail, heavy rail (incl. subways), or commuter rail*<br>*Includes similar projects in Europe that may be more frequently referred to as regional rail. |
| Groundbreaking Date | Year project broke ground |
| Year Opened for Service | Year project opened for revenue service |
| Length (km) | Length of project track |
| Percent Tunneled | Share of project length that is underground |
| Tunnel Length (km) | Length of project that is underground |
| Percent Elevated | Share of project length that is above-ground |
| Elevated Length | Length of project that is above-ground |
| Percent At Grade | Share of project length that is at-grade |
| At Grade Length | Length of project that is at-grade |
| Stations | Number of new stations included in the project |
| Average Station Spacing (km) | Average distance (km) between stations. For new lines, calculated as Length / (Number of Stations - 1) to account for terminal stations. For extensions, calculated as Length / Number of Stations |
| Currency | Currency of project's unadjusted reported cost |
| Construction Midpoint | Year of midpoint of project's construction period as measured from groundbreaking year to opening year |
| PPP Conversion | Purchasing Power Parity rate: conversion rate for international currencies to US Dollars in a given year, taking difering price levels between countries into account (measured as foreign currency needed to purchase $1 worth of goods). PPP rates based on OECD values and project construction mid-point year.<br>*NOTE: Values manually inputted for Paris Metro Line 14 values to account for PPP rate between Francs and USD prior to adoption of the Euro |
| Inflation Conversion | Value of $1 USD in project's midpoint year in 2020 dollars using ENR Construction Cost Index |
| Unadjusted Reported Cost | Reported cost of project in original currency |
| PPP Adjusted Cost | Cost of project in USD, adjusted using PPP rate during project's midpoint year (international projects) |
| Inflation Adjusted Cost | Cost of project in 2020 US Dollars, adjusted for inflation and PPP (international projects) |
| Final Adjusted Cost | Final cost adjusted for both currency and inflation. |
| Cost per KM | Cost of project divided by project length in 2020 USD |
| Cost Reference | Reference for project's unadjusted reported cost |
| Cost Note/Source | Brief description of project cost reference (i.e. whether cost information was obtained through reporting, government documents, or academic studies), including publication year when availabl |

# Appendix A6: Oil and Gas Pipeline Construction Costs - Global Energy Monitor

# Oil and Gas Pipeline Construction Costs

Contents



**This article is part of the Global Fossil Infrastructure Tracker, a project of Global Energy Monitor.**

***Sub-articles:***

- FrackSwarm portal
- Coal terminals
- Coal transport and infrastructure
- Oil and gas pipelines
- LNG terminals
- Pipeline construction costs
- Methodology and data notes

## Summary

The following are ranges for pipeline cost estimates. For further discussion, see below:

- Oil & Gas Journal 2015-2016: $4.75 million/km (US onshore gas)
- Oil & Gas Journal 2014-2015: $3.23 million/km (US onshore gas)
- American Petroleum Institute 2017: $3.32 million/km (US onshore gas, national average)
- Global Fossil Infrastructure Tracker median for 64 onshore and offshore projects: $2.34 million/km (date unspecified, worldwide)

## Background

There are four categories of pipeline construction costs; material, labor, miscellaneous, and right-of-way (ROW). The cost per category, expressed as a percentage of total construction costs, tends to vary by both location and year. Materials may include line pipe, pipe coating, and cathodic protection. Miscellaneous costs generally cover surveying, engineering, supervision, contingencies, telecommunications equipment, freight, taxes, allowances for funds used during construction (AFUDC), administration and overheads, and regulatory filing fees. ROW costs include obtaining rights-of-way and allowing for damages.[1]

## Current Trends

Pipelines built in 2015 and 2016 were historically expensive, as determined by the costs for new projects as filed by operators with FERC, according to an *Oil & Gas Journal* analysis. For proposed onshore US gas pipeline projects in 2015-16, the average cost was $7.65 million/mile ($4.75 million/km), up from both the 2014-15 average cost of $5.2 million/mile ($3.23 million/km) and the 2013-14 average cost of $6.6 million/mile ($4.10 million/km). In 2012-13 the average cost was $4.1 million/mile ($2.55 million/km) as compared with $3.1 million/mile ($1.93 million/km) in 2011-12; $4.4 million/mile ($2.73 million/km) in 2010-11; $5.1 million/mile ($3.17 million/km) in 2009-10; and $3.7 million/mile ($2.30 million/km) in 2008-09.[1]

For the 33 land spreads filed for in 2015-16, cost-per-mile projections rose in all categories except material. In 2011 miscellaneous charges passed material to become the second most expensive cost category and they retained this position through 2016. Material-$992,991/mile, down from $1,012,698/mile 2014-15. Labor-$3,603,334/mile, up from $1,977,938/mile for 2014-15. Miscellaneous-$2,615,028/mile, up from $1,867,393/mile for 2014-15. ROW and damages-$441,548/mile, up from $378,255/mile for 2014-15. The continued rise in miscellaneous costs is driven by companies increasing the amount set aside for contingencies in their estimates.[1]

Labor spiked as a portion of land construction costs, reinforcing its place as the single most expensive category. Labor's portion of estimated costs for land pipelines jumped to 47.08% in 2016 from 37.77% in 2015, 42.36% in 2014, 38.84% in 2013, 44.61% in 2012, 44.27% in 2011, and 44.61% in 2010. Material costs for land pipelines, meanwhile, eased to 12.98% from 19.34% in 2015, 13.6% in 2014, 23.2% in 2013, 15.99% in 2012, and 14.54% in 2011.[1]

# Average Pipeline Size

Pipeline cost is often estimated per inch-mile. According to NaturalGas.org, the average diameter of an interstate pipeline is between 24 inches and 36 inches, or an average of 30 inches.[2]

# Offshore versus Onshore

According to USAID, offshore costs per mile for pipelines were about 1.96 times as high as costs per mile for onshore pipelines in 2000-2001, in 1995-1996 the cost ratio was 1.79.[3]

# Gazprom Costs

An analysis of Gazprom offshore construction costs found the following:[4]

- Nord Stream - €3.4 million/km
- South Stream - €2.7 million/km
- Dzhubga-Sochi - >€5.0 million/km

# BTU Analytics Survey or U.S. Northeast and Central U.S. Pipelines

A survey by BTU analytics of 9 gas pipelines in the U.S. Northeast found a range of $5.5 million - $13.14 million per mile, with a median of $8.45 million/mile, or $5.25 million/km. The pipelines were onshore and ranged from 118 to 600 miles length. The pipelines were built from 2017 to 2020. The analysis also cited two pipelines in the Great Plaints and West Texas/Gulf Coast regions. Those pipelines included a pipeline built in 2009 that cost $2.98 million/mile in 2009 dollars, and two pipelines that cost $3.51 million and $5.15 million per mile respectively in 2019.[5]

# American Petroleum Institute 2017 Estimate

In its study of infrastructure through 2035, the API estimated average U.S. pipeline costs of $178,000 per inch-mile for 2016 (in nominal dollars) for large gas transmission pipelines. Combined with the estimate of 30 inches for average pipeline size, that amounts to $5.34 million per mile for gas pipelines, or $3.32 million per km. The API also estimate regional costs multipliers:[6]

- Central - 0.65
- Midwest - 1.20
- Northeast - 1.68
- Offshore - 1.00
- Southeast - 0.80
- Southwest - 0.74
- Western - 0.94

# Estimating Construction Costs

The average cost-per-mile for the projects rarely shows consistent trends related to either length or geographic area. In general, however, the cost-per-mile within a given diameter decreases as the number of miles rises, suggesting that fewer and longer pipelines are more cost efficient. Lines built nearer populated areas tend to have higher unit costs. Additionally, road, highway, river, or channel crossings and marshy or rocky terrain each strongly affect pipeline construction costs.[1]

A 2011 study published in the Journal of Oil, Gas, and Coal Technology identified the variability within the four main cost categories. The percentage share of material cost of pipeline construction increased when pipeline diameter increased. In term of pipeline lengths, the share of material cost rose from 28% for short pipelines to 35% for long pipelines, with share of the other cost components decreasing except ROW, which was constant at 7% regardless of the total pipeline length. Therefore, the share of material cost increased when pipeline diameter and length increased, but the labour cost maintained as the primary cost component for all diameters and lengths, averaging 40% of total cost. The shares of cost components were also different for different regions in the United States. The material cost in the Central region made up around 41% of the total cost, while it was only 24% of the total cost in the Northeast and Southeast regions. The share of labour cost is between 34% and 48% in different regions. This may be influenced by differing costs of living by region. Miscellaneous cost was often a small part of the total cost, but the share of miscellaneous cost in the Southeast region reached to 30% of the total cost, even higher than share of material cost. The share of ROW cost of US pipelines ranged from 4% to 12% of total cost, while the share of ROW cost in Canada share was only 1% of total cost. The share of material cost and labour cost were approximately the same for Canadian pipelines, about 40%. The results agree with the conclusion that the shares of costs vary by countries and categories.[7]

# Stranded Assets

Stranded assets refers to the amount of fossil fuel reservers that would have to remain in the ground, or fossil fuel infrastructure that wold have to remain unused at some point prior to providing a return on the investment, if the world were to transition to non-fossil fuel energy sources. For example, according to a 2015 study in *Nature*, an estimated 33% of oil reserves, 50% of gas reserves and more than 80% of known coal reserves should remain unused in order to meet global temperature targets under the Paris Agreement. Assets become stranded when new government regulations that limit the use of fossil fuels (like carbon pricing) are instituted, from a change in demand (for example, a shift towards renewable energy because of lower energy costs), or by legal action. Those who have invested in the fossil fuel industry are at most risk, including people who have bought stocks or bonds. This can include a wide variety of people and institutions such as individual investors, banks, pension funds, insurance companies, and universities, among others. Although the ‘stranded assets’ discussion often focuses on fossil fuels, it’s not just companies extracting oil, gas, and coal that could be affected by transition risk. Other companies that use fossil fuels as inputs for production, or are otherwise energy or carbon-intensive, could also be affected by new climate legislation, technological advances, or a shift in demand.[8]

A 2018 study published in *Nature Climate Change* suggests that part of the stranded assets would occur as a result of an already ongoing technological trajectory, irrespective of whether or not new climate policies are adopted. This loss would be amplified if new climate policies were adopted to reach the 2 °C target of the Paris Agreement, or if low-cost producers (such as some OPEC countries) maintain their level of production, or sell out, despite declining demand. The magnitude of the loss from stranded assets may amount to a discounted global wealth loss of US$1–4 trillion. Net importers, such as China or Europe, would fair better as fossil fuel prices drop. But net exporters, for example, Russia, the United States, or Canada, could see their fossil fuel industries nearly shut down. The two effects would largely offset each other at the level of aggregate global GDP.[9]

Meanwhile, a 2018 report indicated that major banks have increased fossil fuel financing. A report by Rainforest Action Network, Oil Change International, BankTrack, Indigenous Environmental Network, Sierra Club, and Honor The Earth, found that the major banks funneled $115 billion into extreme fossil fuels (defined as: tar sands, Arctic, and ultra-deepwater oil; coal mining and coal-fired power; and liquefied natural gas export in North America) in 2017, an increase of 11% from 2016. The single biggest driver of the increase in financing came from the tar sands sector, where financing grew by 111% from 2016 to 2017. The massive hike in bank support for tar sands to nearly $47 billion, led tar sands to overtake coal power as the most heavily funded extreme energy sector.[10] Further investments increase the carbon bubble and therefore the potential negative future consequences caused by the bursting of it.

# Survey

The following table shows the results of a survey of projects documented by the Global Fossil Infrastructure Tracker. The survey is based on a diverse collection of projects worldwide. It shows the wide range in costs per km, which can likely be attributed primarily to differences between offshore and onshore projects, the inclusion or exclusion of additional infrastructure such as drilling platforms or pressurization stations, regional cost differences, and variations by year. For that reason, these results should be viewed as non-conclusive. A more reliable global finding would require careful project definition (including exclusion of secondary infrastructure), thereby allowing apples-to-apples comparisons. The median cost in the survey is $2,338,492 per km, lower than the $4.75 million/km estimated by *Oil and Gas Journal* in November 2018 for U.S. onshore gas pipeline projects in 2015-2016, but within the range of reported costs in the preceding 8 years, which ranged from $2.30 million/km in 2008-09 to $4.1 million/km in 2013-14 (see above).

| Wiki | Name | Owner | Status | Estimated Investment (US$) | Lengthkm | Inv per km (US$) |
|---|---|---|---|---|---|---|
| http://bit.ly/2PmmZHc | Saddle West Pipeline | TransCanada | Proposed | 655,000,000 | 29 | 22,586,207 |
| http://bit.ly/2gqy1bb | Alaska LNG Pipeline (AKLNG) | Alaska Gasline Development Corp (AGDC) | Proposed | 55,000,000,000 | 2760 | 19,927,536 |
| http://bit.ly/2z9PJeY | Driftwood LNG Pipeline | Tellurian Inc. | Proposed | 2,900,000,000 | 154 | 18,831,169 |
| http://bit.ly/2RB09JD | Kukrahati-Itinda Gas Pipeline | H-Energy | Proposed | 1,828,846,000 | 125 | 14,630,768 |
| http://bit.ly/2BPP9Ba | Rio Bravo Gas Pipeline | NextDecade | Proposed | 2,200,000,000 | 220 | 10,000,000 |
| http://bit.ly/2Pk8x2B | Eagle Spirit Pipeline | Eagle Spirit Energy Holdings Ltd. | Proposed | 16,000,000,000 | 1601.3 | 9,991,882 |
| http://bit.ly/2RnomCZ | TEMAX Project | Spectra Energy (50%), ConocoPhillips (50%) | Proposed | 500,000,000 | 53.1 | 9,416,196 |
| http://bit.ly/2PzmJVt | 2019 NGTL System | TransCanada | Proposed | 2,400,000,000 | 275.2 | 8,720,930 |
| http://bit.ly/2JfrAFN | Sooner Trails Pipeline | | Proposed | 3,500,000,000 | 402.3 | 8,699,975 |
| http://bit.ly/2Je5SC1 | Granite Bridge Pipeline | Algonquin Power & Utilities Corp. | Proposed | 340,000,000 | 43.5 | 7,816,092 |
| http://bit.ly/2Rk8wcc | Buckeye Xpress Pipeline | TransCanada | Proposed | 709,000,000 | 103 | 6,883,495 |
| http://bit.ly/2PyoSk6 | North Montney Mainline Pipeline | TransCanada | Proposed | 1,400,000,000 | 206 | 6,796,117 |
| http://bit.ly/2PzmJVt | 2018 NGTL System | TransCanada | Proposed | 570,000,000 | 88.5 | 6,440,678 |
| http://bit.ly/2Rnu1ZS | Wyndwood Pipeline Expansion Project | Spectra Energy | Proposed | 170,300,000 | 27.4 | 6,215,328 |
| http://bit.ly/2JfajfN | South Saskatchewan Access Pipeline | | Proposed | 47,000,000 | 8 | 5,875,000 |
| http://bit.ly/2z8EW4K | Eagle Mountain-Woodfibre gas pipeline | FortisEnergy B.C. | Proposed | 250,000,000 | 47 | 5,319,149 |
| http://bit.ly/2Jkk5gZ | Haynesville Global Access Pipeline | Tellurian | Proposed | 1,400,000,000 | 321.9 | 4,349,177 |
| http://bit.ly/2JfpJAP | Delmarva Pipeline | H4 Capital Partners LLC | Proposed | 1,300,000,000 | 305.8 | 4,251,145 |
| http://bit.ly/2Je683X | Buncombe County Pipeline | SCANA | Proposed | 72,500,000 | 19.3 | 3,756,477 |
| http://bit.ly/2gAgk8W | Keystone XL Oil Pipeline | TransCanada | Proposed | 7,000,000,000 | 1900 | 3,684,211 |
| http://bit.ly/2PmwBBY | Permian Global Access Pipeline | Tellurian Inc. | Proposed | 3,700,000,000 | 1005.8 | 3,678,664 |
| https://bit.ly/2CTIisZ | Cirebon-KHT Gas Pipeline | Rekind | Proposed | 300,000,000 | 84 | 3,571,429 |
| http://bit.ly/2ptQvws | West-East Gas Pipeline | | Proposed | 5,000,000,000 | 1500 | 3,333,333 |
| http://bit.ly/2BSPbbq | Northern Access Gas Pipeline | National Fuel Gas Company | Proposed | 500,000,000 | 155 | 3,225,806 |
| http://bit.ly/2RtenMu | East Med Gas Pipeline | | Proposed | 7,000,000,000 | 2200 | 3,181,818 |
| http://bit.ly/2RwOzPk | Bay of Bengal-Chittagong Oil Pipeline | Bangladesh Petroleum Corporation | Proposed | 694,000,000 | 220 | 3,154,545 |
| http://bit.ly/2Rsr8GU | Bay of Bengal-Chittagong Oil Pipeline 2 | Bangladesh Petroleum Corporation | Proposed | 694,000,000 | 220 | 3,154,545 |
| http://bit.ly/2gA9TD5 | Pilgrim Oil Pipeline | Ares Management | Proposed | 900,000,000 | 286 | 3,146,853 |
| http://bit.ly/2JgiMzw | Big Foot Oil Pipeline | Enbridge | Proposed | 200,000,000 | 64.4 | 3,105,590 |
| http://bit.ly/2PIMXoM | Israel Jordan Gas Pipeline | | Proposed | 200,000,000 | 65 | 3,076,923 |
| http://bit.ly/2JdyiMl | Southern Reliability Link Pipeline | New Jersey Resources | Proposed | 130,000,000 | 48.3 | 2,691,511 |
| http://bit.ly/2JdyYBn | Whistler Pipeline | Targa Resources | Proposed | 2,600,000,000 | 997.8 | 2,605,733 |
| http://bit.ly/2PiDpQR | Permian to Gulf Coast Pipeline | | Proposed | 2,000,000,000 | 965.6 | 2,071,251 |
| http://bit.ly/2JfqlX9 | Marquette Connector Pipeline | AltaGas | Proposed | 137,500,000 | 67.6 | 2,034,024 |
| http://bit.ly/2BRlXdl | Spire STL Pipeline | Spire | Proposed | 210,000,000 | 106 | 1,981,132 |
| http://bit.ly/2Jg62cf | Risberg Line Pipeline | RH Energytrans | Proposed | 86,000,000 | 45.1 | 1,906,874 |
| http://bit.ly/2Jfeecs | Palmetto Pipeline | Kinder Morgan | Proposed | 1,100,000,000 | 579.4 | 1,898,516 |
| http://bit.ly/2PoRZGL | Energia Mayakan Pipeline Expansion | | Proposed | 300,000,000 | 159.3 | 1,883,239 |
| http://bit.ly/2RxJ6YJ | Ennore-Nellore Gas Pipeline | Gas Transmission India Private Ltd. | Proposed | 779,672,880 | 430 | 1,813,193 |
| http://bit.ly/2PCaLu9 | Israel Cyprus Gas Pipeline | Energean | Proposed | 350,000,000 | 200 | 1,750,000 |
| https://bit.ly/2OndckB | Cirebon-Semarang Gas Pipeline | PT Pertamina Gas | Proposed | 400,000,000 | 235 | 1,702,128 |
| http://bit.ly/2toFVeU | Reedy Creek Walumbilla Pipeline | APA Group | Proposed | 80,000,000 | 49 | 1,632,653 |
| http://bit.ly/2JiImUA | Arkoma Residue Capacity Pipeline | Tall Oak Midstream | Proposed | 200,000,000 | 128.7 | 1,554,002 |
| http://bit.ly/2z9Q80Y | Eastern Shore Gas Pipeline Expansion | Chesapeake Utilities | Proposed | 99,000,000 | 67 | 1,477,612 |
| http://bit.ly/2Jf2PJD | Roadrunner Pipeline | Fermaca (50%), ONEOK (50%) | Proposed | 475,000,000 | 321.9 | 1,475,614 |

| Wiki | Name | Owner | Status | Estimated Investment (US$) | Lengthkm | Inv per km (US$) |
|---|---|---|---|---|---|---|
| https://bit.ly/2Q6HN32 | Cactus 2 Oil Pipeline | Plains All American Pipeline | Proposed | 1,100,000,000 | 829 | 1,326,900 |
| http://bit.ly/2PAwBhO | Neka Jask Pipeline | National Iranian Oil Company | Proposed | 2,000,000,000 | 1515 | 1,320,132 |
| http://bit.ly/2RwyZTT | Hon La-Thakhek Oil Pipeline | Petro Lao | Proposed | 380,000,000 | 306 | 1,241,830 |
| http://bit.ly/2JdfKfr | Arctic Fox Pipeline | Fairbanks Pipeline Company | Proposed | 1,000,000,000 | 827.2 | 1,208,897 |
| http://bit.ly/2Prs29D | Iron Horse Pipeline | Tallgrass Energy (50%), Silver Creek Midstream (50%) | Proposed | 150,000,000 | 128.7 | 1,165,501 |
| http://bit.ly/2PeJ36P | Knight Warrior Pipeline | Blueknight Energy Partners | Proposed | 300,000,000 | 257.5 | 1,165,049 |
| https://bit.ly/2Ps2Yz6 | Salina Cruz-Tapachula Gas Pipeline | Afinan | Proposed | 442,000,000 | 440 | 1,004,545 |
| http://bit.ly/2DHBYSf | Western Slopes Pipeline | APA Group | Proposed | 450,000,000 | 450 | 1,000,000 |
| https://bit.ly/2pU3kjO | Natuna-West Kalimantan Gas Pipeline | TBD | Proposed | 550,000,000 | 687 | 800,582 |
| http://bit.ly/2z11vlV | Yamoussoukro-Ferkessédougou Petroleum Products Pipeline | Petroci | Proposed | 250,000,000 | 357 | 700,280 |
| http://bit.ly/2oZrgBj | Queensland Hunter Gas Pipeline | Hunter Gas Pipeline Pty Ltd | Proposed | 500,000,000 | 825 | 606,061 |
| https://bit.ly/2CgE7ak | Central Kalimantan-South Kalimantan Gas Pipeline | TBD | Proposed | 97,000,000 | 162 | 598,765 |
| http://bit.ly/2RwKV8k | Barauni-Guwahati Gas Pipeline | | Proposed | 414,900,000 | 750 | 553,200 |
| http://bit.ly/2JeJZTg | Mountaineer Gas Pipeline | IGS Utilities | Proposed | 45,000,000 | 90.8 | 495,595 |
| http://bit.ly/2RDXjUf | Contai-Paradip-Dattapulia Gas Pipeline | H-Energy | Proposed | 333,858,720 | 705 | 473,558 |
| http://bit.ly/2RtwnWW | Mehsana-Bhatinda Gas Pipeline | Gujarat State Petronet; Indian Oil; Bharat Petroleum; Hindustan Petroleum | Proposed | 955,674,720 | 2052 | 465,728 |
| http://bit.ly/2JgXd1u | Doosan Bobcat Pipeline | MDU Resources Group | Proposed | 13,800,000 | 33.8 | 408,284 |
| http://bit.ly/2PzmJVt | 2021 NGTL System | TransCanada | Proposed | 140,000,000 | 350.8 | 399,088 |
| https://bit.ly/2IYxniG | West Kalimantan-Central Kalimantan Gas Pipeline | TBD | Proposed | 516,400,000 | 1800 | 286,889 |

# Articles and resources

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## External resources

## External articles

# Appendix A7: Critical Infrastructures Impact due to Subsidence Terrain

# Appendix A7: Critical Infrastructures Impact due to Subsided Terrain

Critical infrastructures are necessary to maintain the normalcy of everyday life. They are also vital, particularly to flood response activities and the health and safety of the public before, during, and after a flood. These include a vast network of transportation infrastructures (airports and runways, roadways, railways, bus facilities, bridges, tunnels, port facilities, etc.), municipal infrastructure (storm sewer, sanitary sewer, water mains, manholes, hydrants, valves, junctions, outfalls, outfall protection, pump), transmission pipelines (drinking and wastewater utilities, oil and gas), electric infrastructures (fiber optic cables, power lines with power poles), communications lines, schools, hazmat facilities, medical facilities, fire stations, police stations, emergency operations, etc. Please refer to the Data Collection Memorandum (Michael Baker International Inc., 2024) for details and sources of Critical infrastructure.

Land subsidence can significantly damage critical infrastructures through the differential settlement of the foundation. This is a separate impact from increased flood risk. Even uniform settlement can cause structural instability due to changes in topographic gradient or surface rupture, increased risk of flooding, or saltwater intrusion in coastal areas. This can result in substantial damage and a significant impact on the property values of the infrastructure.

The economic impact of differential or uniform subsidence on these critical infrastructures was outside the scope of this study and was not included in the overall economic impact. This is a potential area for future study. However, the spatial locations of all structures (including all building critical infrastructures) and some critical infrastructures within the Spring Creek Watershed, along with the subsidence depth contours, are discussed in the following sections.

## 1. Structures

The NSI data indicated there are more than 108,000 structures that have a total estimated asset value of more than $36 billion within the four (4) counties (Montgomery, Harris, Grimes, and Waller) within the Spring Creek watershed, as shown in **Table 1**. However, these structures reflect a different range of subsidence, ranging from 0.25 feet to 3.47 feet**. Table 2** and **Figure 1** show the highest number (52,404 (48%)) and values (~$19 billion (53%)) of structures are subsided by two (2) to three (3) feet whereas the lowest number (3,161 (3%)) and values (~$900 million (3%)) of structures are subsided by less than 6 inches.

**Table 1: Structures Value within Spring Creek Watershed**

| Counties | Structures Value (Million USD) |
|---|---|
| Harris | 8,200 |
| Grimes | 530 |
| Montgomery | 26,200 |
| Waller | 1,400 |
| **Total** | **36,330** |

**Table 2: Number and Percentage of Structures in Different Subsidence Depth Intervals within Spring Creek Watershed**

| Subsidence Depth Range (feet) | Number of Structures | Structure Value (Million USD) |
|---|---|---|
| **0.0 – 0.5** | 3,161 (3%) | 914 (3%) |
| **0.5 – 1.0** | 6,703 (6%) | 1,613 (4%) |
| **1.0 – 2.0** | 24,909 (23%) | 6,449 (18%) |
| **2.0 – 3.0** | 52,404 (48%) | 19,149 (53%) |
| **> 3.0** | 21,564 (20%) | 8,178 (23%) |
| **Total** | **108,741** | **36,302** |

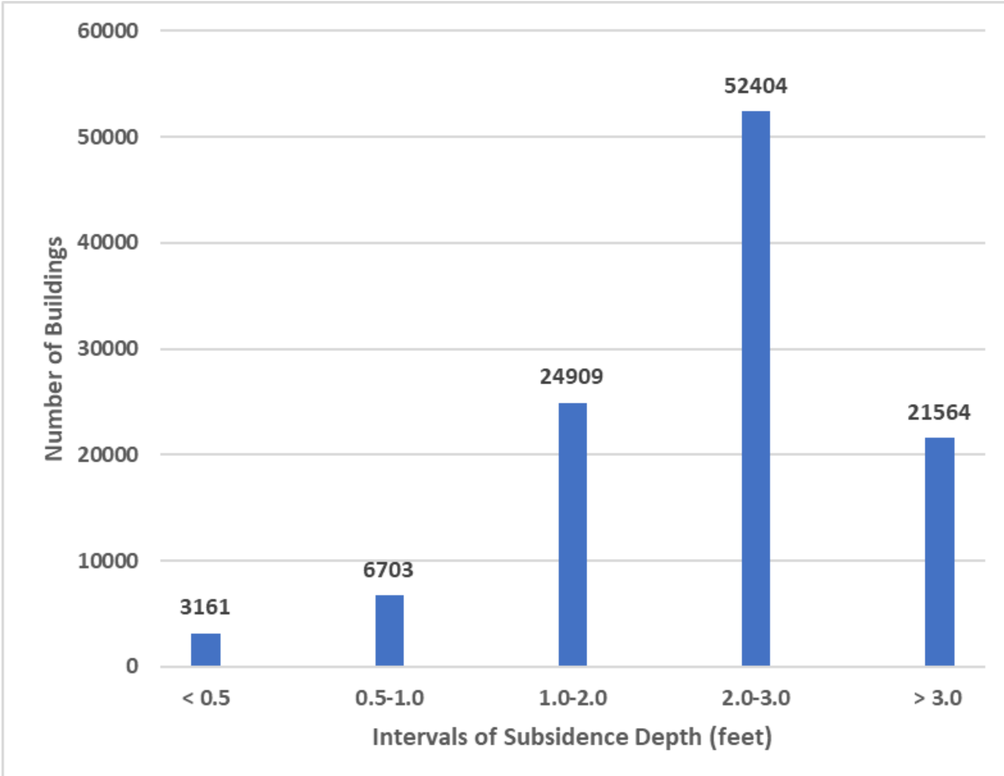



**Figure 1: Number of Structures in different Subsidence Depth Intervals within Spring Creek Watershed**

## 2. Critical Infrastructure

Within Spring Creek watershed, among all critical infrastructures, there are 4 medical facilities, 19 fire stations, 10 police stations, 89 schools, 19 wastewater facilities, one (1) communication center, 6 hazmat facilities, and 110 highway bridges in Spring Creek watershed. These critical infrastructures, along with subsidence depth contours, are shown in **Figure 2**. The critical infrastructure near Woodlands suffers the highest subsidence. The estimated market values of these critical infrastructures are included in the total values of the structures shown in **Appendix A3.**

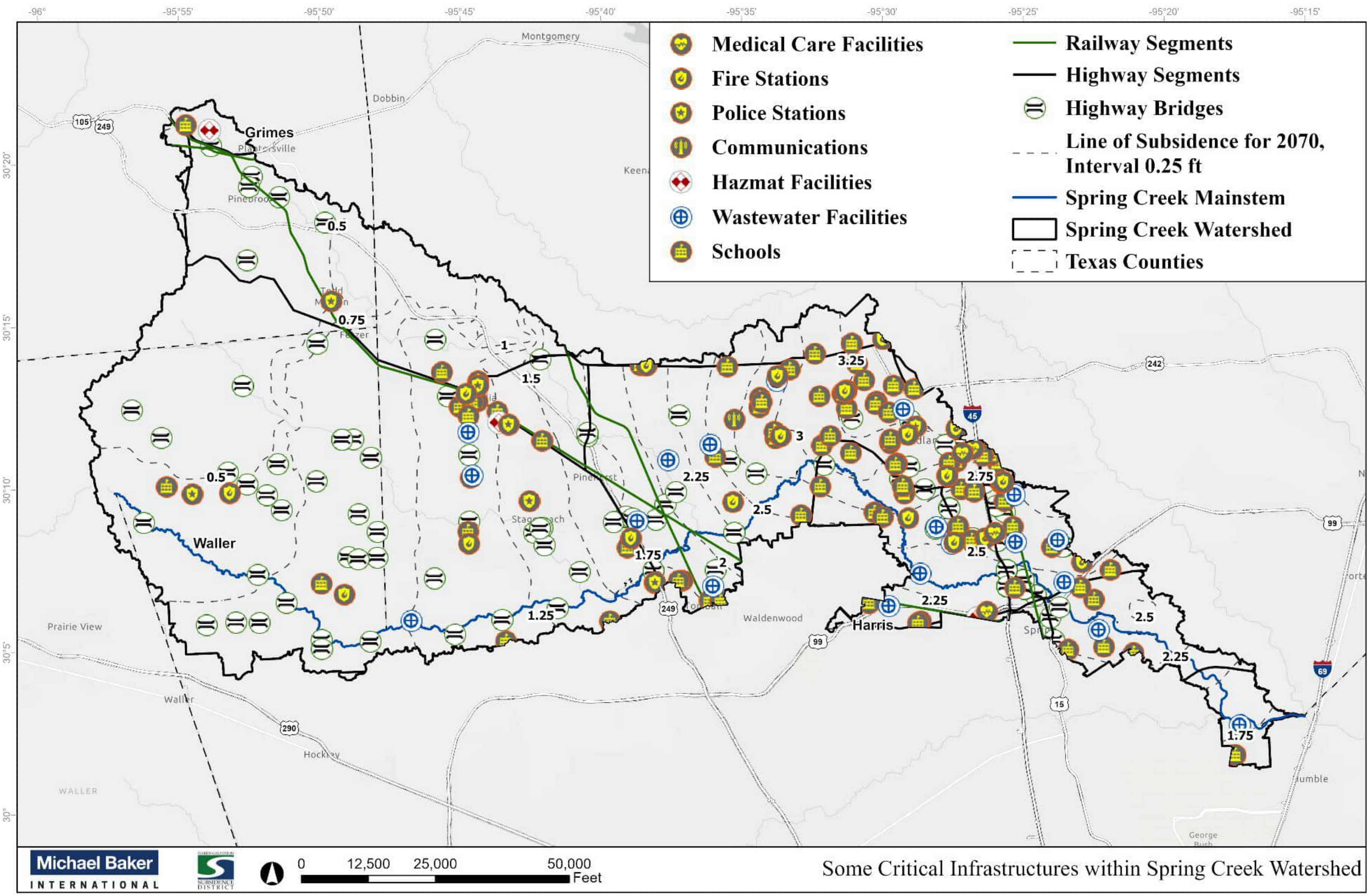
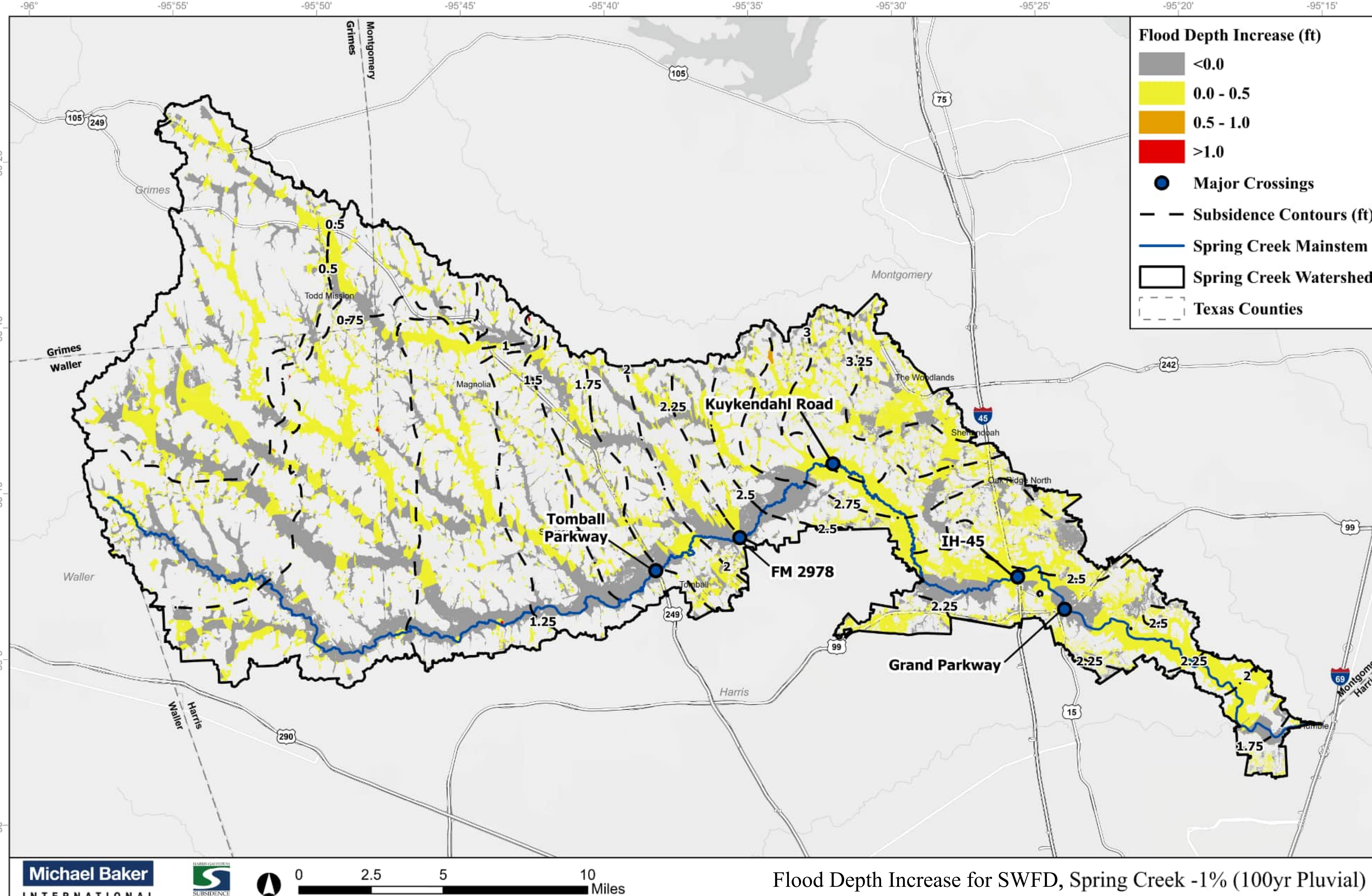
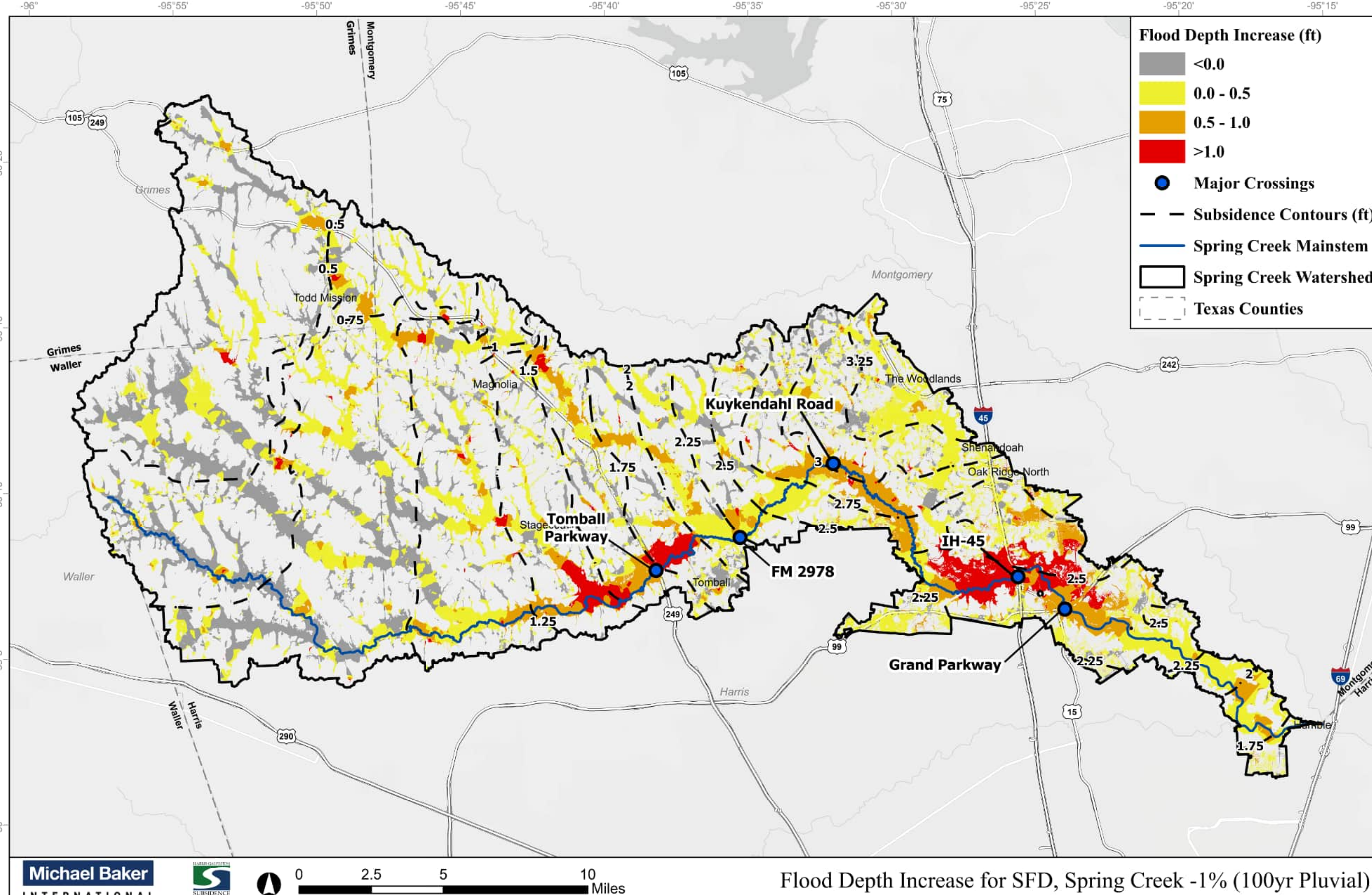



**Figure 2: Some Critical Infrastructure along with Subsidence Depth within Spring Creek Watershed**

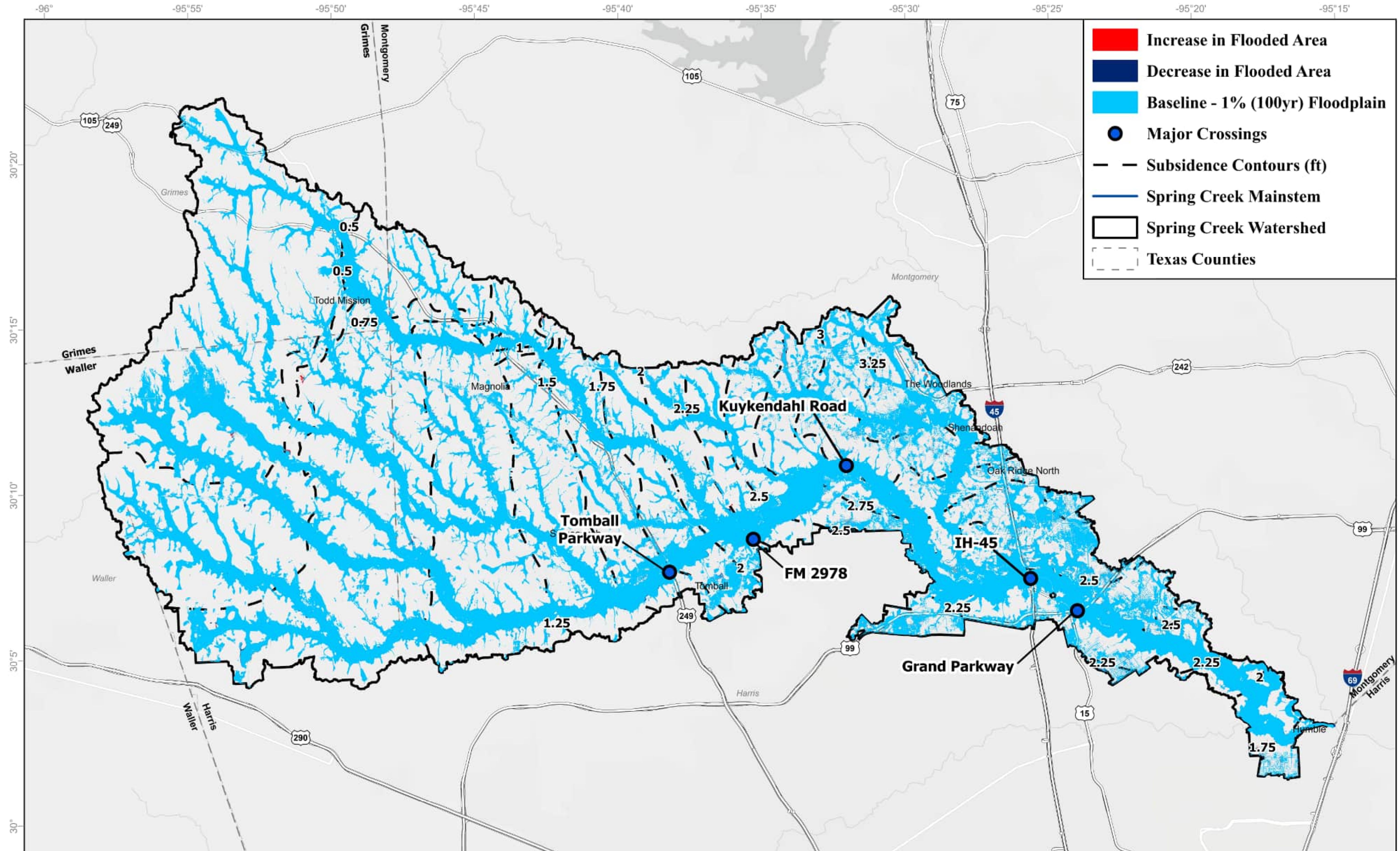
# Appendix B: Exhibits




Flood Depth Increase for SWFD, Spring Creek -1% (100yr Pluvial)

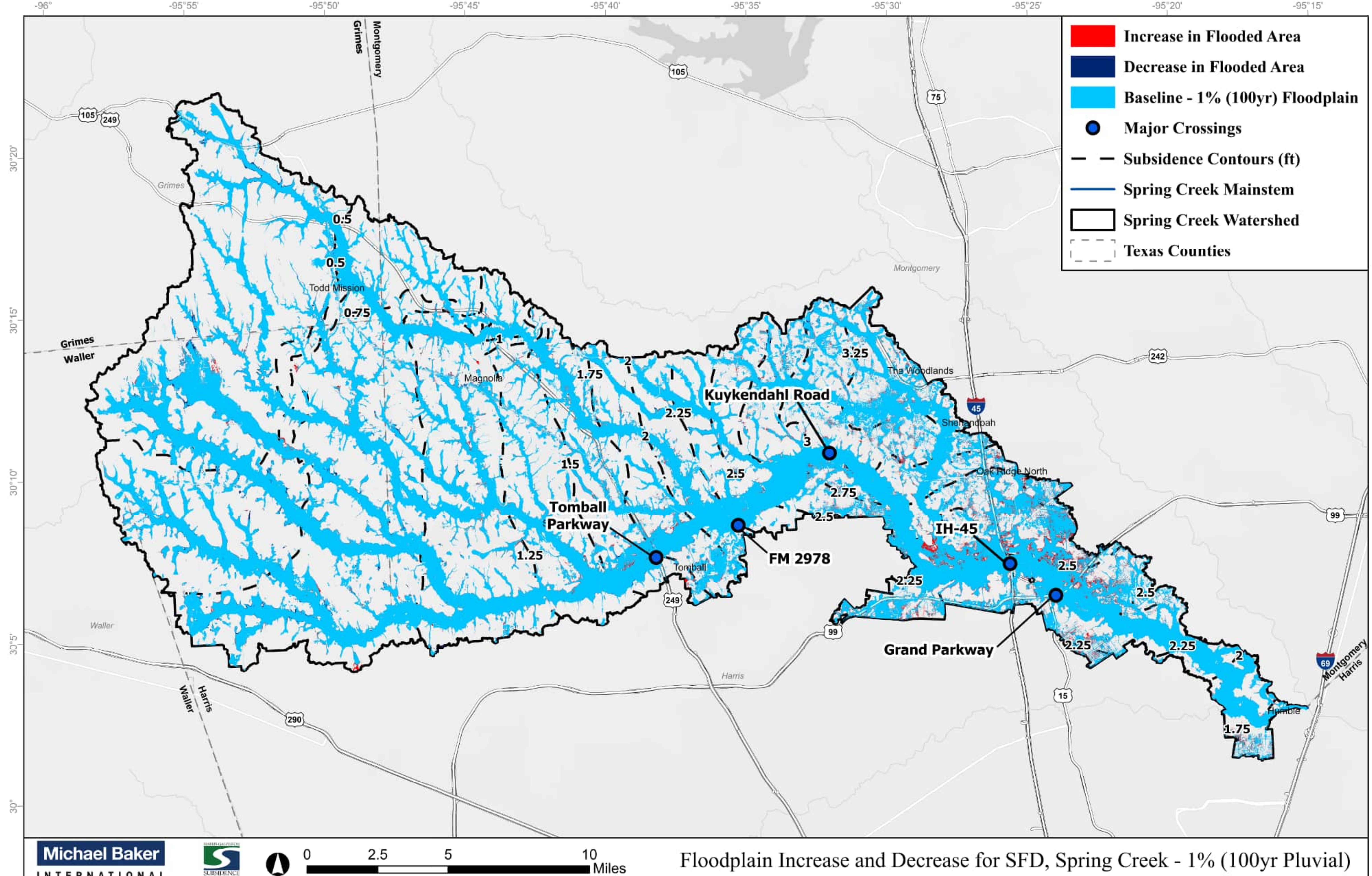



Flood Depth Increase for SFD, Spring Creek -1% (100yr Pluvial)

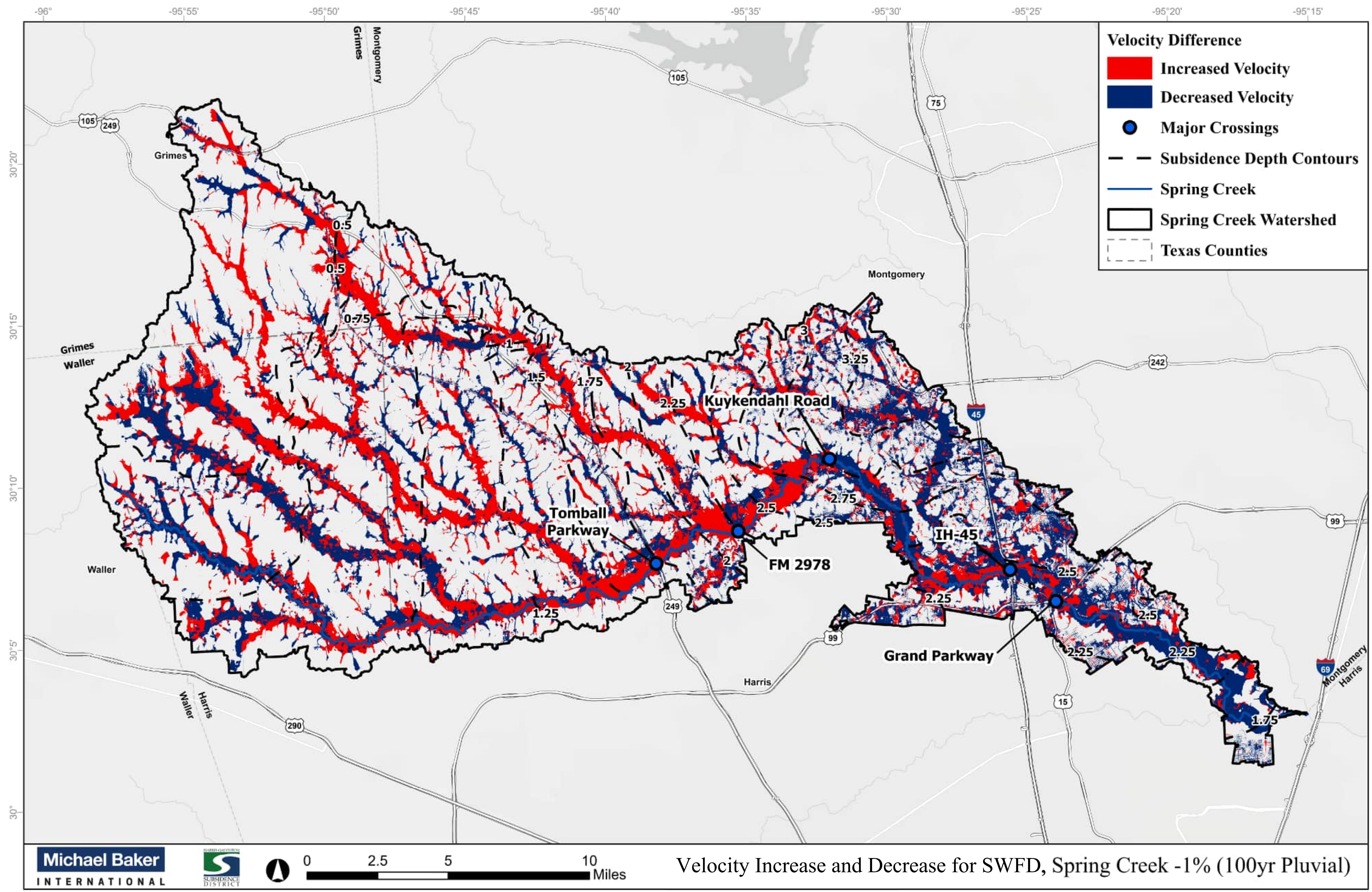



Michael Baker INTERNATIONAL

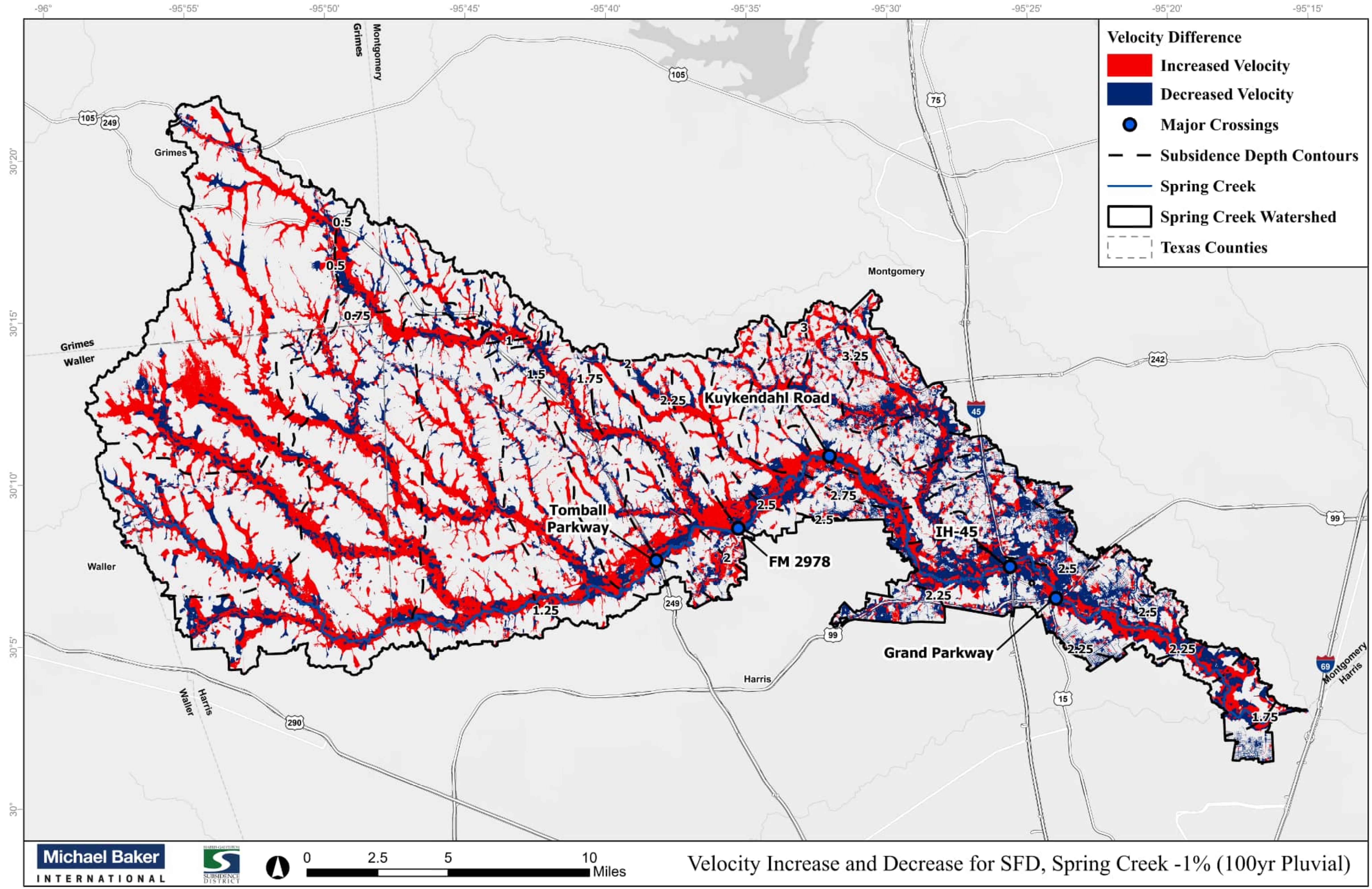
Floodplain Increase and Decrease for SWFD, Spring Creek -1% (100yr Pluvial)



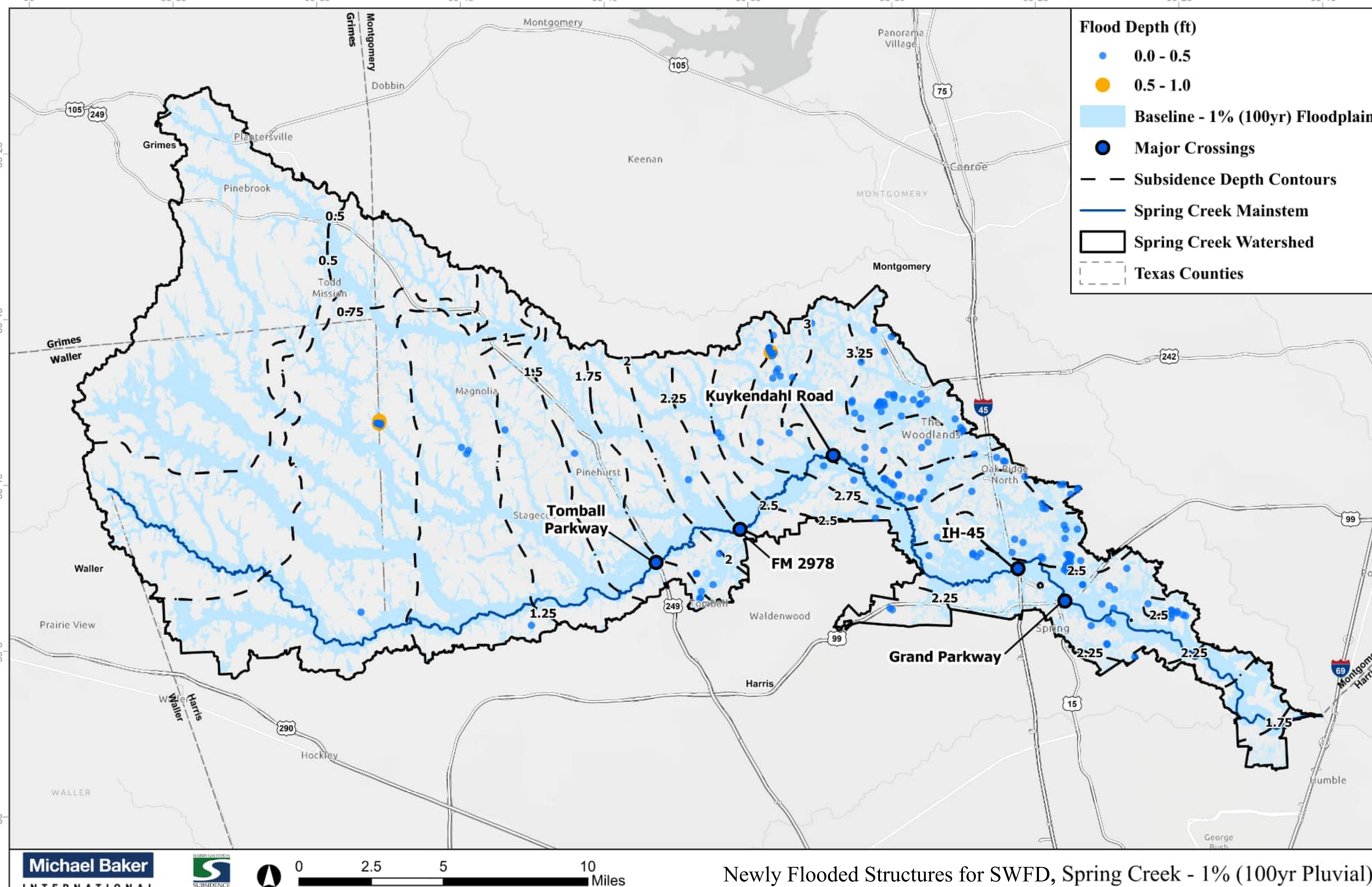

Floodplain Increase and Decrease for SFD, Spring Creek - 1% (100yr Pluvial)



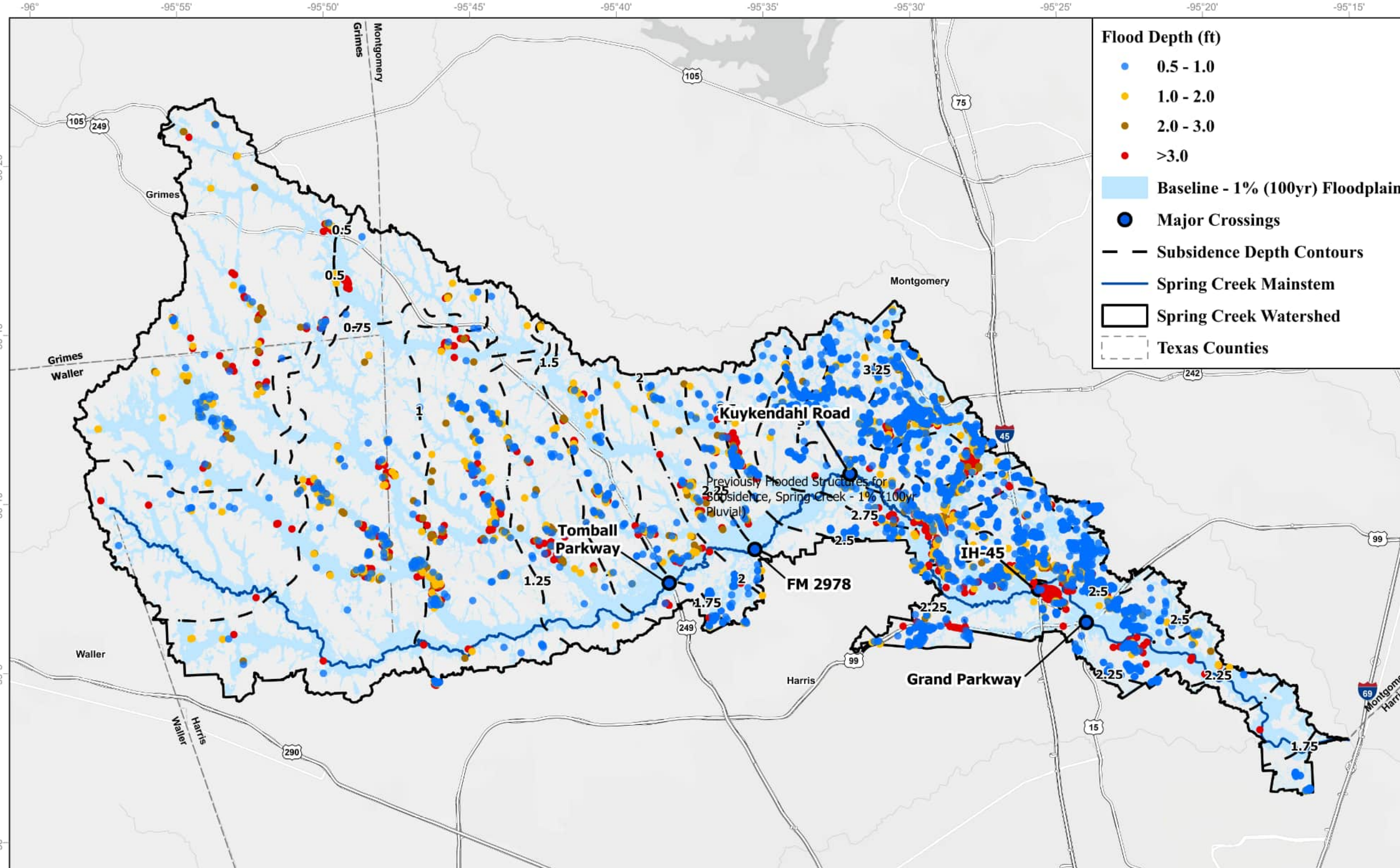

Velocity Increase and Decrease for SWFD, Spring Creek -1% (100yr Pluvial)




Velocity Increase and Decrease for SFD, Spring Creek -1% (100yr Pluvial)

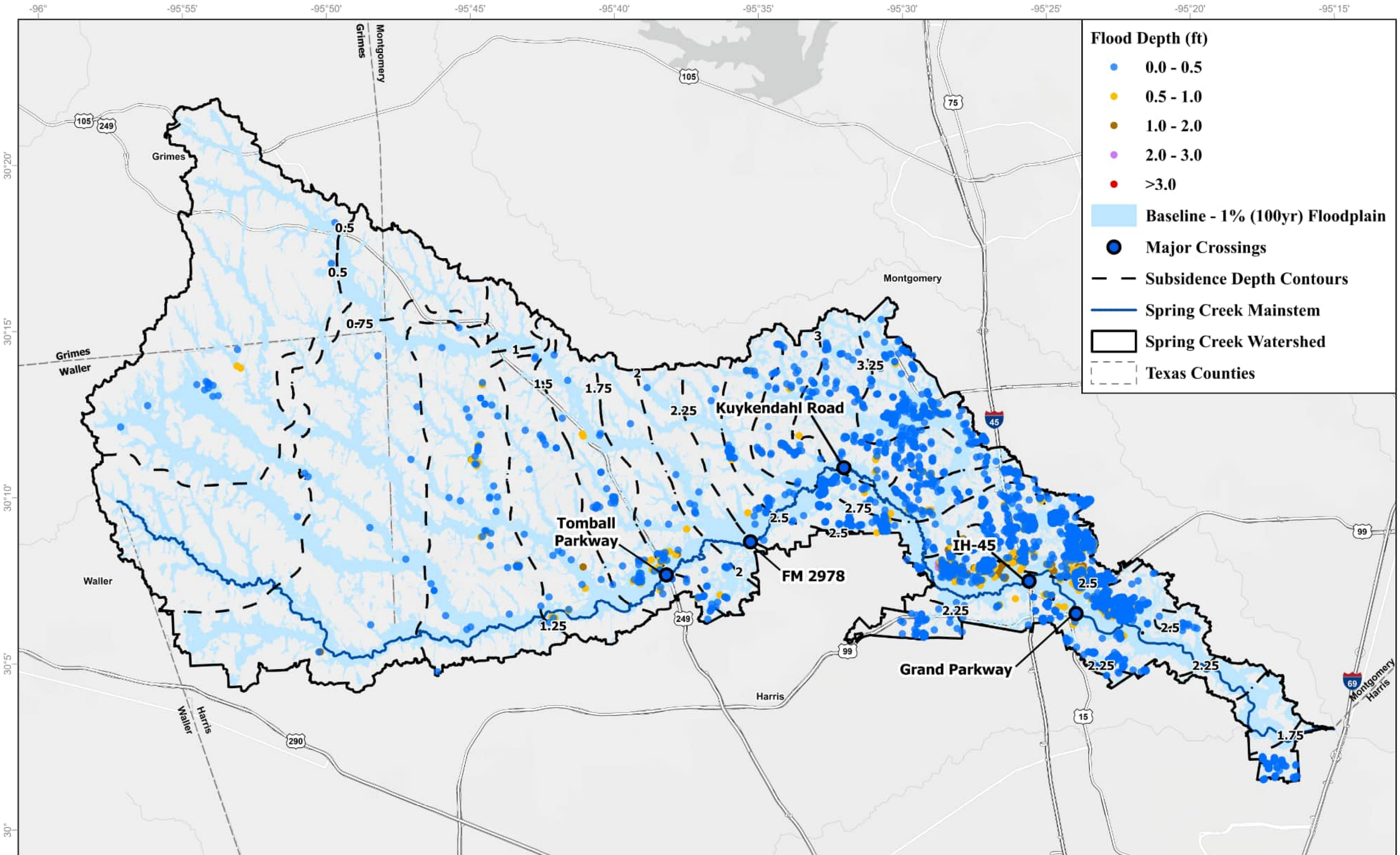



Newly Flooded Structures for SWFD, Spring Creek - 1% (100yr Pluvial)



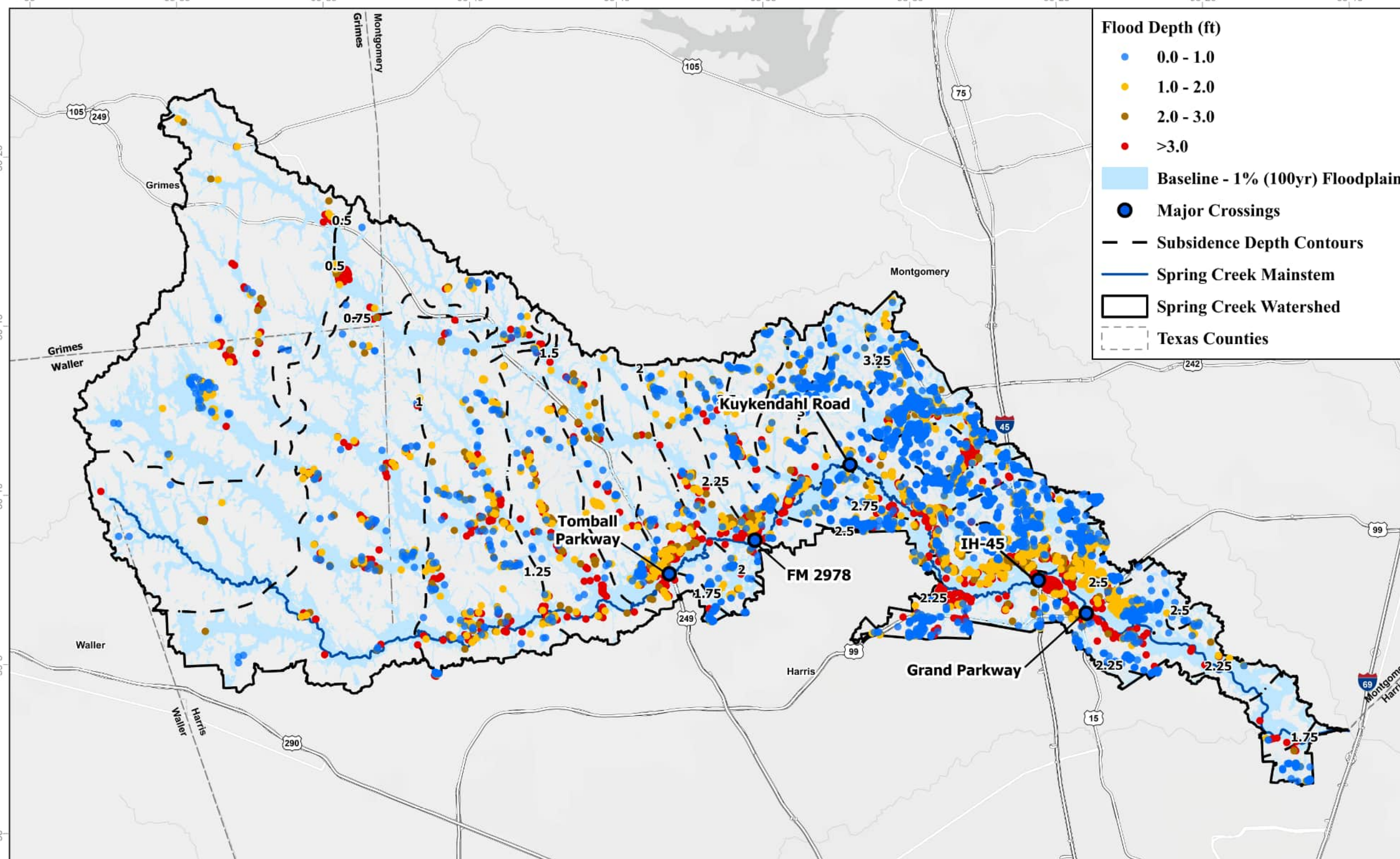

Michael Baker INTERNATIONAL

Commonly Flooded Structures for SWFD, Spring Creek - 1% (100yr Pluvial)

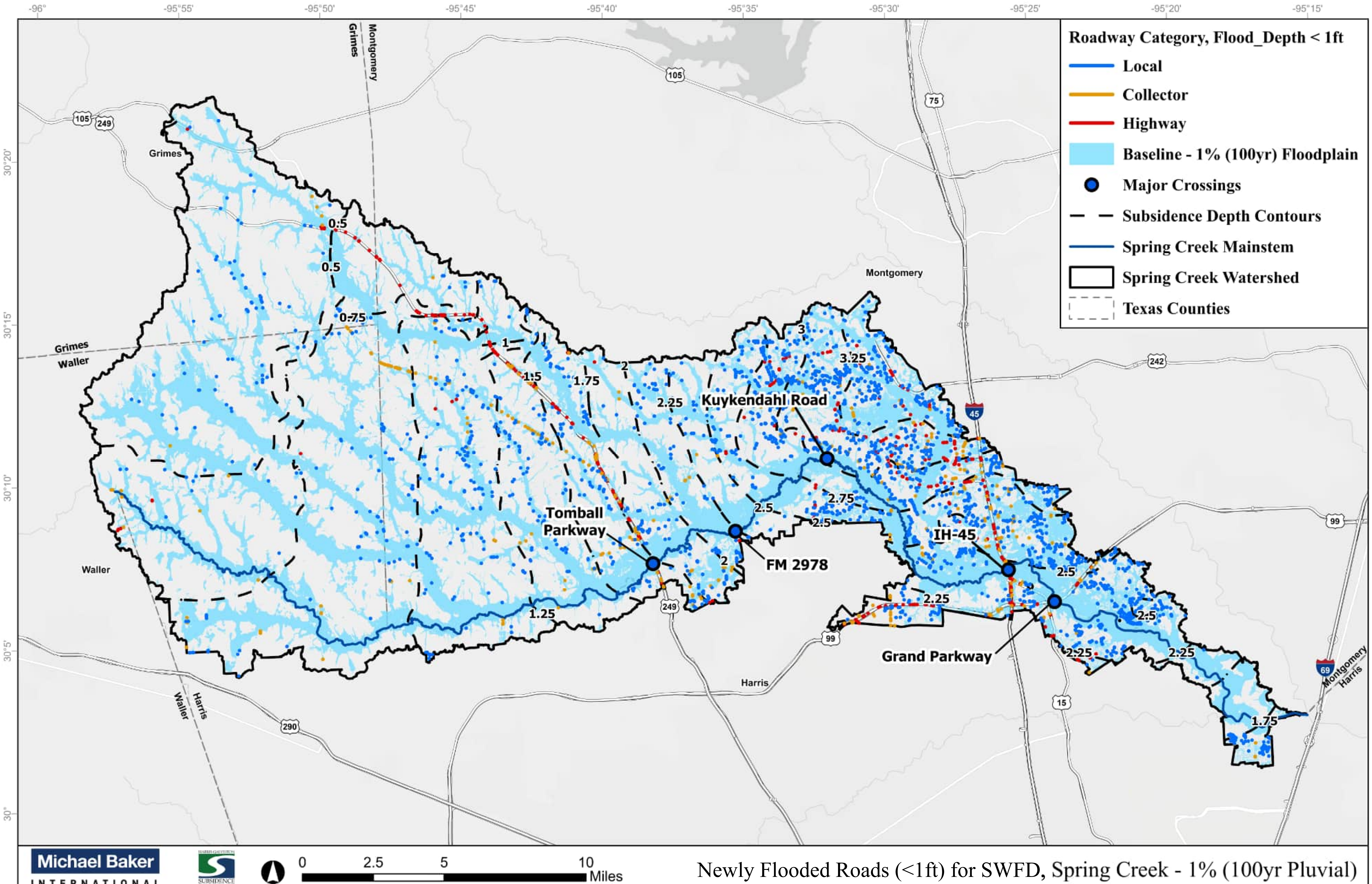



Newly Flooded Structures for SFD, Spring Creek - 1% (100yr Pluvial)

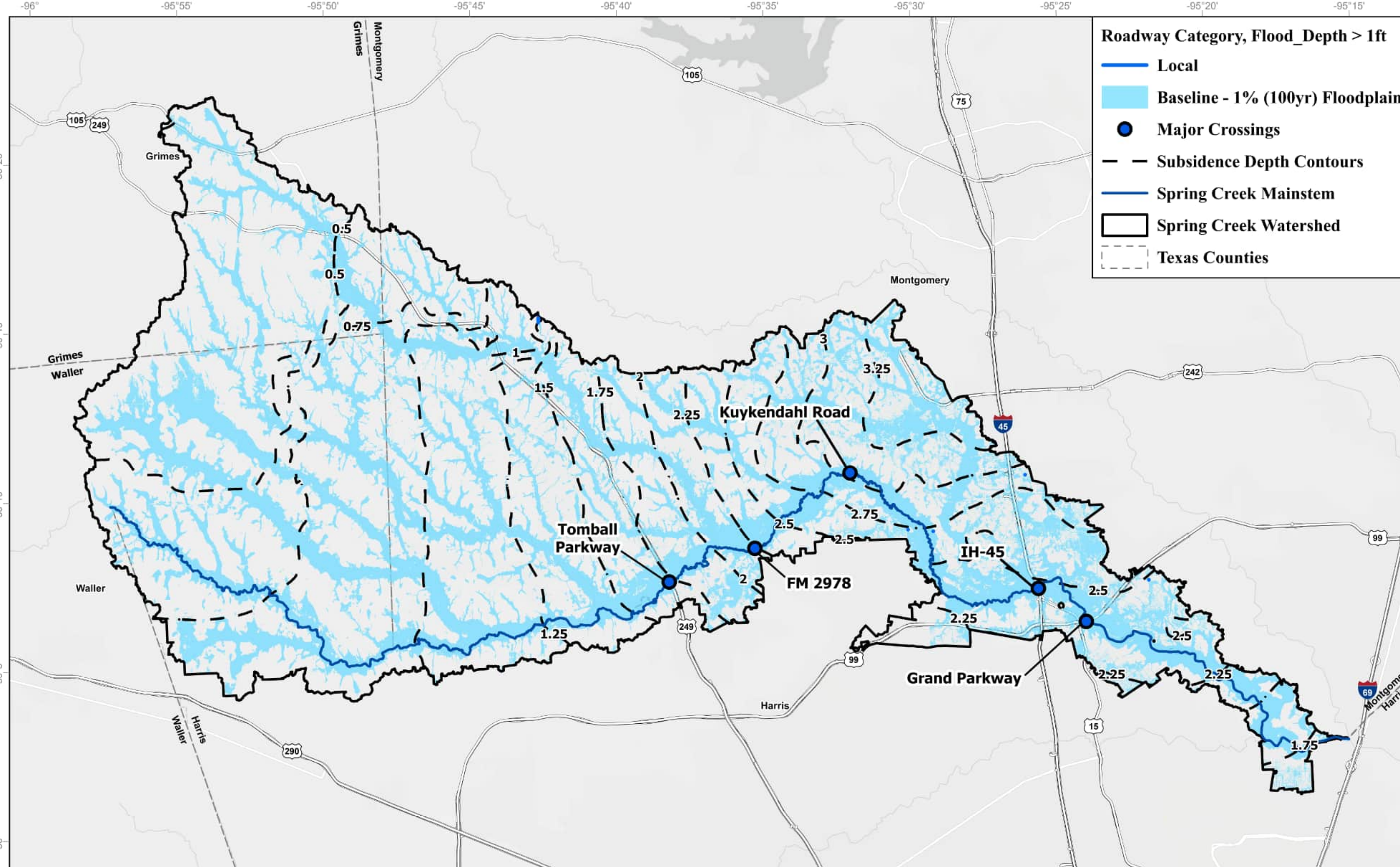
Michael Baker INTERNATIONAL




Commonly Flooded Structures for SFD, Spring Creek - 1% (100yr Pluvial)




Newly Flooded Roads (<1ft) for SWFD, Spring Creek - 1% (100yr Pluvial)



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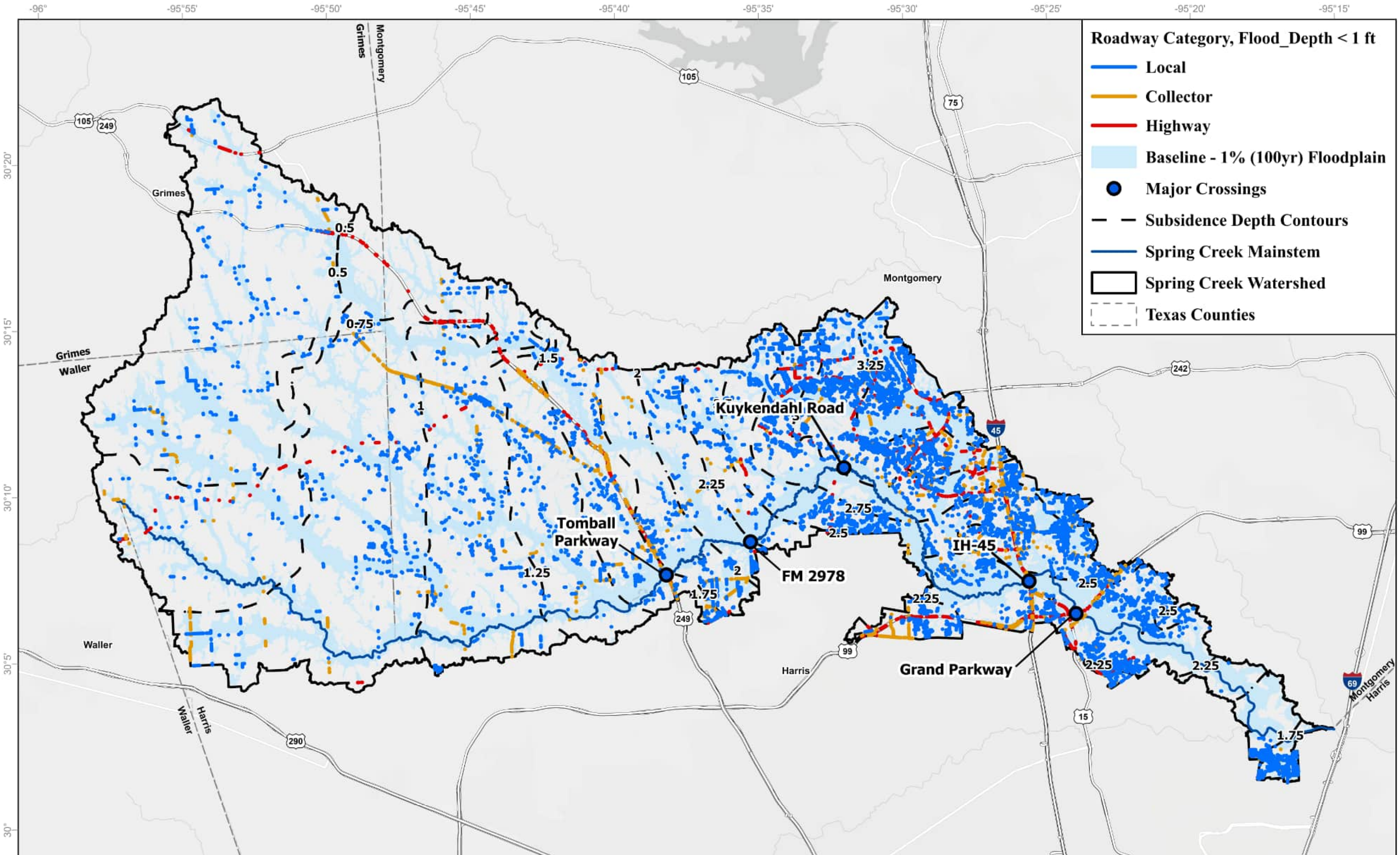
Newly Flooded Roads (>1ft) for SWFD, Spring Creek - 1% (100yr Pluvial)




Commonly Flooded Roads (<1ft) for SWFD, Spring Creek - 1% (100yr Pluvial)

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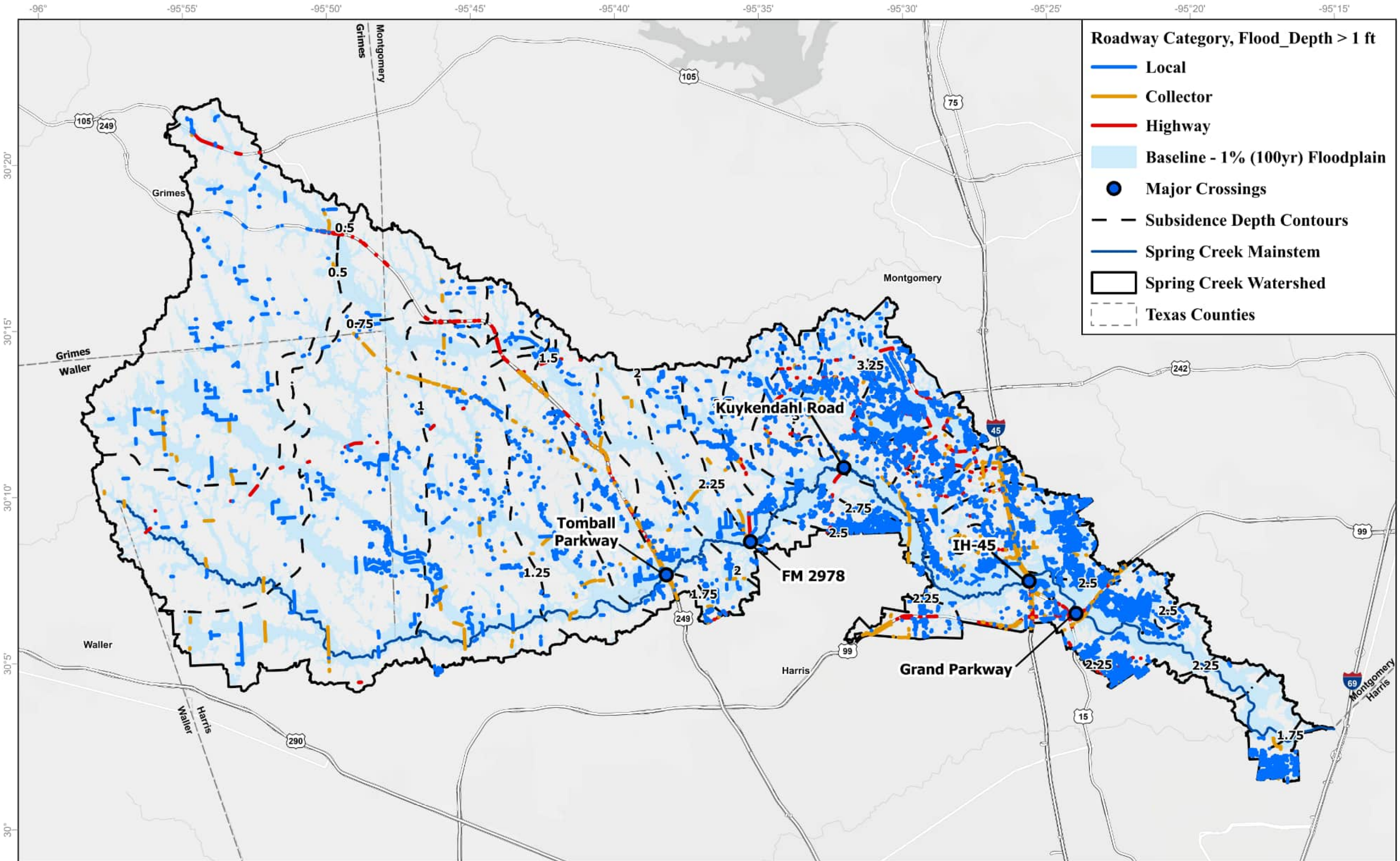
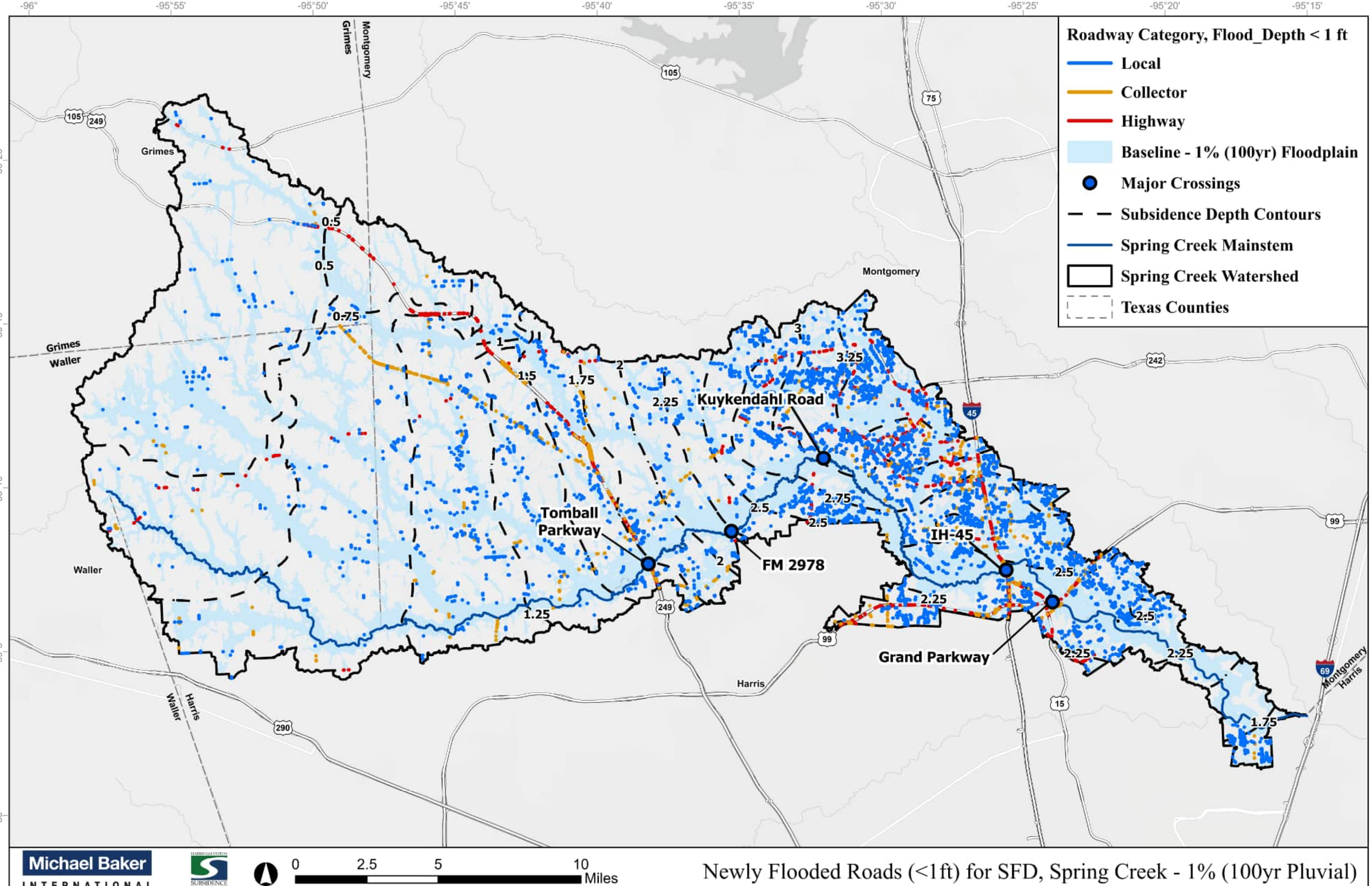
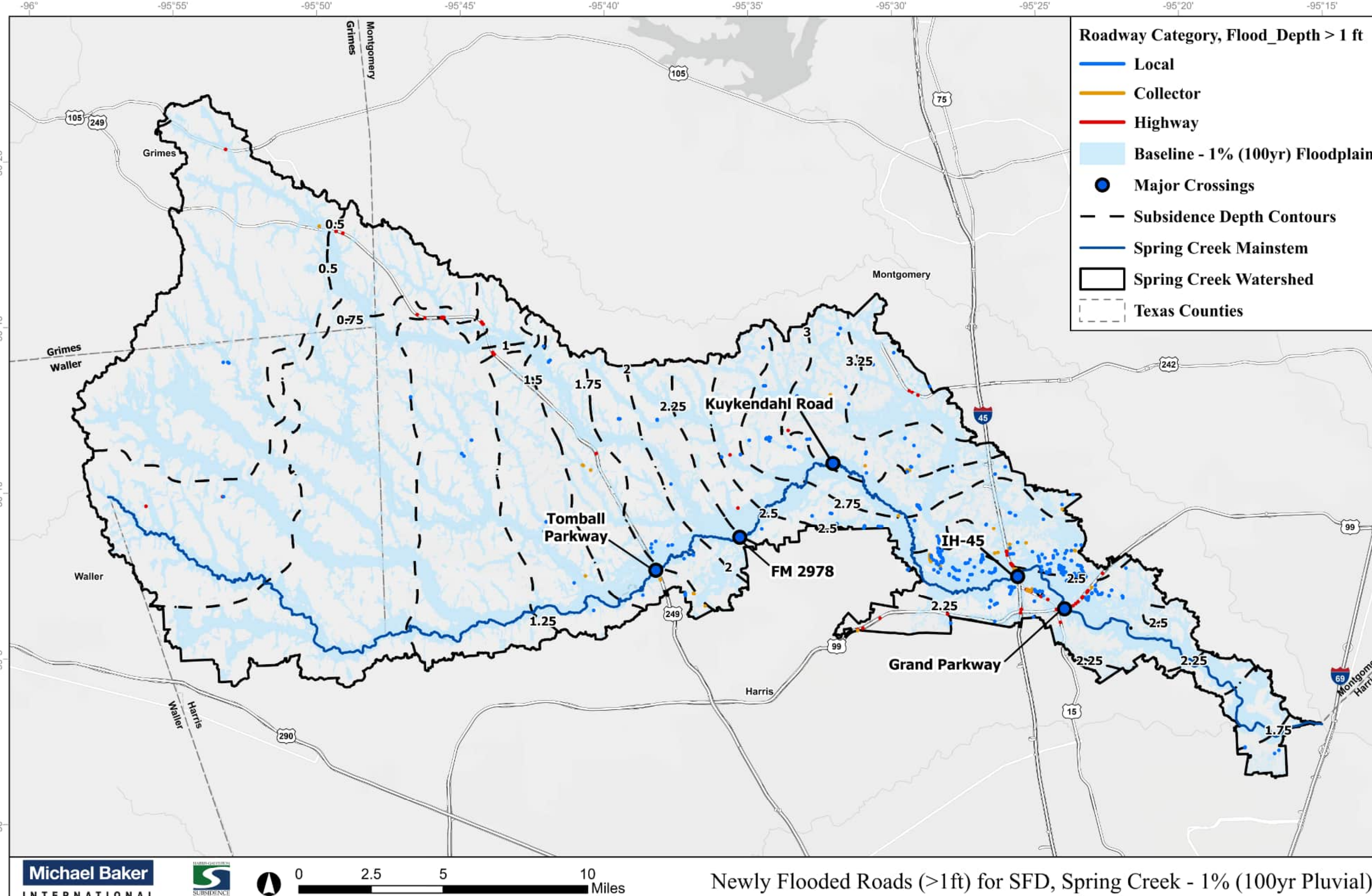


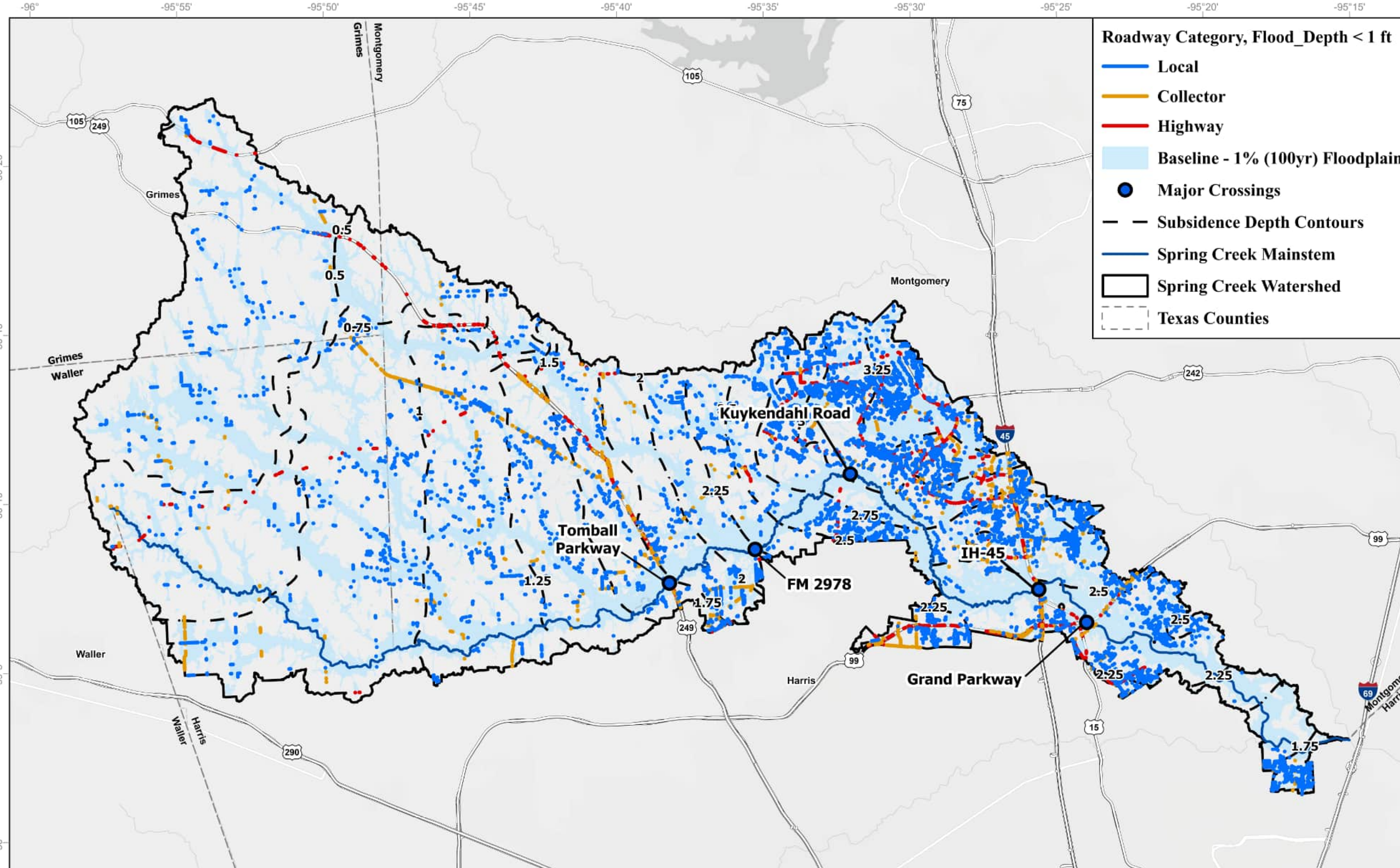

Commonly Flooded Roads (>1ft) for SWFD,Spring Creek - 1% (100yr Pluvial)




Newly Flooded Roads (<1ft) for SFD, Spring Creek - 1% (100yr Pluvial)




Newly Flooded Roads (>1ft) for SFD, Spring Creek - 1% (100yr Pluvial)

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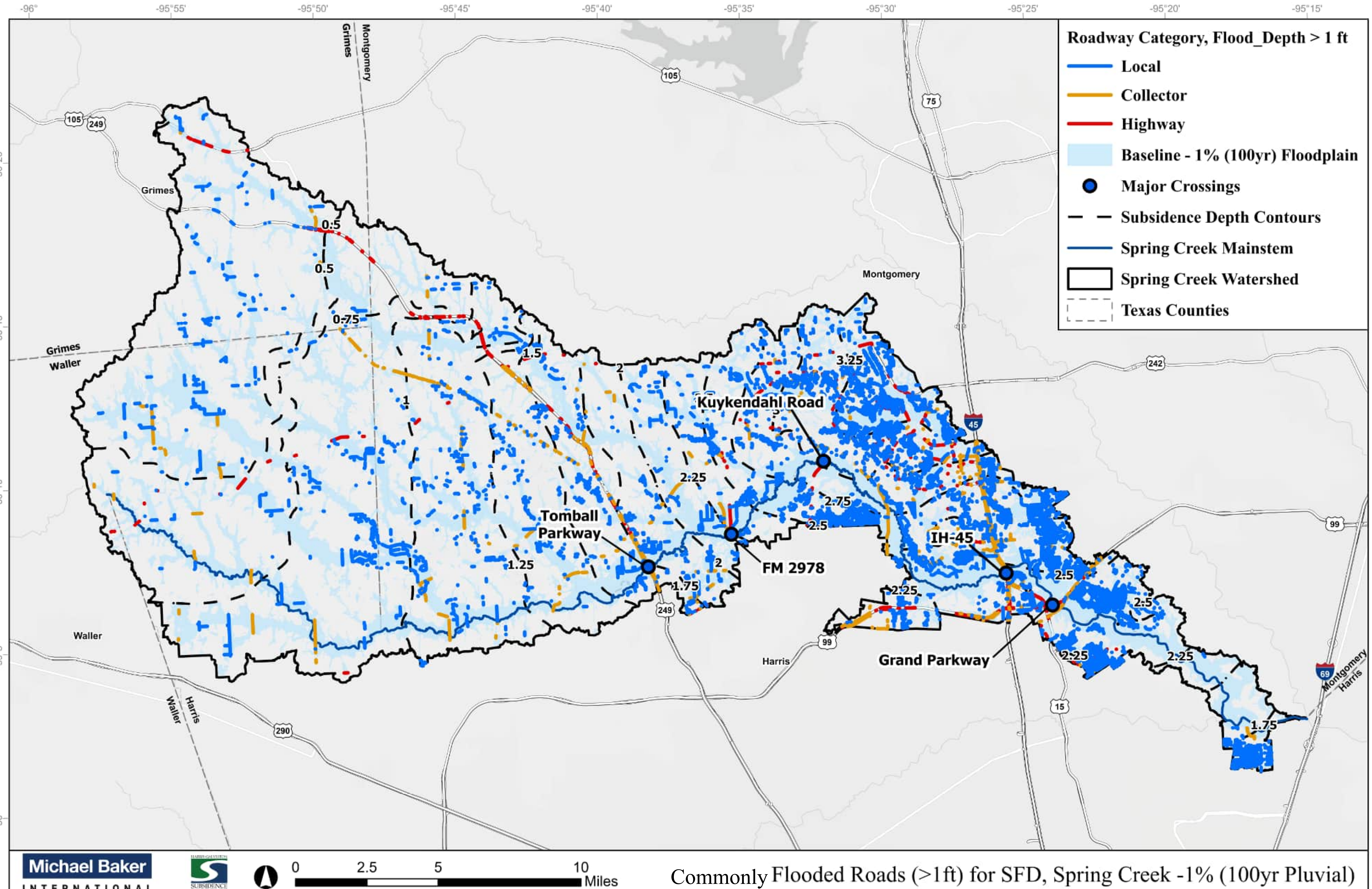
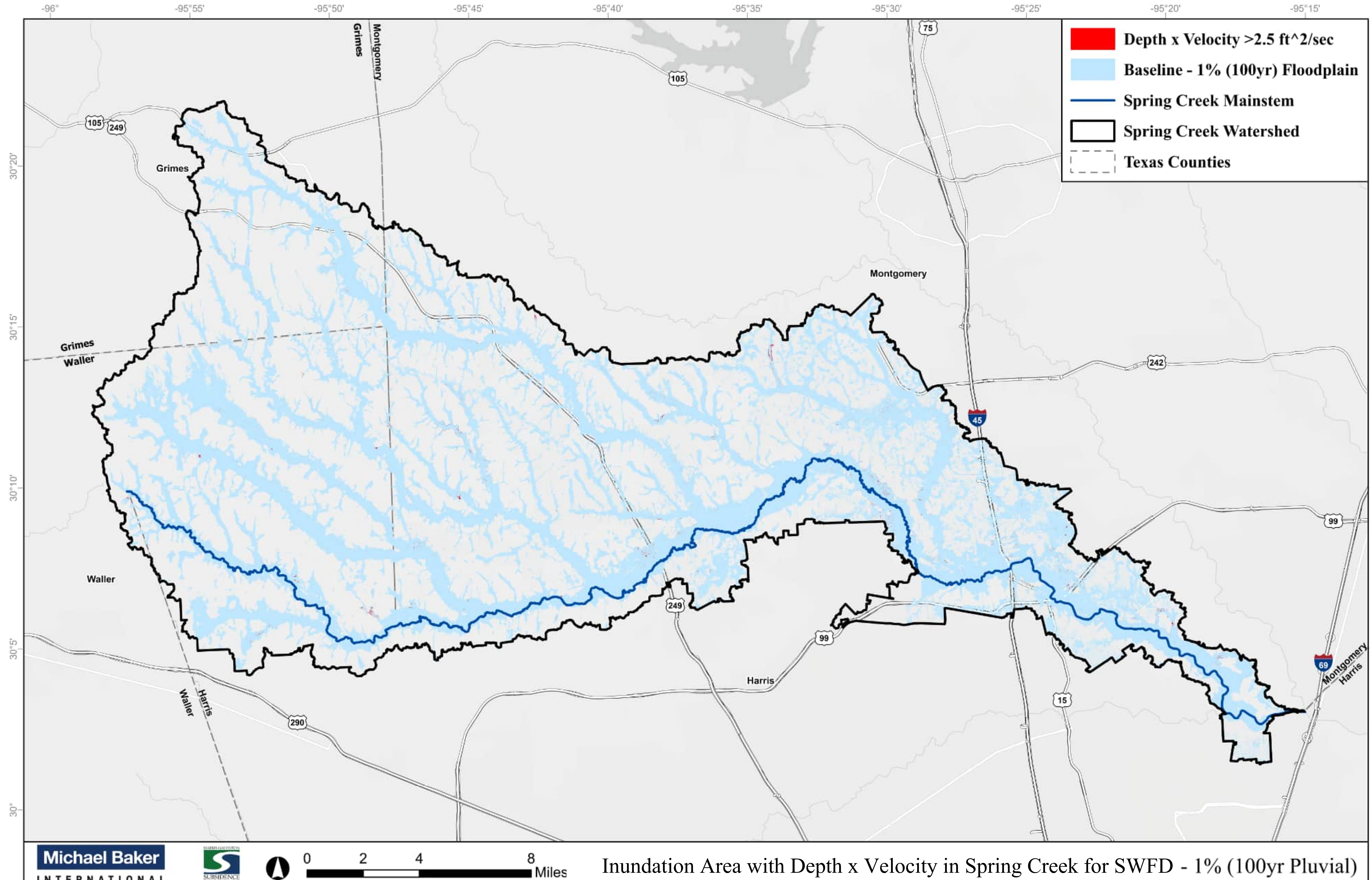
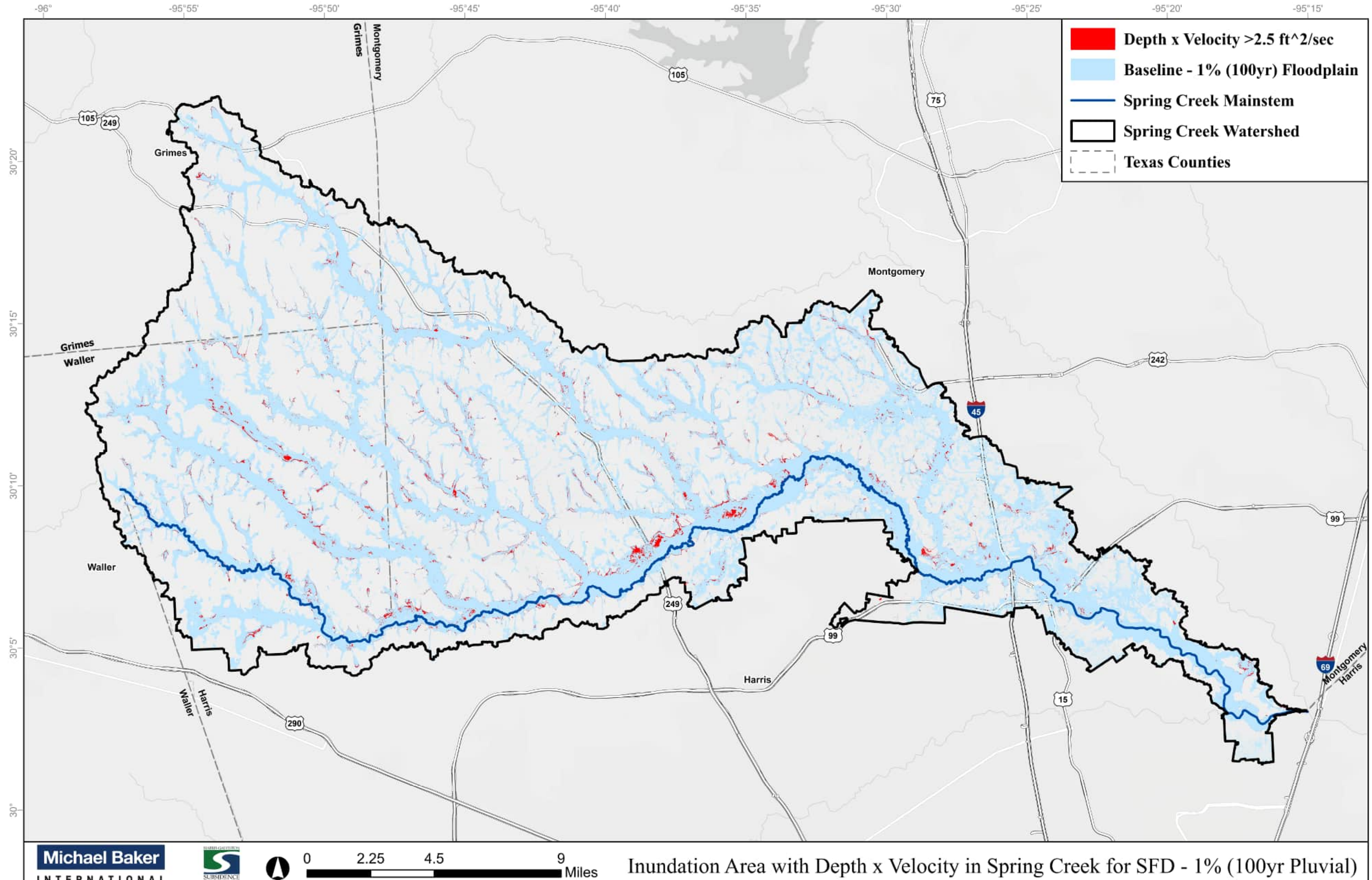
Commonly Flooded Roads (<1ft) for SFD, Spring Creek -1% (100yr Pluvial)



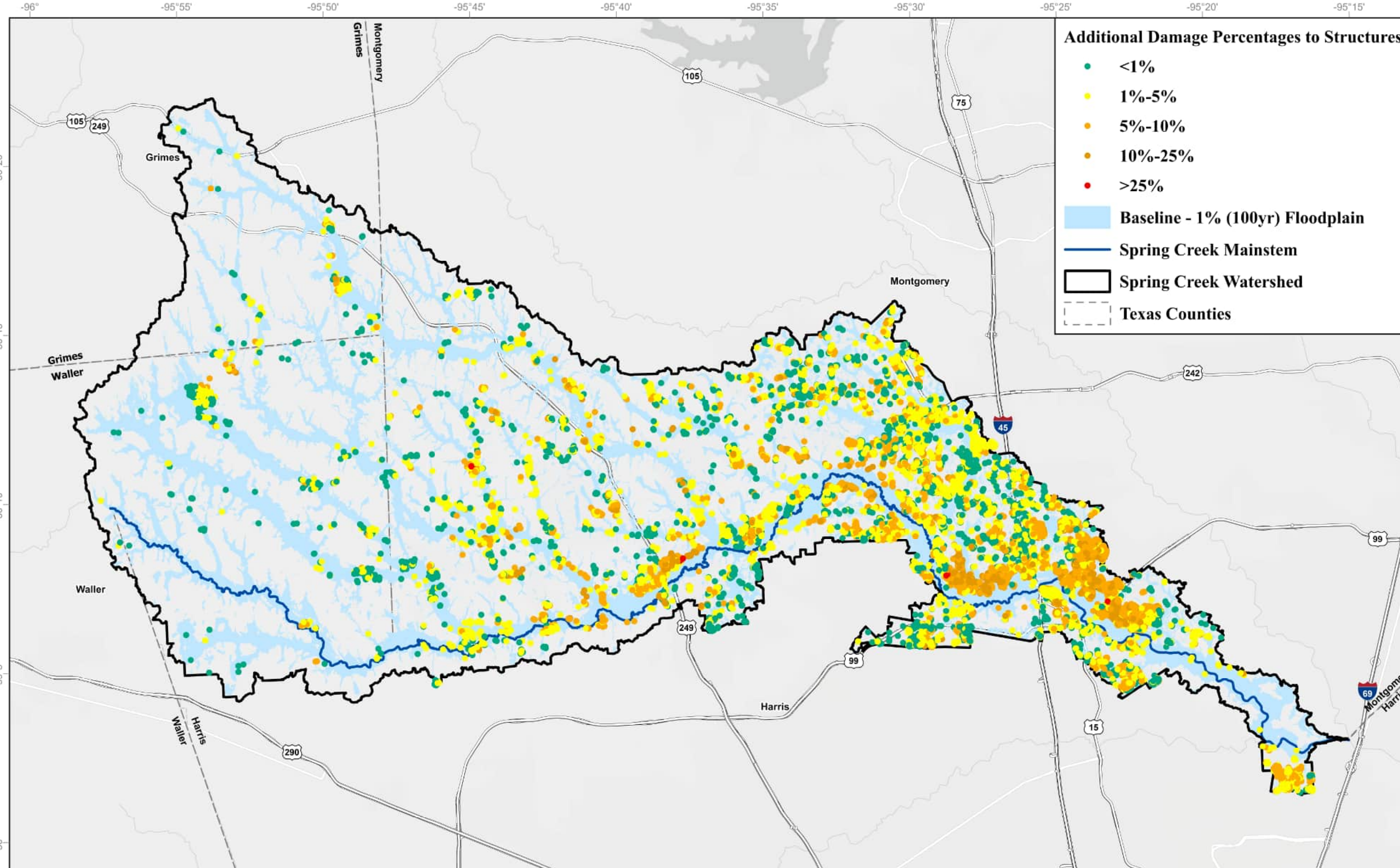

Commonly Flooded Roads (>1ft) for SFD, Spring Creek -1% (100yr Pluvial)




Inundation Area with Depth x Velocity in Spring Creek for SWFD - 1% (100yr Pluvial)




Inundation Area with Depth x Velocity in Spring Creek for SFD - 1% (100yr Pluvial)




0 1.5 3 6 Miles

Additional percent damage to structures in SFD Scenario, Spring Creek - 1% (100yr Pluvial)