Central Texas Extreme Weather and Climate Change Vulnerability Assessment of Regional Transportation Infrastructure

Final Report




prepared for

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City of Austin Office of Sustainability

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Disclaimer

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Executive Summary

The Central Texas Extreme Weather and Climate Change Vulnerability Assessment of Regional Transportation Infrastructure was one of 19 Federally-sponsored projects nationwide intended to "pilot approaches to conduct climate change and extreme weather vulnerability assessments of transportation infrastructure and to analyze options for adapting and improving resiliency." This pilot was led by the Capital Area Metropolitan Planning Organization, or CAMPO, in partnership with the City of Austin, and features the contributions of a host of other state, regional, and local entities.

The specific purpose of this study was to assess the potential vulnerability of a limited selection of critical transportation assets in the CAMPO region to the effects of extreme weather and climate; to highlight lessons learned in the process, and to outline potential next steps toward enhancing the resilience of the region's transportation infrastructure. The assets evaluated include roadways, bridges, and rail, and the climate-related stressors considered were flooding, drought, extreme heat, wildfire, and extreme cold (icing). Commensurate with the region's Long-Range Transportation Plan (LRTP) – under development at the time of writing), the year 2040 was selected as the analysis horizon. The principal sections of this study are:

Transportation Data (Section 2)

Robust, multimodal transportation data are necessary to understand where critical assets are located and to help determine what vulnerabilities they may face as climate patterns change. The project team collected, compiled, and organized data in a Geographic Information System (GIS). These data informed the subsequent selection of critical assets for evaluation, and were integrated with climate projections to identify and assess extreme weather vulnerabilities.

Asset Criticality (Section 3)

To identify assets that—if taken out of service due to extreme weather—would likely result in significant impacts, the team facilitated a workshop of regional stakeholders from the transportation sector and allied disciplines. This input helped the team identify nine critical transportation facilities for focused evaluation (see Table 1, below).

Table 1 Transportation Assets Evaluated

Asset	County	Mode	Potential Vulnerabilities
MetroRail Red Line at Boggy Creek	Travis	Commuter Rail	Flooding, drought, extreme heat
SH 71E at SH 21	Bastrop	Road, Airport Access	Flooding, drought, extreme heat
I-35 at Onion Creek Parkway (study area to include Old San Antonio Road low water crossing)	Travis	Road	Flooding, extreme heat
US 290W/SH 71 – Y at Oak Hill	Travis	Road	Flooding, drought wildfire, extreme heat
Loop 360/RM 2222	Travis	Road	Flooding, drought, wildfire, extreme heat
FM 1431 at Brushy Creek/Spanish Oak Creek	Williamson	Road	Flooding, drought, extreme heat
US 281 and SH 29 Intersection	Burnet	Road	Flooding, extreme heat
US 183 north of Lockhart	Caldwell	Road	Flooding, drought, extreme heat
SH 80 (San Marcos Highway) at the Blanco River	Hays	Road, Airport Access	Flooding, extreme heat

Sensitivity Thresholds (Section 4)

The team convened a series of interviews with local experts to establish the most applicable extreme weather and climate-related sensitivity thresholds for Central Texas. The goal of this exercise was to determine which climate variables to employ in the subsequent vulnerability assessment. The expert interviews included staff from TxDOT, City of Austin Public Works Department, City of Austin Department of Homeland Security and Emergency Management (HSEM), City of Austin Fire Department, Capital Metro, and Austin-Bergstrom International Airport (ABIA). These experts identified sensitivities related to five extreme weather and climate stressors—flooding, drought, extreme heat, wildfires, and extreme cold and icing. The thresholds identified were crucial to defining the climate data requirements for the subsequent vulnerability assessment.

Climate Data (Section 5)

This study leveraged previous peer-reviewed academic research to generate projections using the Weather Research and Forecasting (WRF) regional climate model (RCM), developed by the National Center for Atmospheric Research

(NCAR). The team developed a series of three mid-century climate scenarios —a range of plausible futures reflecting potential climate conditions around the year 2040. The scenarios reflected projections for greater Austin and two proximate areas of Texas, one approximately 133-miles north, the other approximately 133-miles west. Although the projections for Austin are most likely, projections for neighboring regions should be considered possible for Austin as well.

Consistent with other projections for the region, the WRF model projects a warmer future for Central Texas by the middle of the 21st century: average annual temperatures are projected to rise about 2.7° F, and extreme heat events are also projected to increase (temperatures of 100° F or more are projected to increase by an average of 34 days annually). The model also projects an increase in drought conditions for Central Texas (on average, fewer days of rain annually and a potential 10 percent decrease in soil moisture)—but two of three scenarios also project more intense extreme precipitation events, such as the 25-, 50-, or 100-year rainfall.

To gauge the potential impact of increased extreme precipitation magnitudes, a hydrological model currently used by the City of Austin Flood Early Warning System (FEWS), was applied to simulate potential future flood conditions for critical assets within Travis County.

Vulnerability Assessment (Section 6)

Using the U.S. Department of Transportation (DOT) Vulnerability Assessment Scoring Tool (VAST), the team performed desktop vulnerability assessments, outputting preliminary risk ratings for all five climate stressor types for each of the nine critical assets selected for evaluation. The preliminary ratings and associated rationales were then presented to focus groups comprising state, regional, and local experts and officials (typically involving the asset owner and/or operator). Based on the feedback from focus group participants, the initial VAST results were adjusted, as needed, and finalized. The risk ratings presented in this study resulted from a planning-level screening intended to highlight potential threats to critical facilities. More in-depth evaluation would be required to justify investments to manage these risks.

This analysis highlighted a handful of key potential climate-related risks to critical CAMPO assets that may merit more detailed investigation and/or consideration of adaptive measures:

- **Flooding:** Flooding risk varies significantly across the assets studied, based on location and elevation relative to floodplains, condition, design standards, and other factors. SH 71/SH 21 in Bastrop County is estimated to have the highest flood risk, given the potential consequences of flooding on this critical evacuation route. The MetroRail Red Line at Boggy Creek and US 281/SH 29 also have relatively high flood risk.

- **Drought:** All assets are expected to be exposed to drought, as soil moisture is projected to decrease four to ten percent by mid-century. The primary determinant of drought risk is the plasticity of soils underlying a given asset, which may indicate susceptibility to shrinking and swelling with changes in soil moisture—which may in turn cause premature deterioration or damage. The MetroRail Red Line at Boggy Creek and US 183 north of Lockhart are built over the highest plasticity soils of all assets studied.

- **Extreme heat:** All assets are expected to be highly exposed to extreme heat. However, according to the experts consulted, the road assets studied are not expected to experience pavement damage as a result of these temperature increases. Heat poses a moderate risk to the MetroRail Red Line, because temperatures above 100° F increase the chance of thermal misalignments and force Capital Metro to issue slow orders.
- **Wildfire:** Wildfire risk is relatively high for all assets (except the MetroRail Red Line at Boggy Creek, which is located in a non-burnable area). Although wildfires do not typically cause physical damage to roadways, they can cause road closures or other temporary service disruptions. For many of the assets studied—particularly US 290/SH 71 and Loop 360—even small, temporary disruptions from wildfire could create bottlenecks or "choke points" that could interfere with wildfire evacuations and thus threaten human health and safety.
- **Icing:** Icing presents relatively low risks to all road assets, although elevated facilities are relatively more susceptible than at-grade assets. Icing events, which historically have been rare, may occur even less frequently as the century progresses.

Lessons Learned (Section 7)

As a pilot project, the lessons learned throughout the process are among the most valuable outputs of this study. Key lessons include:

- **Partner with municipalities and coordinate across sectors**. The collaboration between CAMPO and the City of Austin was successful, as were the multidisciplinary partnerships forged with agencies like the City of Austin Fire Department and Public Works Department.
- **The nature of inland extreme weather and climate challenges may differ from those faced by coastal communities.** Compared with the potentially catastrophic, often regional effects of storm surge on coastal communities, the extreme weather and climate risks faced by the CAMPO region are generally relatively localized and situational (such as flooding or wildfire) or more gradual and incremental (such as the effects of drought). In line with this realization, two sets of potentially appropriate regional responses emerged: the incorporation of these risks into asset management frameworks and into emergency response plans.
- **Critical assets may not be the most vulnerable assets.** The critical assets selected for evaluation are mostly higher functional classification roadway facilities, which, generally, are more robustly designed (e.g., to withstand

more substantial flooding events) and more reliably maintained. Local and county roadways may therefore exhibit greater sensitivity to extreme weather stressors. In the CAMPO region, legacy roadways in rapidly urbanizing or industrializing areas, in particular, may warrant investigation.

- **Growth and other non-climate stressors can significantly influence extreme weather impacts.** Other, non-climate stressors, such as the growth of heavy truck volumes or the expansion of impervious surface, for example, can serve to amplify a primarily climate-related impact. Moreover, in many instances the non-climate stressor is a significant—or even primary—driver of risk.

Next Steps (Section 8)

The report concludes with suggestions for leveraging the findings of this study and, ultimately, enhancing the resilience of the Central Texas multimodal transportation network to the effects of extreme weather as the century progresses. Recommendations include:

- **Build on and expand the scope of collaboration.** CAMPO and the City of Austin will work with the FHWA Texas Division Office to form an Extreme Weather Resilience Working Group, following a successful interregional Extreme Weather Resiliency Symposium in December, 2014. Both CAMPO and the City of Austin are interested in further engaging peer agencies and cities across Texas—both to share the findings of this work and to learn from the experiences of others.
- **Incorporate extreme weather considerations into the 2040 LRTP.** The 2040 CAMPO LRTP, in progress as of the time of writing, will incorporate selected elements of this study. A particular concern is the potential hazard posed by wildfire to evacuation and emergency response routes.
- **Expand the assessment to selected City and County roads and/or extend the assessment time horizon to consider end-of-century impacts.** Subsequent phases of this work might productively focus on lower functional classification roads—particularly those in rapidly urbanizing or industrializing areas. For several key climate variables (including, for example, extreme heat), projections dramatically increase in severity and/or frequency in the second half of the century. Particularly for long-lived, critical assets like bridges, it may make sense to consider climate scenarios out to the year 2100. A more dire picture of extreme weather risk may well emerge with either of these approaches.
- **Evaluate and implement adaptation options.** The purpose of this study was to identify and characterize potential extreme weather and climate-related risks to transportation infrastructure. A critical next step for the region is the timely, cost-effective management of those risks—a process called adaptation. Although this report offers a handful of high-level adaptation strategies for each stressor, further investigation is warranted.

1.0 Introduction

The *Central Texas Extreme Weather and Climate Change Vulnerability Assessment of Regional Transportation Infrastructure* was one of 19 Federally-sponsored projects nationwide intended to "pilot approaches to conduct climate change and extreme weather vulnerability assessments of transportation infrastructure and to analyze options for adapting and improving resiliency." This pilot was led by the Capital Area Metropolitan Planning Organization, or CAMPO, in partnership with the City of Austin, and features the contributions of a host of other state, regional, and local entities.

The specific purpose of this study was to assess the potential vulnerability of a limited selection of critical transportation assets in the CAMPO region to the effects of extreme weather and climate; to highlight lessons learned in the process, and to outline potential next steps toward enhancing the resilience of the region's transportation infrastructure. The assets evaluated include roadways, bridges, and rail, and the climate-related stressors considered were flooding, drought, extreme heat, wildfire, and extreme cold (icing). Commensurate with the region's Long-Range Transportation Plan (LRTP) – under development at the time of writing), the year 2040 was selected as the analysis horizon.

The principal sections of this study were:

- **Transportation Data (Section 2)** – The study team collected and integrated a broad selection of data from CAMPO and the region's partners. Building a strong understanding of which transportation assets provide the greatest contribution to regional mobility or economic activity was crucial to the identification of critical facilities for further study.
- **Asset Criticality (Section 3)** – To identify assets that—if taken out of service due to extreme weather—would likely result in significant impacts, the team facilitated a workshop of regional stakeholders from the transportation sector and allied disciplines. This input helped the team identify nine critical transportation facilities for focused evaluation.
- **Sensitivity Thresholds (Section 4)** – The team convened small focus groups of regional and local experts to identify potential extreme weather sensitivity thresholds at which disruption, deterioration, or damage might occur. The thresholds identified were crucial to defining the climate data requirements for the subsequent vulnerability assessment.
- **Climate Data (Section 5)** – The team developed a series of three mid-century climate scenarios —a range of plausible futures reflecting potential climate conditions around the year 2040—which served as key inputs into the vulnerability assessment.

- **Vulnerability Assessment (Section 6) –** Using the U.S. Department of Transportation (DOT) Vulnerability Assessment Scoring Tool (VAST), the team performed desktop vulnerability assessments, outputting preliminary risk ratings for all five climate stressor types for each of the nine critical assets selected for evaluation. The preliminary ratings and associated rationales were then presented to focus groups comprising state, regional, and local experts and officials (typically involving the asset owner and/or operator). Based on the feedback from focus group participants, the initial VAST results were adjusted, as needed, and finalized. However, as noted subsequently, the risk ratings presented in this study resulted from a planning-level screening intended to highlight potential threats to critical facilities. More in-depth evaluation would be required to support investment decision-making.
- **Lessons Learned and Next Steps (Sections 7 and 8)** – As a pilot project, the lessons learned throughout the process are among the most valuable outputs of this study. The lessons are cataloged in two broad categories—Lessons for MPOs and State DOTs and Lessons for FHWA (although, in practice, there is ample overlap between them). The report concludes with suggestions for leveraging the findings of this study and, ultimately, enhancing the resilience of the Central Texas multimodal transportation network to the effects of extreme weather as the century progresses.

2.0 Transportation Data

Robust, multimodal transportation data are necessary to understand where critical assets are located and to help determine what vulnerabilities they may face as climate patterns change. The team coordinated with CAMPO, the City of Austin, and their planning partners to collect, compile, and organize multimodal transportation layers and attribute tables in a geospatial database. To accomplish this, the team first worked with CAMPO and its partners to establish a GIS protocol to ensure that all data were properly formatted, using recognized feature classes and naming conventions. CAMPO also provided a template for all maps, with defined extents, symbology, fonts, and color palettes.

The team evaluated the entire data package for completeness and subsequently recommended supplementation where additional data and/or documentation were needed. These data not only informed the criticality assessment (discussed in Section 3.0), but were also integrated with climate projections to identify and assess vulnerabilities (Section 6.0). Once a limited set of critical assets was selected, additional quantitative and qualitative data were collected and integrated, as needed.

This section sets the context for the study by presenting an overview of the region's transportation system (roadways and bridges, rail, public transit, and airports), current and future congestion, freight corridors, activity centers, and combined population and employment density. It also provides an overview of the geospatial transportation data that were collected from the region's planning partners, presented at a workshop convened to establish a shortlist of critical assets, and used in subsequent steps of the vulnerability assessment.

Table 2, extracted from CAMPO's draft 2040 LRTP, provides a summary of roadway lane miles by type, as measured in 2010 and projected for 2040.

In addition to the roadway assets tallied in Table 2, the CAMPO region possesses many non-highway transportation assets as well. These include approximately 259 miles of Class I freight railroad, 13 public use airports[1], 32 miles of commuter rail, and 27 miles of bus rapid transit. Figure 1 provides an overview of transportation systems in the Central Texas region, including the roadway system, bridges, airports, passenger rail, and freight rail.

[1] Only the highest functional classification facilities are shown in Figure 1.

Table 2 CAMPO Region Roadway Lane Miles
2010 and projected 2040

Type	2010	2040
Non-toll highways	855	913
Principal Arterials	4,543	5,263
Minor Arterials	3,834	3,952
Collectors	1,251	1332
Locals	509	519
Non-toll: Frontage Roads, Ramps and Direct Connectors	995	1,279
Toll Express Lanes	0	192
Toll: Roads, Ramps and Direct Connectors	417	697
Total	12,402	14,150

Source: CAMPO. All figures are rounded.

Figure 2 highlights the multimodal aspects of the region's transportation network, including airports, Capital Metropolitan Transportation Authority's (Capital Metro) transit service area and MetroRail route and stations, Capital Area Rural Transportation System (CARTS) stations, the Amtrak route and stations, and freight rail alignments.

Congestion levels are shown in Figure 3. Green segments indicate roadways that are not congested (volume-to-capacity (V/C) ratio of 1 or less); yellow roadways are congested (V/C between 1.01 and 1.3); red roadways are very congested (V/C greater than 1.3). Currently the region's most congested corridors are those that provide north-south connectivity (I-35, Mopac, Loop 360) as well as those that provide radial connectivity from outlying communities to Austin's core (US 183, US 290, SH 71, RM 2222, and RM 2244).

Projected congestion levels for 2035[2] are shown in Figure 4 with the same V/C tiers as Figure 3. A significant increase in very congested and congested roadway segments is expected by 2035. The severity of congestion is projected to increase on the region's radial corridors connecting Austin to the other growing cities in the six county area. Given the stresses congestion poses to the transportation network, it becomes even more crucial to manage the risk of failure on key regional facilities, in particular.

[2] 2035 was the prevailing future plan year at the time this study was performed.

Figure 1 Transportation Assets in Central Texas

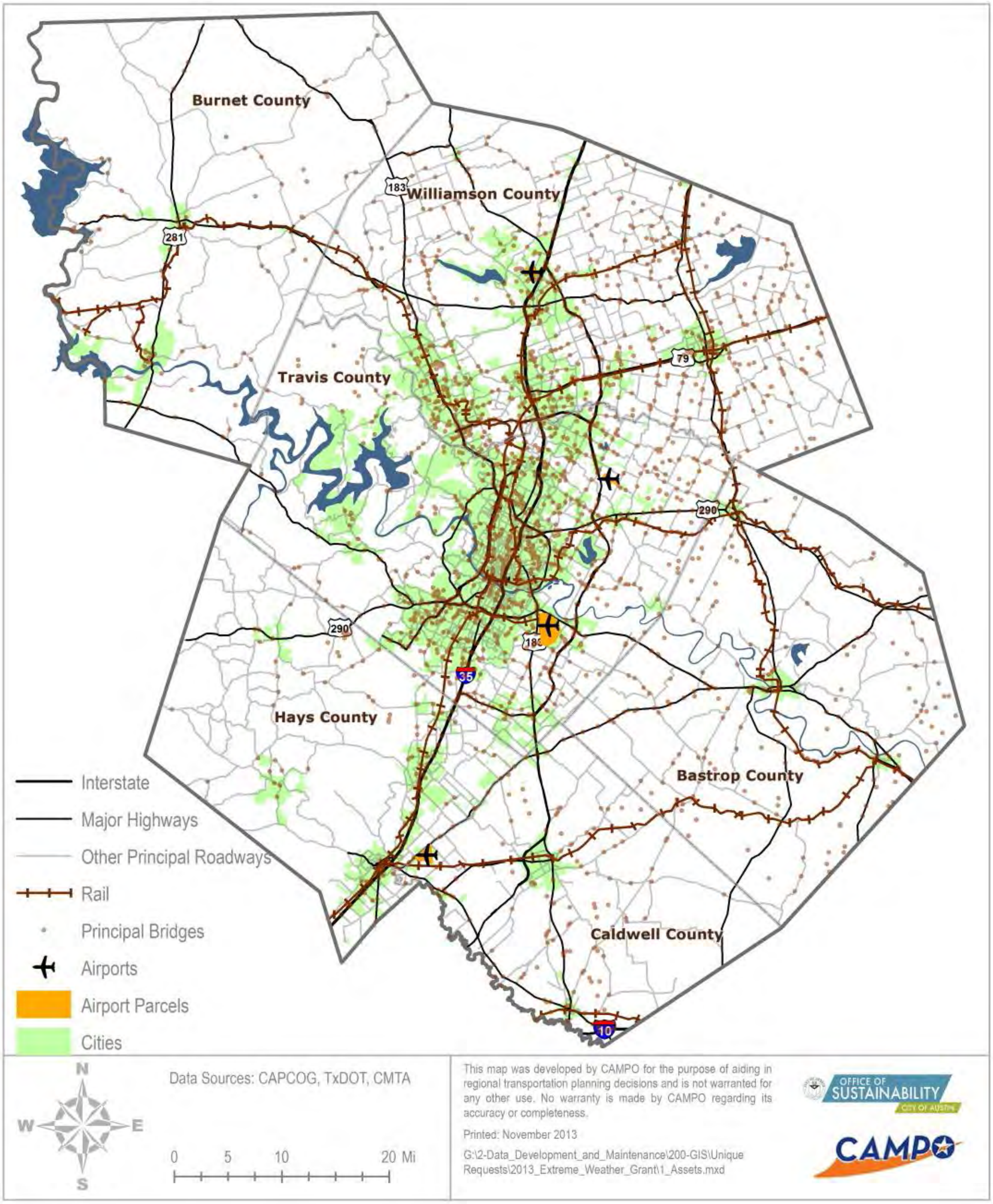


Figure 5 depicts the freight corridors in the Central Texas region. Orange lines indicate truck volumes on area roadways. Blue lines represent freight rail traffic densities—a proxy for freight volumes—on regional railways. Intermodal facilities are shown in red. I-35 is clearly the most heavily used truck corridor in the region, although the region's radial highways provide important connectivity to Houston and other Texas markets. Most rail-based freight in the region travels along three Union Pacific (UP) corridors: one in far southern Caldwell County, another through Hays, Caldwell, and Bastrop Counties, and a third through Hays, Travis, and Williamson Counties.

Regional activity centers and points of interest are shown in Figure 6. These include hospitals, institutions of higher education, fixed guideway transit stations, CAMPO Draft 2040 Plan centers, Environmental Justice (EJ) areas, and military installations. These centers provide insight into some of the destinations critical to the prosperity and wellbeing of the region and its communities.

Combined 2010 population and employment densities, by Traffic Analysis Zone (TAZ), are shown in Figure 7. Darker orange zones indicate areas of higher population and employment density—with the highest numbers generally in the central Austin area. Other areas of high population and employment density include the I-35 corridor in Travis County (Austin, Pflugerville), southern Williamson County (portions of Cedar Park, Round Rock, and Georgetown) and the I-35 corridor in Hays County (Kyle, Buda, and San Marcos).

Projected population and employment densities are shown in Figure 8 with the same combined population and employment density tiers as Figure 7. Significant job and population growth are expected in the CAMPO region by 2035, centered mainly along the I-35 corridor. Much like current densities, the projected population and employment densities are expected to be highest in central Austin. While the City of Austin will experience higher densities, population and employment growth are also projected to radiate outward from the center of the region, most notably in Williamson and Hays counties, and generally centered along the I-35 and US 183 corridors. Other outlying areas—such as Taylor, Elgin, Bastrop, and Lockhart—are also projected to experience increased population and employment density.

Figure 2 Multimodal Transportation Network in Central Texas

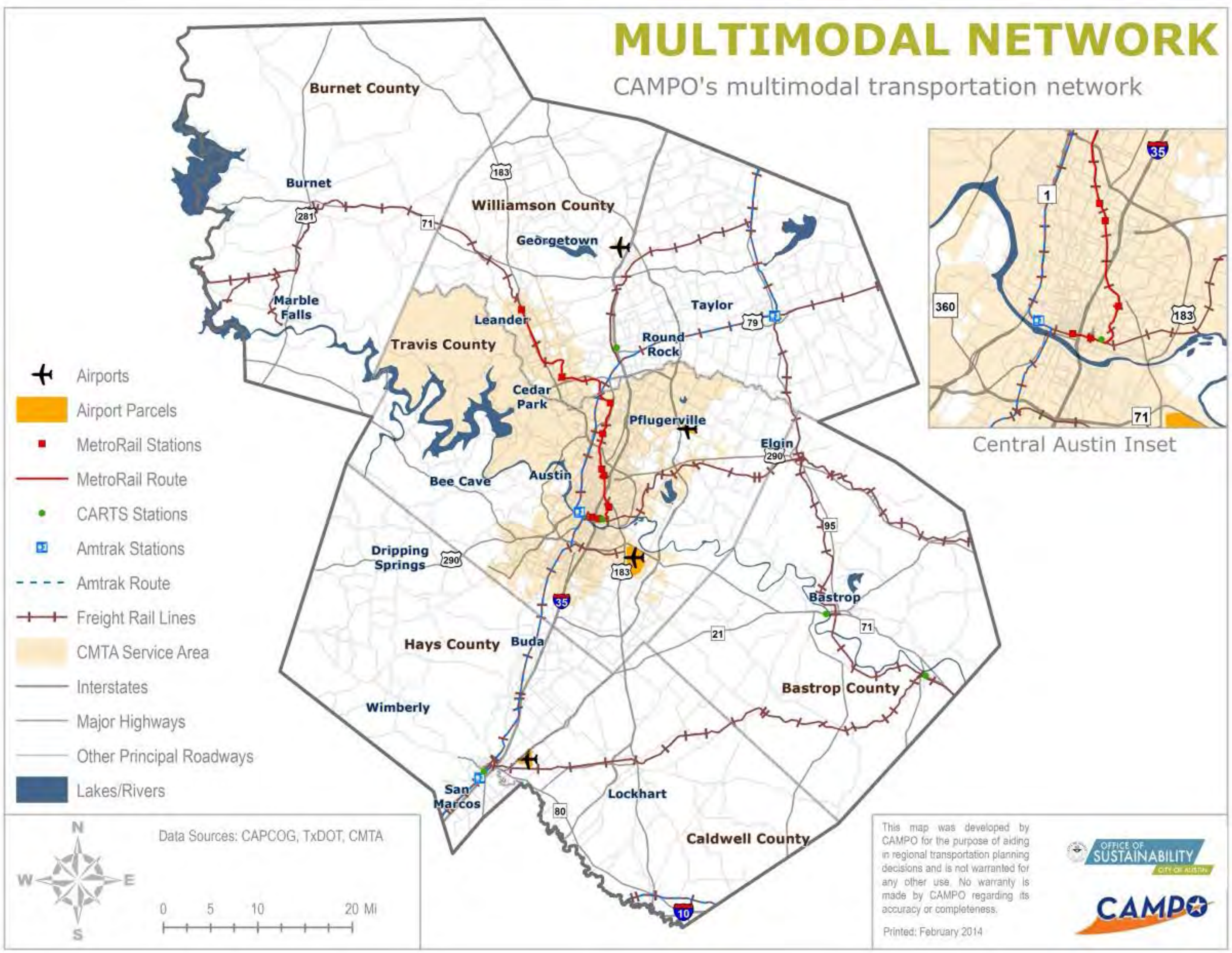


Figure 3 Current Congestion
2010

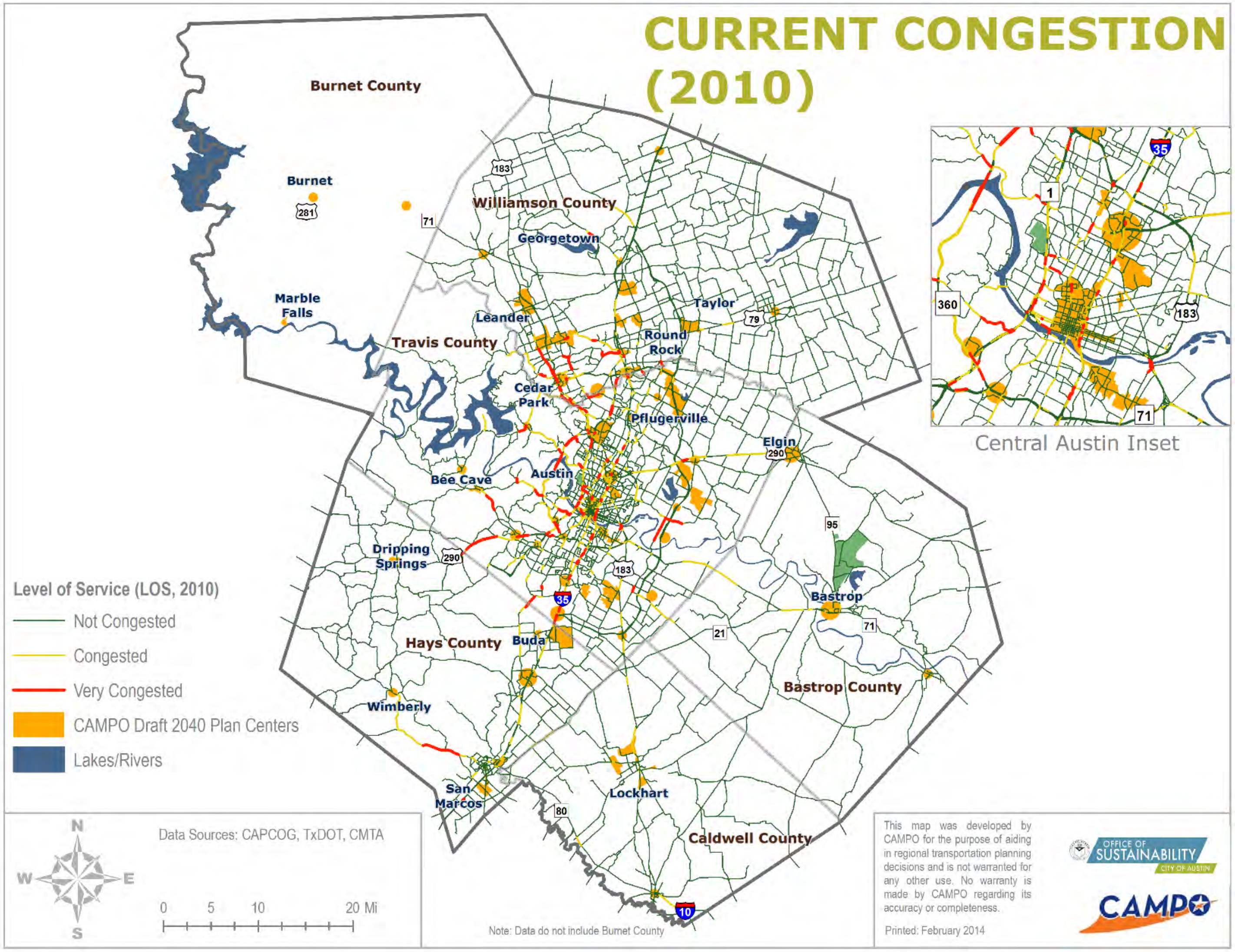


Figure 4 Future Congestion
2035

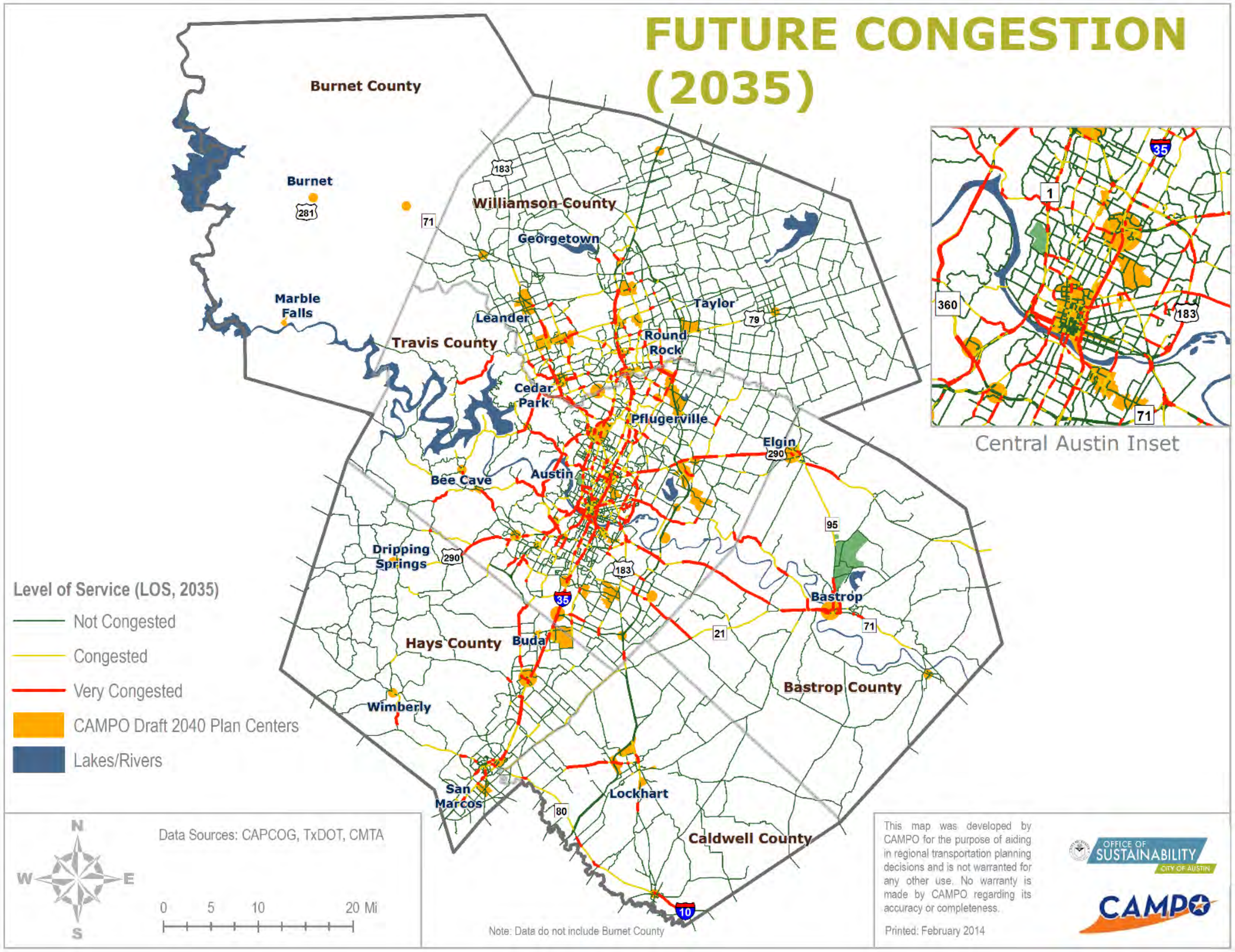


Figure 5 Central Texas Freight Corridors

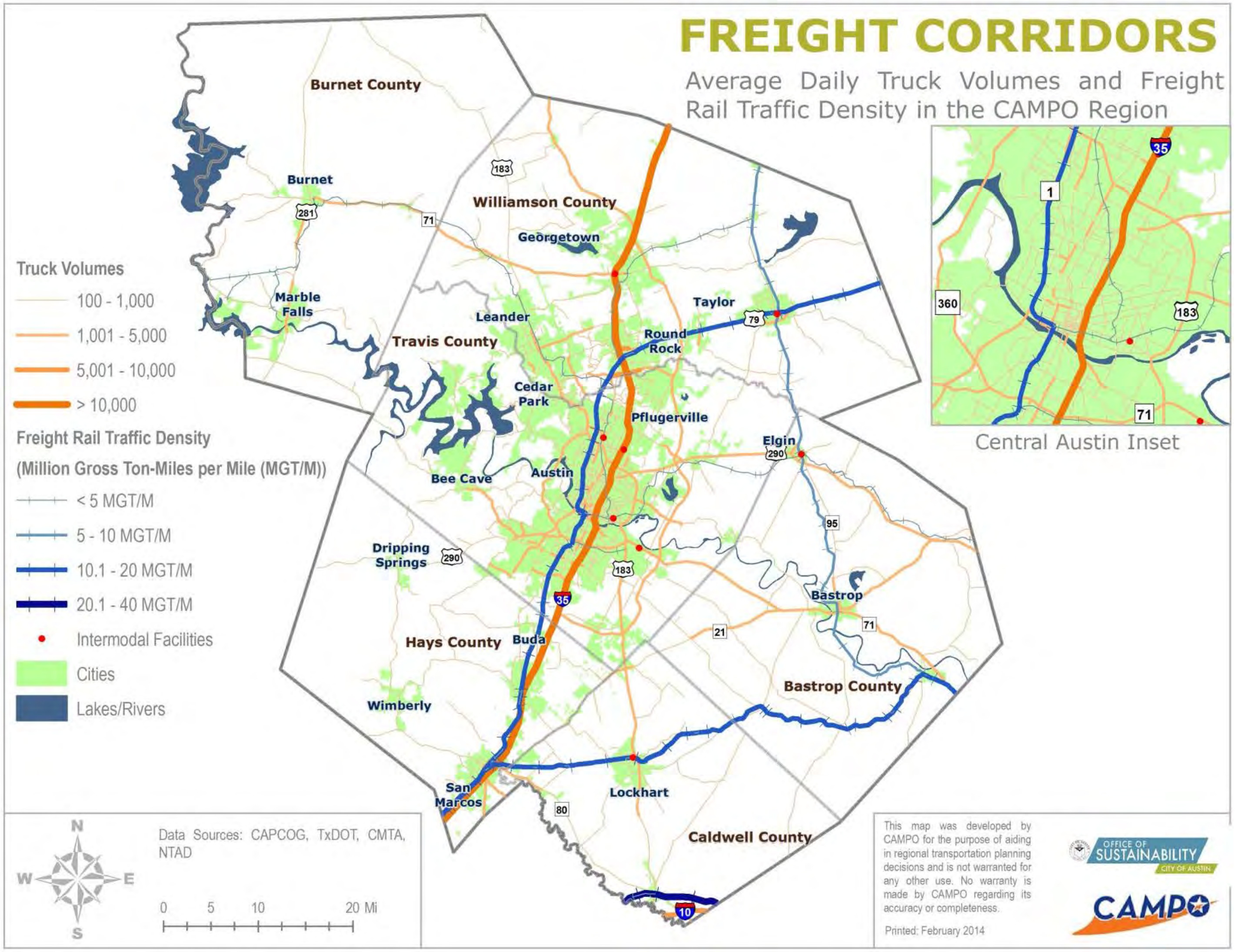


Figure 6 Central Texas Activity Centers

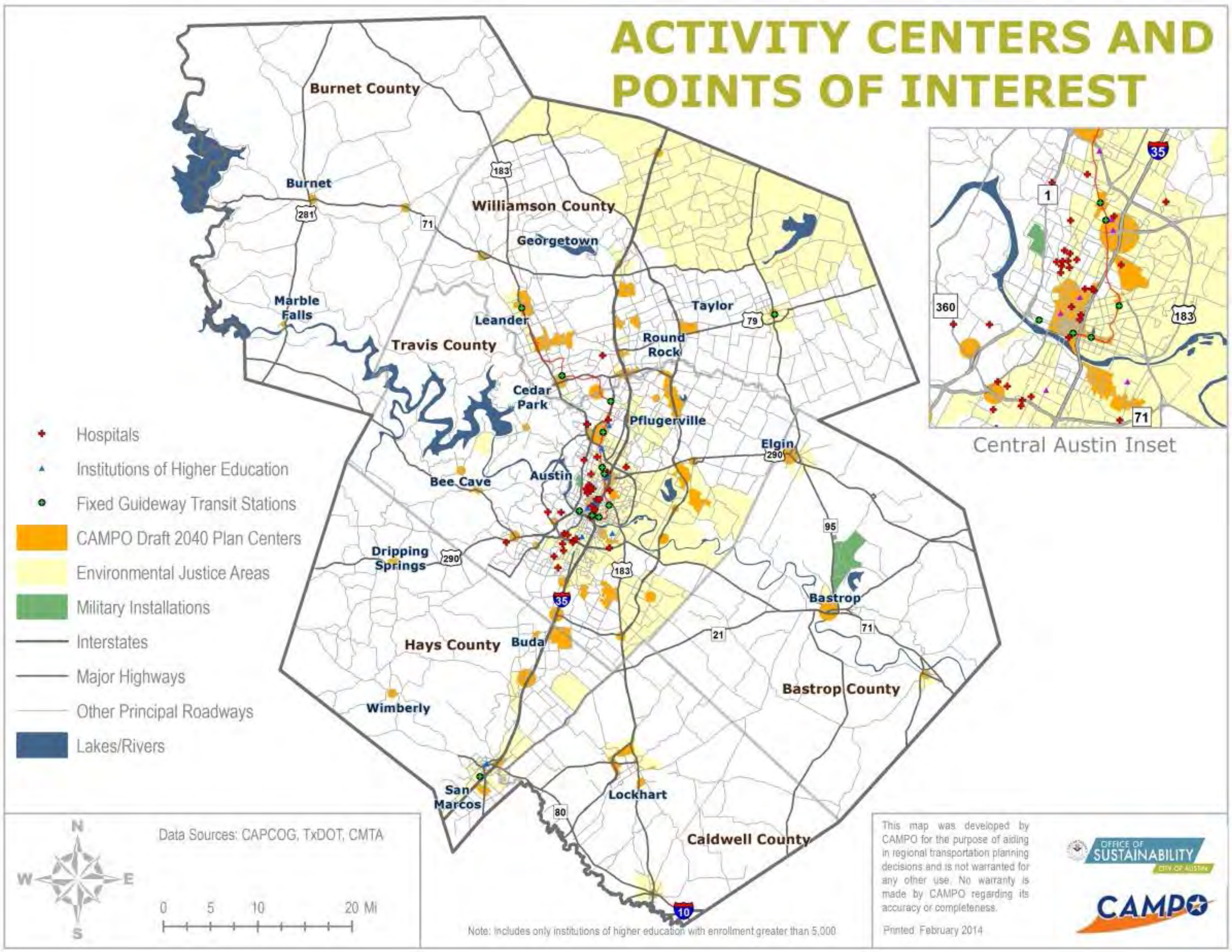


Figure 7 2010 Combined Population and Employment Density

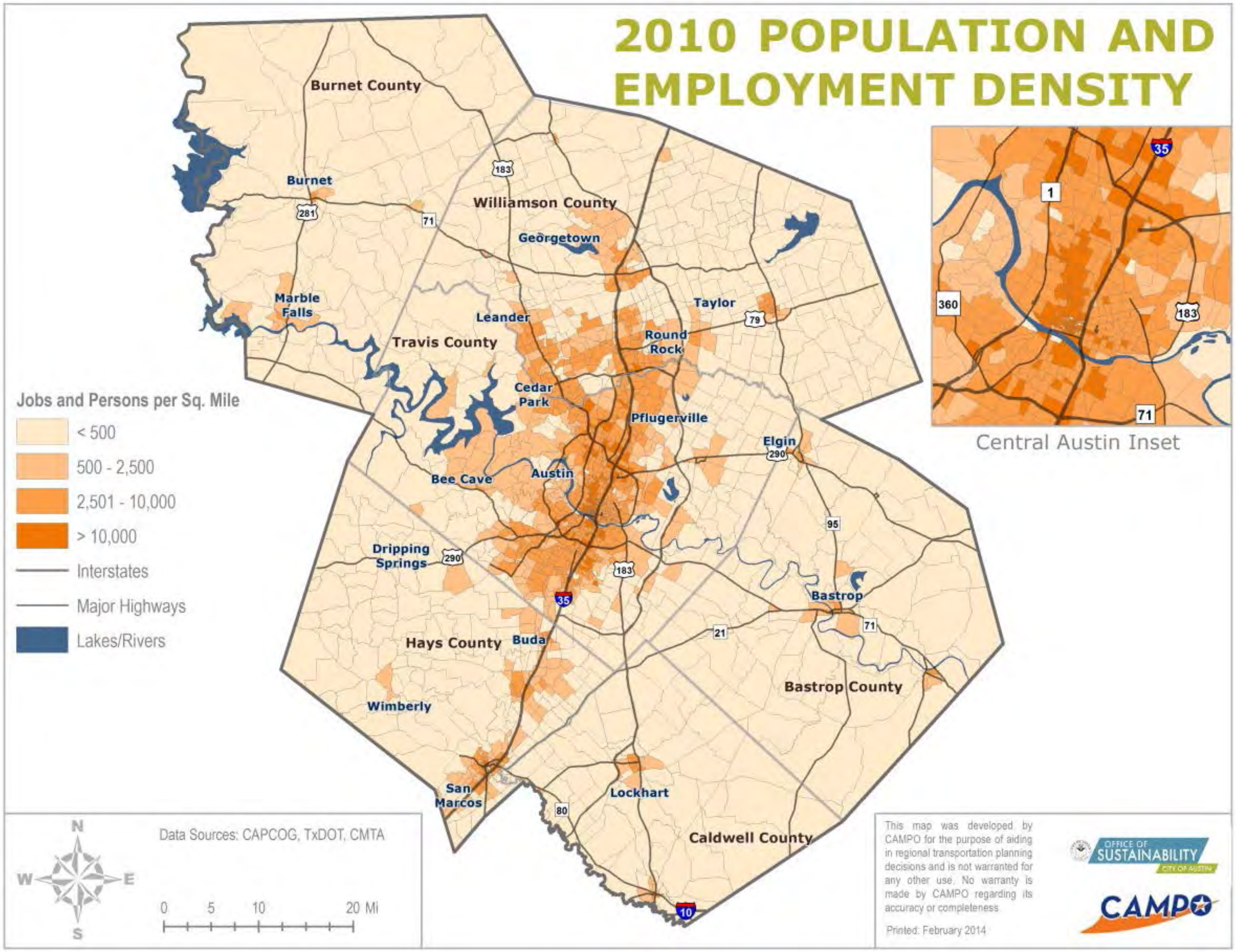
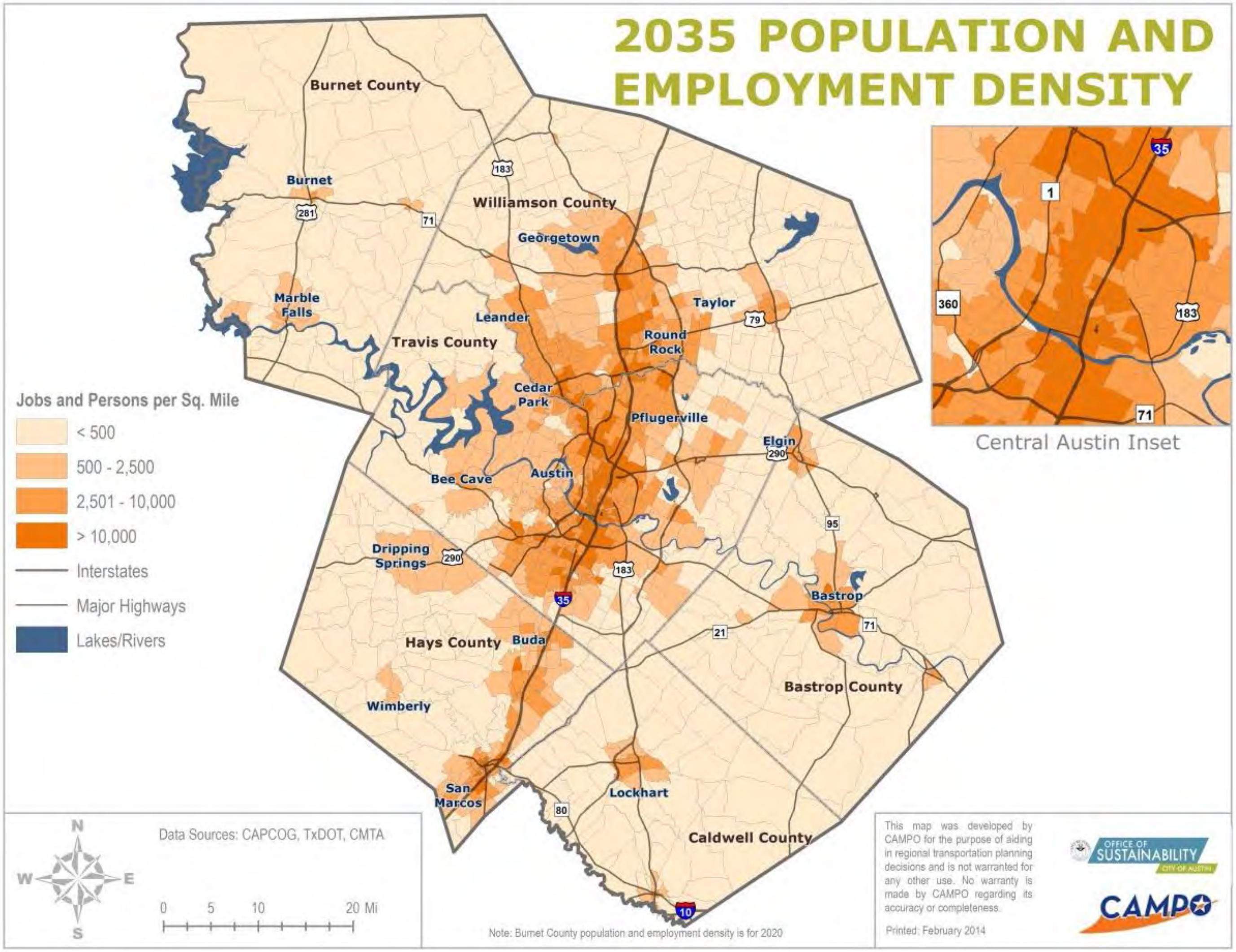


Figure 8 2035 Combined Population and Employment Density



3.0 Asset Criticality

An assessment of asset criticality provides a basis for establishing which transportation assets provide significant contributions to regional mobility and/or economic activity. This exercise screens down the number of assets for the subsequent in-depth vulnerability assessment, ensuring that analytical resources can be more effectively focused to produce more robust results. Likewise, from a regional planning and risk management perspective, it is important to identify critical assets that, if damaged or disrupted due to extreme weather, would likely result in notable regional mobility and/or economic impacts.

3.1 Defining Criticality Criteria

To identify critical assets in the CAMPO region as candidates for further study, the team brought together transportation stakeholders from across the region for a half-day workshop. Participants in attendance represented Travis and Bastrop counties, the cities of Austin, Georgetown, Hutto, and Leander, CAMPO, the Texas Department of Transportation (TxDOT), and the Central Texas Regional Mobility Authority (CTRMA). Using the detailed asset maps and transportation data (described in Section 2.0) to inform discussion, the workshop participants engaged in a facilitated conversation on the role of the regional transportation system, which in turn established context for the selection of critical assets for the subsequent vulnerability assessment. The group was asked to brainstorm the role of the regional transportation system in the region and its communities, and developed the following principles:

- Connect people to jobs, healthcare and medical facilities, education, government services, and residences/settlements;
- Facilitate the transport of goods and connect the Central Texas region to regional, national, and international markets;
- Provide military/security access;
- Support special events and tourism;
- Allow for coastal evacuation and access to emergency services;
- Support the economy and local industries (manufacturing, energy, logistics, etc.)

Based on this discussion, the group collaboratively developed a set of advisory criteria to facilitate critical asset selection. It was determined that the selection of critical transportation assets should:

- **Align with the regional transportation vision and goals defined in CAMPO's draft 2040 Regional Transportation Plan.** As reflected in the vision and goals, desired attributes of the regional transportation system include safety and security, efficiency, equity, multimodality, accessibility, context sensitivity, resiliency and redundancy, connectivity, sustainability, reliability, cost effectiveness, and well-maintained.
- **Provide regionally-significant access and connections.** Critical assets connect the region's key activity centers, population and employment, emergency evacuation routes, hospitals, and other vital public infrastructure;
- **Reflect the region's multimodal system**. The Central Texas transportation system is more than just roads and bridges – freight and passenger rail, transit, and airports also play an important role in regional mobility.
- **Take into account the region's extreme weather vulnerabilities**. Analyze assets that present potential vulnerabilities to one or more climate stressors.
- **Broadly represent similar assets**. Identify assets that share similarities with other locations in the six-county area (design characteristics, soil conditions, proximity to floodplain, etc.) to maximize the transferability of the findings.
- **Consider geographic and social diversity.** The six-county Central Texas region includes four different ecoregions, three distinct climate divisions, and two distinct topographical and geological areas defined by the rocky hill country in the west and flat, softer clay soils in east. Given this regional diversity, stakeholders felt that it was important to select assets that capture the range of conditions found in the region.

3.2 ASSETS FOR ASSESSMENT

At the workshop, the participants were divided into groups. Each group was tasked with voting for up to 10 critical assets in the Central Texas region. To ensure a multimodal selection of critical assets, the groups were required to select at least one asset from each modal category (roads/bridges, freight rail, aviation/airport access, and transit (bus and commuter rail). After voting was complete, the participants came together to discuss the results and identified clusters of critical assets. The results of the cluster discussion are summarized in Appendix C.

Although the workshop provided the primary basis for final asset section, due to resource constraints not all clusters could be analyzed, and some original selections were adjusted due to data sufficiency issues and to provide a broader representation of asset types and geographies. Table 3 lists the final selection of nine[3] critical assets for further study, and provides a summary of some of the key attributes impacting criticality and vulnerability, including average annual daily traffic (AADT) volumes, soil plasticity, proximity to the 100-year flood plain, and whether or not the roadway is designated as a hurricane evacuation route. The approximate location of each is shown in Figure 9. The assets selected were as follows:

- **(#2) MetroRail Red Line at Boggy Creek** – Capital Metro's Red Line provides the region's only commuter rail service, connecting the northwest suburbs to downtown Austin. The specific study area is located adjacent to the Boggy Creek 100-year floodplain and is characterized by high plasticity soils.
- **(#3) SH 71E at SH 21** – This corridor provides access to Austin Bergstrom International Airport (ABIA) for residents in Bastrop County and is also designated as a hurricane evacuation route. SH 71E is expected to become severely congested by 2035. The selected segment has been subject to flooding in the past and is located in an area with high plasticity soils.
- **(#4) I-35 at Onion Creek Parkway** – I-35 is of vital significance not only to Austin and the Central Texas region, but also to the Texas, national, and international economies.
- **(#5) US 290W/SH 71 (Y at Oak Hill)** – This location is the confluence of two heavily used roadways into and out of Austin that provide critical connectivity to the region's western communities. The area is potentially vulnerable to wildfires and is located adjacent to a 100-year floodplain.
- **(#6) Loop 360/RM 2222** – This intersection is the gateway to many of Austin's hill country neighborhoods. Located adjacent to Bull Creek and in a wooded area, this location is potentially vulnerable to flooding and wildfires.
- **(#7) FM 1431 at Brushy Creek/Spanish Oak Creek** – This segment of FM 1431 from Arrow Point Drive to just east of Brushy Creek/Spanish Oak Creek in Williamson County is a relatively high volume road today that is forecasted to become very congested by 2035. This particular location was closed due to flooding caused by Tropical Storm Hermine.
- **(#8) Intersection of US 281 and SH 29 in Burnet** – While traffic volumes at the intersection of US 281 and SH 29 are relatively low, both facilities provide critical connectivity in Burnet County. All four intersection approaches pass through the 100-year floodplain.
- **(#9) US 183 north of Lockhart** – US 183 provides connectivity between Caldwell County and the Austin metropolitan area and also serves as a

[3] US 290E at Johnny Morris Road, originally "Asset #1," was later removed due to data availability issues.

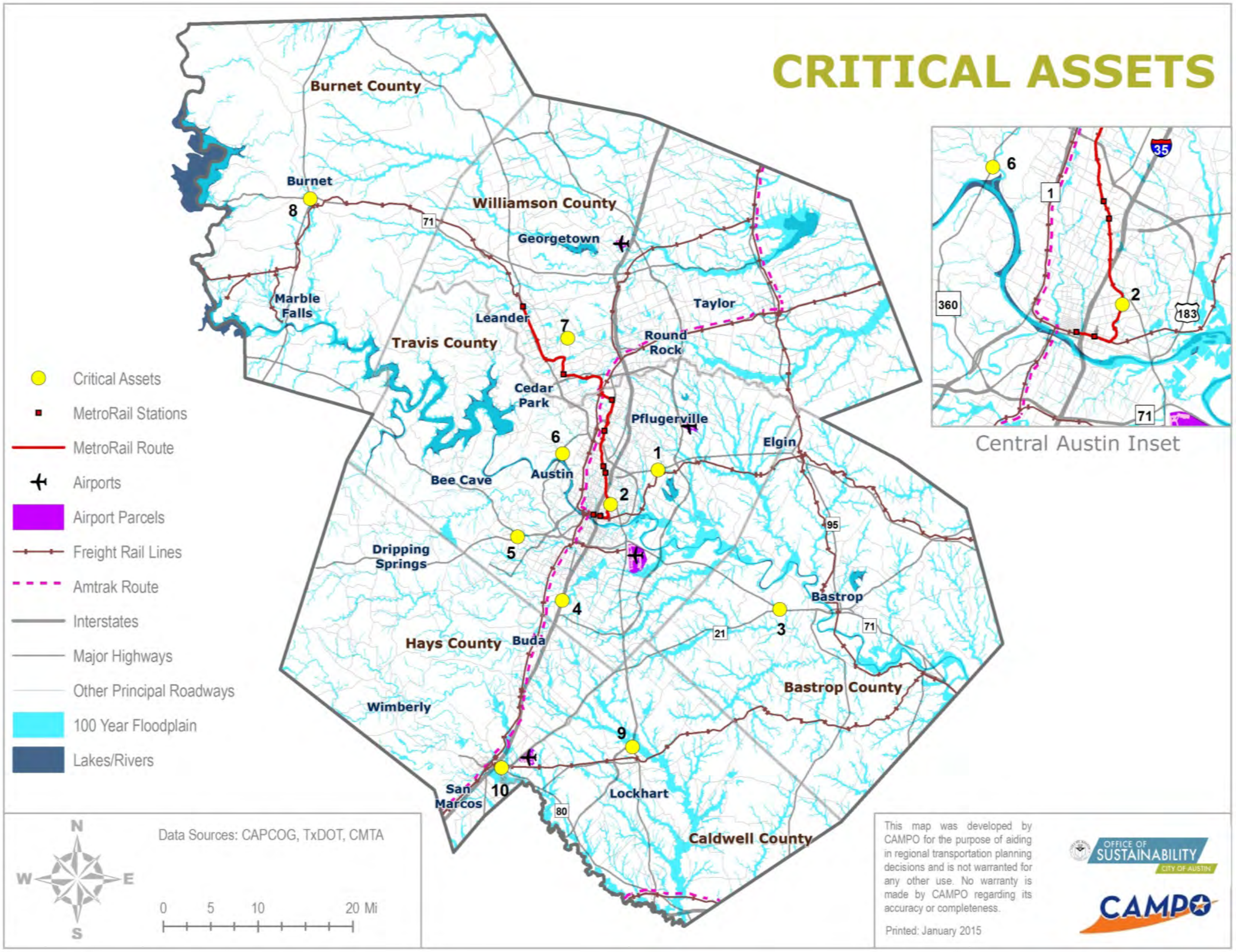
hurricane evacuation route for the state's coastal areas. The study segment is located on high plasticity soils and passes through the 100-year floodplain.

- **(#10) SH 80 (San Marcos Highway) over the Blanco River** – SH 80 (San Marcos Highway) provides connectivity between the City of San Marcos and the San Marcos Municipal Airport. The study location intersects a 100-year floodplain.

Table 3 Assets for In-Depth Evaluation

Fig. 9 ID	Recommended Asset for Evaluation	County	Mode	Potential Vulnerabilities	AADT	Soil Plasticity	Proximity to 100-Year Floodplain	Evacuation Route?
2	MetroRail Red Line at Boggy Creek	Travis	Commuter Rail	Flooding, drought, extreme heat	N/A	High	0 ft.	No
3	SH 71E at SH 21	Bastrop	Road, Airport Access	Flooding, drought, extreme heat	27,000 (SH 71), 9,500 (SH 21)	High	1,000 ft.	Yes
4	I-35 at Onion Creek Parkway (study area to include Old San Antonio Road low water crossing)	Travis	Road	Flooding, extreme heat	186,000	Low	0 ft.	No
5	US 290W/SH 71 – Y at Oak Hill	Travis	Road	Flooding, drought wildfire, extreme heat	38,000 (US 290W), 29,000 (SH 71)	Moderate	600 ft.	No
6	Loop 360/RM 2222	Travis	Road	Flooding, drought, wildfire, extreme heat	40,000 (Loop 360) 44,000 (RM 2222)	Moderate	100 ft.	No
7	FM 1431 at Brushy Creek/Spanish Oak Creek	Williamson	Road	Flooding, drought, extreme heat	30,000	Moderate	0 ft.	No
8	US 281 and SH 29 Intersection	Burnet	Road	Flooding, extreme heat	11,000 (US 281) 11,000 (SH 29)	N/A	0 ft.	No
9	US 183 north of Lockhart	Caldwell	Road	Flooding, drought, extreme heat	13,000	Moderate	0 ft.	Yes
10	SH 80 (San Marcos Highway) at the Blanco River	Hays	Road, Airport Access	Flooding, extreme heat	9,500	N/A	0 ft.	No

Figure 9 Assets for In-Depth Evaluation



4.0 Sensitivity Thresholds

The project team convened a series of interviews with local experts to establish the most relevant extreme weather and climate-related sensitivity thresholds applicable to the Central Texas transportation system. The goal of this exercise was to guide the project team in determining which climate variables to employ in the subsequent vulnerability assessment.

Sensitivity thresholds refer to the points at which the transportation system (or a component thereof) is likely to be impacted by a given climate stressor. These thresholds can be considered in two general categories:

- ***Design Thresholds -*** Weather or climate-related thresholds embedded in asset design, such as in materials specifications. Design thresholds typically denote the point at which failure risk increases beyond a tolerable level, but actual asset failure is unlikely to correspond precisely with these thresholds.
- ***Empirically-Derived Impact Thresholds -*** Circumstances associated with previous failures, which may occur well beyond design thresholds or, in the case of assets that are in poor condition or are particularly stressed (by high volumes of truck traffic, for example), prematurely.

The expert interviews included staff from TxDOT, City of Austin Department of Public Works (DPW), City of Austin Department of Homeland Security and Emergency Management (HSEM), City of Austin Fire Department, Capital Metro, and Austin-Bergstrom International Airport (ABIA).

These experts identified sensitivities related to five extreme weather and climate stressors—**flooding**, **drought**, **extreme heat**, **wildfires**, and **extreme cold and icing**. Precipitation variability – from flash flooding to drought – emerged as a primary concern for the area, affecting roadway structures, the ability to move goods and people, and pavement condition. In addition, it was noted that stresses on the transportation system from rapid development and growth may exacerbate extreme weather sensitivities. Information on specific sensitivity thresholds is found in the following sections.

4.1 Flooding

Heavy downpours can cause flash flooding in the Austin area, with the worst flooding typically occurring west of the city. The impacts of these floods on the transportation system range from temporary service disruptions to washouts of roads. The severity of flooding impacts depends on several factors, including rainfall intensity, ground perviousness and degree of prior saturation, and presence of debris (e.g., post-wildfire), which can block drainage facilities.

Design Thresholds

Exact design thresholds will vary by project, but in general, drainage facilities in the City of Austin are designed based on the 25- and 100-year frequency storms for the 24-hour event. Values for those events are shown in Table 4.

Table 4 24-hour Precipitation Totals and Recurrence Intervals for Austin and Travis County, Texas

Recurrence Interval (years)	2	2.5	3.33	5	10	25	50	100	250	500
24-hour Rainfall (inches)	3.44	3.84	4.33	4.99	6.10	7.64	8.87	10.2	12.0	13.5

Source: City of Austin Drainage Criteria Manual, Appendix B, Table 1, Depth-duration frequency of precipitation for Austin and Travis County, Texas.

TxDOT indicated that design return intervals vary by functional classification and structure type. Freeways are typically designed to withstand the 50-year event, and all projects are evaluated against the 100-year event. Local roads and streets may be designed to the 2, 5, or 10-year events (associated with 3.44, 4.99, and 6.10 inches of precipitation in 24 hours, as shown above). TxDOT also noted that roadways designed to lower standards in formerly rural and now rapidly urbanizing areas may no longer satisfy current standards.

Empirical Thresholds

Tropical Storm Hermine in 2010 and the Halloween Floods of 2013 stand out as recent flood events with major impacts on the Central Texas transportation system, flooding roads and rail lines. Hermine brought 10-16 inches of rain in central Williamson County and northern Travis County, roughly representing a 100-year rainfall event. The Halloween Floods came after 6-10 inches fell in Hays and Travis Counties, with 12-14 inches falling between Wimberley and Driftwood. See Appendix E for further details.

Anecdotally, stakeholders concurred that some flooding typically occurs when the area experiences at least two inches of rain in fewer than 12 hours.

Roads

Stakeholders noted that flooding events pose particular challenges in rural or formerly rural (urbanizing) areas, where in some cases roads providing critical connectivity cannot withstand even the 2-year flood event.

Rail

Rail lines in the area cannot operate if the depth of water is three inches or more above the rail. Lines are also subject to washouts from flood events.

4.2 DROUGHT

Areas in Central Texas, especially east of I-35, often feature moderate- to highly-expansive (plastic) clay soils, which are particularly sensitive to changes in soil moisture from prolonged drought or cycles between wet and dry periods. The primary effect of soil moisture fluctuations on transportation infrastructure is on pavements, road beds, and buried utilities. Soil contraction and expansion causes pavement distortion and cracking and causes the most pronounced damage on the edges of pavements, a response exacerbated by heavy truck traffic.

Design Thresholds

No design thresholds were identified.

Empirical Thresholds

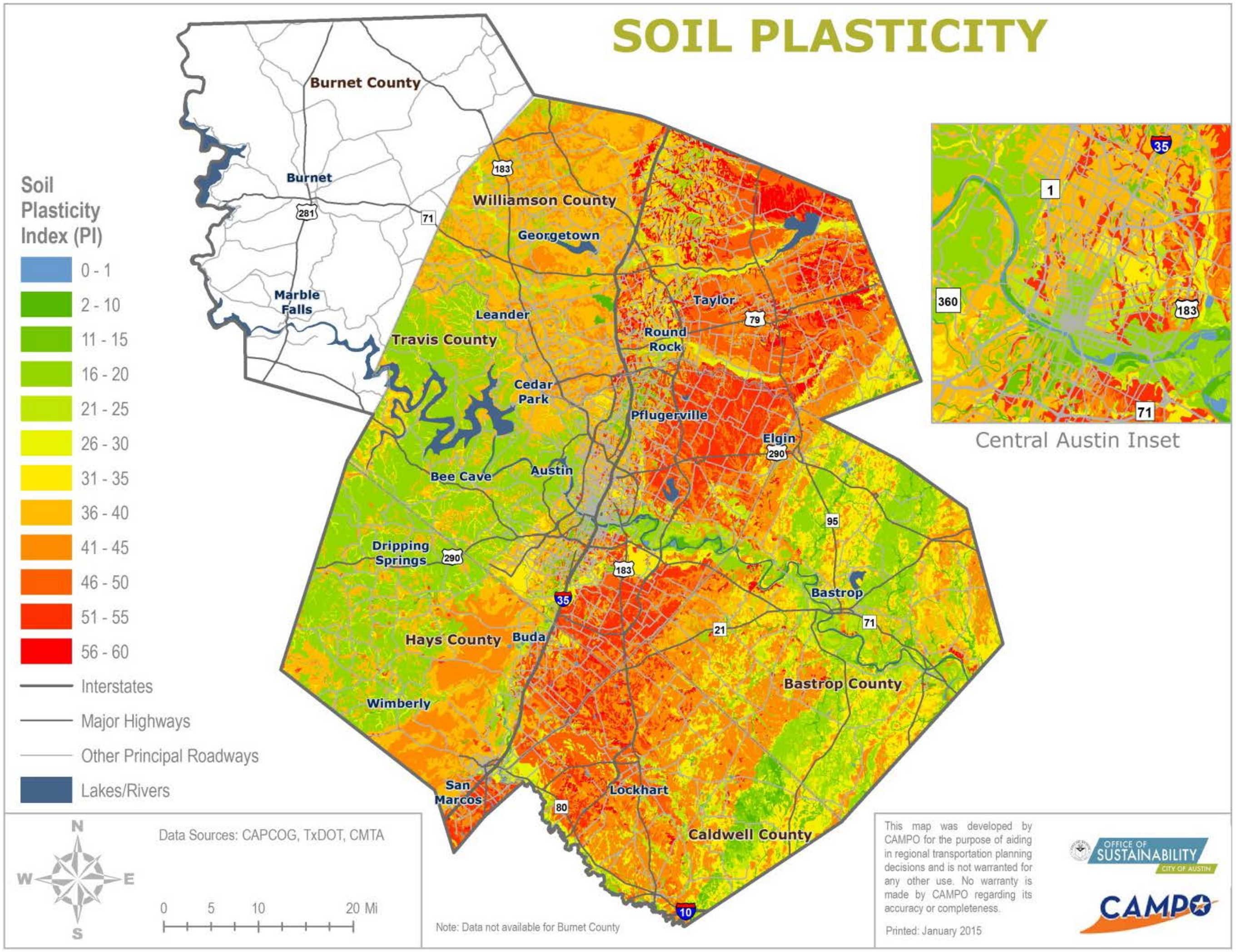
Interviewees noted that several weather variables drive pavement sensitivity to drought, especially cycles in wet-dry conditions. They noted that sensitivity may increase under the following conditions:

- Extended drought conditions, defined as periods of weeks to months with no precipitation;
- Alternating wet and dry weather patterns, with a frequency of between a few days and a few weeks; or
- Extremely wet conditions for one month or longer.

In all cases, these effects are most pronounced where pavements are stressed or in poor condition due to the presence of very heavy vehicles. This is particularly true in the southern extent of the CAMPO region—where increases in industrial activity (particularly in the energy sector) have led to unusually high volumes of heavy and overweight vehicles—and in the formerly rural but rapidly developing areas surrounding Austin.

A soil plasticity map for the region is shown in Figure 10 (data for Burnet County were not available). Reds and oranges indicate relatively higher plasticity soils, which, all else being equal, may exhibit greater sensitivity to drought conditions.

Figure 10 Soil Plasticity Index



Source: USDA.

4.3 EXTREME HEAT

Infrastructure in Central Texas is generally designed to withstand relatively high temperatures. However, extreme heat can contribute to accelerated pavement deterioration, thermal misalignments in rail lines, and can affect maintenance and construction crews.

Design Thresholds

Roads and Pavements

According to TxDOT, asphalt pavements in the study area typically use a Performance Grade (PG) 64-22 pavement binder. This binder is designed to withstand an average seven-day maximum pavement temperature of 64° C, or 147° F. This, in turn, roughly equates to an average seven-day maximum ambient temperature of about 108° F.[4] Occasionally, roads are also paved with PG 70-22 or PG 76-22, which correspond to average seven-day maximum ambient temperatures of 119° F and 130° F, respectively.

Rail

Rail lines in the Austin area are set with a rail-neutral temperature between 100° F and 115° F, after which the risk of thermal misalignment increases. Thermal misalignments, in turn, can increase the risk of train derailments and cause operational disruptions and/or slower operating speeds.

The relationship between rail temperature and ambient temperatures is highly variable, though the industry commonly assumes that rail temperature can be as high as 20° F to 30° F above ambient temperatures.[5] Thermal misalignments on Capital Metro rail have occurred in the past, but the agency issues precautionary speed restrictions during high heat days to reduce the risk of derailments.

Empirical Thresholds

Roads and Pavements

Empirically, stakeholders noted that pavements begin to experience deterioration when temperatures exceed 100° F for an extended period of time.

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[4] Calculated based on equation found in U.S. DOT, 2012, *Assessing the Sensitivity of Transportation Assets to Climate Change, Sensitivity Matrix*, U.S. DOT Center for Climate Change and Environmental Forecasting, citing Watson 2010.

[5] Yu-Jiang Zhang and Leith Al-Nazer, 2010, *Rail Temperature Prediction for Track Buckling Warning*, American Railway Engineering and Maintenance-of-Way Association (AREMA) 2010 Annual Conference, p. 7.

Transit

Extreme heat, particularly temperatures exceeding 100° F, can stress bus air conditioning systems. If those systems fail, Capital Metro removes that bus from service. Extreme temperatures also affect the ability of passengers to wait for service at exposed outdoor locations, in particular.

Operations

In addition to having physical impacts on assets, extreme temperatures can affect operations and maintenance across modes. Temperatures above 100° F create a health and safety hazard for maintenance and construction crews. When temperatures reach 105° F, employees must take 10-minute hydration breaks every 50 minutes.

Heat also affects rail operations. Capital Metro, like other rail operators, issues speed restrictions during extreme heat days. Freight lines have lower thresholds for speed restrictions than passenger lines.

4.4 WILDFIRE

Wildfires pose major threats to life and safety. The primary effect of wildfire on transportation is to operations (e.g., traffic disruptions), which, crucially, can also affect evacuation routes by creating critical bottlenecks. Guiderail and posts can be destroyed, and pavements can be oxidized in extremely hot fires, accelerating longer-term deterioration. Post-wildfire, burned trees within the roadway right-of-way may be unstable and have been known to collapse, posing a hazard for motorists, and debris can exacerbate flooding.

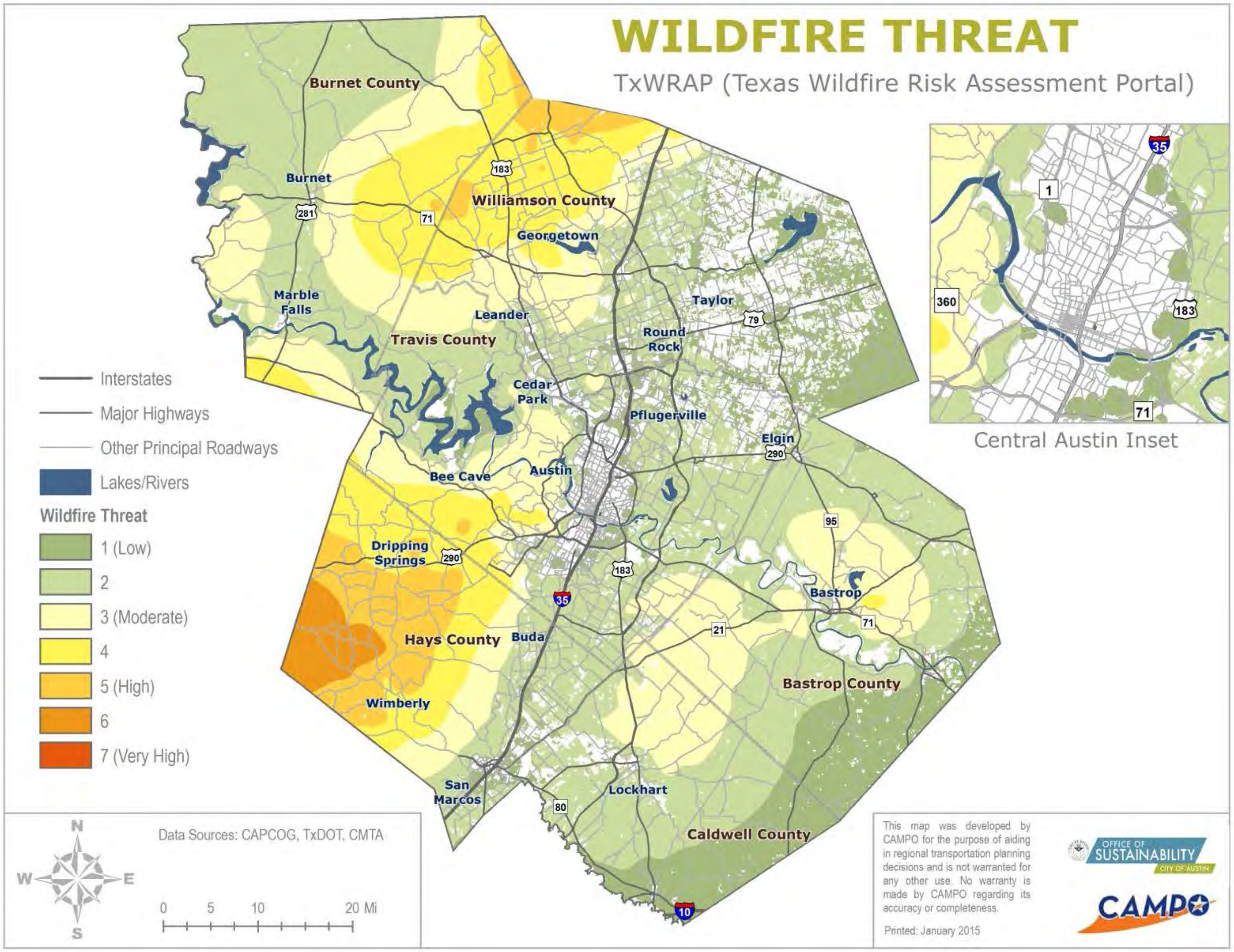
Wildfire Risk Thresholds

Wildfire risk is multifaceted. The severity of a wildfire and probability of fire occurrence are influenced by numerous factors, including fuel availability, fuel moisture, ambient humidity, vegetation type, winds, and more (see the Texas A&M Wildfire Risk Assessment Portal, or TxWRAP, for more detail).

As a proxy for localized wildfire susceptibility, the Wildfire Threat rating from TxWRAP was employed. Wildfire Threat is the "likelihood of a wildfire occurring or burning into an area," derived at 30-meter resolution.[6] Figure 11 Wildfire Threat ***TxWRAP Ratings*** depicts the Wildfire Threat ratings from TxWRAP, with red, orange, and yellow colors representing the areas with the highest threat levels.

[6] http://www.texaswildfirerisk.com/help/txwrap_user_manual.pdf

Figure 11 Wildfire Threat
TxWRAP Ratings



Regionally, wildfire risk is driven by a variety of climate- and weather-related factors. For example, wildfire risk in Central Texas increases when the Keetch-Byram Drought Index (KBDI) is greater than or equal to 575. KBDI is based on daily water balance and is calculated using mean annual precipitation, maximum dry bulb temperature, and the last 24 hours of rainfall.[7] As explained subsequently, future KBDI projections were not developed for this study due to the lack of an established methodology for doing so (this is an area of potential future research). Instead, soil moisture, a measure of the volume of water contained within a given volume of soil, was used as a proxy.

4.5 Extreme Cold (Icing)

Freezing conditions are very rare in the CAMPO planning area, but when they do occur they disrupt operations and present a risk to public safety. Roadways and bridges, especially elevated ones, ice over and create hazardous driving conditions. Extended, hard freezes can also damage pavements and cause cracking.

Design Thresholds

Asphalt pavements in the area are designed to withstand pavement temperatures as low as -22° C, or -7.6° F. The lowest recorded temperature in Austin was -2° F (January 1949).

Empirical Thresholds

Extreme cold and ice become problematic any time temperatures are below freezing and precipitation is present. Any level of ice on roads causes unsafe driving conditions, and any more than 3/16" of ice can break a rail switch, creating service delays.

4.6 Summary of Sensitivity Thresholds

The design and empirical thresholds identified in this task are summarized in Section 6.1. These thresholds do not represent the complete picture of transportation weather sensitivity in Central Texas. Many factors are interrelated (e.g., droughts and flash flooding or wildfire), and no stressors operate in a vacuum. Additional factors such as asset condition, traffic-related stresses, and specific asset design and maintenance practices were assessed on an asset-by-asset basis and contribute significantly to extreme weather sensitivities.

[7] U.S. Forest Service Wildland Fire Assessment System, 2014, "Keetch-Byram Drought Index," http://www.wfas.net/index.php/keetch-byram-index-moisture--drought-49.

5.0 Climate Data

This study leveraged the work of Patricola and Cook (2013)[8] to generate projections for 2041-2060 (in shorthand, the "mid-21st century"). The Weather Research and Forecasting (WRF) regional climate model (RCM), developed by the National Center for Atmospheric Research (NCAR) and partners, was used to simulate climate at a 30-km (18.6-mile) resolution for a domain including Central Texas.[9] Regional climate models, such as WRF, use the same physics as General Circulation Models, but at much higher resolution—accounting for regional surface features such as topography and surface moisture variations, as well as an improved resolution of weather systems and localized convective activity associated with extreme precipitation events. Figure 12 illustrates the performance of the WRF model in simulating historic climate versus observed conditions and coarser GCM output.

The study team developed a series of scenarios — a range of plausible climate futures — to consider the performance of the transportation system under a variety of potential conditions and to reflect the inherent uncertainty associated with climate projections (particularly events of special concern to the transportation sector, like localized extreme precipitation events).

Despite the significant advantages of using an RCM to develop projections, many of the parameters typically toggled to create scenarios—models, emissions, and analysis periods, for example—are built into the RCM application because of the high level of computational resources required for the simulation and, therefore, could not be adjusted within the scope of this study. As an alternative, the team identified geographic-based scenarios, reflecting projections for greater Austin and two proximate areas of Texas, one 2° of latitude north, the other 2° of longitude west.[10] Although the projections for Austin are most likely, projections for neighboring regions should be considered possible for Austin as well (the approximately 133-mile distance (north and west, respectively) from Austin is within the potential margin of error. Scenario 3 (to the West) returned the most significant projected change in extreme rainfall magnitudes, and was selected due to the conservative approach to risk adopted by CAMPO and the City of Austin (e.g., this is the "worst case" among the three scenarios).

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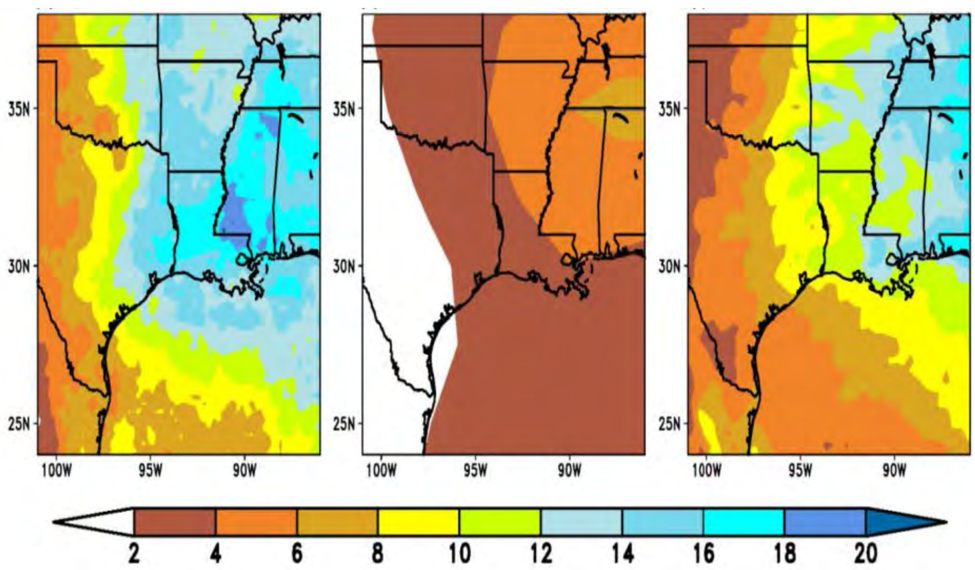
[8] Patricola, C. M., and K. H. Cook, 2013b: *Mid-twenty first century climate change in the central United States. Part II: Climate change processes*. Climate Dynamics, 40, 569-583.

[9] For perspective, selected statistically-downscaled projections performed by parties not affiliated with this study are provided in Appendix A.

[10] Projected change is more uniform to the east, which does not result in a significantly different scenario.

Figure 12 Number of Intense Rainfall Events in Today's Climate[11]



Left: Observed; Middle: 9-member GCM ensemble; Right: Patricola and Cook RCM (2013).

Source: Patricola and Cook (2013).

The key climate data parameters are provided in Table 5.

Table 5 Climate Data Parameters

Parameter	Selection for Assessment
Climate Model (RCM)	Weather Research & Forecasting (WRF). National Center for Atmospheric Research
Emissions Scenario	A2[12] (moderately-high)
Horizontal Spatial Resolution	30 km
Time Frame	1981-2000, 2041-2060
Geography	1) City of Austin, 2) 133 miles north of Austin, 3) 133 miles west of Austin (see Figure 13)

The three scenario locations, shown in Figure 13, are as follows:

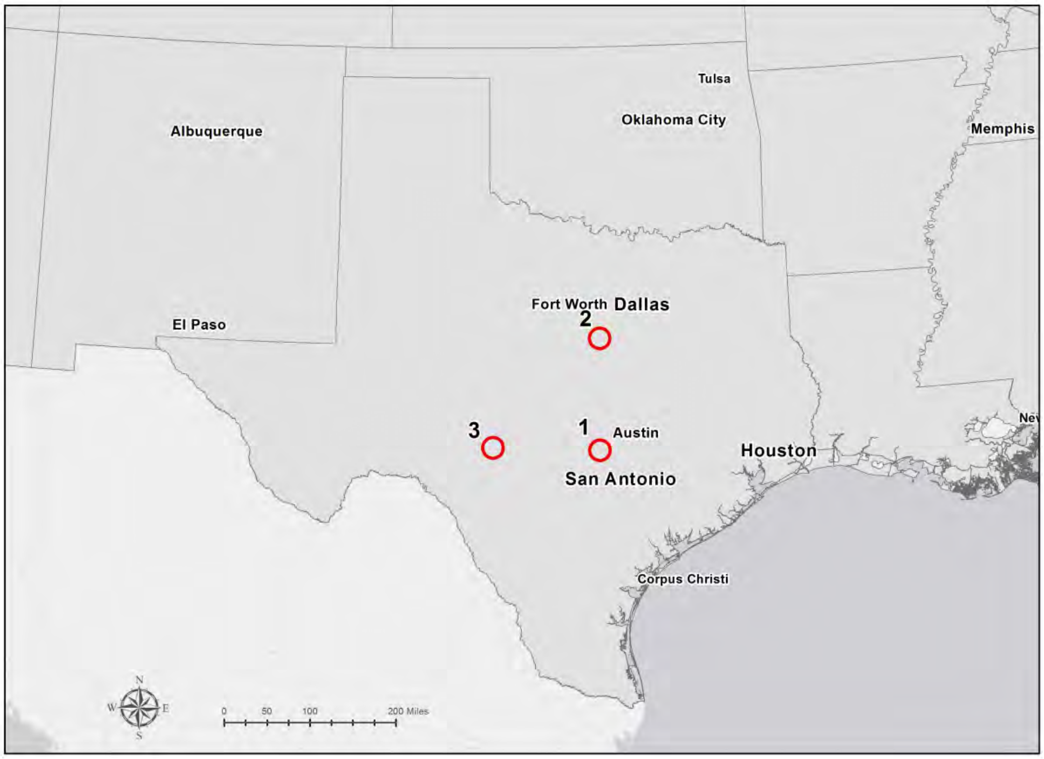
- **Scenario 1:** Greater Austin (30.3°N and 97.8°W);

[11] Average number of days per year when the daily rainfall rate exceeds 25 mm day in the (from left to right) TRMM 1998-2009 climatology, IPCC AR4 AOGCM multi-model ensemble (9 members), and the 30-km regional climate model simulation for Patricola and Cook (2013).

[12] This emissions scenario represents a storyline of "continuously increasing population" and "more fragmented and slower … per capita economic growth and technological change." See the Intergovernmental Panel on Climate Change's *Special Report on Emissions Scenarios* (2000) for further information. www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf

- **Scenario 2:** 133 miles north of Austin (in the general vicinity of Fort Worth);
- **Scenario 3** (analysis scenario): 133 miles west of Austin.

Figure 13 Scenario Locations



The selection of climate variables retrieved corresponds, as closely as possible, to the list of stressors of concern (e.g., extreme heat) and key design thresholds (e.g., 100° F days) identified through the Sensitivity Focus Group interviews (although, in selected cases, proxy variables were used). Extreme precipitation, for which percent change was derived, was used as a key factor in the flood modeling detailed subsequently. Table 6 provides a summary by variable of the projected change (the Scenario 3 result) and range of change (across all three scenarios). Baseline (historical or simulated past) data, where available, are provided in the subsequent narrative.

Table 6 Summary of Projected Changes (1981-2000 to 2041-2060) *Key Variables*

	Projected Change	Range of Change	Stressor Indicator
Temperature			
Annual temperatures (F)	+ 2.7° F	+ 2.7° F to + 2.9° F	n/a (Supplemental)
Winter average mean temp (F)	+ 2.2° F	+ 2.2° F (no variance)	n/a (Supplemental)
Summer average mean temp (F)	+ 2.9° F	+ 2.9° F to + 3.6° F	n/a (Supplemental)
Annual average # days ≥ 100° F/year, average (days)	+ 34 days	+ 34 days (no variance)	Extreme Heat
Annual average 7-day maximum temp (F)	+ 3.9° F	+ 3.9° F to + 4.1° F	Extreme Heat
Precipitation			
Annual average precipitation (%)	No change	-7.5% to +5%	n/a (Supplemental)
Summer average precipitation (%)	No change	-15% to +10%	n/a (Supplemental)
Annual average dry days (< 0.01" precipitation) (days)	+ 3 days	+ 3 to + 4 days	Drought
Magnitude of very heavy (99th percentile) 24-hour rainfall event (inches)	+20%	-20% to +20%	Flooding (input into Flood Early Warning System model)
Frequency of 24-hour precipitation events ≥ 3.44 inches (~25-year) (days annually)	None	0 to -0.25 (one fewer event every four years)	n/a (Supplemental)
Other			
Annual Soil Moisture (m^3/m^3)	-2%	No change to -5%	n/a (Supplemental)
Summer Soil Moisture (m^3/m^3)	-4%	-4% to -10%	Drought, Wildfire
Annual average potential "Ice Days" (≤ 32° F and (> 0.01" precipitation) (days)	-1 day (-50%)	-1 day (no variance)	Extreme Cold (Icing)

Temperature

The WRF model projects a warmer future for Central Texas by the middle of the 21st century, consistent with other available downscaled projections. Average annual temperatures are projected to rise about 2.7° F, with a slightly greater degree of increase projected for summer months (2.9° F). Correspondingly (and more directly relevant to transportation agencies), extreme heat events are also projected to increase. Days equal to or greater (≥) than 100° F are projected to increase by an average of 34 days annually (this result is uniform across all three analysis scenarios), which would result in an average of nearly 50 days in Austin[13] by the mid-20th century. Annual average 7-day maximum temperature,[14] a critical threshold for selecting asphalt binder grade, is projected to increase by about 3.9° F, climbing from 99.7° to 103.6° F. Applying these deltas to Camp Mabry temperature readings from 2000, the hottest year from 1981-2000, would yield 76 days and nearly 112° F, respectively.

Table 7 **Annual Days ≥ 100° F and Annual 7**-day Tmax
Projected Change

Variable (Average)	Change	Base (Camp Mabry) End of 20th Century	Projected Mid 21st Century
Annual days ≥ 100° F	+34 days	14.8 days	48.8 days
Annual average 7-day maximum	+3.9° F	99.7° F	103.6° F

Figure 14 displays the observed record of days in which the maximum temperature equaled or exceeded 100° F (bars). Over the period of observation, there was significant variation from year-to-year—from zero days in 1987, one day in 1981, 1983, 1992, and 1997 to 42 days in 2000 and 38 in 1998. Ninety days ≥ 100° F were recorded at Camp Mabry in 2011.

Also represented in Figure 14 are the highest 7-day average maximum temperatures (suns). The highest value, recorded in September of 2000, was over 107° F (the next highest value was 102.4° F in 1998), and the lowest was 95° F, recorded in 1983, 1992, and 1997 (95.9°, 95.3°, and 95.8° F, respectively). However, the standard deviation was about 2.8° F, reflected by the fairly steady record of readings from 1981 to 2000.

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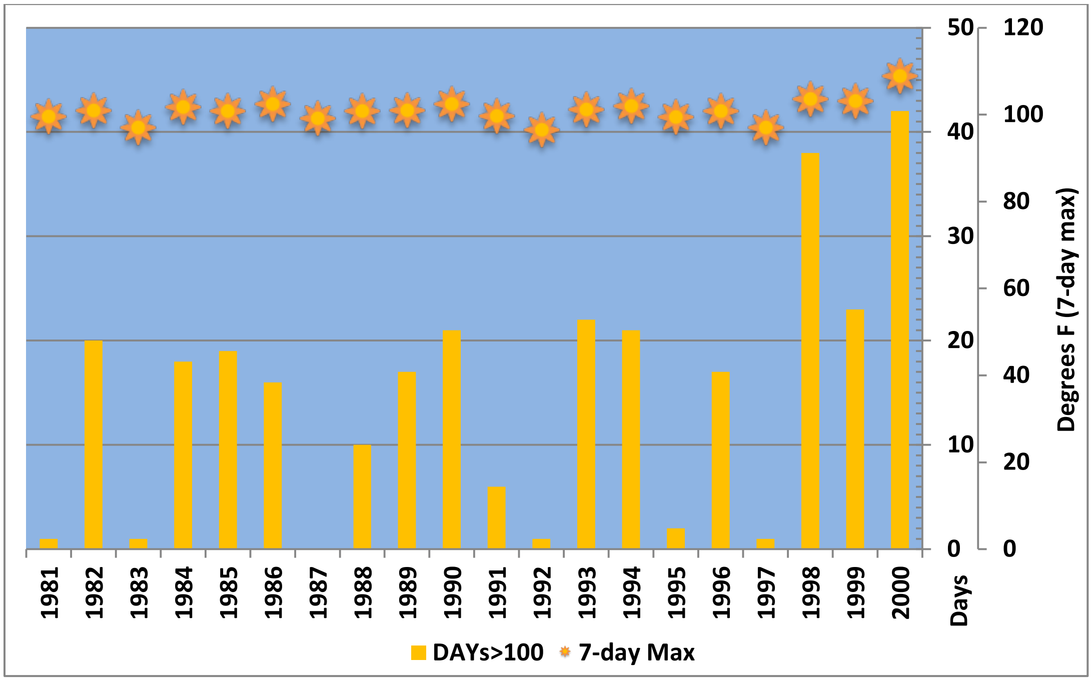
[13]Camp Mabry weather station data from 1981-2000, retrieved from the National Climate Data Center, was selected to represent baseline climate in and around Austin because it remained at a consistent location throughout the historical baseline period (unlike the airport, which relocated in 1999), and because it was used by ATMOS Research and Consulting in the development of statistically-downscaled projections for the City of Austin (2014).

[14] The average maximum temperature, or Tmax, of any seven consecutive days within a given year.

Figure 14 **Days ≥ 100° F and Average 7-day Tmax**
1981-2000, Austin, Texas



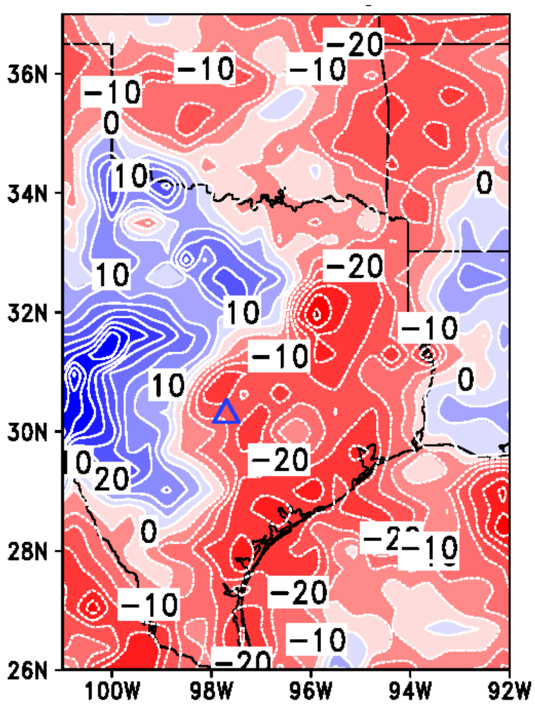
Source: National Climatic Data Center (NOAA), Camp Mabry Station

Precipitation

According to the Intergovernmental Panel on Climate Change (IPCC), there is less confidence in precipitation projections than in temperature, particularly at more granular geographic scales.[15] Precipitation is also, generally, a more localized phenomenon than temperature, which is reflected in the relatively wide range of results across the three geographic scenarios. This is also seen in the fine variegation of average summer (June-July-August) rainfall projections in Figure 15, which shows a 15 percent reduction in Austin (Scenario 1), a 10 percent increase to the north (Scenario 2), and no change for Scenario 3.

[15] Randall, D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi and K.E. Taylor, 2007: *Climate Models and Their Evaluation. In: Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning,Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter8.pdf

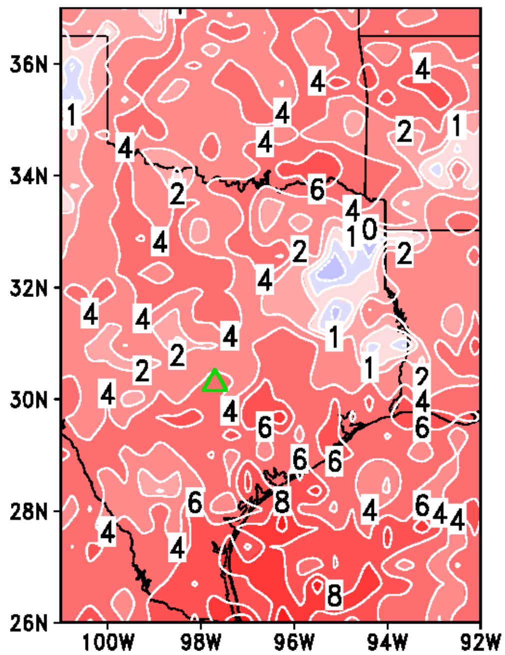
Figure 15 Change Average Seasonal Precipitation (1981-2000 to 2041-2060) *%,Summer*



Source: WRF

The WRF model projects a dryer future for Central Texas by the middle of the 21st century. Across the scenarios, the average annual number of dry days (during which total precipitation is 0.01 inches or less) are expected to increase modestly, from 1.0 to 1.5 percent (the equivalent of about three to four days). Added to the Camp Mabry 1981-2000 baseline of about 276 days, the projection is for 279-280 days, on average, by mid century.

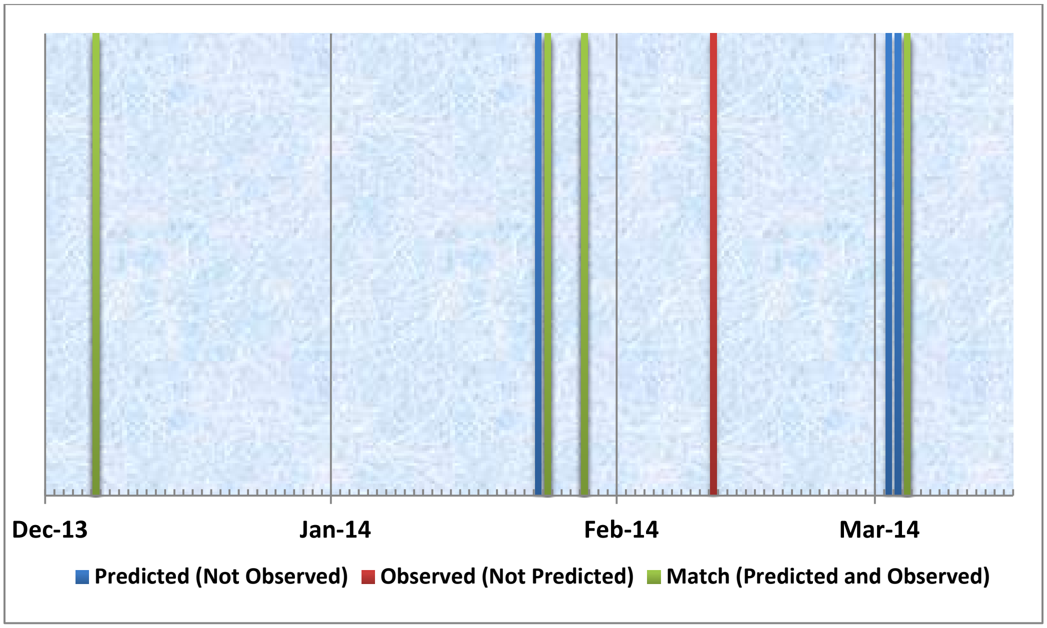
Figure 16 Change in Average Annual Dry Days (1981-2000 to 2041-2060)
Absolute



Source: WRF

Although the precise conditions responsible for roadway or rail icing are highly localized and cannot be simulated reliably with a climate model, potential meteorological precursors to icing events can be modeled. For the purposes of this study, a potential "Icing" Day is considered as a proxy. An Icing Day is characterized by 1) more than a trace amount of precipitation, total, and 2) a minimum temperature (Tmin) of 32° F or less—although the temporal alignment of these factors was not measured. Although the "Icing" Day, as defined here, is far from a perfect predictor, an overlay of potential "Icing Days" and observed Icing Days over the winter of 2013-2014 (during which these events were abnormally abundant) shows reasonable coincidence. Of seven potential Icing Days, significant roadway icing was reported on four (represented as green bars in Figure 17). One reported roadway icing day, February 11, 2014, had a recorded minimum temperature of 33° F (0.6° C)—not, therefore, a potential icing day, but clearly in line with the presence of freezing temperatures in the region.

Figure 17 Potential Icing Days vs. Observed Icing Days
2013-2014



Source: Camp Mabry station data and recorded roadway icing incidents, Tech Memo #2

The first precursor, days with more than a trace amount of precipitation, is the reverse of a Dry Day; an average of 276.3 dry days plus an average of 88.95 "wet" days equals 365.25 days (including the intercalary year). The second precursor, freezing temperatures, was recorded an average of 13.3 days annually from 1981-2000. Both conditions were satisfied just 32 times from 1981-2000, an average of 1.6 times annually. The WRF projects that days meeting these criteria will decrease by about one per year by the mid-21st century to 0.6 days annually, on average.

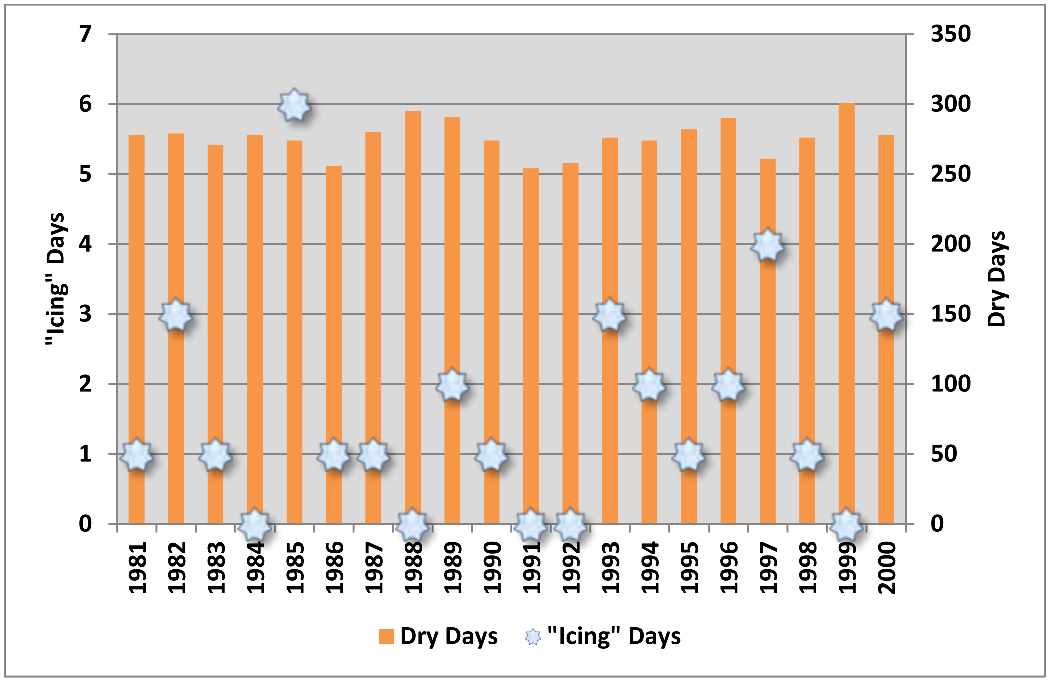
Table 8 Annual Dry Days and "Icing" Days
Projected Change

Variable (Average)	Change	Base (Camp Mabry) End of 20th Century	Projected Mid 21st Century
Annual dry days (≤ 0.01" 24-hour precipitation)	+3 days	276.3 days	279.3 days
Annual "icing" days (≤32° F AND ≥ 0.01" precipitation)	-1 day	1.6 days	0.6 days

Figure 18 displays the observed record of days in which less than 0.01 inch was recorded (bars). Although some interannual variability exists, with results ranging from 254 (1991) to 301 (1999) Dry Days, the standard deviation is about 12.5 days, or 3.4 percent.

Also represented in Figure 18 are potential Icing Days (stars). Although there is significant variability from year to year, outside of 1985 (six days) and 1997 (four days), records for all years indicate three or fewer days, with zero days recorded in five separate years. The projections reflect this variability, but average around one day annually for the 20-year analysis period.

Figure 18 Dry Days and "Icing" Days
1981-2000, Austin, TX



Source: National Climatic Data Center (NOAA), Camp Mabry Station

For the purposes of the subsequent flood modeling exercise (see following subsection), the percent change in the magnitude of the 99th-percentile (very heavy) 24-hour rainfall event was obtained from WRF (Figure 19), and then applied as a delta to precipitation recurrence intervals commonly referenced in roadway and rail design guidelines, as established in the Sensitivity Focus Groups. The delta varies significantly across the three scenario locations: Scenario 1 (Austin) shows a 20 percent decrease, Scenario 2 a 15 percent increase, and Scenario 3 shows a 20 percent increase in magnitude. Consistent with the conservative (averse) approach to risk adopted by this study, Scenario 3 (20 percent increase) was employed as the projection delta to adjust the magnitude of precipitation associated with the 5-, 25-, 50-, and 100-year events, as stated in the City of Austin Drainage Criteria Manual. The resulting values are computed in Table 9.

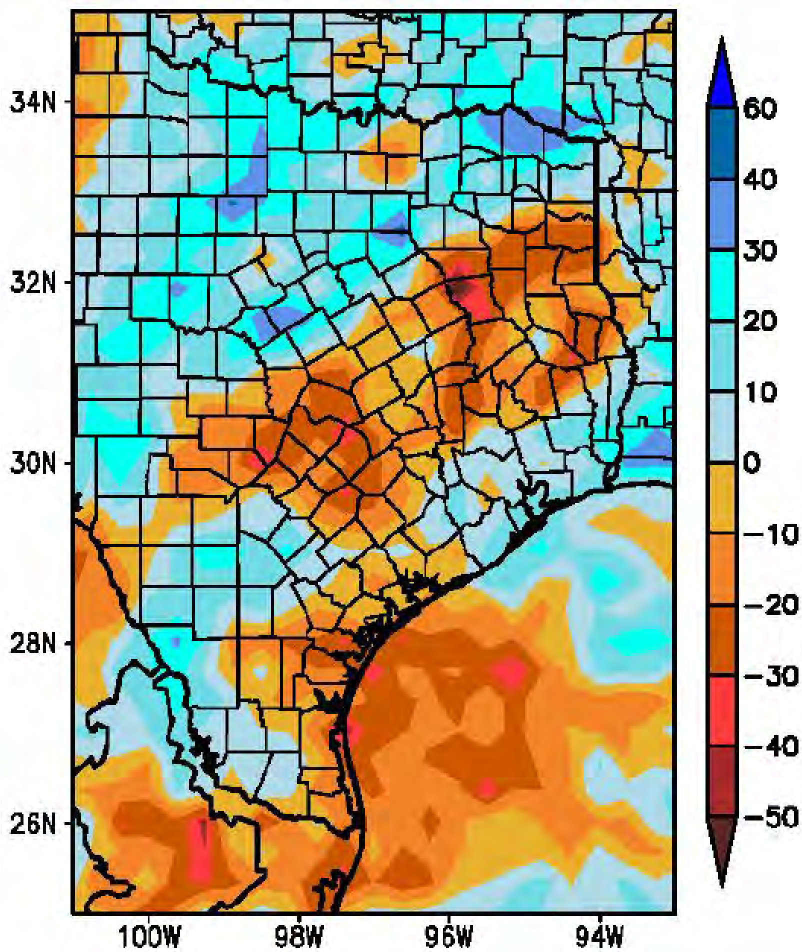
Table 9 Extreme Precipitation Magnitudes
24-hour, Projected Change

Variable (Magnitude, 24-hour precipitation event)	Change	Base (City of Austin Drainage Criteria Manual[16])	Projected Mid 21st Century
99th-percentile	+20%	1.73 inches (Camp Mabry, 1981-2000)	2.07 inches
100-year	+20%	10.2 inches	12.24 inches
50-year	+20%	8.87 inches	10.64 inches
25-year	+20%	7.64 inches	9.17 inches
5-year	+20%	4.99 inches	5.99 inches

The 99th-percentile, 24-hour precipitation value at Camp Mabry (1981-2000) was approximately 1.73 inches. The highest value recorded during that period—6.24 inches—is approximately equivalent to the 10-year event of 6.1 inches, as specified in the Drainage Criteria Manual. The 5-year value of 4.99 inches was exceeded three times in three separate years.

[16] *City of Austin Drainage Criteria Manual*, Appendix B, Table 1, Depth-duration frequency of precipitation for Austin and Travis County, Texas.

Figure 19 Projected % Change in Magnitude (1981-2000 to 2041-2060)
99th-percentile 24-hour Precipitation Event



Source: WRF

Soil Moisture

The WRF model projects decreasing soil moisture for Central Texas by the middle of the 21st century. Under the analysis scenario (Scenario 3), a potential drop of four percent occurs during the summer months of June-July-August (Table 10), and decreases of up to 10 percent are projected under other scenarios. Baseline soil moisture, also derived from WRF, averages around 0.2 m^3/m^3[(17)] during the summer, although significant month-to-month or even week-to-week fluctuations can occur.

[17] Volumetric water content (i.e., cubic meters of water per cubic meter of soil). 0.2 m^3/m^3, for example, means that 20% of the volume of a given cubic meter of soil is water (the remainder being soil and air).

Figure 20 shows soil moisture readings for Austin from April 2010 to April 2012. During the unusually hot summer of 2011, readings range from 0.38 m^3/m^3 on June 23rd down to 0.07 m^3/m^3 from September 5th to 15th (at five cm depth). Changes in the rate of decline at deeper depths tend to be more gradual (e.g., 0.35 m^3/m^3 to 0.15 m^3/m^3 during the same period at a depth of 10 cm).

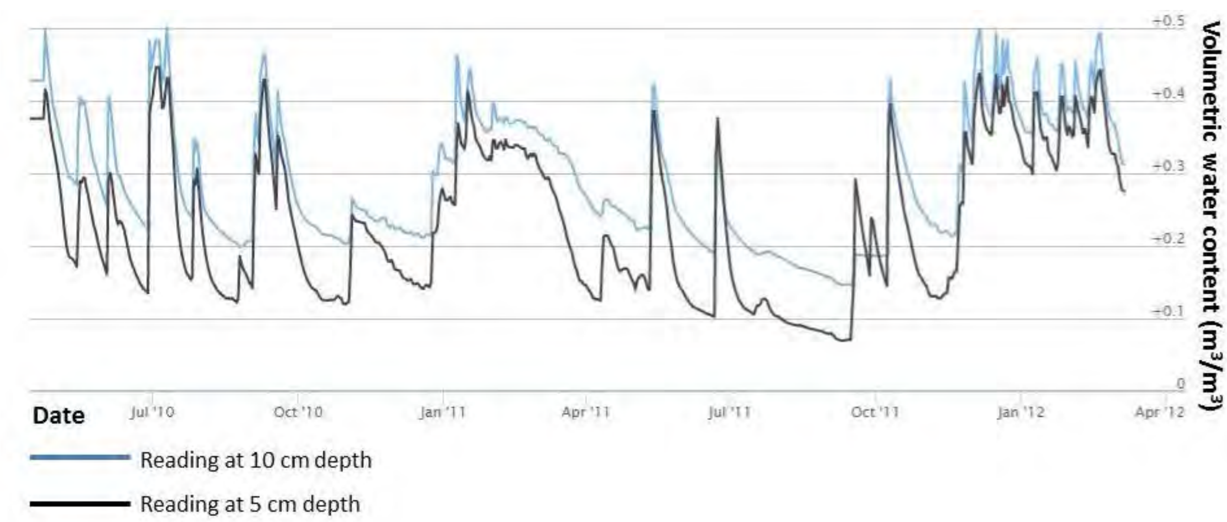
A reduction in soil moisture is a key indicator of drought conditions and can contribute to increased wildfire ignition risk. Given the absence of projections for more complex indicators, such as the Keetch-Byram Drought Index (KBDI), soil moisture is employed as one indicator of wildfire risk.

Table 10 Soil Moisture (m^3/m^3)
Projected Change

Variable (Average)	Change	Base (WRF) End of 20th Century	Projected Mid 21st Century
Soil Moisture (Summer)	-4%	About 0.2 m^3/m^3	About 0.19 m^3/m^3

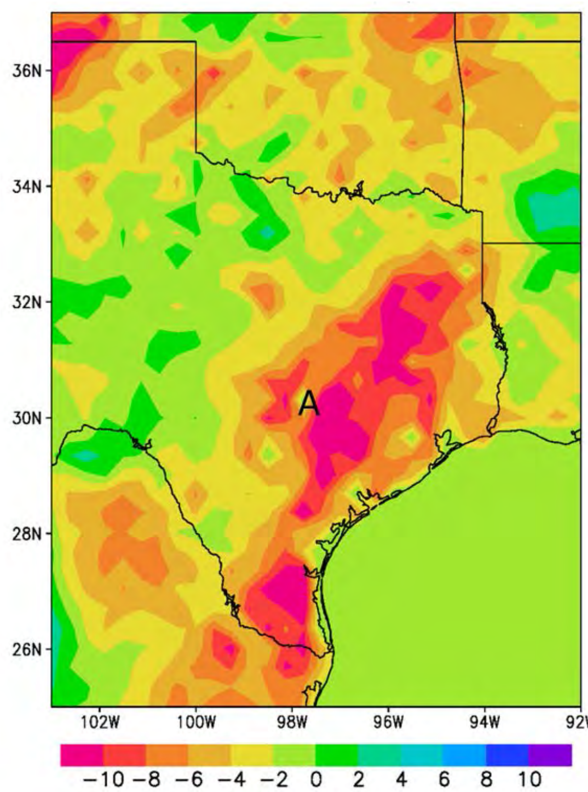
The CAMPO region straddles multiple baseline average summer soil moisture readings, ranging from about 0.1 to 0.3 m^3/m^3 at 10 cm (3.94 inches) depth. Even within the CAMPO region, the projected change ranges from about a four percent decrease to an approximate 10 percent decrease, as shown in Figure 21.

Figure 20 Soil Moisture, Austin, Texas
April 2010-April 2012



Source: http://soilmoisture.tamu.edu/data/map. StationId=0070960712

Figure 21 Projected Percent Change in Average Summer (June-July-August) Soil Moisture
Late 20th to Mid 21st Century, 10 cm (3.94 in) depth



Source: WRF

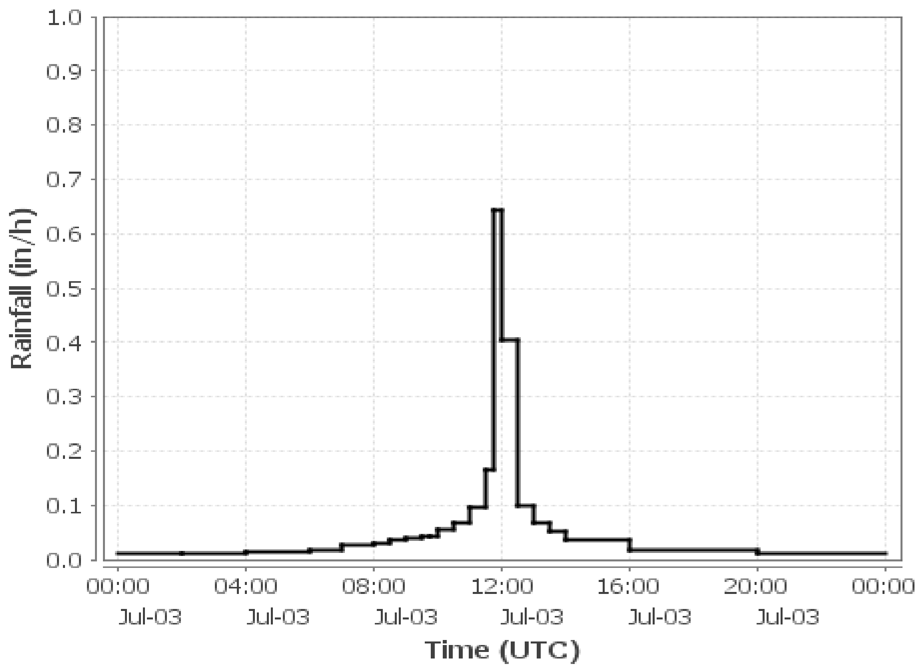
Flood Modeling

To gauge the potential impact of increased extreme precipitation magnitudes (under Scenario 3), a physics-based model called Vflo® (Vieux, 2004) was used to model flooding within select hydrological basins. The City of Austin Watershed Protection Department currently uses Vflo as a component of the Flood Early Warning System (FEWS). The model is parameterized with land use/cover, soils, channel hydraulics and topography (10-meter resolution LiDAR). Further information about the Vflo model and the methodology developed for this study is available in Appendix B.

The study team modified two key model parameters to simulate potential future flooding conditions (roughly associated with the year 2040). First, as described previously, the team adjusted the projected magnitude of key 24-hour design storms by applying the projected percentage change (delta) of the 99th-percentile rainfall event to storm totals from the City of Austin Drainage Criteria Manual.

Because rainfall intensity distributions are not projected, a synthetic distribution[18] often used in sizing hydraulic infrastructure was employed instead (represented in Figure 22).

Figure 22 SCS Type III Incremental Rainfall Distribution

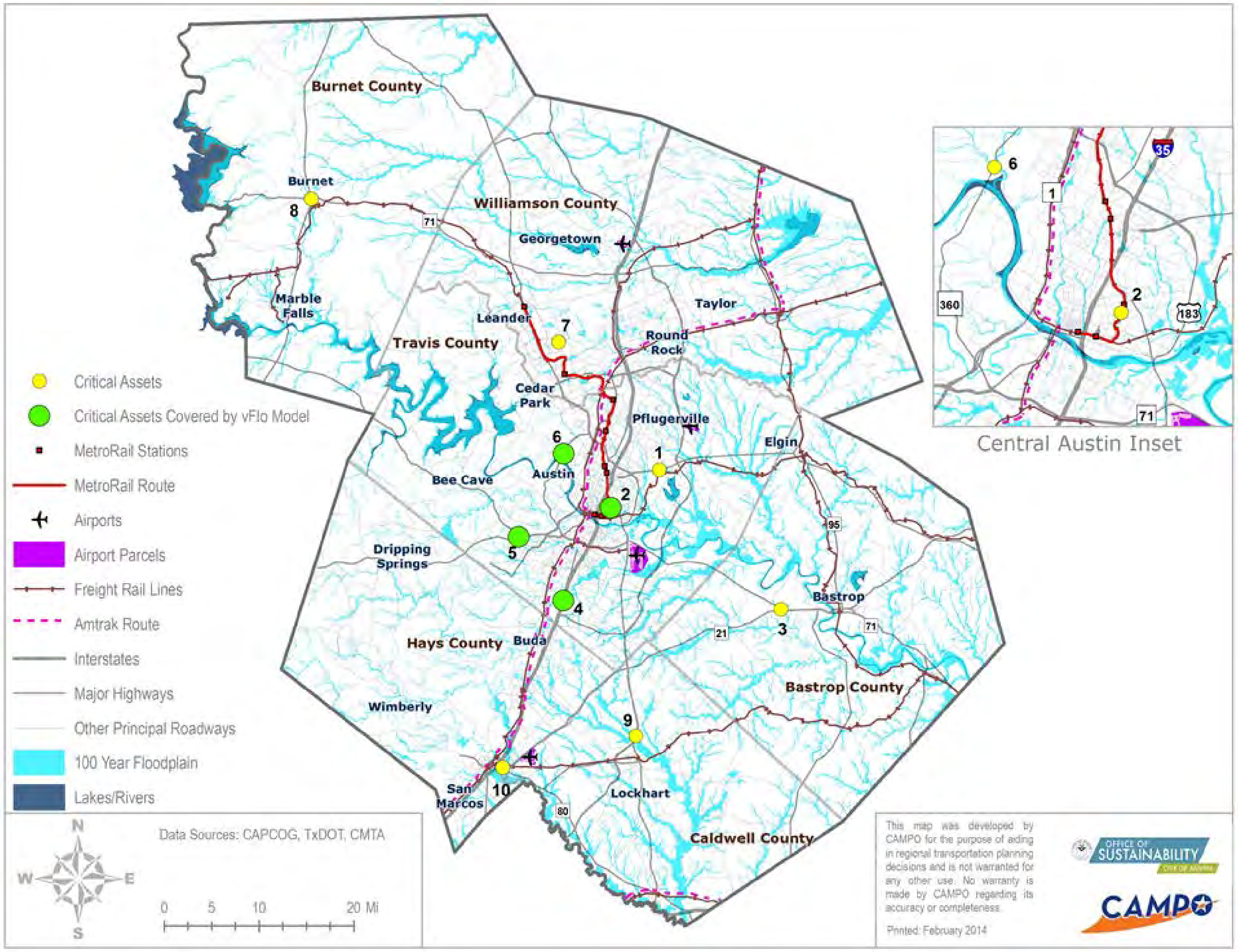


Source: VFlo

Second, the team employed a proxy methodology to adjust the amount of impervious surface within the modeled watersheds based on projected demographic growth (consistent with projections from the CAMPO 2040 LRTP). The Vflo-modeled watersheds are all located in Travis County, which is projected to grow in population from 812,000 in 2000 to 1.7 million in 2040—an increase of 210 percent. Accordingly, a factor of 2.1 was applied to areas of existing impervious coverage (with maximum imperviousness not to exceed 100%), and areas of zero impervious coverage today—assumed to be park or preserve land—were not adjusted. The objective was to develop a sketch assumption for the regional increase in impervious surface consistent with CAMPO's regional growth forecast (assumptions will not hold for each individual parcel, nor were they intended to).

[18] Soil Conservation Service (SCS) Type III.

Figure 23 Location of Assets Covered by Vflo/FEWS



Four (4) of the assets selected for assessment are located in modeled FEWS watersheds. Their geographic distribution is shown in Figure 23, and further described in Table 11. The storm frequencies modeled (two per asset) were determined in consultation with agency representatives. Both the baseline (circa 2004) and projected future extreme rainfall event (with change in impervious cover) were modeled for all four assets—a total of four flooding simulations per asset.

Table 11 Assets Covered by Vflo/FEWS and Scenarios Modeled

Asset #	Asset Description	Frequency Storms	Combination
2	MetroRail Red Line at Boggy Creek	100-year 5-year	Baseline x 100 yr Baseline x 5 yr (Scenario #3 + Imp) x 100 yr (Scenario #3 + Imp) x 5 yr
4	I-35 at Onion Creek Parkway (study area to include Old San Antonio Road low water crossing)	50-year 100-year	Baseline x 100 yr Baseline x 50 yr (Scenario #3 + Imp) x 100 yr (Scenario #3 + Imp) x 50 yr
5	US 290W/SH 71 – Y at Oak Hill	50-year 25-year	Baseline x 50 yr Baseline x 25 yr (Scenario #3 + Imp) x 50 yr (Scenario #3 + Imp) x 25 yr
6	Loop 360/RM 2222	25-year 50-year	Baseline x 25 yr Baseline x 50 yr (Scenario #3 + Imp) x 25 yr (Scenario #3 + Imp) x 50 yr

Baseline = frequency depth based on past climate plus impervious coverage, 2004.

Imp = future impervious coverage (projected).

For each of the four assets, the following measures were estimated (for all four simulations):

- **Extent**. The estimated area of flooding, at any depth, as shown in Figure 24.
- **Top Width** (feet). The width of the flood extent from one bank to the other, as measured along a particular cross-sectional location. All subsequent measures reflect values at this cross section, indicated on each flood map.

- **Flow Rate** (cubic feet per second). The volume of water that moves through/past the cross section in one second.
- **Depth** (feet). The maximum depth of the flood, as measured from the water surface to the lowest point within the cross section.
- **Average Velocity** (feet/second). The speed of flood waters, measured in feet per second.
- **Cross Sectional Area** (square feet). The area (two dimensional) of water between the surface and the stream bed/ground surface (as shown in a sectional view).

Note that the results are not directly comparable to the corresponding Federal Emergency Management Agency (FEMA) flood recurrence interval. Reasons for this include differences in model representation of topography between Vflo and the flood insurance model used in the FEMA Digital Flood Insurance Rate Maps (DFIRMs). Also, as with any model, the 100-year precipitation event does not necessarily result in the 100-year flood, as represented in the DFIRM. However, DFIRMs are used as a flood risk indicator for the five assets that fall outside of FEWS watersheds.

Figure 24 Example: Estimated Current and Future Flood Extent
100-year Rainfall, MLK Station

These measures, in particular flood extent, depth, and average velocity, were translated into flood vulnerability indicators for the Vulnerability Assessment Scoring Tool (VAST), as described in Section 6.0. Full flood modeling parameters and results for each asset are included in Appendix B.

For the five assets located outside of established FEWS basins, proximity to and approximate elevation above the FEMA 100-year floodplain were used as proxies in the VAST assessment. Figure 25 and Figure 26 show the current FEMA-designated Special Flood Hazard Areas, equivalent to the one percent chance annual change flood—more commonly known as the 100-year floodplain—in both the six-county region and zoomed in on the Austin area. Areas depicted in blue lie within the 100-year floodplain. Yellow zones illustratively show areas that were flooded during Tropical Storm Hermine in 2010 (from archived FEWS data).

Figure 25 Central Texas Flood Exposure

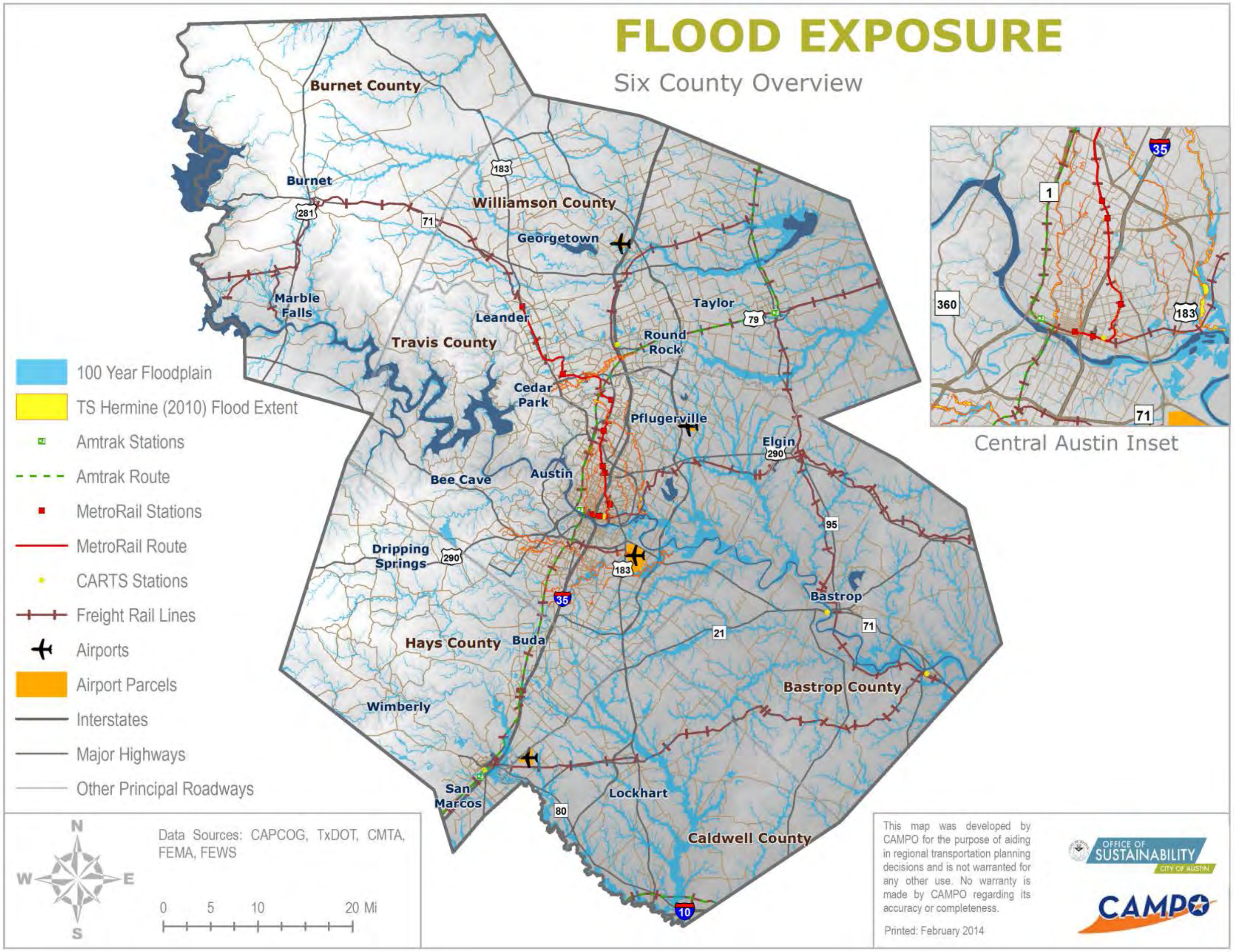
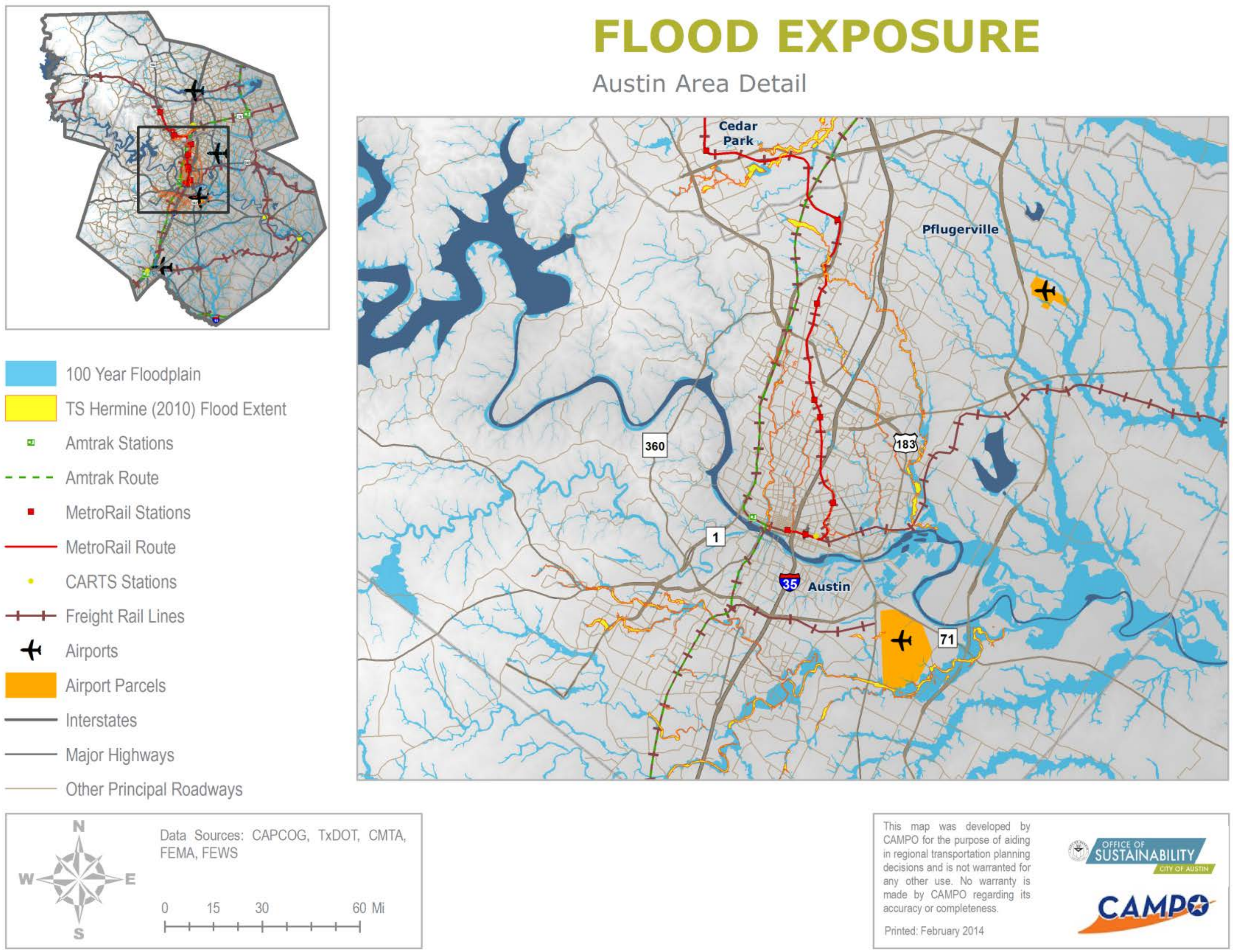


Figure 26 Flood Exposure—Austin Area Detail



6.0 Vulnerability Assessment

This study used the U.S. DOT Vulnerability Assessment Scoring Tool (VAST)[19] to facilitate vulnerability assessments for each of the nine critical CAMPO assets.[20] The vulnerability assessment was carried out in three principal stages:

1. **Configure the initial VAST approach:** Select indicators, establish preliminary indicator weights, and develop preliminary scoring methods (see below);
2. **Review initial (desktop) results with focus groups:** Gather expert and/or asset-owner feedback on the initial vulnerability indicators and results and solicit additional information about each asset's vulnerability (including anecdotal or qualitative information);
3. **Refine the initial VAST approach and output based on focus group feedback:** Revise data, assumptions, and selected results to reflect expert input and non-quantitative vulnerability factors.

At the end of the process, each asset received an overall risk rating (Low-High) for each of the five climate stressors evaluated (flooding, drought, extreme heat, wildfires, and icing). These risk ratings were determined based on a composite of risk components, namely the *likelihood* of the stressor occurring and the *consequences* of the occurrence. The factors comprising these key risk elements are described in the sections that follow.

6.1 The Vulnerability Assessment Scoring Tool

VAST provides a structured process (see Figure 27) for assessing the climate-related vulnerabilities of transportation assets, using a combination of available data and expert judgment. The tool breaks vulnerability into three components, corresponding with those highlighted in the FHWA *Vulnerability Assessment Framework*:

- **Exposure -** Whether an asset might experience a given stressor;
- **Sensitivity -** Whether an asset might be damaged or disrupted if exposed to a stressor;, and

[19] VAST and the VAST User's Guide are publicly available online at:

http://www.fhwa.dot.gov/environment/climate_change/adaptation

[20] Asset #1 was removed from consideration prior to the VAST assessments due to data sufficiency issues, as described in Section 3.

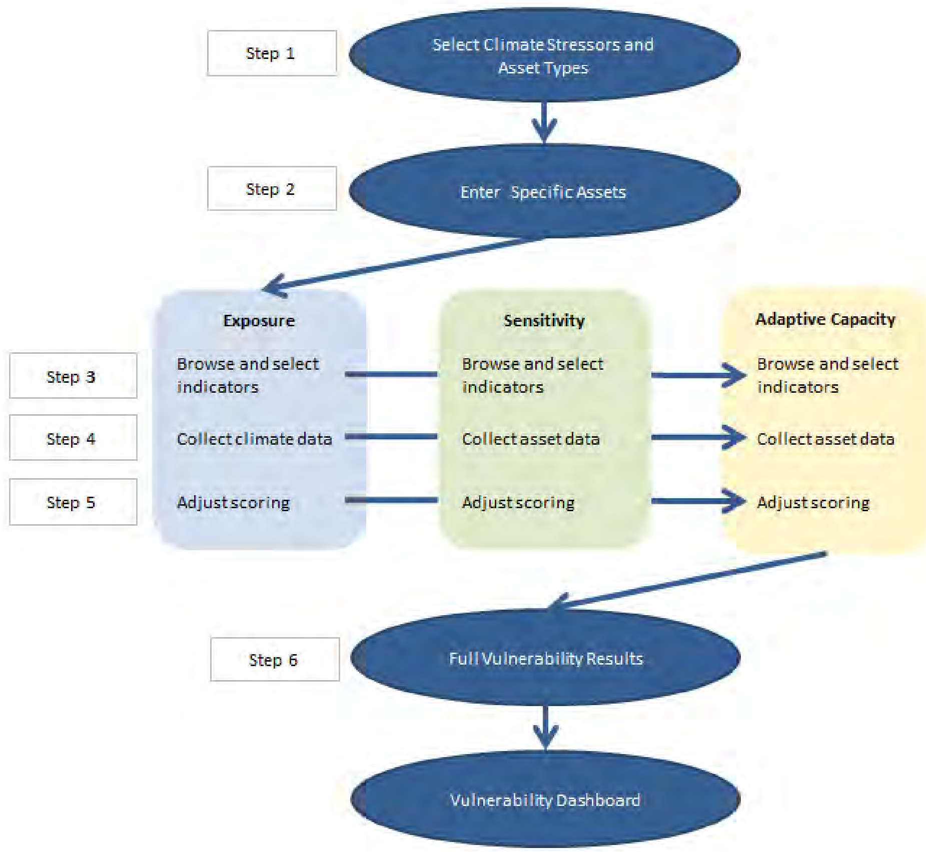
- **Adaptive Capacity -** The ability of the transportation system at large to cope with the consequences of damage or disruption to the asset).

In order to rate the Exposure, Sensitivity, and Adaptive Capacity components of each asset, VAST requires the establishment of *indicators*—characteristics or attributes of the asset that reflect its exposure, sensitivity, and adaptive capacity to a given stressor. To establish indicators, the assessment team must:

- **Steps 1 & 2.** Determine the climate stressors and specific assets to evaluate (determined in the early stages of the project);
- **Step 3.** Choose indicators for each risk component (VAST provides suggestions, and users can input their own. Indicators can be quantitative or qualitative);
- **Step 4**. Collect data on each of the indicators for each asset;
- **Step 5.** Score each indicator on a scale of 0–4 (where 0 is not exposed, 1 is least vulnerable, and 4 is most vulnerable). This may require the establishment of scoring bins/ranges for numerical indicators;
- **Step 5**. Assign a weight to each indicator.

The VAST process is shown in Figure 27. Steps 1 and 2, *scoping the vulnerability assessment*, were completed in the early stages of this project, as described previously.

Figure 27 VAST Approach Diagram



Source: U.S. DOT Vulnerability Assessment Scoring Tool

Exposure

Each asset received an exposure score for each stressor, on a scale of 0 to 4 based on the indicators below. A higher score indicates higher vulnerability. Exposure, defined as the likelihood of each asset experiencing a given stressor, was defined *relative to each stressor* (as opposed to across stressors). In other words, the likelihood of experiencing a particular stressor was *not* defined in terms of the absolute projected frequency of occurrence, but rather relative to current frequencies for each stressor. For example, high temperatures are a frequent phenomenon in Central Texas, potentially occurring many times in a given year. In contrast, significant flooding is a relatively

Exposure Score Definitions

- 0/NE = Not Exposed
- 0.5 = Very low likelihood of experiencing stressor (relative to other assets)
- 1 = Low likelihood of experiencing stressor
- 2 = Moderate likelihood of experiencing stressor
- 3 = High likelihood of experiencing stressor
- 4 = Very high likelihood of experiencing stressor

rare event (the 100-year flood, for example, is projected to have a 1% chance annual probability). Therefore, whereas an asset projected to experience three days per year above 100° F might be assigned a "Low" heat exposure risk, if three days of flooding annually were projected the appropriate exposure risk rating might be "High."

Table 12 shows the list of exposure indicators used for this assessment. Details on the indicators, data sources, and scoring methods used are found in Appendix F. In specific cases, the project team overrode the default (indicator-based) exposure score for the asset based on focus group feedback. Exposure was initially evaluated under two climate scenarios—the low and high projections for each indicator—but the risk results did not differ substantially. Therefore, for the sake of clarity, only the *high* scenario results, generally associated with Scenario 3, are presented.

Table 12 Summary of Exposure Indicators

Stressor	Indicator
Flooding[1]	Modeled available freeboard for future rain event; or
	Vertical proximity to the 100-year floodplain; or
	Demonstrated past exposure (anecdotal)
Drought	Projected change in average summer soil moisture
	Projected change in number of dry days per year
Extreme Heat	Projected change in number of days per year ≥ 100° F
	Projected change in average seven-day maximum temperature
Wildfire	Wildfire Threat (TxWRAP)
	Projected change in average summer soil moisture
Extreme Cold (icing)	Projected change in number of "ice days" (days with both freezing temperatures and non-trace precipitation) per year

[1] The specific flood risk indicator used for each asset was dependent on data availability

Sensitivity

Each asset also received a sensitivity rating for each relevant stressor to describe the anticipated consequences of exposure, expressed as the estimated degree of damage or disruption. Sensitivity was initially rated, per VAST guidance, on a scale of 0 to 4, but focus group members suggested that sensitivity was so negligible in some instances (e.g., the effect of heat on I-35) that the custom creation of lower sensitivity tiers was warranted. Ultimately, sensitivity scores were defined as shown in the text box at right, where a higher score indicates higher vulnerability.

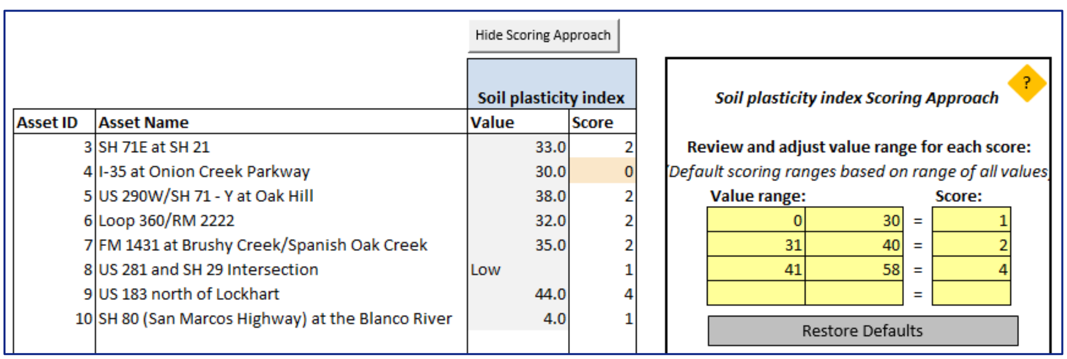
> **Sensitivity Score Definitions**
>
> - 0/NS = Exposure would not cause any damage or disruption
> - 0.5 = Exposure is very unlikely to cause any damage or disruption
> - 1 = Exposure would cause minimal damage or disruption
> - 2 = Exposure would cause moderate disruption (hours) and/or minor damage
> - 3 = Exposure would cause major disruption (days) and/or moderate damage
> - 4 = Exposure would cause severe damage and associated long-term disruption

Sensitivity indicators varied by stressor and by mode (different sensitivity indicators were used for highway and rail assets). Table 13 and Table 14 list the final sensitivity indicators used for highway and rail infrastructure. Details on the indicators, data sources, and scoring methods used are found in Appendix F.

As an illustrative example, Figure 28 shows a screenshot of the highways drought sensitivity scoring tab in VAST. The yellow cells at the right of the image show the "scoring approach pane," where the scoring bins for Soil Plasticity Index (SPI)[21] have been defined (e.g., SPI of 0-30 is considered low plasticity, indicated by a corresponding low sensitivity score of "1").

Each asset studied received a drought sensitivity score based on the SPI of its underlying soils, according to its relation to the scoring bins. In the case of I-35 at Onion Creek Parkway (Asset 4) the initial score was overridden based on the feedback of experts, who indicated that the asset is not sensitive to drought.

Figure 28 Example of Highways Drought Sensitivity Scoring tab in VAST



Hide Scoring Approach

Asset ID	Asset Name	Soil plasticity index Value	Soil plasticity index Score
3	SH 71E at SH 21	33.0	2
4	I-35 at Onion Creek Parkway	30.0	0
5	US 290W/SH 71 - Y at Oak Hill	38.0	2
6	Loop 360/RM 2222	32.0	2
7	FM 1431 at Brushy Creek/Spanish Oak Creek	35.0	2
8	US 281 and SH 29 Intersection	Low	1
9	US 183 north of Lockhart	44.0	4
10	SH 80 (San Marcos Highway) at the Blanco River	4.0	1

Soil plasticity index Scoring Approach

Review and adjust value range for each score:

Default scoring ranges based on range of all values

Value range:			Score:
0	30	=	1
31	40	=	2
41	58	=	4
		=	

Restore Defaults

21 As explained in Appendix F, Soil Plasticity Index is a measure of how likely soils are to expand or contract with changes in soil moisture. Infrastructure constructed over high plasticity soils is more sensitive to damage from drought, as shifts in the underlying soil can undermine structural stability.

Table 13 Summary of Highway Sensitivity Indicators

Stressor	Indicator
Flooding	24-hour precipitation design threshold
	Scour Critical status (bridges)
	Average inundation velocity associated with future rain event
	Wildfire Threat[1]
Drought	Soil Plasticity Index
Extreme Heat	Pavement binder
	Truck traffic volume
Wildfire	Wildfire sensitivity rating[1]
	Values Response Index[2]
Extreme Cold (icing)	Whether roadway is elevated

[1] Post-wildfire conditions can exacerbate flooding by, for example, reducing vegetation and increasing debris.

[2] Initially, all assets were assigned a proxy value of "2", equating to "moderate disruption (hours) and/or minor damage." The Sensitivity Rating was then refined for each asset based on input from the agency focus groups.

[3] Values Response Index is defined by TxWRAP as "the potential impact of a wildfire on values or assets."

Table 14 Summary of Rail Sensitivity Indicators

Stressor	Indicator
Flooding	Rail flooding sensitivity rating
Drought	Soil Plasticity Index
Extreme Heat	Rail Neutral Temperature
	Freight traffic volume
Wildfire	Wildfire sensitivity rating
	Values Response Index
Extreme Cold (icing)	Rail icing sensitivity rating

Adaptive Capacity

Adaptive capacity reflects the regional transportation system's capacity to cope with damage and/or disruption to a given asset. Adaptive capacity ratings were based on each asset's criticality to the region (as determined by local stakeholders in workshops and focus groups), its role in moving people and freight in the region (e.g., traffic volume and functional class), and functional redundancy (e.g., estimated shortest detour length). Adaptive capacity was scored in a scale of 1 to 4 using the definitions shown in the text box, where a higher score indicates higher vulnerability (and *lower* adaptive capacity).

Adaptive Capacity Score Definitions

- 1 = Damage or disruption to the asset would have a minimal effect on activity in the CAMPO region
- 2 = Damage or disruption to the asset would have a moderate effect on activity in the CAMPO region
- 3 = Damage or disruption to the asset would have a severe effect on activity in a discrete portion of the CAMPO region
- 4 = Damage or disruption to the asset would have a severe effect on activity in the CAMPO region

Table 15 shows the list of adaptive capacity indicators used in this assessment. Details on the indicators, data sources, and scoring methods used are found in Appendix F.

Table 15 Summary of Adaptive Capacity Indicators

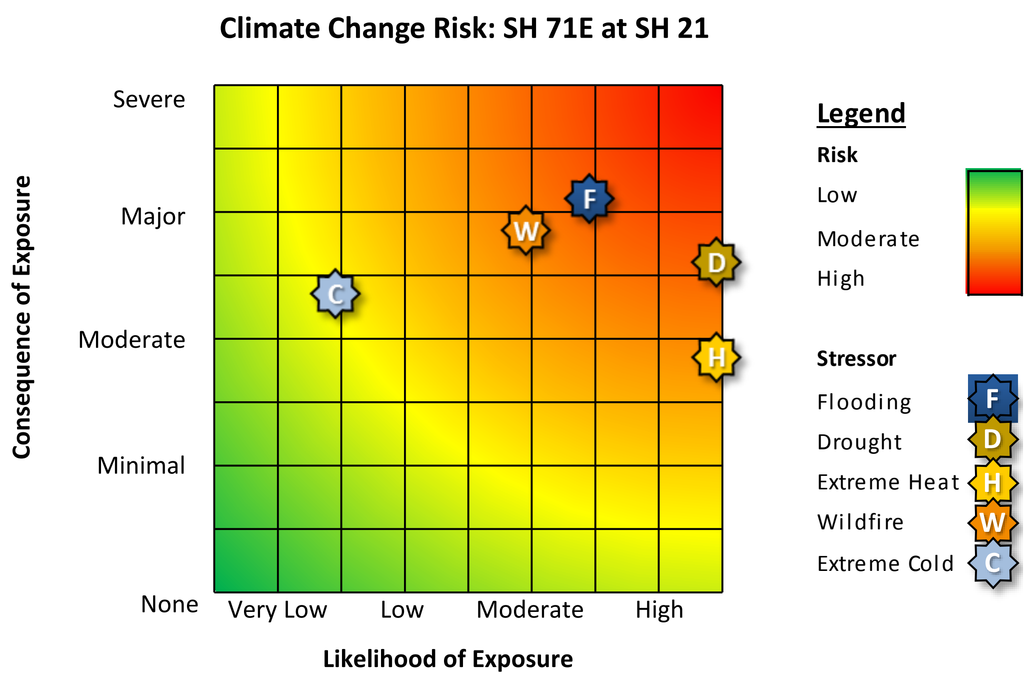
Asset Type	Indicator
Highways	Whether asset is part of an evacuation route
	Asset criticality
	Functional Classification
	Annual Average Daily Traffic
	Truck traffic volume
	Detour length
Rail	Asset criticality
	Average daily ridership

Summary of Key Risks

For each asset, the result of the VAST process was the designation of a risk rating estimate for *each* stressor based on the respective Exposure, Sensitivity, and Adaptive Capacity scores. The risk rating was determined by plotting the scores onto a grid, as shown in Figure 29. The *Likelihood of Exposure* (the horizontal axis on the chart), was determined directly using the Exposure score. The *Consequence of Exposure* (the vertical axis), was determined by blending the asset's Sensitivity and Adaptive Capacity scores, because they represent the degree of damage and/or disruption experienced by the asset specifically and the broader regional consequences of that damage and/or disruption, respectively.

In the example shown in Figure 29, the asset has high risk to flooding, moderate-high risk to drought, moderate risk to extreme heat (subsequently adjusted to "low-moderate" based on expert feedback), moderate-high risk to wildfire, and low-moderate risk to extreme cold (icing).

Figure 29 Example Risk Rating Matrix



6.2 VAST Summary Results

This analysis highlighted a handful of key potential climate-related risks to critical CAMPO assets that may merit more detailed investigation and/or consideration of adaptive measures. For example, drought risk to US 183 north of Lockhart, flooding risk to SH 71/SH 21 in Bastrop County, and wildfire risk to US 290W/SH71 Y at Oak Hill and Loop 360/RM 2222 all emerged as high potential extreme weather risks, especially given projected future climate trends. Table 16 provides a summary of the final risk rating for each asset, by stressor.

As depicted in Table 16, wildfire presents consistently high risk across assets, while flooding and drought risk are more variable (localized) in nature. Icing and heat, on the other hand, are considered relatively low risks. Icing is low risk because of the infrequency of occurrence in Central Texas (projected to become even less frequent), whereas extreme heat is common (and projected to increase in frequency), but the transportation infrastructure analyzed is designed to accommodate high temperatures.

This section provides a brief summary of the risk results by stressor, across all assets. Following, in Sections 6.3-6.11, the results are described by asset.

Flooding

Flooding risk varies significantly across the assets studied, based on location and elevation relative to floodplains, condition, design standards, and other factors. SH 71/SH 21 in Bastrop is estimated to have the highest flood risk, given the potential consequences of flooding on an evacuation route. The MetroRail Red Line at Boggy Creek and US 281/SH 29 also have relatively high flood risk. The MetroRail line may experience washouts two to three times per year, and those washouts historically have caused at least one to two days of delays. Less historical information is available for US 281/SH 29, but stakeholders indicate that it has a history of flooding, disrupting activity in Burnet County.

Next Steps and Adaptation Strategies

- *Conduct more detailed flood risk analyses for assets identified as potentially high risk, but with limited flood exposure information available: SH 71/SH 21 in Bastrop County and US 281/ SH 29 in Burnet County.*
- *For high risk assets, consider increasing drainage capacity and/or elevating flood-prone assets to help mitigate washouts or damage (conduct more detailed studies, first).*
- *Evaluate the potential for flooding to interfere with the hurricane evacuation route functions of SH 71/SH 21 and US 183.*

Table 16 Risk Rating Summary

ID	Asset	Flooding	Drought	Heat	Wildfire	Extreme Cold
2	MetroRail Red Line at Boggy Creek	Moderate-High	Inconclusive	Moderate	None	Low-Moderate
3	SH 71E at SH 21	High	Moderate-High	Low-Moderate	Moderate-High	Low-Moderate
4	I-35 at Onion Creek Parkway	Low	None	None	Moderate-High	Low-Moderate
5	US 290W/SH 71 - Y at Oak Hill	Moderate	Moderate	None	High	Low
6	Loop 360/RM 2222	Moderate	Moderate	None	High	Low-Moderate
7	FM 1431 at Brushy Creek/Spanish Oak Creek	None	Moderate	Low	Moderate-High	Low
8	US 281 and SH 29 Intersection	Moderate-High	Low	Low	Moderate	Low
9	US 183 north of Lockhart	Low-Moderate	High	Low-Moderate	Moderate-High	Low-Moderate
10	SH 80 (San Marcos Highway) at the Blanco River	Moderate	Low	Low	Moderate	Low

Drought

All assets are expected to be exposed to drought, as soil moisture is projected to decrease four to 10 percent by mid-century. The primary determinant of drought risk is the soil underlying a given asset, and how likely that soil is to shrink and swell with changes in soil moisture—which may cause premature deterioration or damage. The MetroRail Red Line and US 183 are built over the highest plasticity soils of all assets studied. At the other end of the spectrum, I-35, US 281/SH 29, and San Marcos Highway are built over relatively low plasticity soils, and are therefore considered low risk.

Drought risk is considered inconclusive for the MetroRail Red Line because, although soil map data show that the asset is built over high plasticity soils, the asset has not experienced drought-related damage in the past—despite the severe drought of 2011. Additional investigation, such as localized soil sampling, is warranted before determining whether the Red Line could be sensitive to damage from soil expansion and contraction.

Next Steps and Adaptation Strategies

- *Conduct local soil samples to confirm whether MetroRail Red Line and SH 71/SH 21 are indeed over—and susceptible to—highly expansive soils.*
- *Consider improving or widening shoulders and using geosynthetic reinforcement to reduce the potential for drought-related damage at the SH 71/SH 21 intersection.*

Extreme Heat

All assets are expected to be highly exposed to extreme heat. The climate model used for this study projects that the region may experience 34 additional days per year above 100° F by mid-century, on average. In addition, average 7-day maximum temperatures may increase by about 4° F, by mid-century.

However, according to the experts consulted, the **road assets** studied are not expected to experience pavement damage as a result of these temperature increases. TxDOT design guidelines call for roads in the area to use pavement binder PG 64-22, which is designed to withstand extended temperatures of 108° F. This is still higher than the projected mid-century average 7-day maximum temperatures of about 104° F.

For three assets—I-35, US 290, and Loop 360/RM 2222—stakeholders suggested that they are designed for both heavy use and extreme conditions. These assets are rated as having no extreme heat risk.

For SH 71/SH 21 and US 183, extreme heat risk is considered Low-Moderate because their status as evacuation routes elevates the consequences of any heat-related issues.

Heat poses a moderate risk to the **MetroRail Red Line**, because temperatures above 100° F increase the chance of thermal misalignments and force Capital Metro to issue slow orders, which reduce the speed of service.

Next Steps and Adaptation Strategies

- *Monitor ambient temperatures, pavement temperatures, and pavement conditions to identify whether increased temperatures are affecting pavements.*
- *Consider increasing the rail neutral temperature for the Red Line at Boggy Creek, incorporating anticipated speed restrictions in rail planning and forecasting, identifying and cataloguing problem areas for thermal misalignments, installing rail temperature monitors, and/or monitoring the frequency of heat-related speed restrictions.*

Wildfire

Wildfire risk is relatively high for all assets (except the MetroRail Red Line, which is located in a non-burnable area). Although wildfires do not typically cause physical damage to roadways, they can cause road closures or other temporary service disruptions. For many of the assets studied—particularly US 290/SH 71 and Loop 360—even small, temporary disruptions from wildfire could create bottlenecks or "choke points" that could interfere with wildfire evacuations and thus threaten human health and safety.

Next Steps and Adaptation Strategies

- *Assess the potential for wildfire evacuation choke points at the Y at Oak Hill, Loop 360/RM 2222, and FM 1431 at Brushy Creek, in particular.*
- *Incorporate potential increases in wildfire frequency and severity in emergency planning.*

Extreme Cold and Ice

Icing presents low to low-moderate risk to all road assets. In all cases, exposure to icing is low. Icing events, which historically have been rare, may occur even less frequently as the century progresses—less than once per year on average by mid-century, according to the projections used for this study.

Two key factors differentiate the assets with low-moderate risk compared to those with low risk. First, elevated roadways or bridges—like I-35 and Loop 360—are more likely to ice (i.e., have higher *sensitivity*). Second, evacuation routes like SH 71 and US 183 would present higher potential consequences if icing were to occur while the routes were needed during an evacuation (i.e., have lower *adaptive capacity*).

Next Steps and Adaptation Strategies

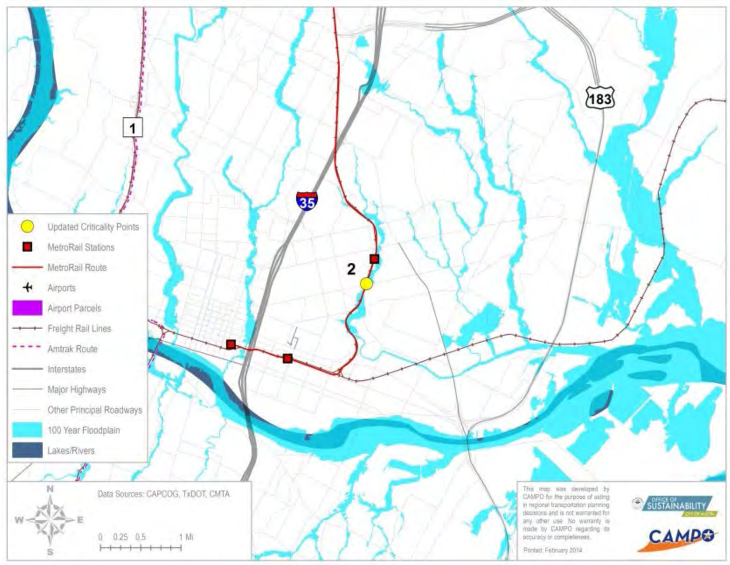
- *Communicate with the public early and often about road conditions and road closures on days with the potential for icing.*

6.3 METRORAIL RED LINE AT BOGGY CREEK (#2)

The Red Line provides the region's only commuter rail service connecting the northwest suburbs to downtown Austin. Table 17 and Figure 30 summarize the extreme weather vulnerabilities and risks to this asset.

Flooding

The Red Line is located in the floodplain of Boggy Creek and washes out frequently. When washouts occur, the line experiences service suspensions and delays for one to two days while Capital Metro makes repairs.



Drought

Soils maps indicate that the Red Line at Boggy Creek is built over high plasticity soils, which may swell or contract with changes in soil moisture. Drought thus has the potential to destabilize the Red Line, though it has not posed a problem in the past, even in the severe 2011 drought. Further investigation of drought risk is warranted.

Extreme Heat

Projected increases in the number of days above 100° F would increase the frequency of speed restrictions on the line, as well as the risk of thermal misalignments.

Wildfire

The Red Line at Boggy Creek is located in a non-burnable area with no wildfire threat. The asset is thus not at risk from wildfire.

Extreme Cold and Ice

Though icing days are rare, when they occur, rail switches can break and cause service disruptions.

Table 17 Summary of Vulnerabilities and Risks to MetroRail Red Line at Boggy Creek

	Flooding	Drought	Extreme Heat	Wildfire	Extreme Cold and Ice
Exposure	High Heavy precipitation events may become more intense, and future 100-year events could cause ~2 feet of inundation	High Soil moisture projected to decrease 4-10% by mid-century	High 34 additional days per year above 100° F by mid-century, on average	Not Exposed Located in a non-burnable area with no Wildfire Threat	Low Projected to experience 1 icing day per year by mid-century, on average
Sensitivity	Moderate-High Washouts; Rail unable to operate if > 3 inches of water over the line	High* High plasticity soils	Low Rail neutral temperature of 100-115° F, but no heavy rail traffic	N/A Not applicable, because asset is not exposed	Moderate Icing can break switches and cause service disruptions
Adaptive Capacity	Moderate-High Capital Metro can run buses to replace trains				
Impact Description	Service disruptions for duration of flood, washouts, 1-2 days of delays	Potential destabilization of rail foundation, increased maintenance costs	Increased risk of thermal misalignment, increased frequency of speed restrictions	Not exposed to wildfire	Short-term service disruptions and delays
Likelihood of Exposure	High	High	High	None	Low
Consequence of Exposure	Moderate	Major*	Low	N/A	Moderate
Risk	Moderate-High	Inconclusive*	Moderate	None	Low-Moderate

Likelihood of Exposure based on VAST Exposure rating; *Consequence of Exposure* based on VAST Sensitivity and Adaptive Capacity ratings

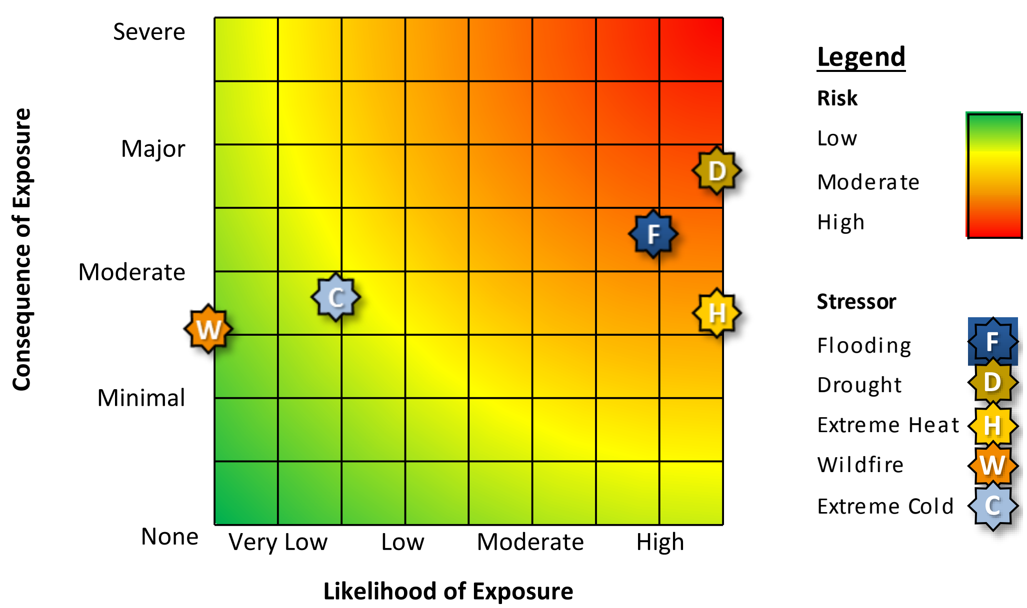
*Soil type indicator used suggests High consequence and risk, but drought has not caused issues for this asset in the past, even in the severe drought of 2011. Further investigation of drought risk is warranted.

Summary of Key Risks

Flooding poses the greatest risk to the Red Line at Boggy Creek compared to other stressors. It is highly exposed (washes out two to three times per year), and those washouts historically have caused at least one to two days of delays when they occur. **Extreme heat** is another concern because of the frequency at which temperatures are projected exceed 100° F. Extreme heat increases the chance of thermal misalignments and forces Capital Metro to issue slow orders, reducing the speed of service. However, generally the consequences of extreme heat are relatively low.

The Red Line at Boggy Creek's vulnerability to **drought** is inconclusive. Soils data suggest that the line is built over highly plastic soils that could destabilize the line with severe swings in soil moisture (caused, for example, by fluctuations between drought and wet conditions). However, despite severe droughts in the past, this effect has not been observed. Additional investigation is warranted to determine whether the Red Line could be sensitive to damage from soil expansion and contraction.

Figure 30 Risk Rating Matrix: MetroRail Red Line at Boggy Creek

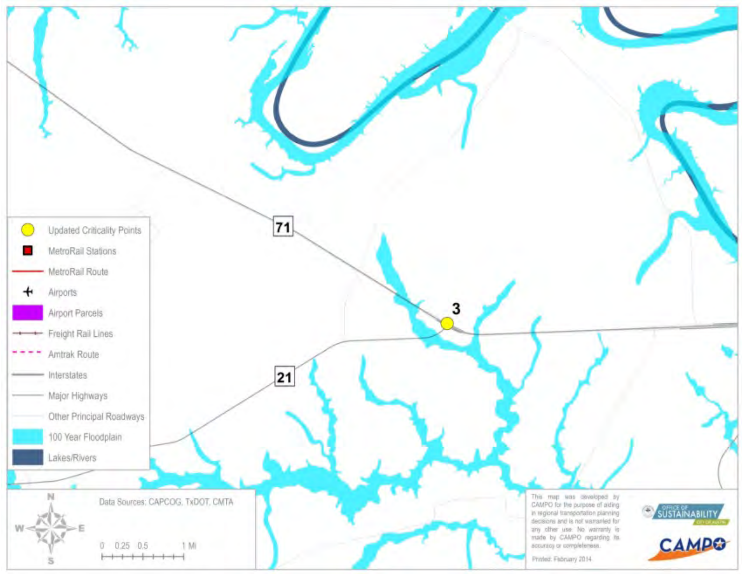


6.4 SH 71E AT SH 21 (#3)

SH 71E at SH 21 is a critical junction in Bastrop County. SH 71E is a major east-west corridor that serves as a hurricane evacuation route and provides access to Austin-Bergstrom International Airport (ABIA). Table 18 and Figure 31 summarize the extreme weather vulnerabilities and risks to this asset.

Flooding

Heavy precipitation events may become more intense as the century progresses. While the junction of SH 71E/SH 21 is not located in the 100-year floodplain, flooding during extreme events cannot be ruled out, and the asset has been subject to flooding in the past. Further, the asset is highly prone to erosion if flooding was to occur.



Drought

Surface soil maps indicate that the intersection is located on moderately expansive soils that could damage roadways, particularly on the edge of pavements. Furthermore, soil moisture is projected to decrease 4-10 percent by mid-century.

Extreme Heat

The likelihood of extreme heat exposure is high. However, minimal damage or disruption is likely to occur as a result.

Wildfire

The junction is located in an area with low-to-moderate fire likelihood. Wildfire could cause temporary traffic disruption and the destruction of guiderail and sign posts. Wildfires would be particularly disruptive if they were to occur during an evacuation event.

Extreme Cold and Ice

Icing is infrequent, projected to occur less than one day per year by mid-century. Icing, when it does occur, can create traffic disruptions and safety issues that typically last a few hours.

Table 18 Summary of Vulnerabilities and Risks to SH 71E/SH 21

	Flooding	Drought	Extreme Heat	Wildfire	Extreme Cold and Ice
Exposure	High	High	High	Moderate	Low
	History of flooding, and heavy precipitation events may become more intense	Soil moisture projected to decrease 4-10% by mid-century	34 additional days per year above 100° F by mid-century, on average	Located in an area with low-to-moderate Wildfire Threat	Projected to experience 1 icing day per year by mid-century, on average
Sensitivity	High	Moderate	Very Low	Moderate	Low
	Flooding could cause erosion and damage	Medium plasticity soils	PG 64-22; Low truck volumes	Wildfire causes temporary service disruptions but not long-term damage	Roadway not elevated, but still capable of experiencing icing; Icing temporarily disrupts traffic, but does not cause damage
Adaptive Capacity	Low				
	SH 71E/SH 21 is a critical junction. SH 71 is a major east-west corridor and serves as a hurricane evacuation route, and provides access to ABIA				
Impact Description	Flooding could cause erosion and roadway damage; up to 35,000 auto trips impacted during flood events at this junction	Increased annual maintenance costs; increase in pavement cracking	Minimal impacts	Disruption, destruction of guiderail/sign posts	Short-term traffic disruptions and delays
Likelihood of Exposure	High	High	High	Moderate	Low
Consequence of Exposure	Major	Moderate	Minimal-Moderate	Moderate-Major	Moderate
Risk	High	Moderate-High	Low-Moderate*	Moderate-High	Low-Moderate

Likelihood of Exposure based on VAST Exposure rating; *Consequence of Exposure* based on VAST Sensitivity and Adaptive Capacity ratings

* Rating is highly influenced by the low degree of adaptive capacity

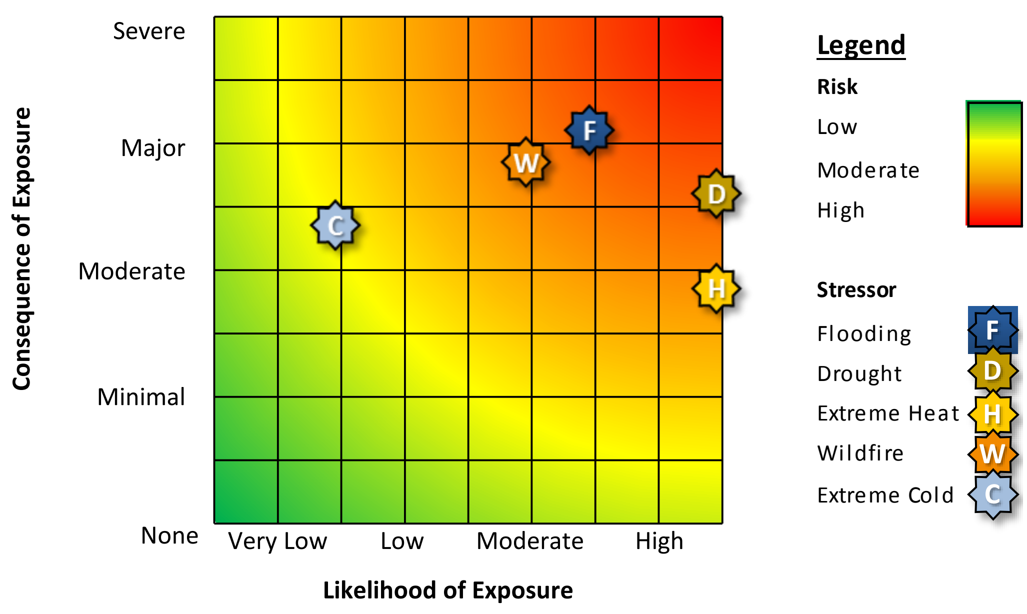
Summary of Key Risks

Overall, **flooding** and **drought** present the highest risks to SH 71E/SH 21. Drought may be more likely, but poses a slightly lower consequence, while flooding may occur less often, but with higher consequences. The same soils that make the intersection vulnerable to drought are also susceptible to erosion from flooding. However, limited information is available about flood exposure at the intersection, so additional investigation is warranted.

Wildfire also presents moderate-high risk to SH 71E/SH 21. Though the intersection itself sits in an area of low-moderate wildfire threat, access points pass through areas of higher wildfire likelihood, and fire likelihood is projected to increase in the future due to decreases in soil moisture. The consequences of wildfire disrupting the intersection are high because SH 71E is an evacuation route.

Across all stressors, risks are considered to be relatively high because of its status as an evacuation route. The potential consequences of any type of damage are amplified, since evacuation effectiveness could be compromised if the roadway was damaged or otherwise unusable. In addition, this intersection serves an area of rapid population growth, where capacity is becoming increasingly strained.

Figure 31 Risk Rating Matrix: SH 71E at SH 21



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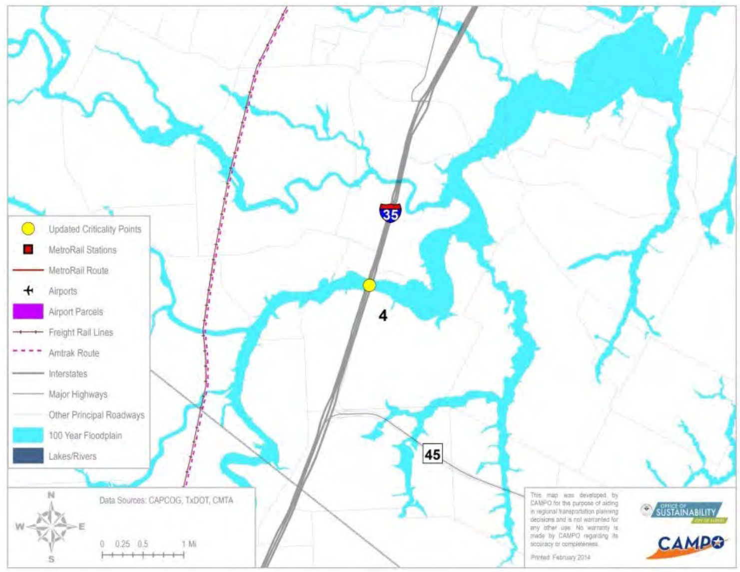
6.5 I-35 AT ONION CREEK PARKWAY (#4)

I-35 is the major corridor through the CAMPO area and is of vital significance—not only to Austin and the Central Texas region, but also to the Texas, national, and international economies. Table 19 and Figure 32 summarize the extreme weather vulnerabilities and risks to this asset.

Flooding



I-35 at Onion Creek is built high above the floodplain, and flood exposure is estimated to be very low. However, any temporary closure of the segment could have major effects on the region since it carries over 114,000 vehicles per day.

Drought

I-35 is not projected to be sensitive to drought.

Extreme Heat

Minimal damage or disruption is likely to occur to I-35 due to extreme heat, despite projections that the area could experience an additional 34 days per year above 100° F by mid-century, on average.

Wildfire

This segment of I-35 is located in an area of low-moderate wildfire threat. Wildfires are thus not very likely, but when they occur they could cause significant disruption because of the high traffic volumes on I-35.

Extreme Cold and Ice

Though icing days are rare, I-35 at Onion Creek is susceptible to icing. Icing results in severe, but temporary, traffic disruptions and safety issues.

Table 19 Summary of Vulnerabilities and Risks to I-35 at Onion Creek Parkway

	Flooding	Drought	Extreme Heat	Wildfire	Extreme Cold and Ice
Exposure	Very Low	High	High	Moderate	Low
	Ample freeboard for 50- and 100-year flood events	Soil moisture projected to decrease 4-10% by mid-century	34 additional days per year above 100° F by mid-century, on average	Located in an area with low-moderate fire risk	Projected to experience less than 1 icing day per year by mid-century, on average
Sensitivity	Low	Not Sensitive	Not Sensitive	Moderate	Moderate
	Designed to withstand 50-year flood, no scour issues	Low plasticity soils and robust design	Designed for heavy use	Wildfire causes temporary service disruptions but not long-term damage	Elevated structure, prone to icing; Icing temporarily disrupts traffic, but does not cause damage
Adaptive Capacity	Low Critical artery with highest passenger and freight traffic volumes in CAMPO region				
Impact Description	Flooding of the roadway is unlikely, though over 114,000 auto trips could be impacted during flood events	No impacts expected	No impacts expected	Possible road closure, regional disruption	Short-term, but severe, traffic disruptions and delays
Likelihood of Exposure	Very Low	High	High	Moderate	Low
Consequence of Exposure	Moderate	None	None	Moderate-Major	Moderate
Risk	Low	None	None	Moderate-High	Low-Moderate

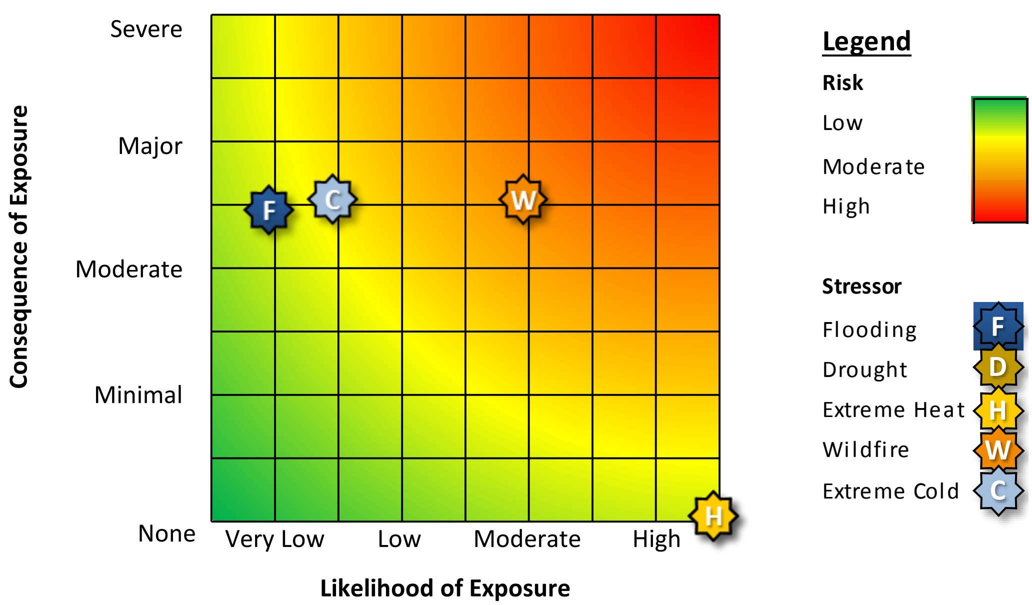
Likelihood of Exposure based on VAST Exposure rating; *Consequence of Exposure* based on VAST Sensitivity and Adaptive Capacity ratings

Summary of Key Risks

Wildfire and **icing** pose the greatest risks to I-35. In both cases, the stressor is not likely to cause long-term damage to the roadway, but could temporarily disrupt traffic. Because the I-35 corridor is such an important artery, even temporary traffic disruptions can have significant regional consequences.

Overall, however, risk is low to this asset, which has been constructed to mitigate damage from common stressors, such as **extreme heat**, **drought**, or **heavy rainfall**.

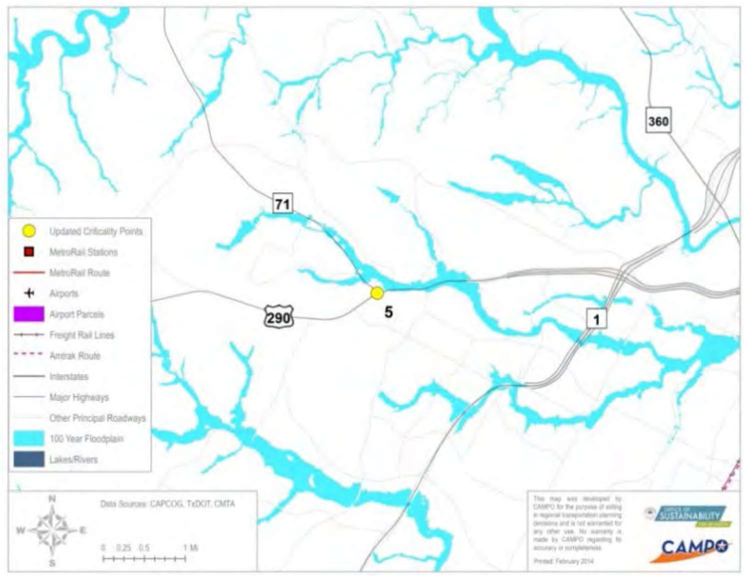
Figure 32 Risk Rating Matrix: I-35 at Onion Creek Parkway



6.6 US 290W AND SH 71 – Y AT OAK HILL (#5)

The Y at Oak Hill (US 290W and SH 71) is a key junction serving western communities in the greater Austin area. Table 20 and Figure 33 summarize the extreme weather vulnerabilities and risks to this asset.

Flooding



The intersection may be susceptible to flooding associated with the future 50-year, 24-hour rainfall event. However, flooding in the area tends to be low velocity and unlikely to cause long-term damage. When the intersection floods, it may restrict access to western communities.

Drought

The intersection is located on soils with medium plasticity and thus may be at risk to damage from drought. Summer soil moisture in Central Texas is projected to decrease 4-10 percent by mid-century.

Extreme Heat

Minimal damage or disruption is likely to occur at the intersection due to extreme heat, despite projections that the area could experience an additional 34 days per year above 100° F by mid-century, on average.

Wildfire

The Y at Oak Hill is located in an area with moderate fire threat, but serves as a critical evacuation corridor for an area with high threat. Therefore, wildfire risk is designated as "high."

Extreme Cold and Ice

Icing is infrequent, projected to occur less than one day per year by mid-century. Icing, when it does occur, can create traffic disruptions and safety issues that typically last a few hours.

Table 20 Summary of Vulnerabilities and Risks to US 290W and SH 71 *Y at Oak Hill*

	Flooding	Drought	Extreme Heat	Wildfire	Extreme Cold and Ice
Exposure	Moderate Modeling suggests intersection could be flooded by up to 9 feet in future 50-year rain events, though local experts believe exposure is lower	High Soil moisture projected to decrease 4-10% by mid-century	High 34 additional days per year above 100° F by mid-century, on average	High Located in an area with moderate fire risk and decreasing soil moisture, adjacent to high risk area	Low Projected to experience less than 1 icing day per year by mid-century, on average
Sensitivity	Low Not scour critical and expected to experience relatively low flood velocities; flooding may not cause significant damage	Moderate Medium plasticity soils	Not Sensitive Designed to accommodate high temperatures	High Potential wildfire evacuation choke point	Low Roadway not elevated, but still capable of experiencing icing; Icing temporarily disrupts traffic, but does not cause damage
Adaptive Capacity	Moderate Junction of two critical corridors (US 290 and SH 71) serving western communities; few arterial roadways in the area to help carry detoured traffic				
Impact Description	Temporary road closures	Increased pavement maintenance costs due to pavement cracking, edge failure	No impacts expected	Disruption to normal or evacuation traffic; destruction of guiderail/sign posts	Short-term, but severe, traffic disruptions and delays
Likelihood of Exposure	Moderate	High	High	High	Low
Consequences of Exposure	Moderate	Moderate	None	Major	Low-Moderate
Risk	Moderate	Moderate	None	High	Low

Likelihood of Exposure based on VAST Exposure rating; *Consequence of Exposure* based on VAST Sensitivity and Adaptive Capacity ratings

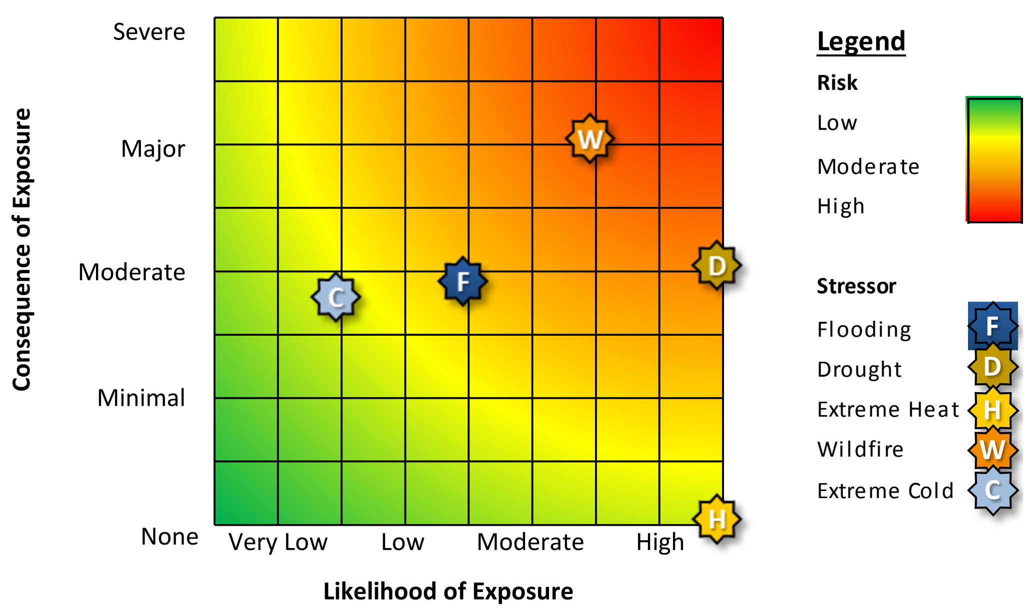
Summary of Key Risks

Wildfire poses the most serious risk of all climate stressors evaluated. The high wildfire hazard in or west of the area means that the intersection could become a choke point in west-east evacuations.

Drought is also a potential concern for the asset. Available soils data suggests the intersection could experience pavement deterioration as a result of swings in pavement moisture (although a site-specific soil study would be needed to confirm this risk).

Flooding also poses a potential risk to the Y at Oak Hill. The Flood Early Warning System (FEWS) model projects that large stretches of US 290 and SH 71 approaching the intersection could be flooded under today's 50-year rainfall event, with greater flood extents if the 50-year event becomes more intense in the future. However, stakeholders noted that flooding is not considered a great risk in this area and that, when floods occur, they are short-lived and non-destructive.

Figure 33 Risk Rating Matrix: US 290W/SH 71 – Y at Oak Hill

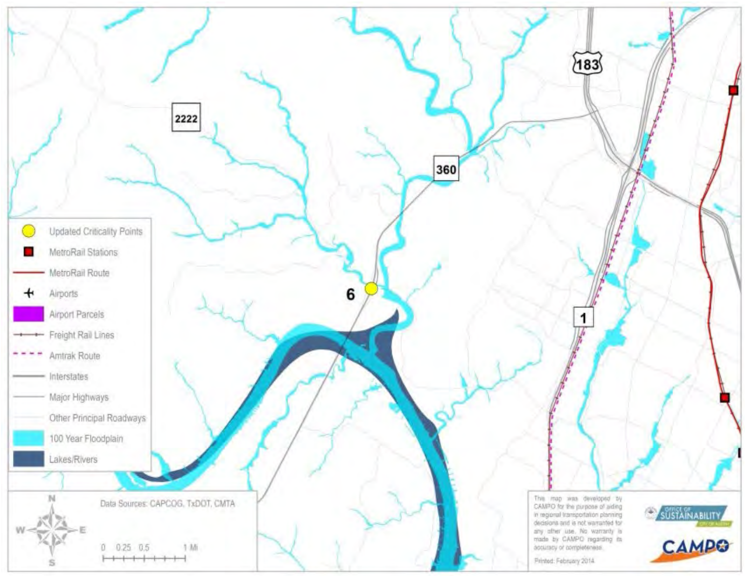


6.7 LOOP 360/RM 2222 (#6)

Loop 360 at RM 2222 is a critical junction in the Austin area, located in Travis County. RM 2222 is a major east-west corridor that spans Bull Creek near the junction, while Loop 360 carries high traffic volumes. Table 21 and Figure 35 summarize the extreme weather vulnerabilities and risks to this asset.

Flooding

RM 2222 has been re-designed to withstand flooding after being severely damaged by floods in 2010. Heavy precipitation events may become more intense as the century progresses, and future 50-year rain events could cause two feet of inundation at RM 2222/Bull Creek bridge, but it is not expected to sustain damage.



Drought

The interchange is located on moderate plasticity soils and thus may be at risk to damage from drought. Summer soil moisture in Central Texas is projected to decrease 4-10 percent by mid-century.

Extreme Heat

Minimal damage or disruption is likely to occur at the intersection due to extreme heat, despite projections that the area could experience an additional 34 days per year above 100° F by mid-century, on average.

Wildfire

The Loop 360/RM 2222 interchange is located in an area with moderate Wildfire Threat, and has been identified by wildfire officials as a potential wildfire evacuation bottleneck point. Wildfire risk to the asset is high.

Extreme Cold and Ice

Icing is infrequent, projected to occur less than one day per year by mid-century. Icing, when it does occur, can create traffic disruptions and safety issues that typically last a few hours.

Table 21 Summary of Vulnerabilities and Risks to Loop 360/RM 2222

	Flooding	Drought	Extreme Heat	Wildfire	Extreme Cold and Ice
Exposure	High Heavy precipitation events may become more intense; Future 50-year events could cause 2 feet of inundation at RM 2222/Bull Creek bridge	High Soil moisture projected to decrease 4-10% by mid-century	High 34 additional days per year above 100° F by mid-century, on average	High Located in an area with moderate Wildfire Threat	Low Projected to experience less than 1 icing day per year by mid-century, on average
Sensitivity	Low Reconstructed after serious damage from Hermine to withstand major flood events	Moderate Medium plasticity soils	Not Sensitive Designed to accommodate high temperatures	High Potential wildfire evacuation choke point	Moderate Elevated structure, prone to icing; Icing temporarily disrupts traffic, but does not cause damage
Adaptive Capacity	Moderate Loop 360 at RM 2222 is a critical junction. RM 2222 is a major east-west corridor that spans Bull Creek near the junction, while Loop 360 carries considerable traffic.				
Impact Description	Temporary road closures, traffic congestion	Increased pavement maintenance costs due to pavement cracking, edge drop-off	No impacts expected	Disruption to normal or evacuation traffic; destruction of guiderail/sign posts	Short-term, but severe, traffic disruptions and delays
Likelihood of Exposure	High	High	High	High	Low
Consequence of Exposure	Moderate	Moderate	None	Major	Moderate
Risk	Moderate	Moderate	None	High	Low-Moderate

Likelihood of Exposure based on VAST Exposure rating; *Consequence of Exposure* based on VAST Sensitivity and Adaptive Capacity ratings

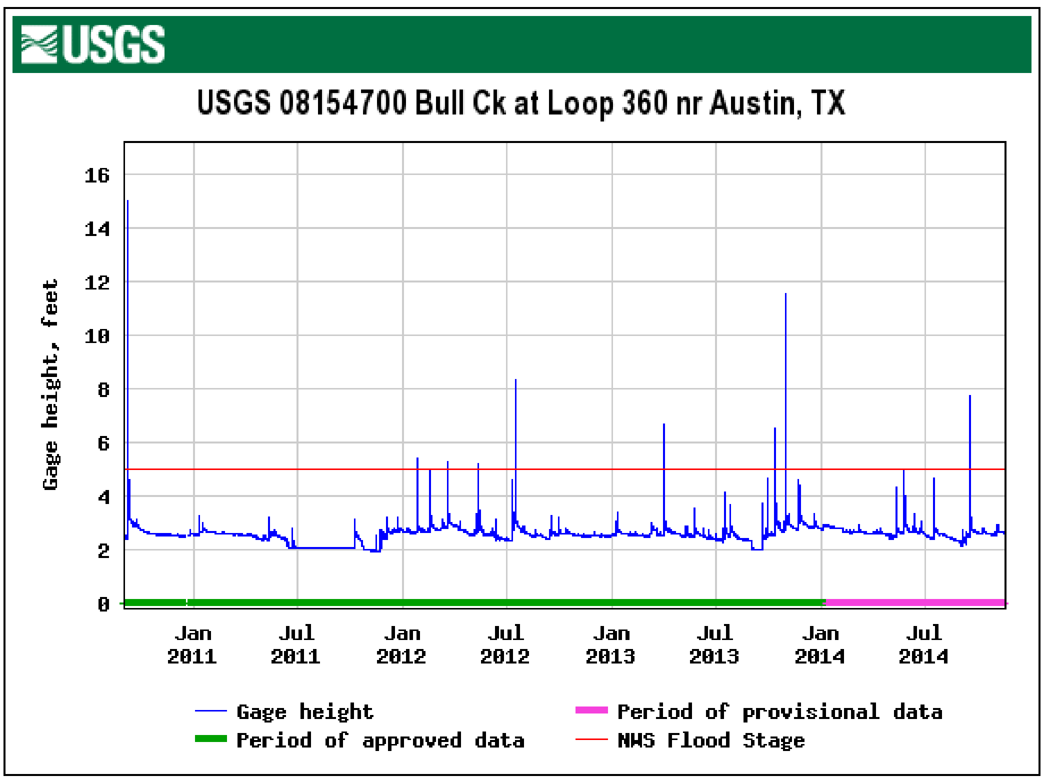
Summary of Key Risks

Wildfire presents the greatest projected risk at the Loop 360/RM 2222 interchange. Though the interchange itself is unlikely to be damaged by wildfire, the interchange could become a bottleneck in the wildfire evacuation process.

Drought is also a potential concern for the asset. Available soils data suggests the intersection could experience pavement deterioration as a result of swings in pavement moisture (although a site-specific investigation would be needed to confirm this risk).

F**looding** is another stressor of concern for the interchange. RM 2222 experienced severe damage from flooding during Tropical Storm Hermine in 2010. The asset is still located in a flood-prone area, but TxDOT engineers indicate that it has been redesigned to minimize future flood damage. Though the asset has not experienced Hermine-like flood levels since it was rebuilt, it withstood the Halloween Flood in October 2013 and flooding in September 2014 (see Figure 34). **Icing** and **heat** are projected to pose negligible risk to the asset.

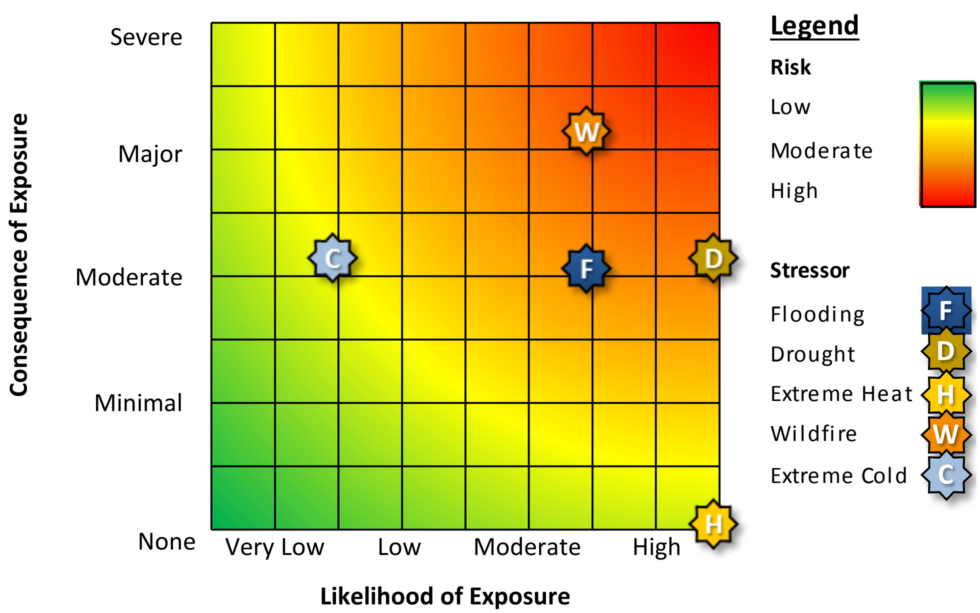
Figure 34 Gauge Height, Bull Creek at Loop 360
9/1/2010–11/18/2014



The peak gage height on the far left of the graph of about 15 feet is associated with Tropical Storm Hermine. More recent spikes are associated with the Halloween Floods in October 2013 (about 12 feet) and September 2014 flooding (about 8 feet).

Source: USGS National Water Information System, USGS gauge 08154700

Figure 35 Risk Rating Matrix: Loop 360/RM 2222

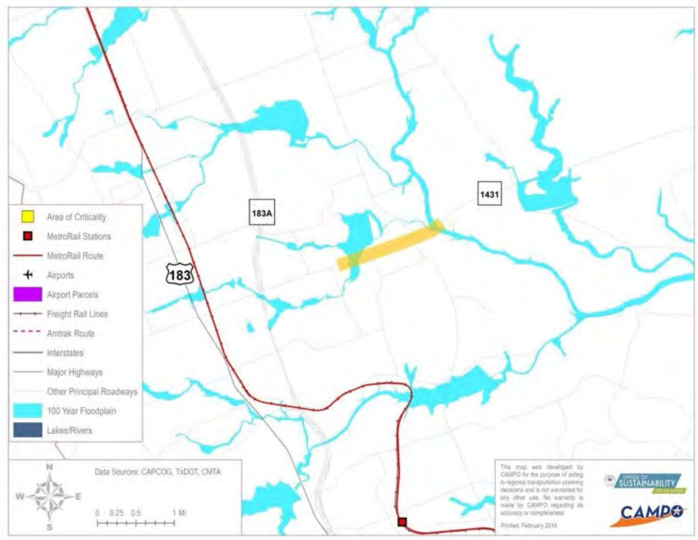


6.8 FM 1431 AT BRUSHY CREEK/SPANISH OAK CREEK (#7)

This asset, the segment of FM 1431 at Brushy Creek/Spanish Oak Creek, is located in a fast-growing area and provides an important east-west connection between two of the region's major north-south freeways (I-35 and US 183). It carries moderate traffic volumes (AADT of 30,000), but relatively low truck traffic (1,050 AADTT). Table 22 and Figure 36 summarize the extreme weather vulnerabilities and risks to this asset.

Flooding

Flooding is not expected to affect FM 1431 at the Brushy Creek/Spanish Oak Creek bridge. Although the bridge is located adjacent to the 100-year floodplain, it is elevated approximately 10 feet above the associated flood depth.



Drought

The asset is located on moderate plasticity soils and thus may be at risk to pavement damage from drought. Summer soil moisture in Central Texas is projected to decrease 4-10 percent by mid-century.

Extreme Heat

Extreme heat is projected to become more common in Central Texas by mid-century. However, this location has a relatively low sensitivity to extreme heat, potentially resulting in minor deterioration.

Wildfire

This asset is located in an area with moderate wildfire risk, with a high number of potential bottleneck points that could occur during a wildfire evacuation. As population grows in the vicinity, wildfire risk is expected to increase.

Extreme Cold and Ice

Although this asset is elevated, it is expected to have low risk to extreme cold and icing events. While the roadway may ice when conditions are right (icy conditions cause moderate traffic disruptions), these conditions last only for a few hours and do not cause long-term physical damage to the roadway.

Table 22 Summary of Vulnerabilities and Risks to FM 1431 at Brushy Creek/Spanish Oak Creek

	Flooding	Drought	Extreme Heat	Wildfire	Extreme Cold and Ice
Exposure	Not Exposed Asset situated ~10 ft. above FEMA 100-yr floodplain	High Soil moisture projected to decrease 4-10% by mid-century	High 34 additional days per year above 100° F by mid-century, on average	Moderate Located in an area with low-moderate Wildfire Threat, but decreasing soil moisture	Low Projected to experience less than 1 icing day per year by mid-century, on average
Sensitivity	N/A Not applicable, because asset is not exposed	Moderate Medium plasticity soils	Very Low Low truck volumes	High Potential to create a wildfire evacuation choke point in a fast-growing area	Low Bridge is more susceptible to icing; Icing temporarily disrupts traffic, but does not cause damage
Adaptive Capacity	Moderate Not an evacuation route; Moderate AADT/AADTT				
Impact Description	No impacts expected	Increased pavement maintenance costs due to pavement cracking, edge drop-off	Minimal impact	Disruption to normal or evacuation traffic; destruction of guiderail/sign posts	Short-term traffic disruptions and delays
Likelihood of Exposure	None	High	High	Moderate	Low
Consequence of Exposure	N/A	Moderate	Minimal	Moderate-Major	Low-Moderate
Risk	None	Moderate	Low	Moderate-High	Low

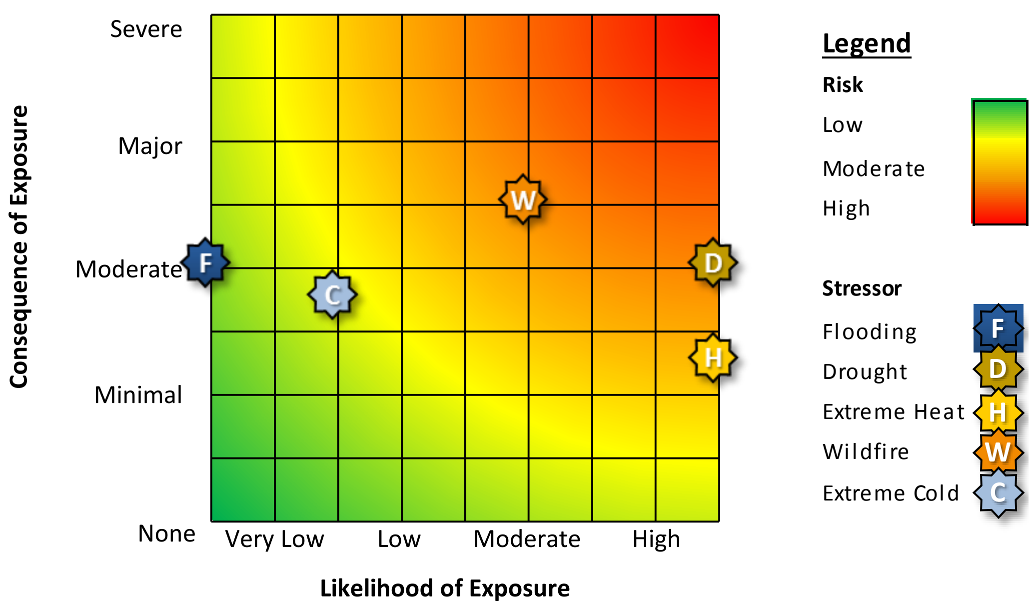
Likelihood of Exposure based on VAST Exposure rating; *Consequence of Exposure* based on VAST Sensitivity and Adaptive Capacity ratings

Summary of Key Risks

FM 1431 at Brushy Creek/Spanish Oak Creek exhibits low risk to **flooding**, **extreme heat**, and **extreme cold**.

The highest estimated risk is from **wildfire**, compounded by population growth and increasing transportation demand in the area. **Drought** also poses a moderate potential risk. Available soils data suggest that the roadway could experience pavement damage because of swings in soil moisture, although a site-specific soil study would be needed to confirm this risk.

Figure 36 Risk Rating Matrix: FM 1431 at Brush Creek/Spanish Oak Creek

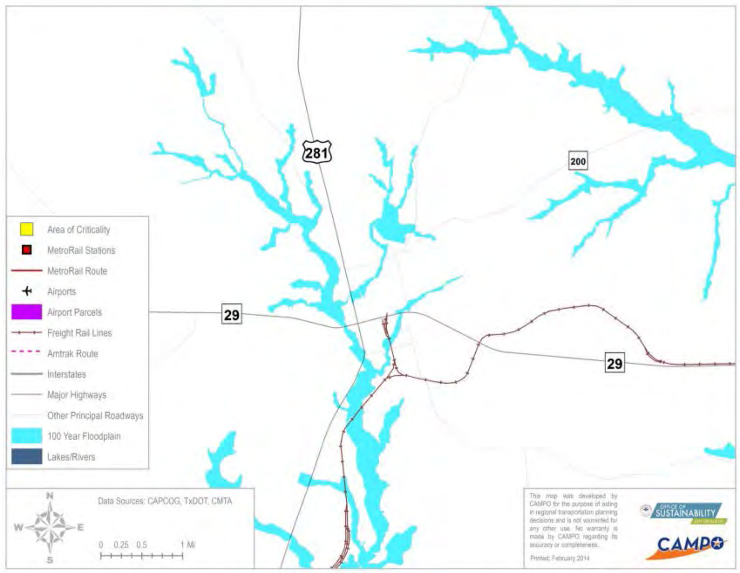


6.9 INTERSECTION OF US 281 AND SH 29, BURNET COUNTY (#8)

Both US 281 and SH 29 provide critical connectivity from Austin to Burnet County, though traffic volumes at the intersection itself are relatively low. Table 23 and Figure 37 summarize the extreme weather vulnerabilities and risks to this asset.

Flooding

All four approaches to the intersection cross the 100-year floodplain. Temporary closure of the intersection due to flooding could reduce connectivity to and from Burnet County.



Drought

The intersection is not projected to be sensitive to drought, since it is not built on high plasticity soils that can shrink or swell with changes in soil moisture.

Extreme Heat

Extreme heat is expected to become more common, with 34 more days per year above 100° F by mid-century, on average. The intersection is not expected to be sensitive to damage from extreme heat, since it is designed to withstand high temperatures and has relatively low heavy truck volumes.

Wildfire

The intersection is located in an area of low-moderate wildfire threat. Wildfires may become more likely in the future, and when they occur, they could cause moderate temporary disruptions.

Extreme Cold and Ice

Icing is infrequent, projected to occur less than one day per year by mid-century. Icing, when it does occur, can create traffic disruptions and safety issues that typically last a few hours.

Table 23 Summary of Vulnerabilities and Risks to Intersection of US 281 and SH 29
Burnet County

	Flooding	Drought	Extreme Heat	Wildfire	Extreme Cold and Ice
Exposure	High Floods semi-regularly, located in the 100-year FEMA floodplain	High Soil moisture projected to decrease 4-10% by mid-century	High 34 additional days per year above 100° F by mid-century, on average	Moderate Located in an area with low-moderate Wildfire Threat	Low Projected to experience less than 1 icing day per year by mid-century, on average
Sensitivity	High Low flooding design capacity	Low Low plasticity soils	Very Low PG 64-22 asphalt binder, low truck traffic	Moderate Wildfire causes temporary service disruptions but not long-term damage	Low Roadway not elevated, but still capable of experiencing icing; Icing temporarily disrupts traffic, but does not cause damage
Adaptive Capacity	Moderate Provides critical intra-regional connectivity				
Impact Description	Reduced access to Burnet County	Minimal impacts expected	Minimal impacts expected	Temporary traffic disruption; destruction of guiderail/sign posts	Short-term traffic disruptions and delays
Likelihood of Exposure	High	High	High	Moderate	Low
Consequence of Exposure	Major	Minimal	Minimal	Moderate	Low-Moderate
Risk	Moderate-High	Low	Low	Moderate	Low

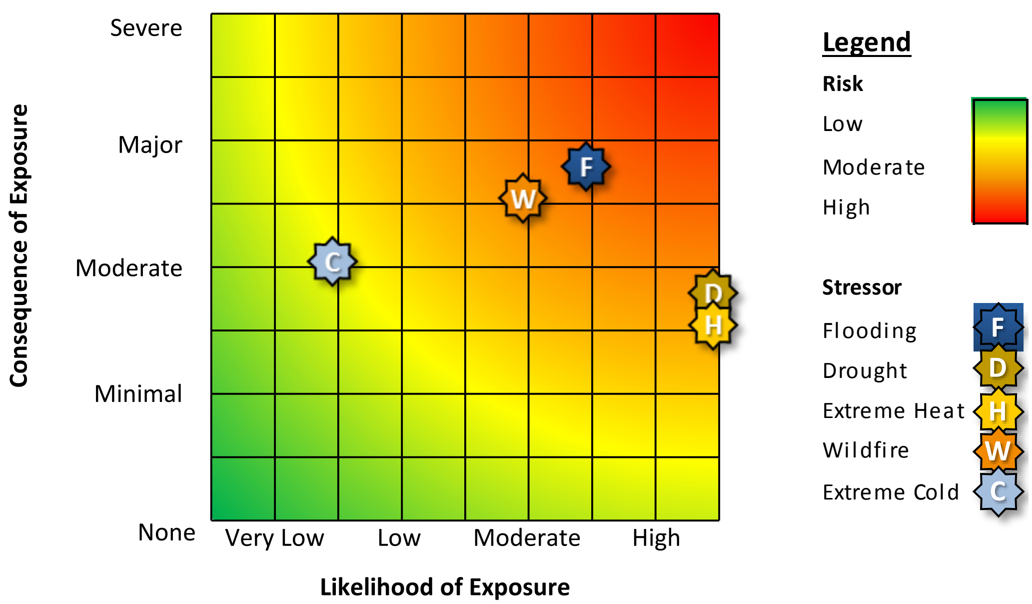
Likelihood of Exposure based on VAST Exposure rating; *Consequence of Exposure* based on VAST Sensitivity and Adaptive Capacity ratings

Summary of Key Risks

Relative to the other assets studied, the project team had relatively fewer data on the US 281 and SH 29 intersection, due to its location in Burnet County. Data were not available for soil plasticity, AADT, truck traffic volume, bridge scour rating, or vertical proximity to the floodplain. Instead, this assessment relied primarily on qualitative or anecdotal evidence from local experts. Therefore, further study is warranted to validate these preliminary conclusions.

Based on this information, **flooding** appears to be the greatest risk to the intersection, occurring semi-regularly. **Wildfire** also appears to be a risk, based on historical wildfire incidence and indications that wildfire risks could increase in the future.

Figure 37 Risk Rating Matrix: US 281 and SH 29 Intersection

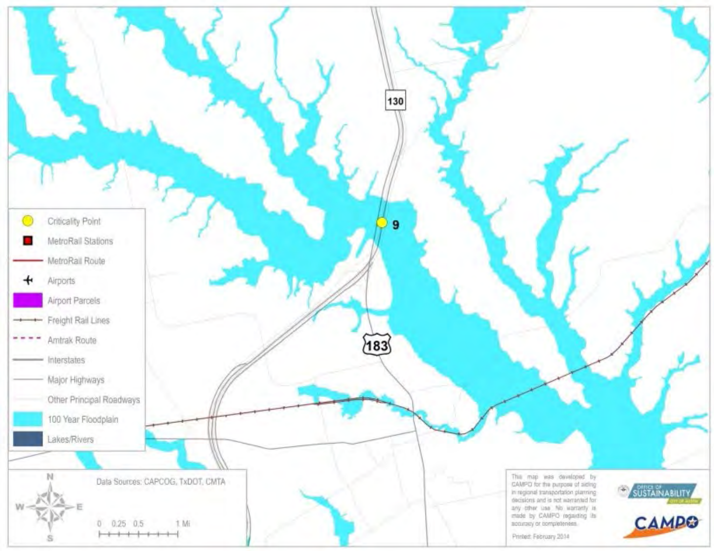


6.10 US 183 North of Lockhart (#9)

This segment of US 183 north of Lockhart provides a critical regional connection between Caldwell County and the Austin core. It provides access to/from Austin Bergstrom International Airport (ABIA) for communities in Caldwell County and is designated by TxDOT as a major hurricane evacuation route for Texas Gulf Coast cities. Table 24 and Figure 38 summarize the extreme weather vulnerabilities and risks to this asset.

Flooding

Although heavy precipitation events may become more intense, the segment sits an estimated two feet above the current 100-year floodplain. However, should a closure occur, it would cut off direct access to the airport for Lockhart residents and other communities in south Caldwell County, and could also compromise the evacuation route.



Drought

This asset is located on high plasticity soils and therefore may be highly sensitive to drought, which could lead to damage or deterioration such as pavement cracking or edge drop-off.

Extreme Heat

Extreme heat is expected to become more common in Central Texas by mid-century. However, this facility is thought to have a relatively low sensitivity to extreme heat (meaning it would experience minimal damage or disruption).

Wildfire

This asset is located in an area with moderate-high likelihood of wildfire. Damage to the asset would likely be minor (resulting in moderate, temporary disruptions to traffic flows), but consequences could be high if a wildfire occurs when the route is needed for hurricane evacuation.

Extreme Cold and Ice

Icing is infrequent, projected to occur less than one day per year by mid-century. Icing, when it does occur, can create traffic disruptions and safety issues that typically last a few hours.

Table 24 Summary of Vulnerabilities and Risks to US 183 North of Lockhart

	Flooding	Drought	Extreme Heat	Wildfire	Extreme Cold and Ice
Exposure	Very Low ~2-foot vertical elevation above 100-year flood plain	High Soil moisture projected to decrease 4-10% by mid-century	High 34 additional days per year above 100° F by mid-century, on average	High Located in an area with moderate Wildfire Threat, with fire likelihood projected to increase	Low Projected to experience less than 1 icing day per year by mid-century, on average
Sensitivity	High Design guidelines for this asset type specify a relatively common flooding event (10-year)	High High plasticity soils	Very Low PG 64-22 asphalt binder; Low-to-moderate truck volumes	Low Wildfire causes temporary service disruptions but not long-term damage	Low Roadway not elevated, but still capable of experiencing icing; Icing temporarily disrupts traffic, but does not cause damage
Adaptive Capacity	Low Provides regional connection between Caldwell County and the Austin core; Designated as major hurricane evacuation route				
Impact Description	Flooding, though unlikely, could cause damage along with temporary road closures	Increased annual maintenance costs; increase in pavement cracking	Minimal impact	Temporary closures or disruption, destruction of guiderail/sign posts	Short-term traffic disruptions and delays
Likelihood of Exposure	Very Low	High	High	High	Low
Consequence of Exposure	Major	Severe	Minimal-Moderate	Moderate	Moderate
Risk	Low-Moderate	High	Low-Moderate*	Moderate-High	Low-Moderate

Likelihood of Exposure based on VAST Exposure rating; *Consequence of Exposure* based on VAST Sensitivity and Adaptive Capacity ratings

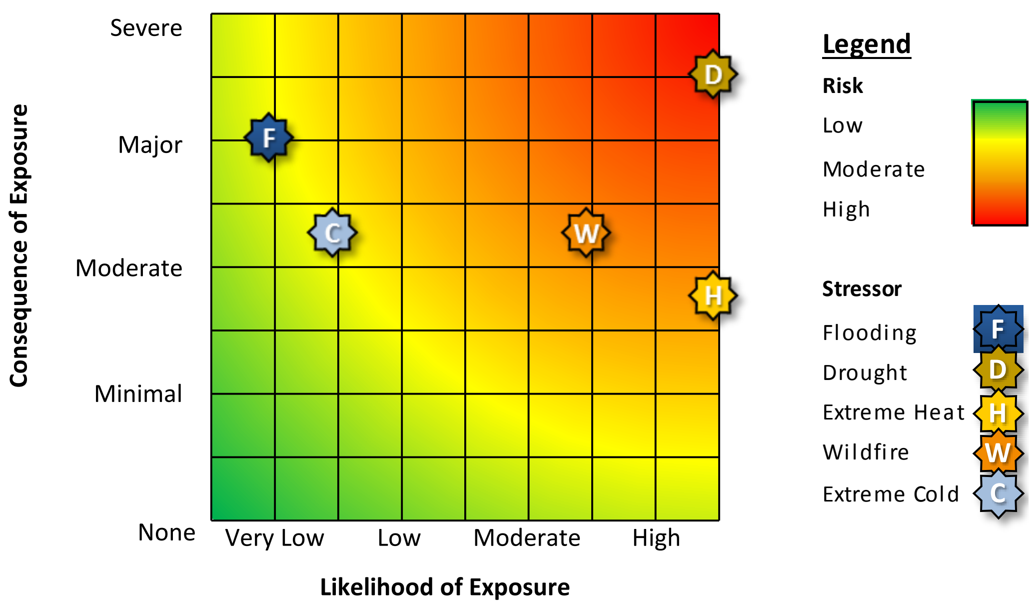
* Rating is highly influenced by the low degree of adaptive capacity

Summary of Key Risks

Drought is estimated to present the greatest risk to US 183 north of Lockhart. The roadway is built over high plasticity soils that can expand and contract with changes in soil moisture. These shrink-swell cycles can, in turn, damage the roadway, particularly along its edges. Finally, roadway edge condition is particularly important for an evacuation route, as the shoulders may be needed to enhance normal capacity.

Across all stressors, risks to this asset are considered to be relatively higher because of its status as an evacuation route. The potential consequences of any type of damage are amplified, since evacuation effectiveness could be compromised if the roadway were damaged or otherwise unusable.

Figure 38 Risk Rating Matrix: US 183 North of Lockhart

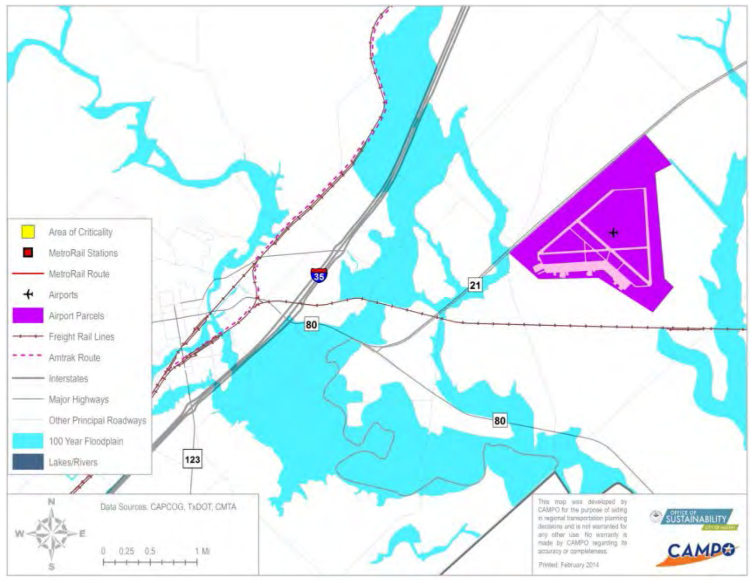


6.11 SH 80 (San Marcos Highway) at the Blanco River (#10)

San Marcos Highway provides connectivity to the City of San Marcos and the San Marcos Municipal Airport. Table 25 and Figure 39 summarize the extreme weather vulnerabilities and risks to this asset.

Flooding

San Marcos Highway is prone to flooding, which may become more common or severe if heavy rainfall magnitudes increase. The roadway is located within the 100-year floodplain. Temporary closure of the asset could affect 9,500 vehicles per day.



Drought

Drought is not expected to affect the asset because the road is not built on high plasticity soils.

Extreme Heat

Although extreme heat is expected to become more common in Central Texas, San Marcos Highway is designed to withstand temperatures higher than those projected and has relatively low heavy truck volumes.

Wildfire

San Marcos Highway is located in an area of low wildfire threat. Wildfires may become more likely based on projections for decreasing soil moisture, but are anticipated to cause only temporary service disruptions.

Extreme Cold and Ice

Icing is infrequent, projected to occur less than one day per year by mid-century. Icing, when it does occur, can create traffic disruptions and safety issues that typically last a few hours.

Table 25 Summary of Vulnerabilities and Risks to SH 80 (San Marcos Highway) at the Blanco River

	Flooding	Drought	Extreme Heat	Wildfire	Extreme Cold and Ice
Exposure	Moderate Located ~1 ft below the 100-year floodplain	High Soil moisture projected to decrease 4-10% by mid-century	High 34 additional days per year above 100° F by mid-century, on average	Moderate Located in an area with low Wildfire Threat, but decreasing soil moisture may increase risk	Low Projected to experience 1 icing day per year by mid-century, on average
Sensitivity	Moderate Asset is in good condition, designed to withstand a 25-year rain event	Low Low plasticity soils	Very Low PG 64-22 asphalt binder; Low truck traffic	Moderate Wildfire causes temporary service disruptions but not long-term damage to roadway	Moderate Elevated structure, prone to icing; Icing temporarily disrupts traffic, but does not cause damage
Adaptive Capacity	High Moderate redundancy and relatively low traffic volumes				
Impact Description	Up to 9,500 auto trips could be impacted during flood events; could cut off access to San Marcos airport	Minimal impacts expected	Minimal impacts expected	Temporary traffic disruption; destruction of guiderail/sign posts	Short-term traffic disruptions and delays
Likelihood of Exposure	Moderate	High	High	Moderate	Low
Consequence of Exposure	Moderate	Minimal	Minimal	Moderate	Low-Moderate
Risk	Moderate	Low	Low	Moderate	Low

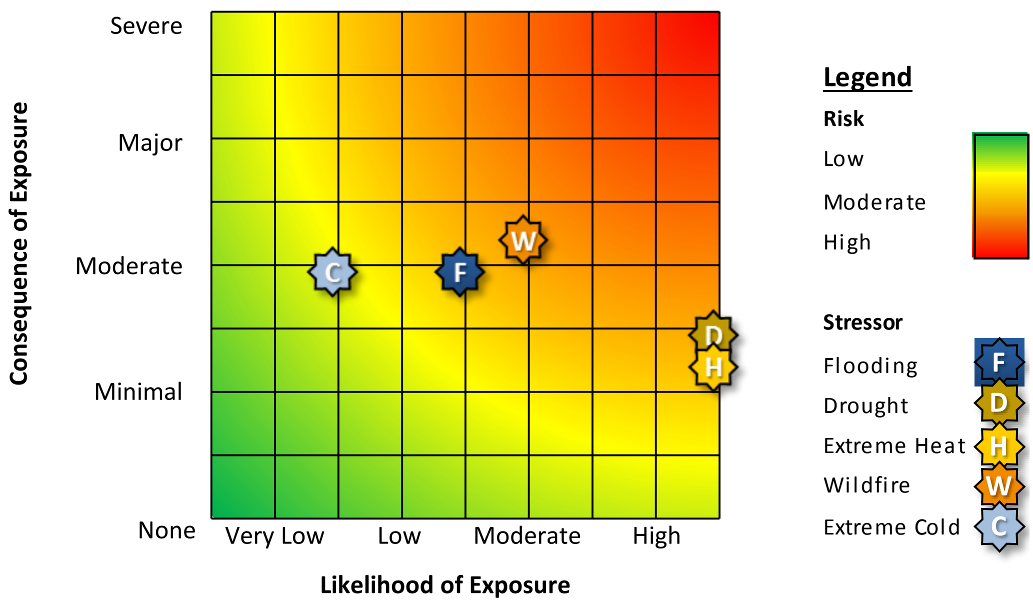
Likelihood of Exposure based on VAST Exposure rating; *Consequence of Exposure* based on VAST Sensitivity and Adaptive Capacity ratings

Summary of Key Risks

Overall (and compared to other assets studied), climate-related risks are relatively low for San Marcos Highway. **Wildfire** and **flooding** present the greatest risks and could result in temporary loss of access to the San Marcos Airport.

Across all stressors, risk is mitigated by the relatively low consequences of damage or disruption to the asset, primarily due to the very low traffic volumes along this segment and the presence of alternate routes.

Figure 39 Risk Rating Matrix: SH 80 (San Marcos Highway) at the Blanco River



7.0 Lessons Learned

The lessons learned in the course of this study can be cataloged in two broad categories—*Lessons for MPOs and State DOTs* and *Lessons for FHWA* (although, in practice, there is ample overlap between them).

7.1 Lessons for MPOs and State DOTs

Many of the lessons for MPOs and state DOTs coalesced around the theme of generating and sustaining productive partnerships and participation, including:

- **Partner with municipalities.** The partnership between CAMPO (an MPO) and the City of Austin (a municipality) was productive, extending the reach and resources of the study. The City of Austin Office of Sustainability was active in establishing the strategic direction of this study and was able to facilitate introductions to City staff in a variety of disciplines, including wildfire risk, public health, emergency management, and roadway maintenance and engineering, for example.
- **Cast a broad net.** Cross-sectoral coordination (i.e., involving disciplines outside of transportation) introduced important perspectives that otherwise may have been overlooked or underrepresented. The active participation of the City of Austin Fire Department, for example, provided valuable insights into the critical issue of wildfire risk.
- **Forge regional connections early on.** Toward the conclusion of this study, the project management team established communication with peers in other regions of Texas, culminating with a statewide Extreme Weather Resilience Symposium. For future efforts, these connections should be leveraged earlier in the process (and sustained through regular communication).
- **Emphasize opportunities for participation.** Three sets of stakeholder/expert workshops or focus groups took place in the course of the study, two at the very beginning, and one near the end (and, at the very end, CAMPO and the City of Austin convened a regional symposium to discuss and disseminate the preliminary results). These in-person meetings facilitated productive interactions and vital feedback and generated significant enthusiasm for the study. For future efforts, more opportunities of this nature would be worth while. In particular, operating agencies—which otherwise may be reluctant to delve into the topic of future extreme weather risk—should be invited to the table early in the process.

Additional lessons, many of which are broadly applicable to other inland regions of the country include:

- **The nature of inland extreme weather and climate challenges may differ from those faced by coastal communities.** The study team found that, generally, inland risks are either situational and relatively localized (e.g., flooding) OR regionwide but less suddenly catastrophic than, for example, coastal storm risk (e.g., extreme heat, drought). In line with this realization, two sets of potentially appropriate regional responses emerged:
  - **Asset management.** The incorporation of extreme weather and climate risk into transportation asset management plans facilitates a deliberate, cost-effective response that also factors in the range of other challenges faced by transportation agencies. This strategy is fully compatible with the MAP-21 requirement to develop risk-based Transportation Asset Management Plans (TAMPs).
  - **Emergency response plans.** In the instances of wildfire and icing, the principal impacts of concern relate to operational disruptions and threat to safety, rather than significant infrastructure damage or deterioration. Particularly in the case of wildfire, the potential for the creation of "choke points" along evacuation routes or at critical intersections warrants special consideration. CAMPO's 2040 LRTP addresses this issue.
- **Critical assets may not be the most vulnerable assets.** Future efforts should be mindful of the tradeoffs inherent in selecting a limited number of representative assets to study. Some of the assets evaluated in this study were likely relatively less vulnerable than lower functional classification facilities in the region that—while not as critical to mobility as I-35, for instance—were built to significantly lower design standards and may, therefore, exhibit much greater sensitivity to extreme weather stressors. In the CAMPO region, legacy roadways in rapidly urbanizing or industrializing areas, in particular, may warrant investigation.
- **Growth and other non-climate stressors can significantly influence extreme weather impacts.** The *sensitivity* component of the vulnerability assessment factors in other, non-climate stressors—the growth of heavy truck volumes or the expansion of impervious surface, for example. In some cases, these stressors serve to amplify a primarily climate-related impact, but in many instances the non-climate stressor is a significant--or even primary—driver of risk.
- **Adopt a transparent, scenario-based approach to considering potential climate futures.** Climate models provide advanced tools for simulating incredibly complex interactions between physical systems under various forcing scenarios (related to greenhouse gas emissions). However, the trajectory of future emissions is fundamentally uncertain—particularly as the century progresses—and, given the computational intensity required, climate models are relatively coarse in scale. For the sake of full transparency, it is

important to properly frame the outputs of climate models as potential futures—scientifically-based scenarios that do reflect specific probabilities. As explained in Section 5, the approach taken by the study team was to develop three scenarios and, reflecting a conservative (averse) approach to risk, adopt the worst-case (among the three scenarios) for this assessment.

- **Avoid the climate change debate.** Among the general population, human-induced climate change is not a universally accepted phenomenon. For those for whom this is a deep-rooted belief, this study will not—and is not intended to—change this perspective. However, extreme weather (e.g., intense rainfall events) and climate (e.g., multi-year droughts) have and will continue to negatively affect transportation infrastructure and operations. Under the regime of natural climate variability, these risks will continue to shift over time. Therefore, particularly in regions where climate change is a challenging topic, the project team recommends focusing on extreme weather (and climate) risk and resilience—themes that are broadly relevant and understood and for which human-induced climate change is not an underpinning assumption.

7.2 Lessons for FHWA

Lessons for FHWA revolve around the application of the Vulnerability Assessment Framework and associated processes and tools.

The Vulnerability Assessment Scoring Tool (VAST) provided a useful framework for organizing available data and sparking focus group conversations to facilitate an assessment of vulnerability at the asset level. The combined use of VAST and focus group discussions worked synergistically—relying on either element in isolation would not have been as successful. VAST provided a structured starting point for focus group conversations and the focus groups helped add nuance and qualitative insight into VAST's data-driven approach. Challenges encountered and overcome in the process included:

- **Allowing for assets to be "not sensitive."** By default, VAST is set up to weight each component of vulnerability (Exposure, Sensitivity, and Adaptive Capacity) equally. For assets that have low Sensitivity (i.e., are not likely to be damaged or otherwise affected by the stressor) as well as low Adaptive Capacity (i.e., would have major consequences if damaged), the tool initially rated them as having high vulnerability (a result driven primarily by the low Adaptive Capacity score). However, in many cases, the study team found that it made sense to conclude that a given asset is not vulnerable if it is not sensitive to damage (effectively rendering the consideration of Adaptive Capacity moot). In those cases, the project team overrode the default results to allow assets to be identified as "not sensitive" (or minimally sensitive), thus leading to low or even very low composite vulnerability scores. The default settings helped flag these counterintuitive situations for review and eventual adjustment, but future users should note that adjustments may be necessary.

- **Evaluating relative exposure given varying robustness of data.** The robustness of exposure data varied significantly across stressors and across assets. For example, to evaluate potential flood exposure, the project team had FEWS flood simulations for some assets, FEMA floodplain and terrain elevation information for others, and anecdotal evidence of past flooding for others. Given the disparity in detail between these sources, it was challenging to establish a scoring approach that allowed for comparisons across assets. Focused discussions between project team members, stakeholders, and local experts—as well as transparency about potential limitations of the specific approaches used—helped overcome this challenge.
- **Defining terms.** The specialized terms commonly used in climate change vulnerability assessments can lead to confusion among project participants: Exposure, Sensitivity, Adaptive Capacity, impact, criticality, consequence, vulnerability, risk, etc. Thus, it was important to establish clear definitions, both for the VAST scoring process and subsequent focus group discussions.
- **Advanced climate stressor research.** Project stakeholders from the City of Austin and CAMPO noted that more detailed climate projections related to precipitation variability, drought, and wildfire risk would be helpful for future efforts. For example, although the Keetch-Byram Drought Index (KBDI) was identified as a key wildfire risk indicator, the study team determined that projecting future KBDI using climate model outputs required significant additional investigation—and ended up using proxy variables (e.g., soil moisture). Particularly for wildfire-prone states, a dedicated study of future KBDI projections is needed—perhaps in conjunction with Federal partners (like FHWA, the US Forest Service, and/or the Bureau of Land Management). The projection of future Intensity-Duration-Frequency (IDF) curves for precipitation is also a topic for which a dedicated study may be warranted.

8.0 Next Steps

Consistent with its role as a pilot project, this study led to the identification of many potentially fruitful trajectories to pursue and needs that remain unmet. Among them, the priorities for CAMPO and the City of Austin include:

- **Form an Extreme Weather Resilience Working Group.** Following the successful inaugural Extreme Weather Resiliency Symposium in December 2014, CAMPO and the City of Austin expect to work with FHWA's Texas Division office to form a multi-stakeholder Working Group. The Working Group will involve participants from interested jurisdictions around Texas, building on the momentum of this project to continue the peer learning process.
- **Incorporate extreme weather considerations into the 2040 LRTP.** The 2040 CAMPO LRTP, in progress as of the time of writing, will incorporate selected elements of this study. A particular concern, which emerged in the course of this study, is the possible hazard wildfire poses to evacuation and emergency response efforts.
- **Expand internal and external collaboration.** The City of Austin Office of Sustainability intends to expand outreach to other City departments, building on the successful coordination with, for example, the Fire Department and Public Works Department, established in the course of this study. Both CAMPO and the City of Austin are interested in further engaging peer agencies and cities across Texas—both to share the findings of this work and to learn from the experiences of others.
- **Explore opportunities for funding, partnerships, and collaboration in order to:**
  - **Expand the assessment to select City and County roads.** Generally, the critical roadways considered in this study (e.g. I-35) were designed to relatively high standards, which, all else being equal, enhances the extreme weather resilience of these facilities. Therefore, subsequent phases of this work might productively focus on lower functional classification roads—particularly those in rapidly urbanizing or industrializing areas. A more dire picture of extreme weather risk may well emerge.
  - **Extend the assessment time horizon.** The time horizon for this study was approximately mid-century— just 25 years from the present—selected in relation to the 2040 LRTP. For several key climate variables (including, for example, extreme heat), projections dramatically increase in severity and/or frequency in the second half of the century. Particularly for long-lived, critical assets like bridges, it may make sense to consider climate scenarios out to the year 2100.

- **Evaluate and implement adaptation options.** The purpose of this study was to identify and characterize potential extreme weather and climate-related risks to transportation infrastructure. A critical next step for the region is the timely, cost-effective management of those risks—a process called adaptation. Although this report offers a handful of high-level adaptation strategies for each stressor, further investigation is warranted.

A. Appendix: Climate Data

As of July 2014, three studies were identified for which custom climate projections were being developed for the Central Texas region/City of Austin. To assist in navigating across the findings of these three studies, and to provide perspective, this document provides a quick overview of the respective methodologies and results, but is not a comparison. The studies, in order of completion, are:

- **ATMOS Research & Consulting:** Climate Change Projections for the City of Austin. Katharine Hayhoe. Draft Report April 2014.
- **GEOS Institute:** Temperature and Precipitation Extremes in Austin, Texas. A report for A Nurtured World and the City of Austin. Draft Report May, 2014.
- **CAMPO (based on the work of Patricola and Cook):** Central Texas Extreme Weather and Climate Change Vulnerability Assessment of Regional Transportation Infrastructure. Final Report January 2015.

The *ATMOS Research & Consulting* and the *GEOS Institute* data appear to based on the same statistically-downscaled data (parameters summarized in the *ATMOS Research & Consulting* report). Some notable differences between these two data sets include: the *GEOS Institute* analysis used only 3 of the 9 climate models used in the *ATMOS Research & Consulting* analysis, and different years were selected for the time periods. The *CAMPO* analysis leverages a regional climate model (Weather Research and Forecasting, or WRF) based on the work of Patricola and Cook (2013)[22]. CAMPO projections are associated with three different geographies (see Figure 13):

- Scenario 1 (S1): Greater Austin (30.3°N and 97.8°W);
- Scenario 2 (S2): 133 miles north of Austin (in the general vicinity of Fort Worth);
- Scenario 3 (S3): 133 miles west of Austin.

Two tables are presented below. The first table summarizes the methodology, to the extent it is known, for each of the downscaling efforts. The second table summarizes the results from each.

[22] Patricola, C. M., and K. H. Cook, 2013b: *Mid-twenty first century climate change in the central United States. Part II: Climate change processes.* Climate Dynamics, 40, 569-583.

Methodology

The table below provides a summary of the methodologies used in each of the three studies.

	GEOS Institute	ATMOS Research & Consulting	CAMPO Study
Spatial scale	1 location (Camp Mabry)	1 location (Camp Mabry)	3 locations: ▪ 1 location at Austin (L1), ▪ 1 location 133 miles north of Austin (L2), ▪ 1 location 133 miles west of Austin (L3)
Observations (network/baseline years)	USHCN Camp Mabry weather station in Austin Texas (lat/lon of 30.320 / -97.760)	USHCN Camp Mabry weather station in Austin Texas (lat/lon of 30.320 / -97.760)	WRF regional hind-casting, supplemented with observations from USHCN Camp Mabry weather station in Austin Texas (lat/lon of 30.320 / -97.760)
Projection years	▪ 1961-1990 ▪ 2010-2039 ▪ 2040-2069 ▪ 2070-2099	▪ 1971-2000 ▪ 2011-2040 ▪ 2041-2070 ▪ 2071-2100	▪ 1981-2000 ▪ 2041-2060
Climate Models	3 WCRP CMIP5 GCMs[23] CNRM-CM5 MIROC 3.2 INM-CM3.0 Projections based on a single grid cell (lat/lon of 30.3475 / -97.7812) near Camp Mabry weather station	9 WCRP CMIP GCMs ▪ CCSM4 ▪ CNRM-CM5 ▪ HadGEM2-CC ▪ INM_CM4 ▪ IPSL-CM5A-LR ▪ MIROC5 ▪ MPI-ESM-LR ▪ MRI-CGCM3 ▪ CSIRO-Mk3-6-0	Regional climate model: Weather Research and Forecasting (WRF) Model, developed and maintained by the National Center for Atmospheric Research (NCAR)
Processing of GCM projections	Statistical downscaling[24] supported by USGS	Statistical downscaling[25] supported by USGS	No additional processing (WRF inner domain is at 30 km resolution)
Additional modeling in the analysis	Wildfire using the MC1 model[26] using the moderately-high A2 emission scenario	None	None

[23] These 3 GCMS were selected from a total of 9 GCMs (CCSM4, CNRM-CM5, HadGEM2-CC, INM_CM4, IPSL-CM5A-LR, MIROC5, MPI-ESM-LR, MRI-CGCM3, CSIRO-Mk3-6-0). Selection reflected the output for the following range: lower, average, higher precipitation; slower, average, faster warming.

[24] Based on treatment described in Hayhoe and Stoner 2013

[25] Based on treatment described in Hayhoe and Stoner 2013

[26] Vegetation model that estimates future wildfire based on projected vegetation and climate.

	GEOS Institute	ATMOS Research & Consulting	CAMPO Study
Emission Scenarios	▪ High (RCP8.5)	▪ Moderate (RCP4.5) ▪ High (RCP8.5)	▪ Moderately-high (A2)
Limitations to methodology	Potentially limited by the methodology in choosing models, 1 location – illustrative purposes , 1 future scenario	1 location – illustrative purposes	1 future scenario (this would be a challenge if this study presented end of century information)

Results

The table below provides a summary of the projections presented by each of the three studies.

	GEOS Institute		ATMOS Research & Consulting			CAMPO Study			
	Time	RCP8.5	Time	RCP4.5	RCP8.5	Time	S1	S2	S3
Temperature									
Annual temperatures (F)						Historic	NA	NA	NA
						2041-2060	+2.9	+2.9	+2.7
Winter average mean temp (F)						Historic	NA	NA	NA
						2041-2060	+2.2	+2.2	+2.2
Summer average mean temp (F)						Historic	NA	NA	NA
						2041-2060	+3.6	+3.4	+2.9
Summer average high temp (F)			Historic	93.8					
			2011-2040	+3.1					
			2041-2070	+4.1	+6.4				
			2071-2100	+4.8	+10				
Number of days per year maximum temperatures above 95ºF	Historic	40 days							
	2010-2039	+8 to +33 (+20 to 82%)							
	2040-2069	+20 to +59 (+50 to 147%)							
	2070-2099	+46 to +99 (+114 to 245%)							
Number of days per year maximum temperatures above 100ºF	Historic	10 days	Historic	11.7 days		Historic	NA	NA	NA
	2010-2039	+2 to +22 (+22 to 230%)	2011-2040	+19.7					
	2040-2069	+12 to +40 (+126 to 417%)	2041-2070	+28.4	+51.5	2041-2060	+34 days	+34 days	+34 days
	2070-2099	+26 to +84 (+274 to 872%)	2071-2100	+34.8	+80.6				
Number of days per year maximum temperatures above 110ºF	Historic	0 days	Historic	0 days					
	2010-2039	+0.1 to +0.3	2011-2040	+1.3 day					
	2040-2069	+0.5 to +1.3	2041-2070	+0.4 day	+11.6 day				
	2070-2099	+1.5 to +10.3	2071-2100	+0.9 day	+19.5 day				
Number of days per year minimum temperatures below 32 ºF (cold nights)	Historic	18 days	Historic	16.6 days					
	2010-2039	-5 to -15 (-25 to -83%)	2011-2040	-6 days					
	2040-2069	-10 o -18 (-55 to -100%)	2041-2070	- 8 days	-10 days				

	GEOS Institute		ATMOS Research & Consulting			CAMPO Study			
	Time	RCP8.5	Time	RCP4.5	RCP8.5	Time	S1	S2	S3
	2070-2099	-18 (-100%)	2071-2100	-9 days	-12 days				
Number of days per year minimum temperatures greater than 80F (warm nights)	Historic	0.4 days	Historic	0.5					
	2010-2039	0 to +1.6 (0 to +433%)	2011-2040	+4.9					
	2040-2069	+0.1 to +19.6 (+33 to +4,766%)	2041-2070	+10	+39				
	2070-2099	+1.6 to +59.4 (+342 to 14,675%)	2071-2100	+16.5	+86.2				
Summer average 7-day maximum temp						Historic			
						2041-2060	+4.1	+4.0	+3.9
Precipitation									
Annual Average Precipitation (inches)			Historic	33.7		Historic	NA	NA	NA
			2011-2040	-1.9					
			2041-2070	-0.1	-0.4	2041-2060	-7.5%	+5%	0%
			2071-2100	-0.7	-2.3				
Winter (DJF) precipitation						Historic	NA	NA	NA
						2041-2060	-5%	+5%	0%
Summer (JJA) precipitation						Historic	NA	NA	NA
						2041-2060	-15%	+10%	0%
Number of days below 0.01 inches (dry days)	Historic	282 days	Historic	277.3		Historic	NA	NA	NA
	2010-2039	-2 to +4 (-0 to +2%)	2011-2040	-3					
	2040-2069	+1 to +11 (+0 to +4%)	2041-2070	-3.3	+5.4	2041-2060	+4 days (+1.5%)	+4 (+1.5%)	+3 (+1.0%)
	2070-2099	+3 to +15 (+1 to +5%)	2071-2100	+4.1	+10.8				
Number of days more than 2 inches	Historic	2 days	Historic	2.2					
	2010-2039	0 to +1 (-24% to +40%)	2011-2040	+0.3					
	2040-2069	+1 (+11 to +30%)	2041-2070	+0.6	+0.5				
	2070-2099	0 to +2 (-9 to +61%)	2071-2100	+0.6	+0.6				
Number of days with at least 3.44 inches (2-year rainfall)						Historic	NA	NA	NA
						2041-2060	-0.25 (1 fewer event every 4 years)	No change	No change
Wettest 5 days (in)			Historic	5.8					
			2011-2040	+1.4					
			2041-2070	+1.8	+1.9				
			2071-2100	+2.0	+2.0				

	GEOS Institute		ATMOS Research & Consulting			CAMPO Study			
	Time	RCP8.5	Time	RCP4.5	RCP8.5	Time	S1	S2	S3
Additional Variables									
Annual Soil Moisture						Historic	NA	NA	NA
						2041-2060	-5%	No change	-2%
Summer Soil Moisture						Historic	NA	NA	NA
						2041-2060	-10%	-4%	-4%
Wildfire: percent burned in Central Texas Region	Historic	9%							
	2035-2045	+9 to +11% (-2 to +23%)							
	2075-2085	+ 8 to +10% (-16 to +9%)							
Wildfire: Biomass consumed in Central Texas Region	Historic	16.6%							
	2035-2045	+12.6 to +21.2% (-24 to +28%)							
	2075-2085	+10.7 to +19.2% (-36 to +16%)							

B. Appendix: Hydrologic Model Simulations

Methodology

The hydrologic model simulations utilized for this analysis are a subset of existing model setups developed for the City of Austin's Flood Early Warning System (FEWS). Figure 1 shows the watershed location and distribution. These models are used to predict flooding for operations that involve emergency response. The configured watershed models have been tested with many storms since inception of operational modeling by FEWS since 2008. Their accuracy has been enhanced through comparison with observed streamflow measured at approximately 22 locations throughout Travis County, and by incorporating watershed characteristics that are representative of current (baseline) conditions. The type of model used for simulation of flood risks is a gridded physics-based hydrologic model, called V*flo*® (Vieux, 2004). Its performance during an extreme storm in 2010 was evaluated by Looper and Vieux (2012) by examination of model accuracy during Tropical Storm Hermine (September 7-8, 2010), which caused significant damage and flooding in Texas, and specifically in Travis County. The model performance was found to be very accurate with predicted peak stage agreeing with observed peak stage within 10-20%. This accuracy was comparable with the rainfall input uncertainty which was of similar magnitude.

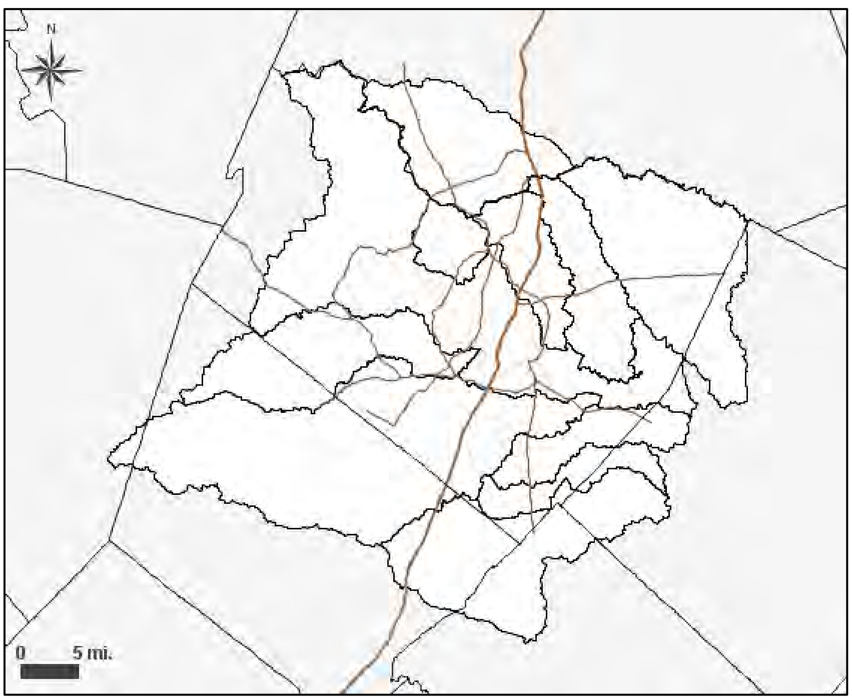


Figure 1 Distribution of modeled watersheds (black outlines) used in this study for flood risk simulation

V*flo* relies on geospatial data to represent the land use and land cover affecting runoff velocities, infiltration properties of the soils including imperviousness, channel hydraulic capacity of streams and drainage ways, and the terrain slope and drainage direction in each grid cell of the model. A portion of the model grid in Bull Creek watershed is seen in Figure 2, showing the gridded nature of the model and a sample channel cross-section taken from a terrain model produced from LiDAR at 10-meter resolution obtained from the Texas Natural Resource Information Service (TNRIS).

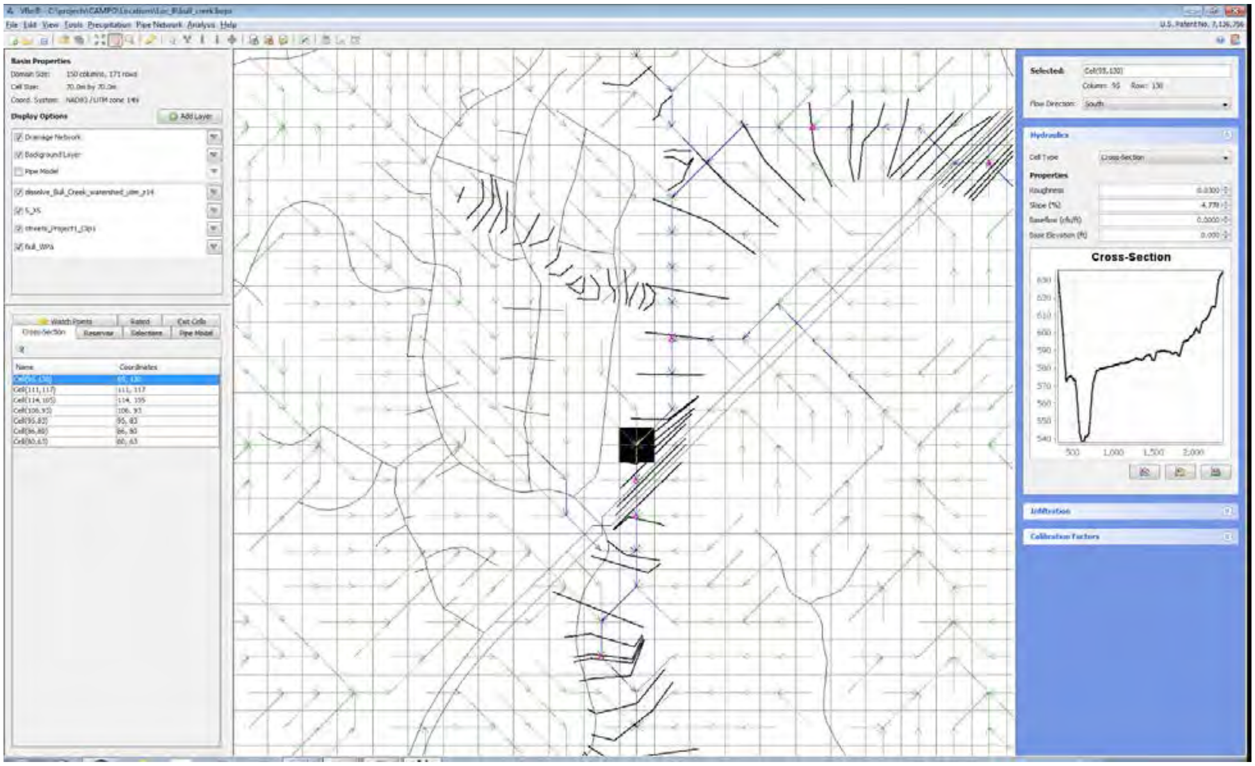


Figure 2 Bull Creek V*flo*® model showing grid connectivity (cells with arrows) and channel cross-section (right center)

Together with rainfall inputs, the model is sensitive to changes in imperviousness and rainfall intensity among other watershed and climatic characteristics. When simulating a storm event, a hypothetical depth must be given a distribution during the event that is representative of how rainfall is expected to accumulate. The form of the rainfall temporal distribution, called a hyetograph, for future climate scenarios is unknown, and therefore, a synthetic distribution is assumed. A hyetograph that is often used in sizing hydraulic infrastructure, bridges and culverts, is called the Soil Conservation Service (SCS) Type I, II, or III (see USDA SCS, 1973). For purposes of applying hyetographs with shapes appropriate to a particular regional climate, the continental U.S. was divided into three zones. The City of Austin and Travis County is in the SCS Type III zone. The hyetograph shown in Figure 3 represents the Type III incremental rainfall depth for 1 inch of rainfall. This same hyetograph is assumed in both baseline and future scenarios for consistency with typical hydraulic design of transportation infrastructure. Table 1 lists the recurrence intervals for 24-hour storm totals from the City of Austin Drainage Criteria Manual.

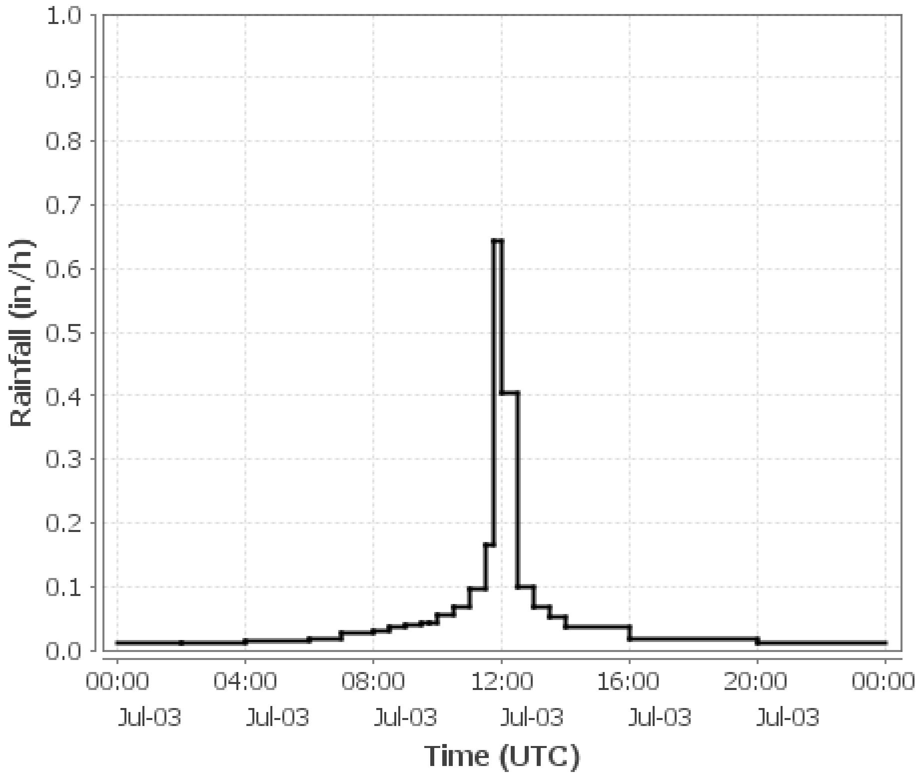


Figure 3 SCS Type III incremental rainfall distribution

Table 1 Precipitation totals and recurrence intervals for Austin and Travis County, Texas

Recurrence Interval (years)	2	2.5	5	10	25	50	100	250	500
24-hour Rainfall (inches)	3.44	3.84	4.99	6.1	7.64	8.87	10.2	12.0	13.5

Source: City of Austin Drainage Criteria Manual, Appendix B, Table 1, Depth-duration frequency of precipitation for Austin and Travis County, Texas.

Climate Scenarios

In support of this project, Dr. Cook identified the following information about changes in the intensity of the upper 1% of storms (i.e., those with extreme rainfall depths). Specifically, changes in the 99th percentile daily rainfall depths were evaluated. For three RCM scenarios, the projected increase in 99th percentile rainfall depths, referred to as the “Delta for 99th Percentile” is presented in Table 2.

Table 2 Deltas identified for each climate scenario

Scenario	Delta for 99th Percentile
1	-20%
2	+15%
3	+20%

Scenario 1 represents the climate grid containing Travis County. Scenario 2 is representative of a grid 200 km to the North. Scenario 3 is representative of a grid 200 km to the West. Scenario 3 represents the largest increase in rainfall due that could impact CAMPO transportation facilities. Scenario 3 has a projected increase of +20%, and is used to compare with the baseline case, to identify how inundation and flooding could increase under this climate change scenario.

Projected Demographic Growth and Projected Imperviousness

The projected demographic growth through 2040 was identified from CAMPO's Long-Range Regional Transportation Plan. The projected growth for the surrounding counties is shown in Table 3. The critical sites that were selected for this phase of the project are all located in Travis County. Travis County is projected to have an increase in population of 210% between 2000 and 2040. This projected increase in population is then used as a proxy for increasing the projected impervious cover for the selected sites. Therefore, the impervious cover for each of the modeled watersheds is increased by a factor of 2.1 to account for projected changes in imperviousness. Note that the imperviousness cannot increase beyond 100%, and areas with zero imperviousness are not increased. Thus, change in imperviousness amounts to areas with existing imperviousness increased by 210%.

Table 3 Projected increase in population and employment for CAMPO area for 2000 – 2040.

County	Population (2000)	Population (2040)	Percentage Increase
Bastrop	58,000	201,000	350%
Burnet	34,000	73,000	215%
Caldwell	33,000	78,000	230%
Hays	98,000	628,000	640%
Travis	812,000	1,709,000	210%
Williamson	250,000	1,407,000	560%

The projected increase in population used to estimate future imperviousness is used along with the projected climate change scenarios. Separate simulations that would isolate only the effect of imperviousness were not investigated since the primary objective is to understand the vulnerability of transportation infrastructure to climate change at critical locations.

Critical Locations

During the earlier phase of the project, nine critical locations (yellow dots) were identified within the CAMPO area depicted in Figure 4. Watershed models exist from the City of Austin FEWS for the major watersheds within the city. There are four critical locations where watershed models are available, as shown by the green dots. These four Locations, assets 2, 4, 5, and 6, were then selected for modeling in V*flo* as described in the next section on simulations.

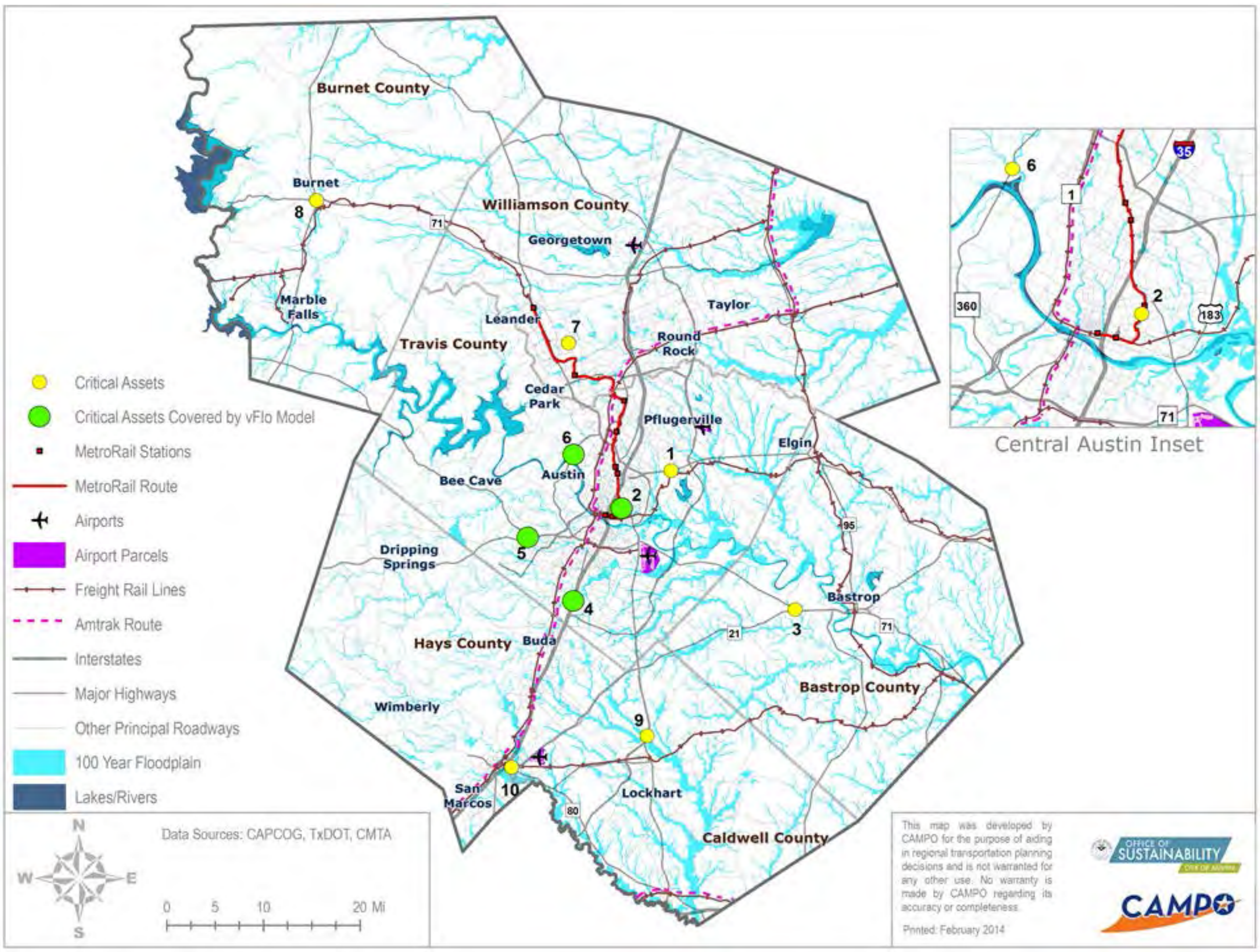


Figure 4 Geographic distribution of identified critical locations

Hydrologic Model Simulation

Hydrologic simulations were performed for the baseline and future climate scenario for each of the four assets, and for two different precipitation return frequencies that are n relevant for the assessment of transportation impacts. Table 4 provides a breakdown of the 16 total modeling scenarios that were performed. The initial saturation for each of the scenarios is assumed to be neither saturated nor completely dry, and thus set to 50%. Future watershed conditions are accounted for by projected population growth and resulting imperviousness associated with urban development. Hydrologic simulations generate distributed estimates of flood stage throughout a watershed. Then the flood stages are combined with a 10-meter resolution digital elevation model to estimate higher resolution estimates of inundation for each of the critical locations. The terrain used for modeling inundation is based on the 10-meter horizontal resolution digital elevation model obtained from TNRIS for Travis County.

Table 4 List of modeling scenarios investigated for each critical location

Critical Asset	Asset Description	Frequency Storms	Modeling Scenarios	Combination
2	MetroRail Red Line at Boggy Creek	100-year 5-year	1. Baseline 2. Scenario #3 + Imp	Baseline x 100 yr Baseline x 5 yr (Scenario #3 + Imp) x 100 yr (Scenario #3 + Imp) x 5 yr
4	I-35 at Onion Creek Parkway (study area to include Old San Antonio Road low water crossing)	50-year 100-year	1. Baseline 2. Scenario #3 + Imp	Baseline x 100 yr Baseline x 50 yr (Scenario #3 + Imp) x 100 yr (Scenario #3 + Imp) x 50 yr
5	US 290W/SH 71 – Y at Oak Hill	50-year 25-year	1. Baseline 2. Scenario #3 + Imp	Baseline x 50 yr Baseline x 25 yr (Scenario #3 + Imp) x 50 yr (Scenario #3 + Imp) x 25 yr
6	Loop 360/RM 2222	25-year 50-year	1. Baseline 2. Scenario #3 + Imp	Baseline x 25 yr Baseline x 50 yr (Scenario #3 + Imp) x 25 yr (Scenario #3 + Imp) x 50 yr

1. Baseline = frequency depth based on past climate plus impervious from 2001
2. imp = future impervious based on increases based on projected county increase in population

Results of the simulations are arranged for each of the four critical assets in the Appendix, consisting of inundation maps; tables summarizing hydrologic and hydraulic results from each simulation; hydrographs showing depth and discharge for baseline and future scenarios; and tabular summaries of model parameter statistics for each of the locations under baseline and future development scenarios.

A sample inundation map is presented in Figure 5, which shows an example of an inundation map for Location 4 within the Onion Creek watershed for the 100-yr event. The blue outline shows the baseline inundation extent and the red outline shows the projected inundation extent resulting from the combination of an increase in rainfall intensity and impervious cover.

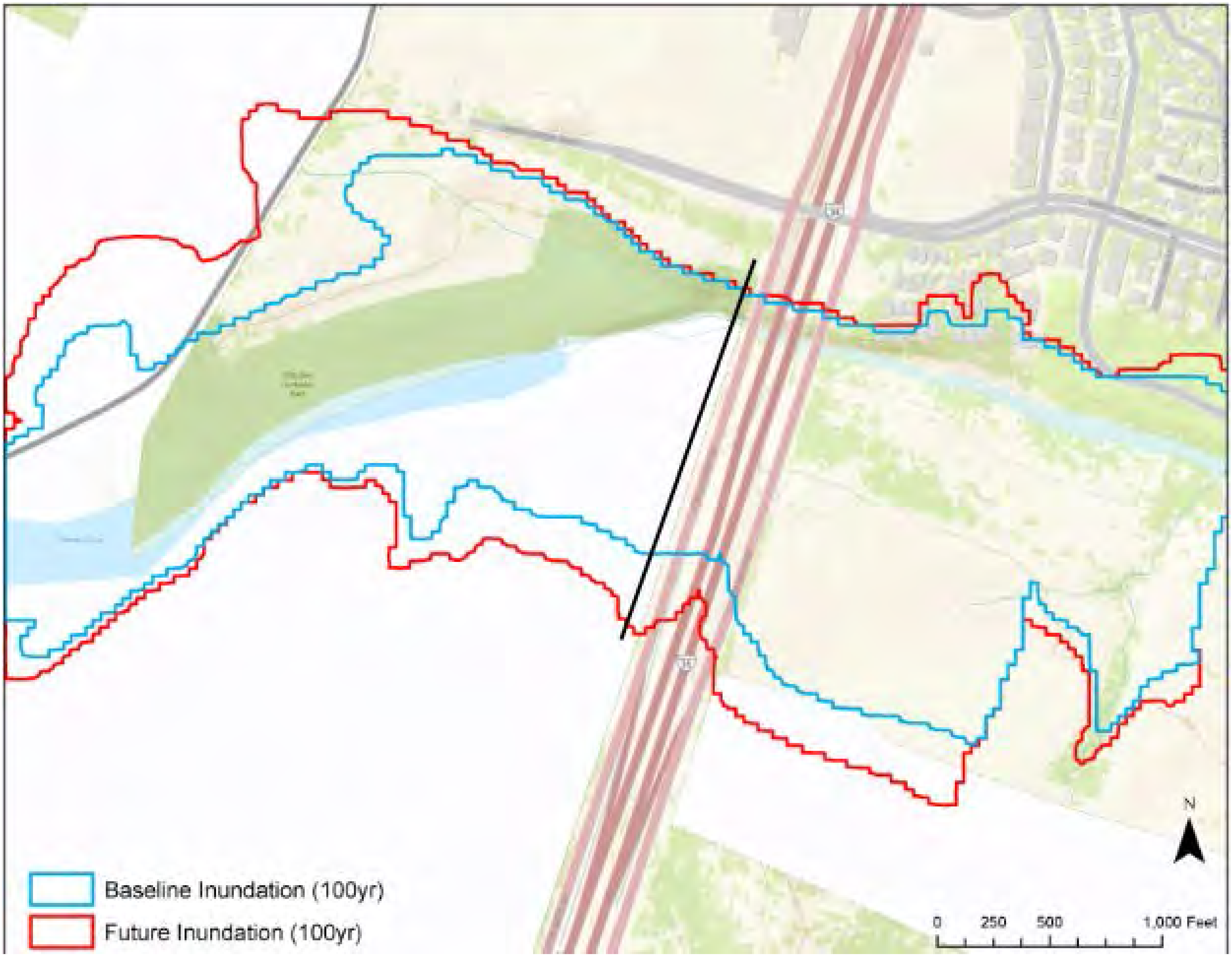


Figure 5 Example inundation map for Location 4 within the Onion Creek watershed. The black line shows where the measurement was taken for top width.

An example table for the hydrologic and hydraulic data is shown in Table 5. Top width referred to in the table represents the change in the inundation extent upstream of I-35. For this location, the inundation top width increased by 220 feet for the 50-year event and 357 feet for the 100-year event future scenario is compared with the respective baseline conditions. Similarly, the peak flow rate increased by 22,000 cubic feet per second (cfs) for the 50-year event and 26,400 cfs for the 100-year event. The results presented as column headings in Table 5 have the following significance:

- Top Width - a measure of inundation extent under assumed scenarios/conditions at the selected location;
- Flow Rate - volume of runoff per unit time or discharge associated with a given rainfall depth and temporal distribution modeled using watershed characteristics including imperviousness;
- Depth - maximum depth of flow or stage simulated at the selected location;
- Average Velocity - the flow rate divided by the cross-sectional area (see following column); and

- Cross-sectional Area - area measured vertically at the location and in a direction that is transverse to flow and representing the area occupied by the flow or discharge.

Table 5 Hydrologic and hydraulic simulation summary for Location 4

Location	Simulation	Top Width (ft)	Flow Rate (cfs)	Depth (ft)	Average Velocity (ft/s)	Cross-Sectional Area (sq. ft.)
4	Baseline x 50 yr	1097	51,500	25.1	5.7	9,005
4	Baseline x 100 yr	1242	67,950	28.5	6.0	11,392
4	[Scenario #3 + Imp] x 50 yr	1317	73,500	29.6	6.0	12,187
4	[Scenario #3 + Imp] x 100 yr	1599	94,350	33.0	6.3	15,089

Hydrographs were also generated for each of the simulations at the critical locations. Figure 6 shows an example of the stage and discharge hydrographs to compare the future (blue) and baseline (red) conditions. The stage is related to the discharge by the hydraulics at the cross-section where these hydrographs were modeled. The stage is an indication of how deep the water will be at that location under the assumed conditions and climate scenarios. The most important difference between these hydrographs is the increase in both peak stage and discharge for the future and baseline conditions. The blue line is the *future* estimate of the impact from climate change, corresponding to the 20% increase in rainfall depths under Scenario 3.

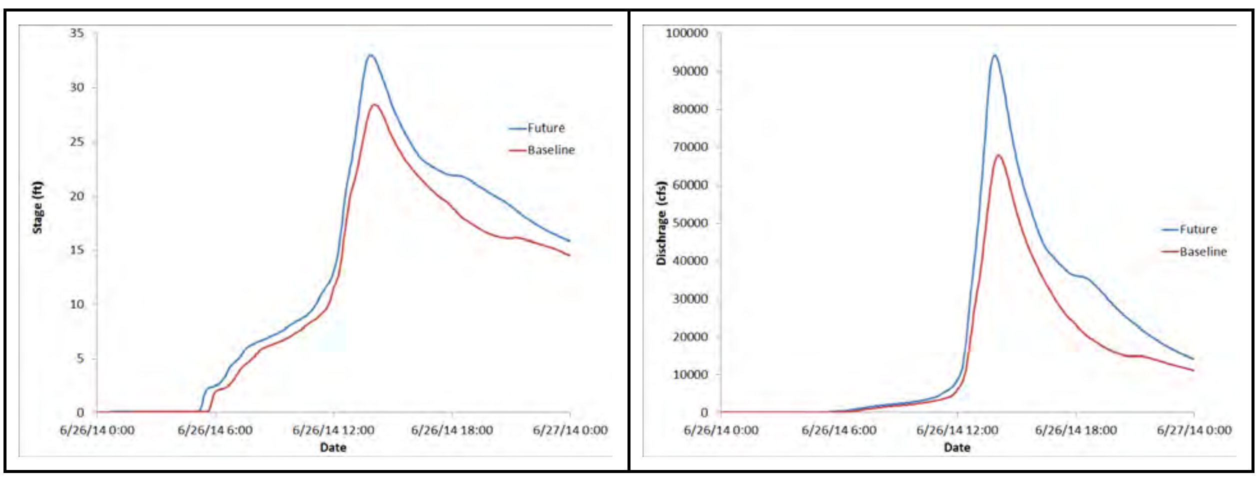


Figure 6 Comparison of stage and discharge for Location 4 for 100-yr event

Results

The model parameters listed for each location under baseline and future conditions have the following interpretation:

- Roughness - hydraulic parameter used to control flow depth and velocity for various surfaces, such as concrete that ranges 0.012-0.015 or grass 0.04-0.10
- Slope (%) - hydraulic parameter of overland areas or channels used to control flow depth and velocity of runoff
- Hydraulic Conductivity (in/h) - soil infiltration parameter used to represent saturated rates of vertical water movement
- Wetting Front (in) - soil infiltration parameter used that increases the rate of infiltration when soils are dry and less than saturated
- Porosity - the air volume contained in pores for a given volume of soil
- Soil Depth (in) - thickness of the soil profile
- Initial Saturation - volumetric water content representing soil wetness that can range from 0-100%
- Imperviousness - percentage of impervious cover within a model cell that ranges from 0-100%
- Abstraction (in) - depressional volume of the soil surface that must be filled before runoff can begin
- Channel Width (ft) - geometric property of a channel cell represented by a trapezoidal shape used as a hydraulic property for routing flow downstream
- Channel Side Slope - geometric property that is the slope of the channel sides expressed as a horizontal to vertical (H:V) ratio

Critical Asset 2: MetroRail Red Line at Boggy Creek

Figure A-1 Inundation extent for baseline (blue) and future (red) 5-yr event at Location 2.

Figure A-2 Inundation extent for baseline (blue) and future (red) 100-yr event at Location 2.

Table A-1 Hydrologic and hydraulic simulation summary for Location 2

Location	Simulation	Top Width (ft)	Flow Rate (cfs)	Depth (ft)	Avg. Velocity (ft/s)	Cross Sectional Area (sq. ft.)
2	Baseline x 5 yr	701	1,500	5.0	2.8	534
2	Baseline x 100 yr	918	4,040	9.7	2.1	1,898
2	[Scenario #3 + Imp] x 5 yr	806	2,330	7.7	2.3	1,021
2	[Scenario #3 + Imp] x 100 yr	952	5,720	10.9	2.0	2,831

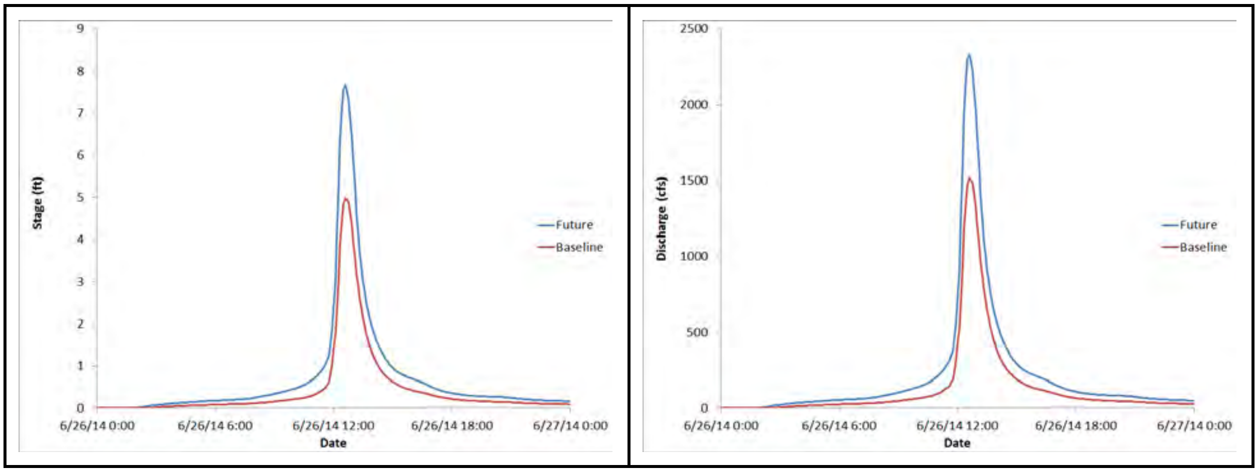


Figure A-3 Comparison of stage and discharge for Location 2 for 5-yr event

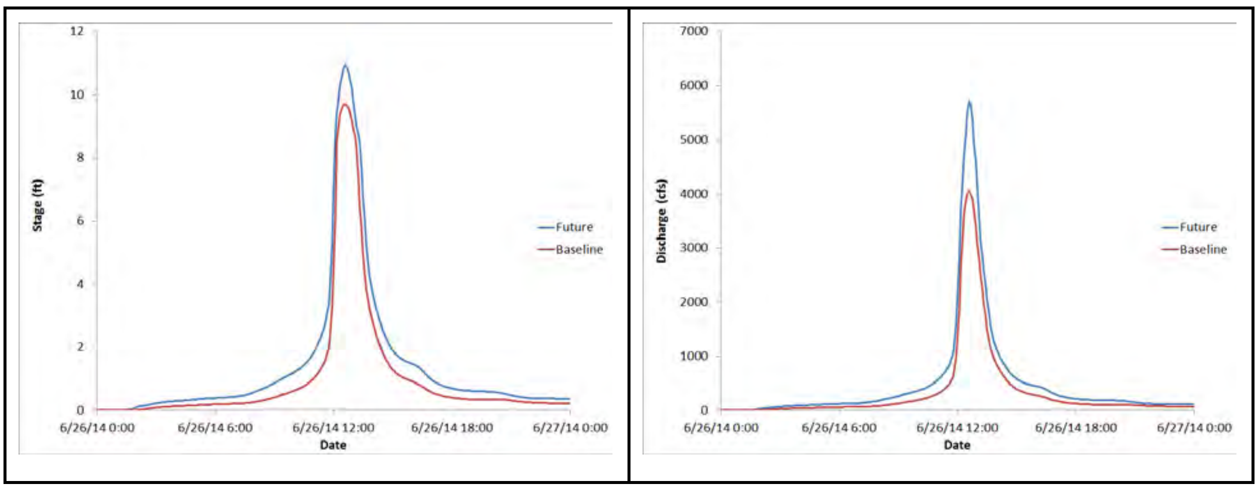


Figure A-4 Comparison of stage and discharge for Location 2 for 10-yr event

Table A-2 Baseline model parameters for Location 2

	Minimum	Mean	Maximum
Roughness	0.010	0.035	0.070
Slope (%)	0.1	2.3	9.6
Hydraulic Conductivity (in/h)	0.0	0.6	2.3
Wetting Front (in)	0	28	45
Porosity	0.00	0.22	0.30
Soil Depth (in)	36	72	79
Initial Saturation	0.5	0.5	0.5
Imperviousness	0.03	0.28	0.83
Channel Width (ft)	15.83	20.48	25.85
Channel Side Slope	2	2	2

Table A-3 Future model parameters for Location 2

	Minimum	Mean	Maximum
Roughness	0.01	0.04	0.07
Slope (%)	0.1	2.3	9.6
Hydraulic Conductivity (in/h)	0	0.56	2.28
Wetting Front (in)	0	28.01	45.24
Porosity	0	0.22	0.3
Soil Depth (in)	35.8	72.3	78.7
Initial Saturation	0.5	0.5	0.5
Imperviousness	0.06	0.58	1
Abstraction (in)	0	0	0
Channel Width (ft)	15.83	20.48	25.85
Channel Side Slope	2	2	2

Critical Asset 4: I-35 at Onion Creek Parkway

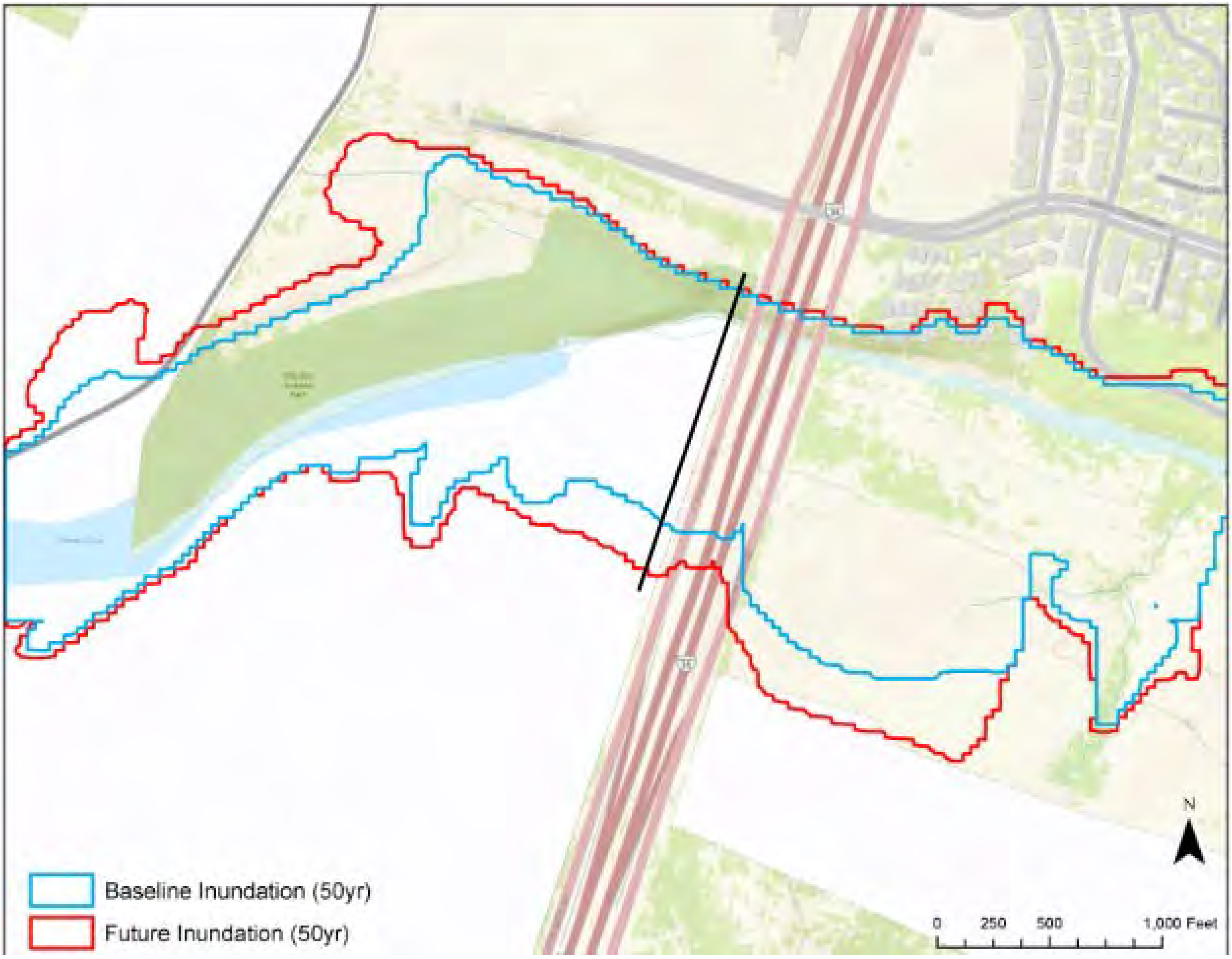


Figure B-1 Inundation extent for baseline (blue) and future (red) 50-yr event at Location 4.

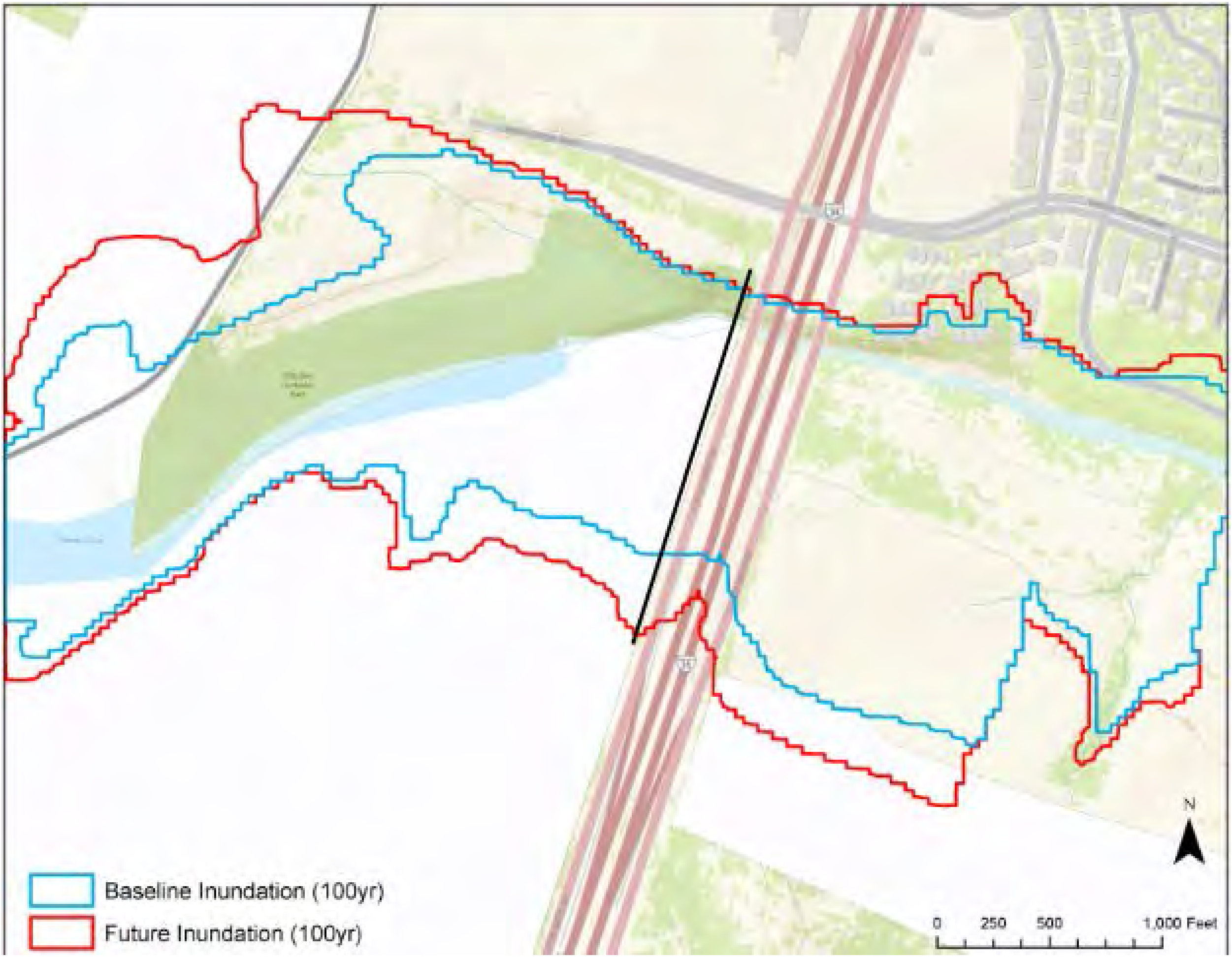


Figure B-2 Inundation extent for baseline (blue) and future (red) 100-yr event at Location 4.

Table B-1 Hydrologic and hydraulic simulation summary for Location 4

Location	Simulation	Top Width (ft)	Flow Rate (cfs)	Depth (ft)	Avg. Velocity (ft/s)	Cross Sectional Area (sq. ft.)
4	Baseline x 50 yr	1097	51,500	25.1	5.7	9,005
4	Baseline x 100 yr	1242	67,950	28.5	6.0	11,392
4	[Scenario #3 + Imp] x 50 yr	1317	73,500	29.6	6.0	12,187
4	[Scenario #3 + Imp] x 100 yr	1599	94,350	33.0	6.3	15,089

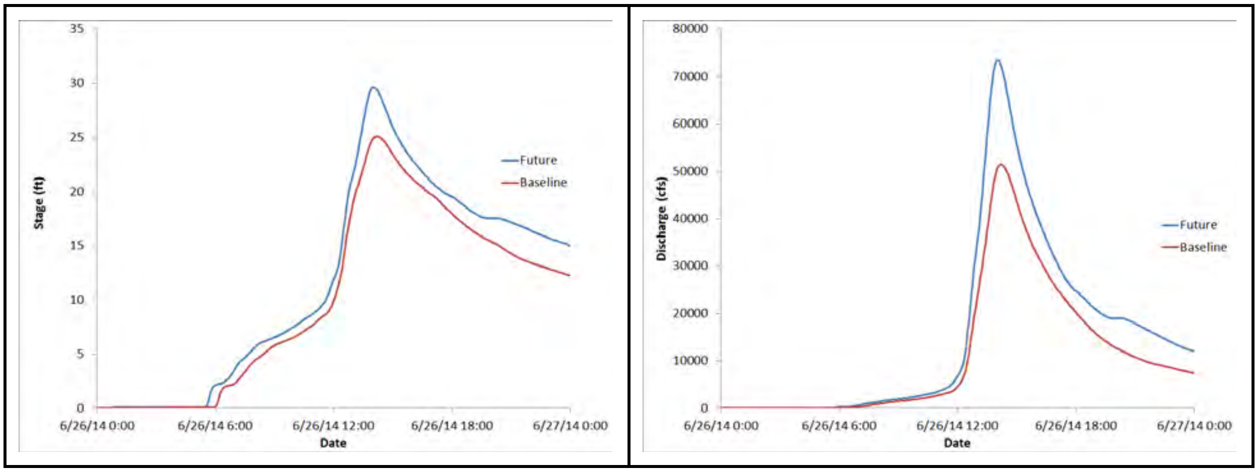


Figure B-3 Comparison of stage and discharge for Location 4 for 50-yr event

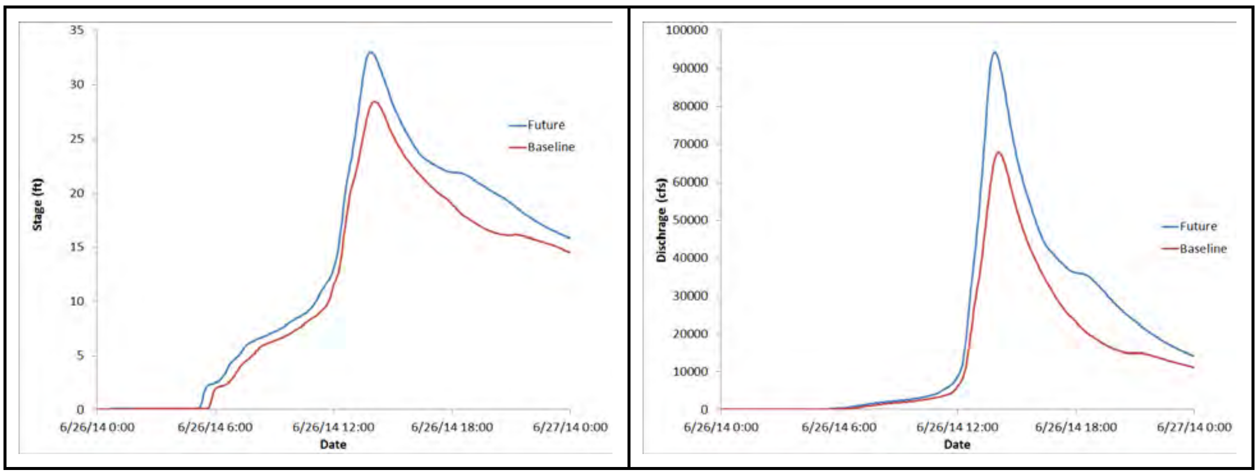


Figure B-4 Comparison of stage and discharge for Location 4 for 100-yr event

Table B-2 Baseline model parameters for Location 4

	Minimum	Mean	Maximum
Roughness	0.012	0.092	0.300
Slope (%)	0.1	4.9	43.8
Hydraulic Conductivity (in/h)	0.0	1.0	33.8
Wetting Front (in)	0	26	45
Porosity	0.00	0.24	0.38
Soil Depth (in)	4	50	272
Initial Saturation	0.5	0.5	0.5
Imperviousness	0	0.01	1
Channel Width (ft)	19.46	41.35	93.49
Channel Side Slope	1	3	3

Table B-3 Future model parameters for Location 4

	Minimum	Mean	Maximum
Roughness	0.01	0.09	0.30
Slope (%)	0.1	4.9	43.8
Hydraulic Conductivity (in/h)	0	0.98	33.81
Wetting Front (in)	0	25.8	45.47
Porosity	0	0.24	0.38
Soil Depth (in)	3.6	49.6	272.3
Initial Saturation	0.5	0.5	0.5
Imperviousness	0	0.02	1
Abstraction (in)	0	0	0
Channel Width (ft)	19.46	41.35	93.49
Channel Side Slope	1	3	3

Critical Asset 5: US 290W/SH 71 – Y at Oak Hill

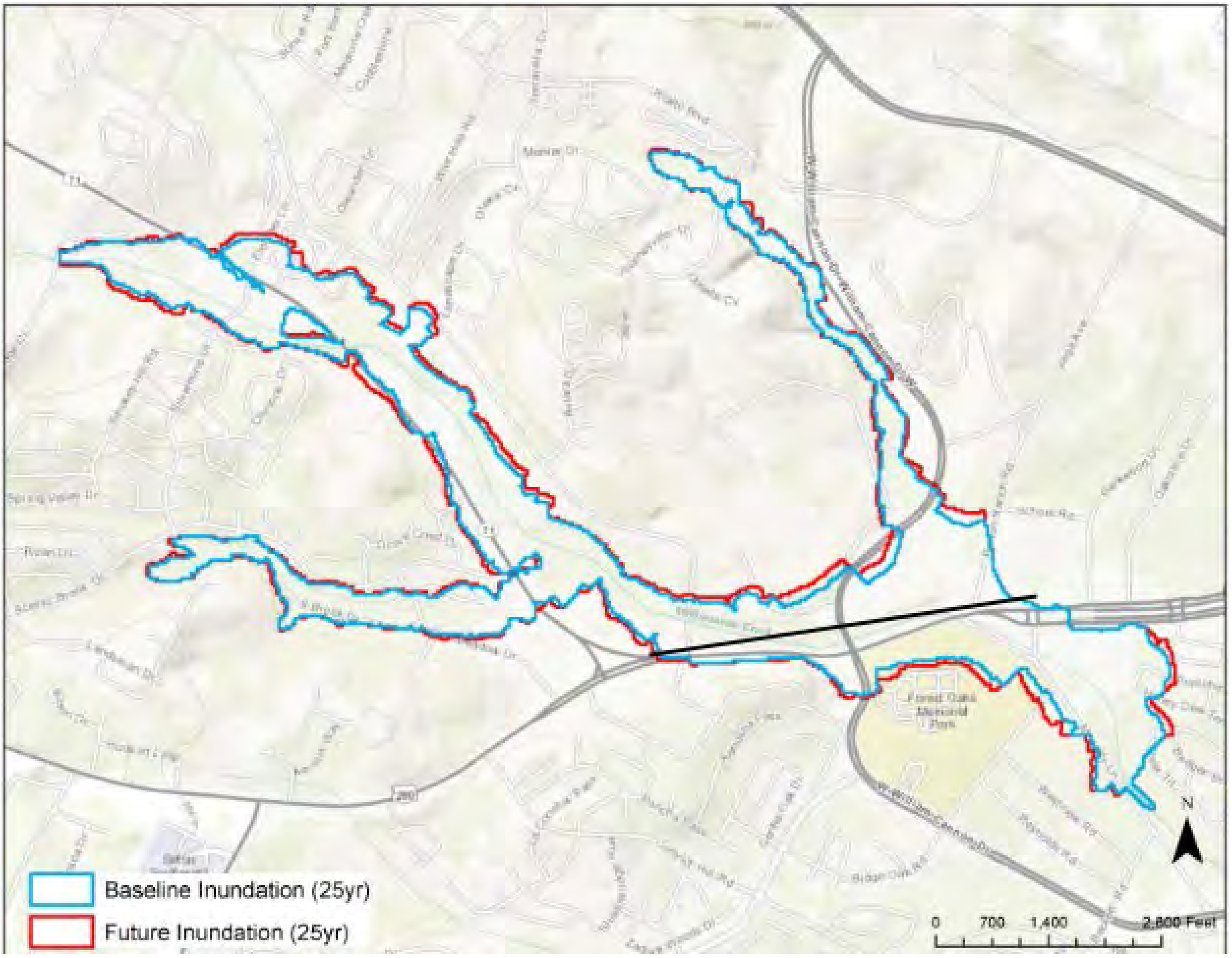


Figure C-1 Inundation extent for baseline (blue) and future (red) 25-yr event at Location 5.

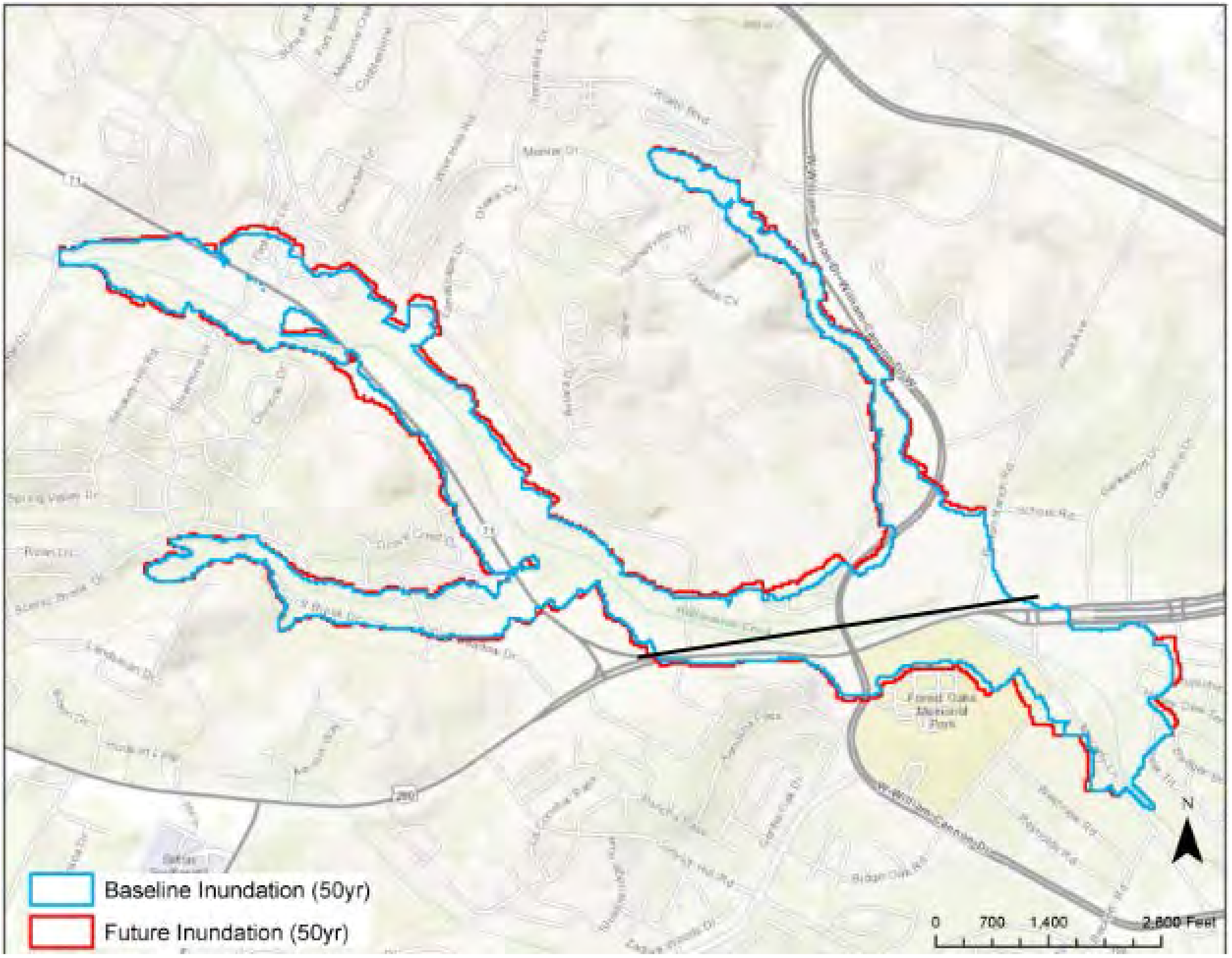


Figure C-2 Inundation extent for baseline (blue) and future (red) 50-yr event at Location 5.

Table C-1 Hydrologic and hydraulic simulation summary for Location 5

Location	Simulation	Roadway Inundation Length for Highway 290 (ft)	Flow Rate (cfs)	Depth (ft)	Avg. Velocity (ft/s)	Cross Sectional Area (sq. ft.)
5	Baseline x 25 yr	5076	3,500	8.0	4.7	745
5	Baseline x 50 yr	5156	4,400	9.0	4.8	932
5	[Scenario #3 + Imp] x 25 yr	5194	4,700	9.3	4.7	998
5	[Scenario #3 + Imp] x 50 yr	5267	5,870	9.9	4.6	1,272

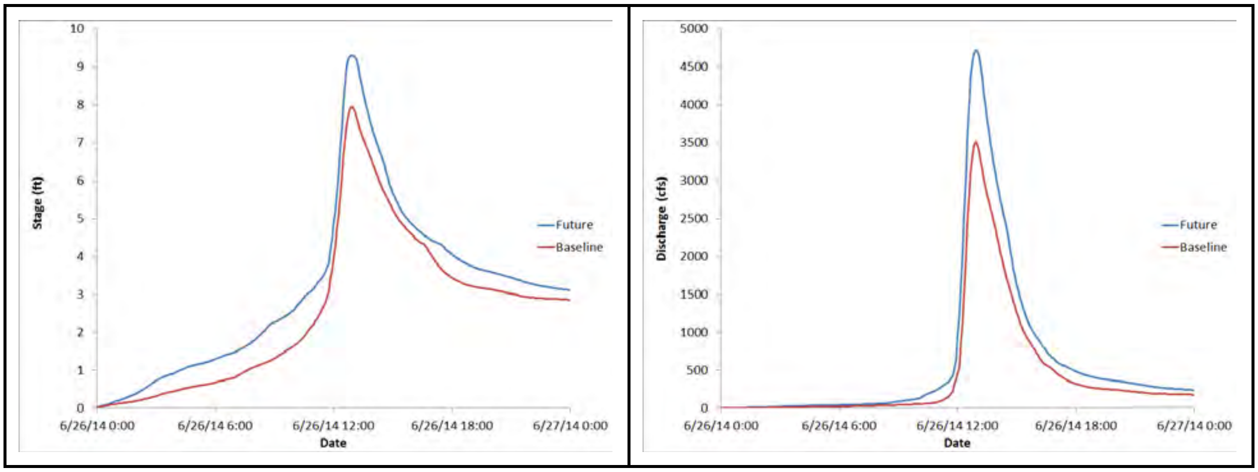


Figure C-3 Comparison of stage and discharge for Location 5 for 25-yr event

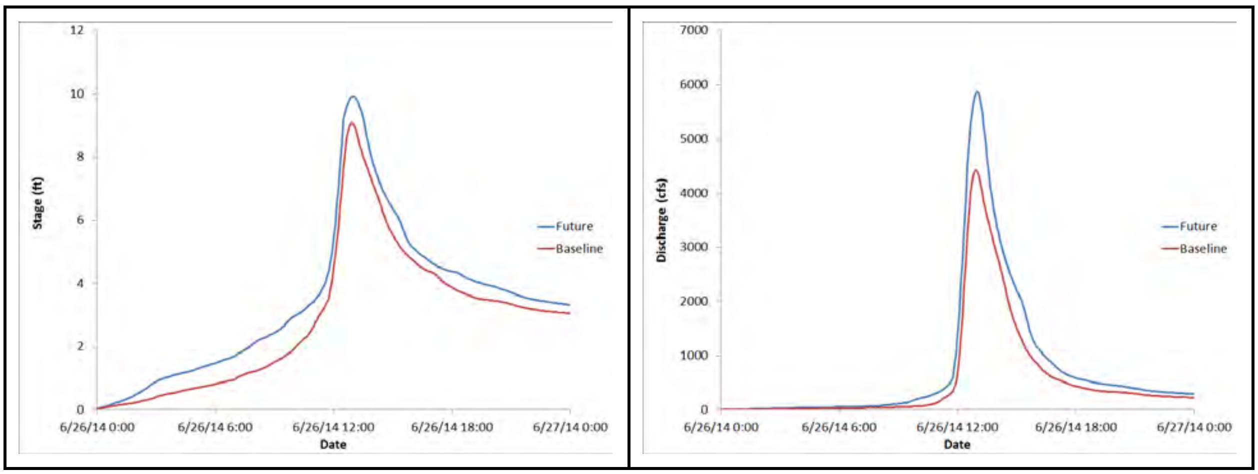


Figure C-4 Comparison of stage and discharge for Location 5 for 5-yr event

Table C-2 Baseline model parameters for Location 5

	Minimum	Mean	Maximum
Roughness	0.027	0.126	0.223
Slope (%)	0.4	4.1	11.4
Hydraulic Conductivity (in/h)	0.0	0.2	2.1
Wetting Front (in)	0	32	48
Porosity	0.00	0.26	0.40
Soil Depth (in)	0	30	101
Initial Saturation	0.5	0.5	0.5
Imperviousness	0	0.1	1
Channel Width (ft)	1.78	3.34	12.59
Channel Side Slope	1	1	1

Table C-3 Future model parameters for Location 5

	Minimum	Mean	Maximum
Roughness	0.03	0.13	0.22
Slope (%)	0.4	4.1	11.4
Hydraulic Conductivity (in/h)	0	0.16	2.06
Wetting Front (in)	0	31.53	48.31
Porosity	0	0.26	0.4
Soil Depth (in)	0	30.1	100.6
Initial Saturation	0.5	0.5	0.5
Imperviousness	0	0.21	1
Abstraction (in)	0	0	0
Channel Width (ft)	1.78	3.34	12.59
Channel Side Slope	1	1	1

Critical Asset 6: Loop 360/RM 2222

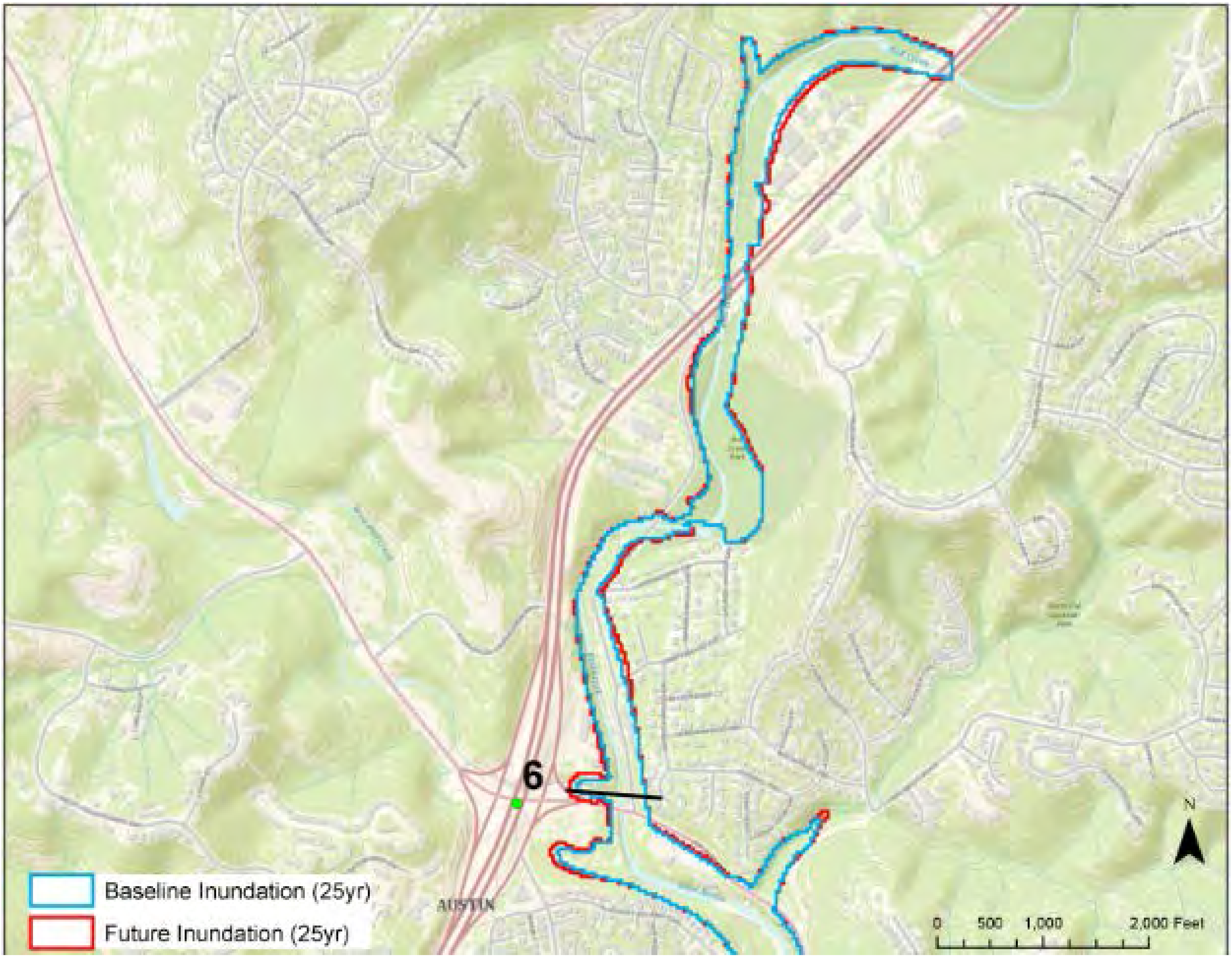


Figure D-1 Inundation extent for baseline (blue) and future (red) 25-yr event at Location 6.

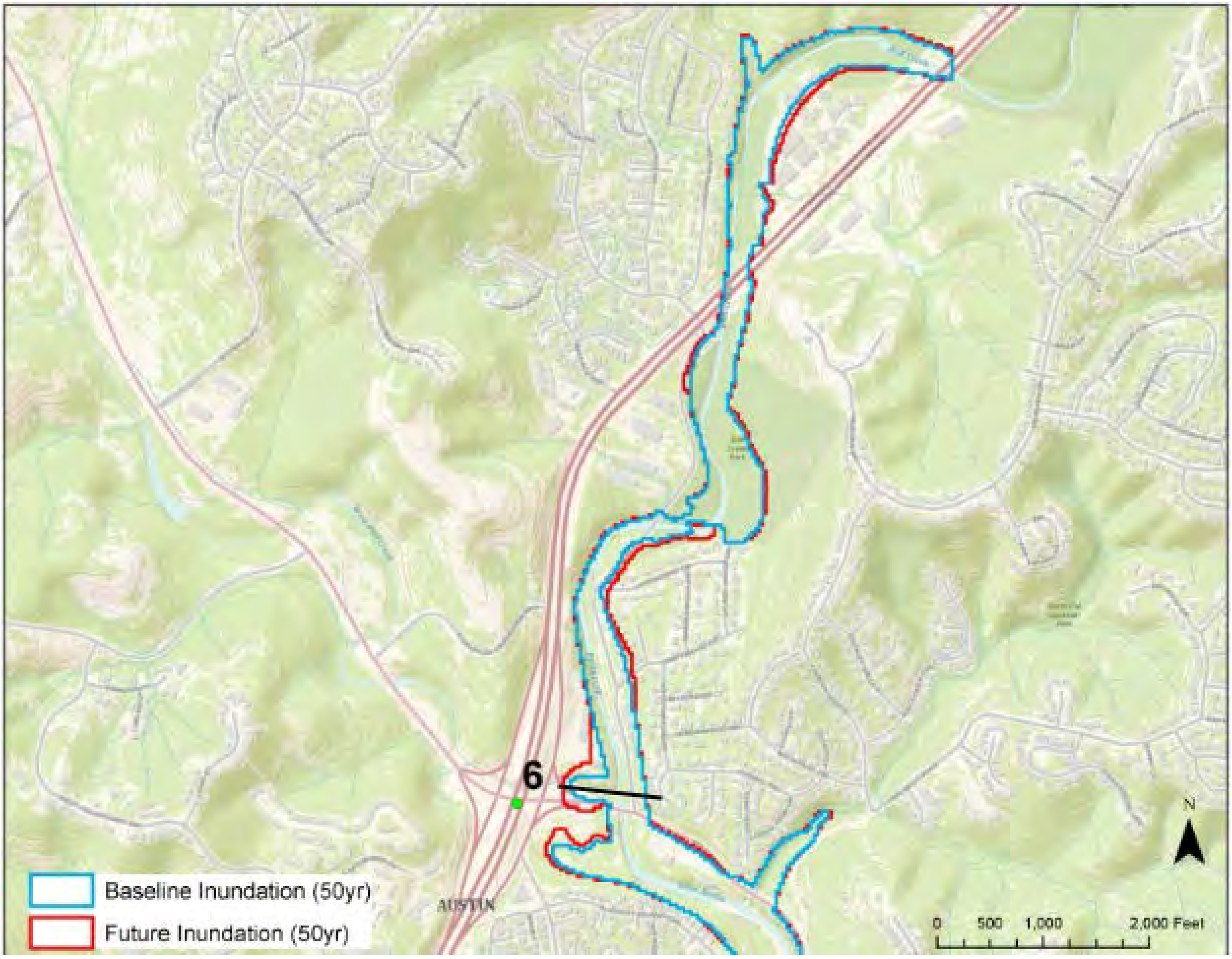


Figure D-2 Inundation extent for baseline (blue) and future (red) 50-yr event at Location 6.

Table D-1 Hydrologic and hydraulic simulation summary for Location 6

Location	Simulation	Top Width (ft)	Flow Rate (cfs)	Depth (ft)	Avg. Velocity (ft/s)	Cross Sectional Area (sq. ft.)
6	Baseline x 25 yr	662	8,500	10.9	7.4	1,150
6	Baseline x 50 yr	720	12,100	14.6	6.4	1,890
6	[Scenario #3 + Imp] x 25 yr	723	13,100	15.6	6.2	2,110
6	[Scenario #3 + Imp] x 50 yr	782	18,100	19.1	6.4	2,850

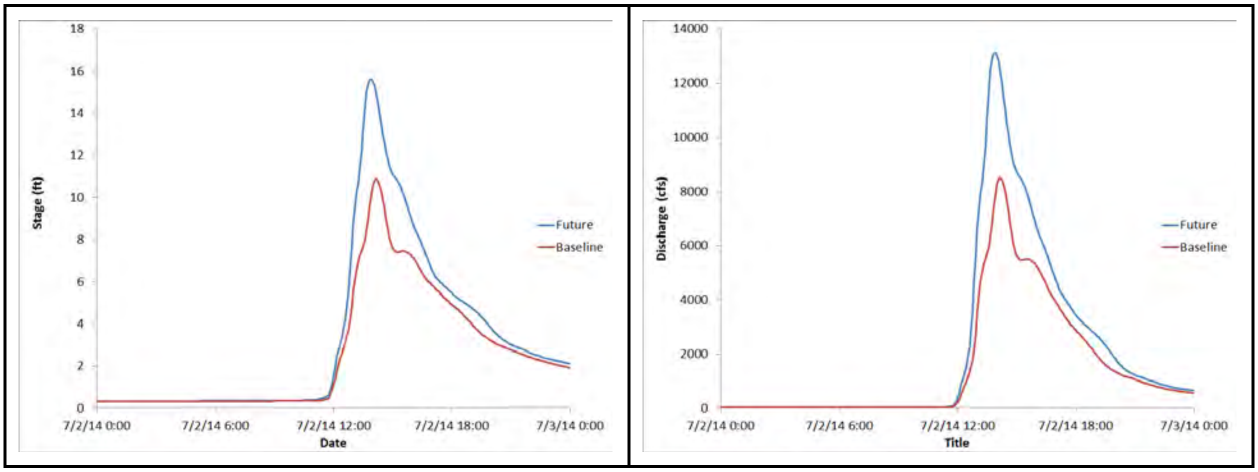


Figure D-3 Comparison of stage and discharge for Location 6 for 25-yr event

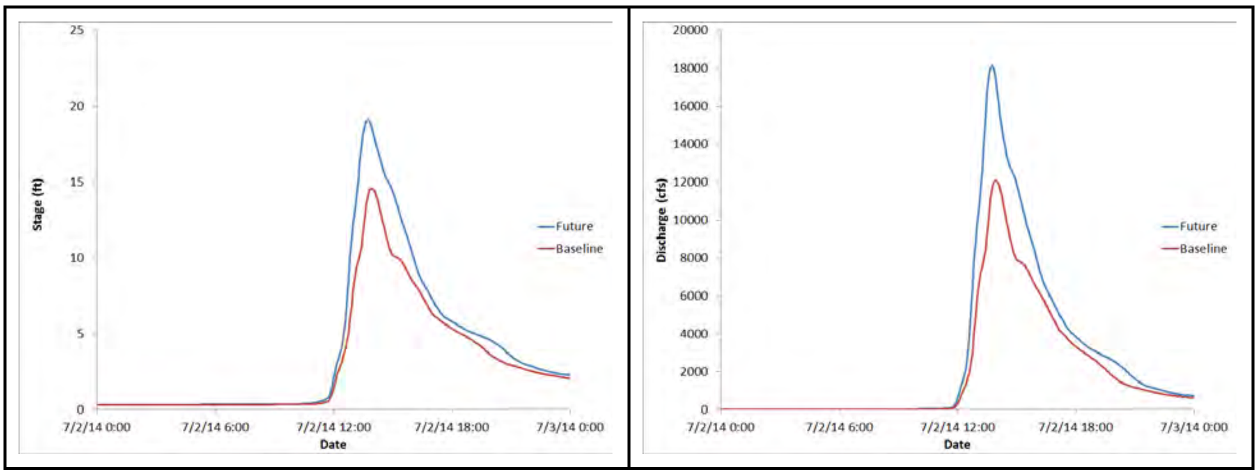


Figure D-4 Comparison of stage and discharge for Location 6 for 50-yr event

Table D-2 Baseline model parameters for Location 6

	Minimum	Mean	Maximum
Roughness	0.011	0.051	0.140
Slope (%)	0.0	10.3	58.8
Hydraulic Conductivity (in/h)	0.0	0.3	1.1
Wetting Front (in)	0	29	48
Porosity	0.00	0.25	0.30
Soil Depth (in)	18	87	91
Initial Saturation	0.5	0.5	0.5
Imperviousness	0	0.01	0.07
Channel Width (ft)	15.63	29.12	65.37
Channel Side Slope	1	15.24	19.78

Table D-3 Future model parameters for Location 6

	Minimum	Mean	Maximum
Roughness	0.01	0.05	0.14
Slope (%)	0.0	10.3	58.8
Hydraulic Conductivity (in/h)	0	0.33	1.06
Wetting Front (in)	0	29.39	48.31
Porosity	0	0.25	0.3
Soil Depth (in)	18.3	86.8	91.4
Initial Saturation	0.5	0.5	0.5
Imperviousness	0	0.02	0.15
Abstraction (in)	0	0	0
Channel Width (ft)	15.63	29.1	65.37
Channel Side Slope	9.47	15.29	19.78

Summary

Baseline and future climate scenarios were modeled for four critical locations. The projected risk of inundation is measured by increases in discharge and related hydraulic characteristics of stage, i.e., width, cross-sectional area, and velocity. The model simulations consist of baseline and assumed imperviousness conditions representing 2001; whereas, the future climate scenario imperviousness is based on estimated population growth associated with 2040. Projected imperviousness by itself resulted in a relatively smaller increase in flooded extent than changes to the projected rainfall intensity associated with Scenario 3. Therefore, only the combination of projected rainfall *and* imperviousness is considered.

For the +20% projected increase in rainfall under climate Scenario 3, the increase in flooding can be more than the percentage increase associated with the rainfall input. This is due to the nonlinear response of runoff simulated by hydrologic models where the proportional increase in output is greater than the increase in the input, rainfall. This nonlinear increase is evidenced by the larger-than-20% increases in response of each watershed for the storms simulated.

The range in peak discharge increases from 33% at Location 5 for the 50-year, and as much as 55% for Location 2 for the 5-year. The response measured in terms of peak stage is more varied than for discharge since stage is a function of both the discharge and the geometry of the stream channel and its associated hydraulics. For example, Location 2 is projected to experience a 12% increase in depth associated with the 100-year event, but a 54% increase at the 5-year rainfall event. Similar to peak stage (depth), the increases in inundation extent measured at selected cross-sections, and range from 2% to 29%. The width of inundated area is dependent on the location selected to measure the width to some extent. From the mapped inundation, some locations have virtually no increase in the area or width as evidenced by the two lines (baseline and future) that overlay each other in Figure 5 above and in the Appendix. Table 6 presents these increases for each storm simulated. Each of the critical locations modeled has two rows that are associated with the percentage increase for a given storm event return frequency. The increase between baseline and future climate is expressed as a percentage increase over baseline conditions.

Table 6 Relative increases in hydrologic and hydraulic response for Locations 2, 4, 5, and 6

Location	Storm Event	Flow Rate	Depth
2	5-yr	55%	54%
2	100-yr	42%	12%
4	50-yr	43%	18%
4	100-yr	39%	16%
5	25-yr	34%	16%
5	50-yr	33%	10%
6	25-yr	54%	43%
6	50-yr	50%	31%

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C. Appendix: Criticality Screening

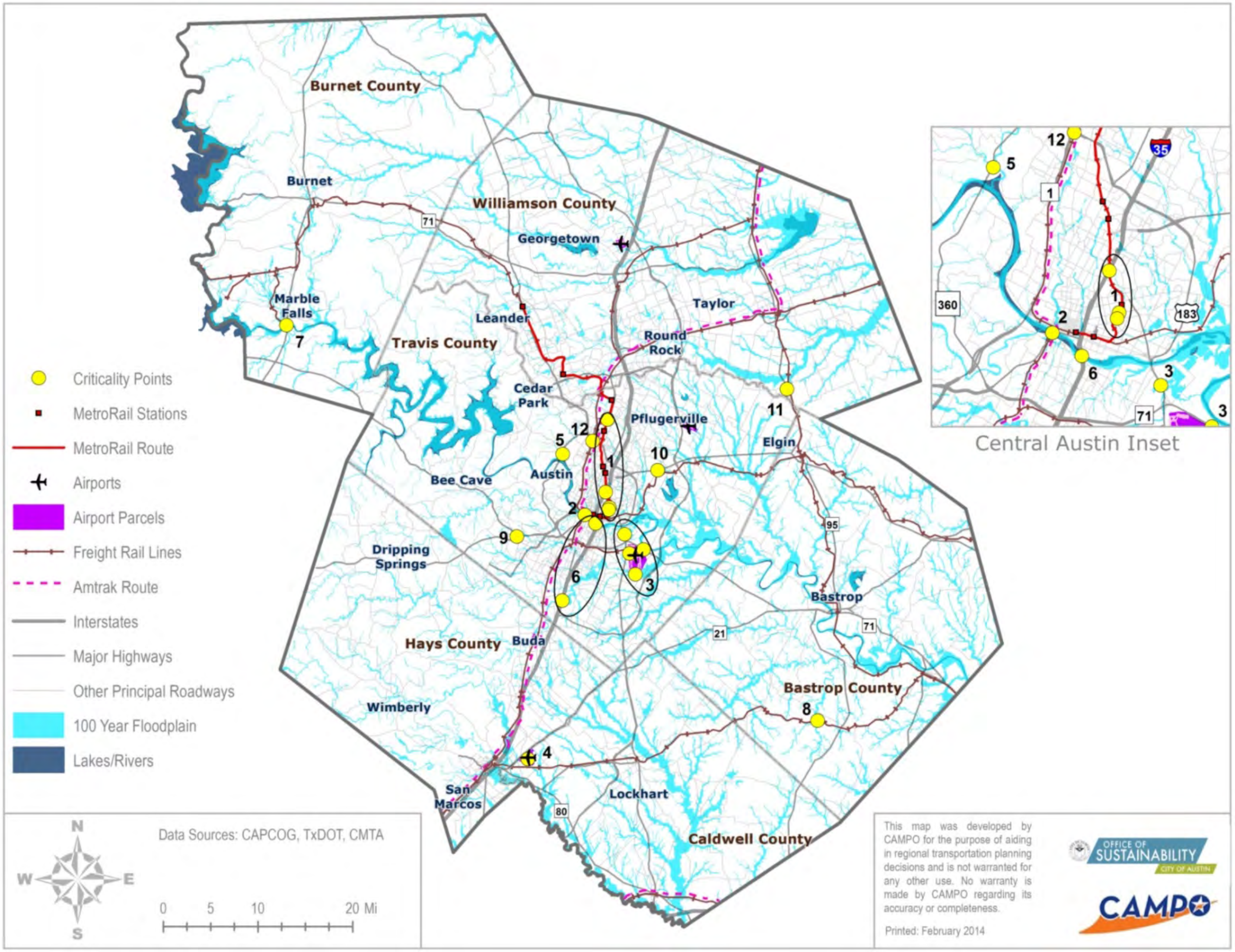
Critical Transportation Asset Vote Clusters

ID	Cluster Description	Why Critical?	Why Vulnerable?
1	MetroRail Red Line (specific locations include Parmer/Mopac, Airport Blvd/I-35, east of I-35 adjacent to Boggy Creek)	Commuter rail for downtown and northwest	Adjacent to floodplains (Walnut Creek, Boggy Creek)
2	Union Pacific (UP) Railroad – Colorado River crossing	Key river crossing/connection for freight and traffic/mobility	Flooding
3	Highway access to Austin-Bergstrom International Airport (ABIA) (specific connections include SH 71E, US 183, Burleson Road at Emma Browning Ave.)	Major international airport for the region, supports local economy, police/emergency helicopter air support, hurricane evacuation route (SH71)	Clay soils (drought), erosion, river crossings (flooding)
4	San Marcos Airport	Support local economy, provides redundancy to ABIA in case of emergency	Flooding, severe weather
5	Loop 360/RM 2222	Major east-west corridor	Flooding (Bull Creek), wildfire
6	I-35 (specific locations include Colorado River crossing, Onion Creek, low water crossing on Old San Antonio road adjacent to I-35)	NAFTA highway, highest volume route, connects cities, military corridor	Flooding, clay soils (drought)
7	US 281 in Marble Falls (Colorado River crossing)	Population/employment connections, regional access, no redundancies	Icing/winter weather, river crossing
8	UP Railroad in Bastrop County (southwest of Smithville)	Heavy freight traffic	Flooding (past incidents), erosion
9	US 290W/SH 71 – Y at Oak Hill	Heavily used roadway into and out of Austin, provides connectivity west of Austin	Flooding (Williamson Creek), wildfire
10	US 290E at Johnny Morris Road	Heavily used roadway into and out of Austin, Hurricane evacuation route, access to gas/fuel distribution facility	Clay soil, potential flooding
11	Hwy 95 near Brushy Creek	Military access, energy security (ERCOT), eastern connectivity	Wildfire, clay soil, flooding
12	US 183/Mopac Interchange	North-South Mobility, connectivity to northwest population and employment	Freezing precipitation

Criticality Cluster Evaluation Matrix

ID	Criticality Cluster Description	County	Mode	Potential Vulnerabilities	AADT	Soil Plasticity	Proximity to 100-Year Floodplain	Evacuation Route?
1	MetroRail Red Line (specific locations include Parmer/Mopac, Airport Blvd/I-35, east of I-35 adjacent to Boggy Creek)	Travis	Commuter Rail	Flooding, clay soils (drought)	120,000 @ Mopac, 215,000 @ I-35	Varies Moderate to High	Varies by location: 0 to 2,200 ft.	No
2	Union Pacific (UP) Railroad – Colorado River crossing	Travis	Freight Rail, Passenger Rail	Flooding	N/A	Low	0 ft.	No
3	Highway access to Austin-Bergstrom International Airport (ABIA) (specific connections include SH 71E, US 183, Burleson Road at Emma Browning Ave.)	Travis	Road	Clay soils (drought), erosion, flooding	400 @ Burleson Road, 87,000 @ SH 71E	Varies Low to High	Varies by location: 0 to 1,900 ft.	Yes
4	San Marcos Airport	Caldwell	Air	Flooding, severe weather	N/A		0 to 6,000 ft.	No
5	Loop 360/RM 2222	Travis	Road	Flooding, wildfire	40,000 (Loop 360)	Moderate	100 ft.	No
6	I-35 (specific locations include Colorado River crossing, Onion Creek)	Travis	Road	Flooding, clay soils (drought)	186,000	Low	0 ft.	No
7	US 281 in Marble Falls (Colorado River crossing)	Burnet	Road	Flooding, freezing precipitation	24,000	Low	0 ft.	No
8	UP Railroad in Bastrop County (southwest of Smithville)	Bastrop	Freight Rail	Flooding, erosion	N/A		0 ft.	No
9	US 290W/SH 71 – Y at Oak Hill	Travis	Road	Flooding, wildfire	38,000 (US 290W), 25,000 (SH 71)	Moderate	600 ft.	No
10	US 290E at Johnny Morris Road	Travis	Road	Flooding, clay soil (drought)	38,000	High	2,800 ft.	Yes
11	Hwy 95	Williamson	Road	Wildfire, clay soil (drought), flooding	4,300	Clay	1,000 ft.	No
12	US 183/Mopac Interchange	Travis	Road	Freezing precipitation	178,000 (US 183), 120,000 (Mopac)	Moderate	0 ft.	No

Critical Asset Clusters



D. Appendix: VAST Assessments

D.1 Asset #2. MetroRail Red Line at Boggy Creek

Adaptive Capacity

The Red Line at Boggy Creek received a VAST adaptive capacity rating of 1.5, meaning the region possesses relatively high capacity to adapt to temporary disruption of the asset. This rating is based on the fact that Capital Metro can provide bus service to replace the Red Line if necessary.

Flooding

Exposure

The MetroRail Red Line at Boggy Creek is expected to have high exposure to floods. The segment sits in the 100-year floodplain of Boggy Creek and would be inundated by just under one foot of water under today's 100-year rain event (8.87 inches of rain in 24 hours). If heavy rain events become more intense and frequent as projected, this segment would be inundated by 2 feet of water under the future 100-year rain event. The asset is also located about 2.6 feet above the 100-year FEMA floodplain. The estimated maximum flood extents for the 100-year rain events (present-day and future) are shown in Figure D-1, with the flood depths along the green cross-section shown in Figure D-2. The Red Line flooded during the Halloween Floods of 2013 and during Tropical Storm Hermine in 2010, when the area received more than five inches of rain in 24 hours.

Further, stakeholders indicate that the Red Line at Boggy Creek experiences flooding even under less extreme rainfall amounts, estimating that the frequency of washouts is 2-3 times per year.

Sensitivity

The MetroRail Red Line at Boggy Creek has high sensitivity to flooding. When it floods, the line may wash out and cause 1-2 days of delays while Capital Metro makes repairs. In heavier rain events, the Boggy Creek bridge experiences scour from increased water flow and debris.

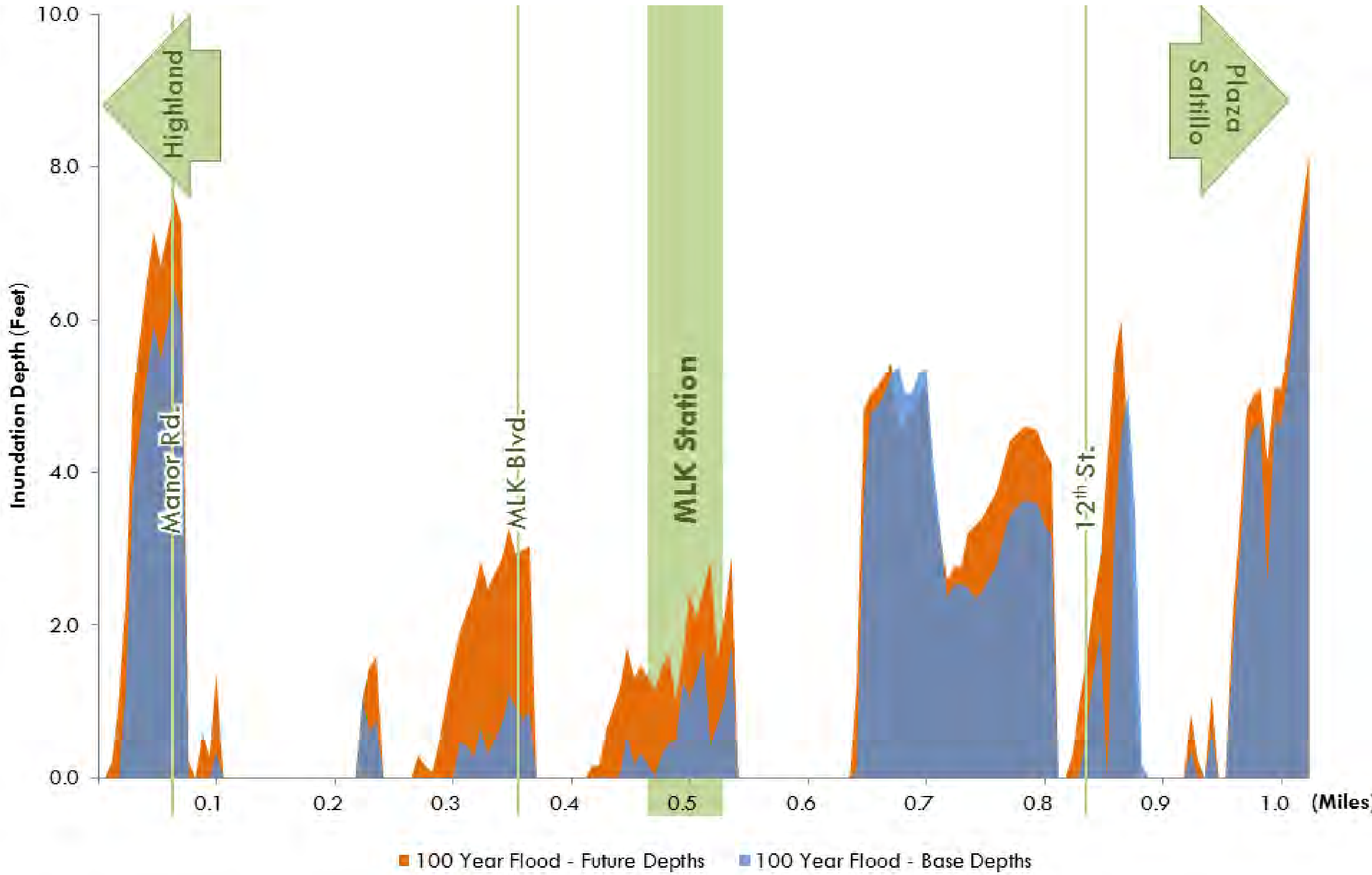
Impact and Risk

Flooding at this asset would disrupt Red Line commuter rail service for at least the duration of the flood, and perhaps longer as post-event inspections and repairs are performed. For example, on September 8, 2010, Tropical Storm Hermine damaged parts of the Red Line track, causing service suspensions for two days. The Red Line serves approximately 3,000 riders daily (with service six days per week).

The risk of flooding—a function of the likelihood and consequences of flooding events—is **Moderate-High** for the Red Line. Flooding is likely at the rail segment, and the estimated consequences of flooding are moderate disruptions or minor damage.

Figure D-1 100 Year Maximum Flood Extents and Cross-section, MetroRail Red Line at MLK Station

Figure D-2 100 Year Flood Depth Along MetroRail Line Near MLK Station



Drought

Exposure

The MetroRail Red Line at Boggy Creek, like all infrastructure in the study area, is expected to have high exposure to drought. Drought is already a recurring issue in central Texas, and the climate model used in this study projects that summer soil moisture—an indicator of drought—may decrease by 4 to 10 percent by mid-century. These changes would exacerbate existing drought patterns and mean the region is very likely to experience drought in the future.

Sensitivity

Available indicators suggest the Red Line at Boggy Creek may have high sensitivity to drought. This rating is based on the soil plasticity near the asset. The Red Line is built over some of the most expansive soils in the region, with a soil plasticity index of 55 (on a scale of 0 to 58). This high plasticity indicates that soils could expand and contract dramatically with changes in soil moisture, and in turn damage infrastructure.

However, agency representatives indicate that drought has not caused problems for this asset in the past, even in the severe drought of 2011. It may be that the structural composition of rail could provide sufficient buffer to prevent issues from soil expansion or contraction. Additional investigation may be warranted to identify whether drought poses a significant risk to the Red Line.

Impact and Risk

Drought can cause soils to contract in response to loss of soil moisture. If the soils underlying the MetroRail Red Line were to contract (or expand) dramatically, it could destabilize the rail.

Drought-related risk *may* be High, but is considered **Inconclusive** until further investigation is undertaken. The likelihood of drought is high, while the consequences could include severe deterioration.

Extreme Heat

Exposure

Like all assets, the MetroRail Red Line at Boggy Creek is expected to have high exposure to extreme heat. The climate model used in this study projects that the region may experience 34 additional days per year above 100°F by mid-century, on average. In addition, average 7-day temperatures may increase by about 4°F by mid-century. These variables indicate that infrastructure in the CAMPO area is very likely to experience extreme heat events in the future.

Sensitivity

Although the intersection is expected to experience very hot conditions, the asset is rated as having low sensitivity to heat, meaning heat is not likely to damage the asset. This rating is based on the neutral temperature of the rail, an indicator of the temperatures the asset is designed to withstand. The Red Line has a rail neutral temperature of between 100 and 115° F. When temperatures exceed this rating, the rail is at risk of thermal misalignment, which in turn can increase the risk of train derailments. MetroRail issues speed restrictions during high heat days, reducing speeds on passenger trains from 60 to 40 miles per hour, and reducing speeds on freight trains from 40 to 20 mph.

Impact and Risk

Increases in the incidence of high temperatures may mean more frequent speed restrictions, which could reduce performance on the line. Capital Metro officials indicated that the agency is working to modernize the track to reduce heat-related impacts, such as updating rail-neutral temperatures and changing rail tying patterns. Capital Metro officials suggested that, though heat does pose a risk, heat risks can be more easily mitigated through preventive action and adaptive action compared to risks from other stressors.

Overall, the risk of impact of extreme heat upon the intersection is **Moderate**. The likelihood of extreme heat is high, while the consequences can be limited by slow orders and other preventive action.

Wildfire

Exposure

The MetroRail Red Line at Boggy Creek is located in an urban, developed area that is not exposed to wildfire. The asset is currently located in a non-burnable area with no Wildfire Threat.[27] Although wildfire likelihood is expected to increase in central Texas as summer soil moisture declines, the analysis assumes that this location will remain non-burnable.

Sensitivity

Because the Red Line is not exposed to wildfire, its sensitivity to wildfire is not applicable.

Impact and Risk

Wildfires are not expected to impact the Red Line at Boggy Creek.

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[27] Wildfire Threat is defined by the Texas Wildfire Risk Assessment Portal (TxWRAP) as "the likelihood of a wildfire occurring or burning into an area."

The risk of impact of wildfire on the intersection is effectively **None** (negligible). Wildfires are not likely to affect the asset, although if they did, the potential consequence likely would be moderate disruption of service on the asset.

Extreme Cold and Ice

Exposure

Like all assets, The MetroRail Red Line at Boggy Creek is expected to have low exposure to extreme cold and icing events. In today's climate, icing events (days where temperatures are below freezing with non-trace precipitation) occur about twice per year, and they are projected to become even less frequent by mid-century, occurring about 1 day per year, on average.

Sensitivity

The Red Line is rated as having moderate sensitivity to extreme cold. Even a small amount of ice (3/16 inches) can break a rail switch, creating temporary service delays. This is consistent with a moderate sensitivity rating, meaning the stressor may cause moderate disruption (on the order of hours) or minor damage.

Impact and Risk

The expected impacts of extreme cold are considered moderate.

The risk of extreme cold—a function of the likelihood and consequences of cold events—to this asset is **Low-Moderate**. Although the likelihood of icing is unlikely, when it happens it can cause moderate disruption.

D.2 ASSET #3. SH 71E AT SH 21

Adaptive Capacity

Adaptive capacity for this asset is low, because of its role as an evacuation route. In addition, the intersection serves an area of rapid population growth, where roadway capacity is becoming increasingly important. Although the asset has other characteristics that may suggest higher adaptive capacity—such as low traffic volumes and short detour lengths around the intersection—the criticality of its role as an evacuation route trumps those other factors, particularly because the asset itself could be vulnerable (e.g., to flooding) at the same time it could be needed for an evacuation.

Flooding

Exposure

SH 71/SH 21 is not located in the FEMA 100-year floodplain, but local experts indicated the intersection has a history of flooding during heavy rain events. Based on this past experience, this asset is conservatively estimated to have high exposure to floods. However, more detailed site-specific research would be warranted to improve the certainty of these findings.

Sensitivity

This asset is also expected to have high sensitivity to this flooding. This rating is based on the asset's 24-hour precipitation design threshold of 6.64 inches (the 25-year event). This is a relatively low threshold compared to events the asset may experience, and suggests potentially high sensitivity. In addition, the intersection is built over alternating clay and silt soil layers, which means there is strong potential for erosion in the case of flooding.

Impact and Risk

Flooding at SH 71/SH 21 could cause erosion or roadway damage. In addition, flooding could render the roadway impassable for the duration of the flood, affecting up to 35,000 car trips per day. Consequences could be even higher if a flood occurred during an evacuation.

The risk of flooding—a function of the likelihood and consequences of flooding events—is, conservatively, **High** for this asset. Past experience suggests there may be a high likelihood of flooding occurring, while the consequences of flooding are major disruption or moderate damage.

Drought

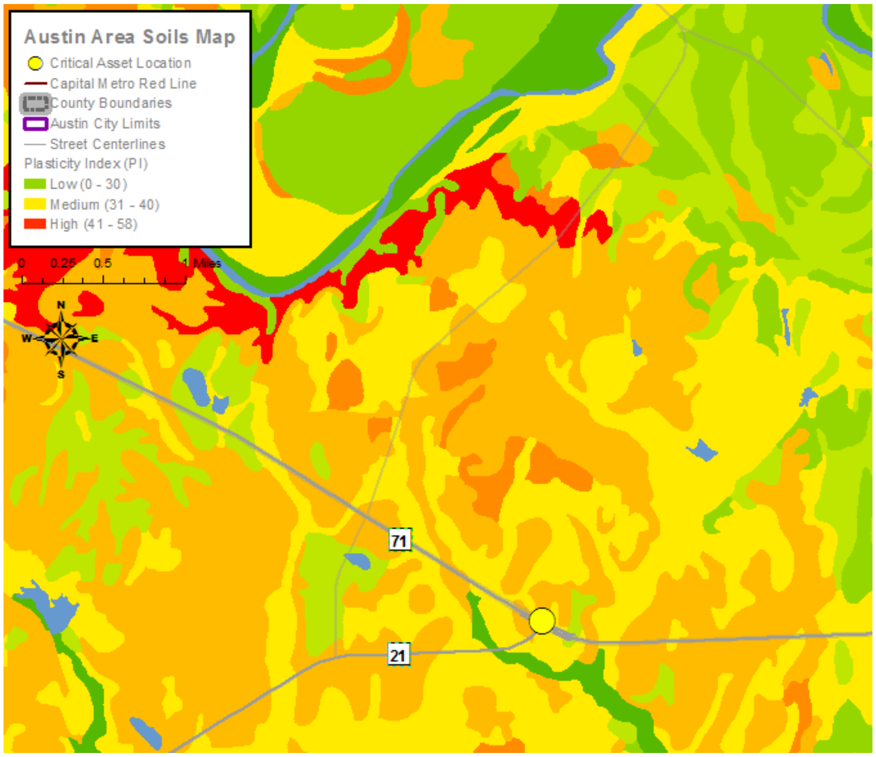
Exposure

SH 71/SH 21, like all infrastructure in the study area, is expected to have high exposure to drought. Drought is already a recurring issue in central Texas, and the climate model used in this study projects that summer soil moisture—an indicator of drought—may decrease by 4 to 10 percent by mid-century. These changes would exacerbate existing drought patterns and mean the region is very likely to experience drought in the future.

Sensitivity

The intersection is moderately sensitive to pavement damage from drought. Surface layer soil maps indicate the intersection is built over medium plasticity soils (plasticity index of 33 on a scale of 0 to 58) (. Bastrop County is known for highly expansive soils prone to shrink-swell issues, caused by fluctuation in soil moisture. The potential for pavement damage is greatest along road edges, and edge drop-off can cause further roadway damage. Therefore, the expected sensitivity of SH 71/SH 21 to drought could be moderate to high. Detailed site-specific soil analysis would be needed to confirm the shrink-swell potential of the soils at the intersection.

Figure D-3   City of Austin Soil Plasticity Index Map, SH 71/SH 21



Other roadways in Bastrop County have been treated with adaptive measures such as improving or widening shoulders and using geosynthetic reinforcement, but these measures have not been adopted at the SH 71/SH 21 intersection.

Impact and Risk

Drought may cause increased annual maintenance costs and traffic delays due to an increase in pavement cracking for this asset. Impacts may be greatest along the pavement edge.

The risk of drought to this asset is **Moderate-High**. The likelihood of drought is high, while the consequences could include moderate-severe pavement damage to an evacuation route.

Extreme Heat

Exposure

Like all assets, SH 71/SH 21 is expected to have high exposure to extreme heat. The climate model used for this study projects that the region may experience 34 additional days per year above 100°F by mid-century, on average. In addition, average 7-day temperatures may increase by about 4°F by mid-century. These variables indicate that infrastructure in the CAMPO area is very likely to experience extreme heat events in the future.

Sensitivity

Although SH 71/SH 21 is expected to experience very hot conditions, the asset is rated as having low sensitivity to heat, meaning heat is not likely to damage the roadway. Factors influencing this rating include pavement binder used and volume of truck traffic. The pavement binder used for the asset (PG 64-22, according to design guidelines) is designed to withstand extended temperatures of 108°F, which is still higher than the projected mid-century average 7-day maximum temperatures of about 101°F. Further, the asset has relatively low truck traffic volume (2,275 trucks per day), so truck traffic is not expected to exacerbate heat-related damage.

Impact and Risk

If heat-related damage were to occur, which stakeholders indicated is unlikely, it would take the form of increased rutting and cracking. This damage typically does not disrupt traffic, but could increase costs or reduce the useful life of the pavement. The consequences of potential damage are increased because of the intersection’s role in an evacuation route.

Overall, the risk of extreme heat—a function of the likelihood and consequences of extreme heat events—to this asset is **Low-Moderate**. The risk is elevated from “Low” to “Low-Moderate” because of the asset’s function in an evacuation route.

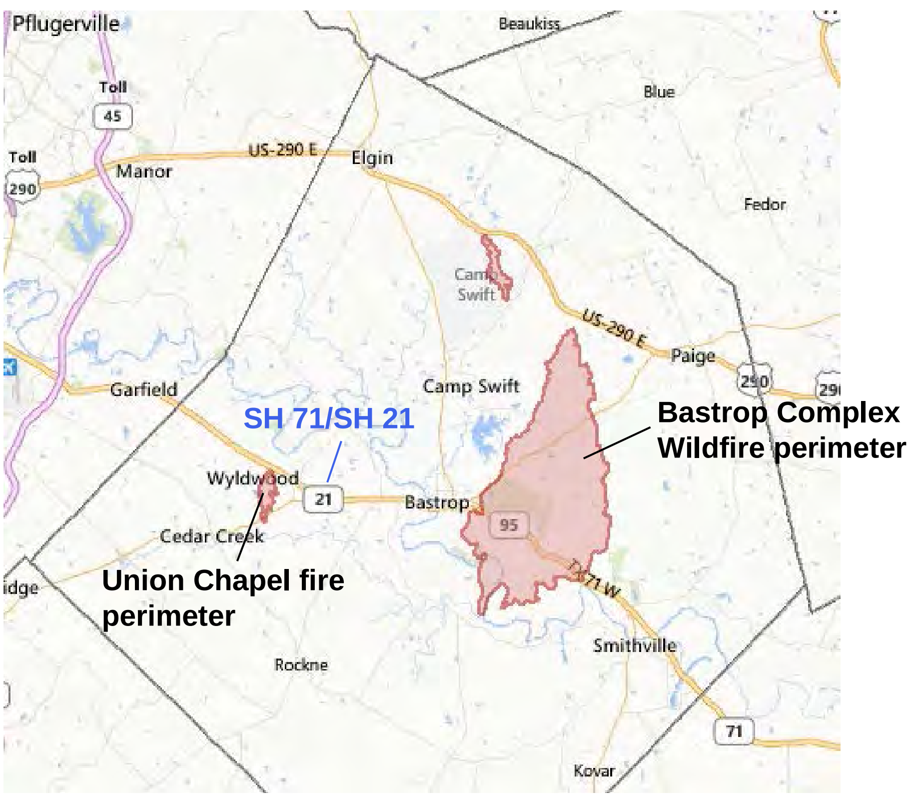
Wildfire

Exposure

SH 71/SH 21 is expected to have moderate exposure to wildfire. The asset is currently located in an area of low-to-moderate Wildfire Threat[28] (though close to an area with moderate Wildfire Threat—see Figure 3), and wildfire likelihood is expected to increase as summer soil moisture declines. The exposure rating is based on the Wildfire Threat (low/moderate), and changes in summer soil moisture.

The intersection is located in the western portion of Bastrop County, and was not affected by the 2011 Bastrop Complex Wildfire, although it was closer to the smaller 2011 Union Chapel wildfire (see Figure D-4). Further east, the Bastrop Complex fire crossed SH 21 and forced the highway to close.

Figure D-4 Bastrop Complex Wildfire Perimeter



Source: Texas Wildfire Risk Assessment Portal, 2011 Large Fire Perimeters layer

[28] Wildfire Threat is defined by the Texas Wildfire Risk Assessment Portal (TxWRAP) as "the likelihood of a wildfire occurring or burning into an area."

Sensitivity

This intersection has moderate sensitivity to wildfire. Wildfires cause temporary service disruptions for their duration, but do not generally cause much long-term physical damage to roadways. However, the asset is also located in an area with a high "Values Response Index"[29] at the intersection, referring to the potential impact of wildfire in that location based on housing density and human structures' relation to wildland fuels.

Impact and Risk

Wildfire may cause temporary disruption and the destruction of guardrail and sign posts for this asset. This was demonstrated during the 2011 Bastrop Complex Wildfire, which crossed a different segment of SH 21. That fire destroyed dozens of guardrails and left debris on the roadways. In addition, SH 71 / SH 21 is also located in an area rated as having relatively high impacts from wildfire because of the wildland-urban interface, which suggests that a wildfire in this location could affect a relatively high number of homes, businesses, or people.

Therefore, the overall risk of wildfire—a function of the likelihood and consequences of wildfire events—to this asset is **Moderate-High**. Although the physical consequences of wildfire to the intersection are relatively low, the potential consequences of road closures from wildfire when the route is needed for an evacuation elevates the risk.

Extreme Cold and Ice

Exposure

Like all assets, SH 71/SH 21 is expected to have low exposure to extreme cold and icing events. In today's climate, icing events (days where temperatures are below freezing with non-trace precipitation) occur about twice per year, and they are projected to become even less frequent by mid-century, occurring about 1 day per year.

Sensitivity

This asset has low sensitivity to icing events. Though it is not as likely to ice as elevated roadway segments or bridges, the roadway may ice when conditions are right. Icy conditions cause severe traffic disruptions. These conditions last

[29] Values Response Index (VRI) is a field from the Texas Wildfire Risk Assessment Portal (TxWRAP). According to TxWRAP, VRI "reflects a rating of the potential impact of wildfire on values or assets," which incorporates Wildland Urban Interface (WUI) and housing density.

only for a few hours, however, and do not cause long-term physical damage to the roadway.

Impact and Risk

Overall expected impacts from icing on SH 71/SH 21 are low. Anticipated impacts include congestion because of slow traffic for the duration of the icing event. Icing events in this area tend to last a few hours.

The risk of extreme cold—a function of the likelihood and consequences of cold events—to this asset is **Low-Moderate**. The likelihood of icing is low, while the consequences are temporary disruption, exacerbated by low adaptive capacity to disruptions at the intersection.

D.3 ASSET #4. I-35 AT ONION CREEK PARKWAY

Adaptive Capacity

The region possesses low capacity to adapt to temporary disruption of the asset. I-35 is the major corridor through the CAMPO area and is of vital significance not only to Austin and the Central Texas region, but also to the Texas, national, and international economies. The adaptive capacity rating takes the following into account:

- The asset is a critical access route in that it serves an area with high population and employment density;
- The asset is an Interstate highway, which indicates that loss of the asset could severely disrupt activity throughout the entire CAMPO region;
- Its AADT of 114,090 is the highest in the CAMPO area, indicative of the critical role I-35 plays in moving people and goods in the Austin area, and that the region may be unable to cope adequately with diminished service;
- The daily truck traffic volume of 16,080 similarly indicates high freight traffic and thus low adaptive capacity; and
- The detour length of 1.24 miles indicates high redundancy serving the area, which improves adaptive capacity.

Flooding

Exposure

I-35 at Onion Creek Parkway is expected to have very low exposure to floods. The roadway is elevated high above Onion Creek, and is expected to maintain about 11 feet of clearance under today's 50-year rain event and 7.5 feet of clearance even under the mid-century 50-year rain event if heavy rain events become more intense and frequent. The roadway is also estimated to maintain about 3 feet of clearance above future 100-year rain event flood levels.[30] The maximum flood depths at the Onion Creek bridge for 100-year rain events (present-day and projected future) are shown in Figure D-5, with estimated flood depths along the green cross-section shown in Figure D-7 D-7. Figure D-6 shows estimated aerial flood extents. The asset has never been overtopped in the past, even during the area's most severe floods (like the Halloween Flood of 2013 or Tropical Storm Hermine).

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[30] Freeboard was estimated using Onion Creek inundation depths from the Austin Flood Early Warning System V*flo* model and I-35 roadway and bridge elevations from engineering diagrams obtained from the Texas Department of Transportation.

Figure D-5 Est 100-Year Rain Event Inundation Depths at I-35 at Onion Creek

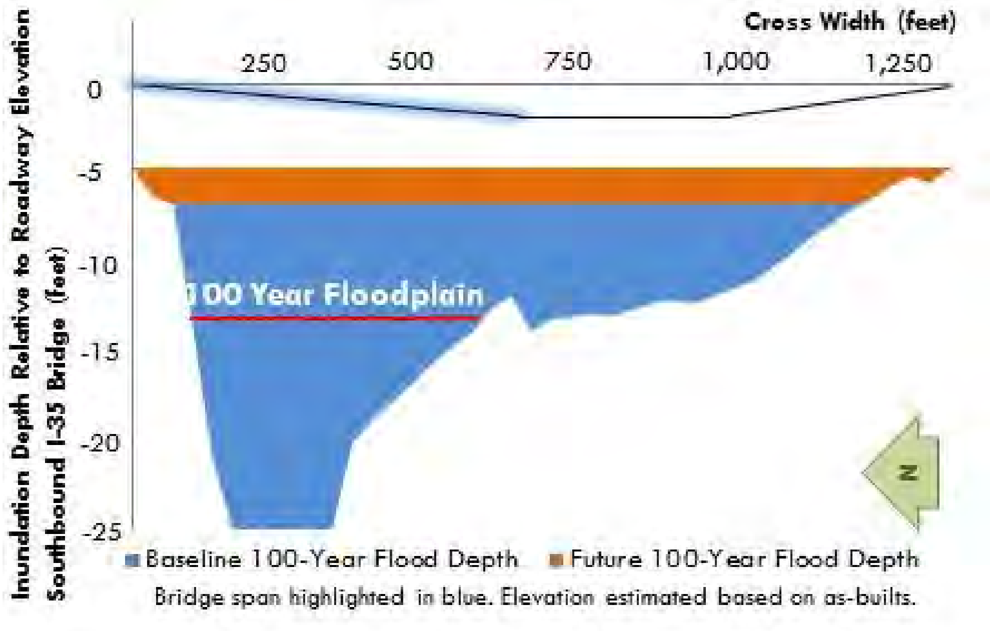


Figure D-6 100 Year Maximum Flood Extents and Depths, I-35 Bridge at Onion Creek

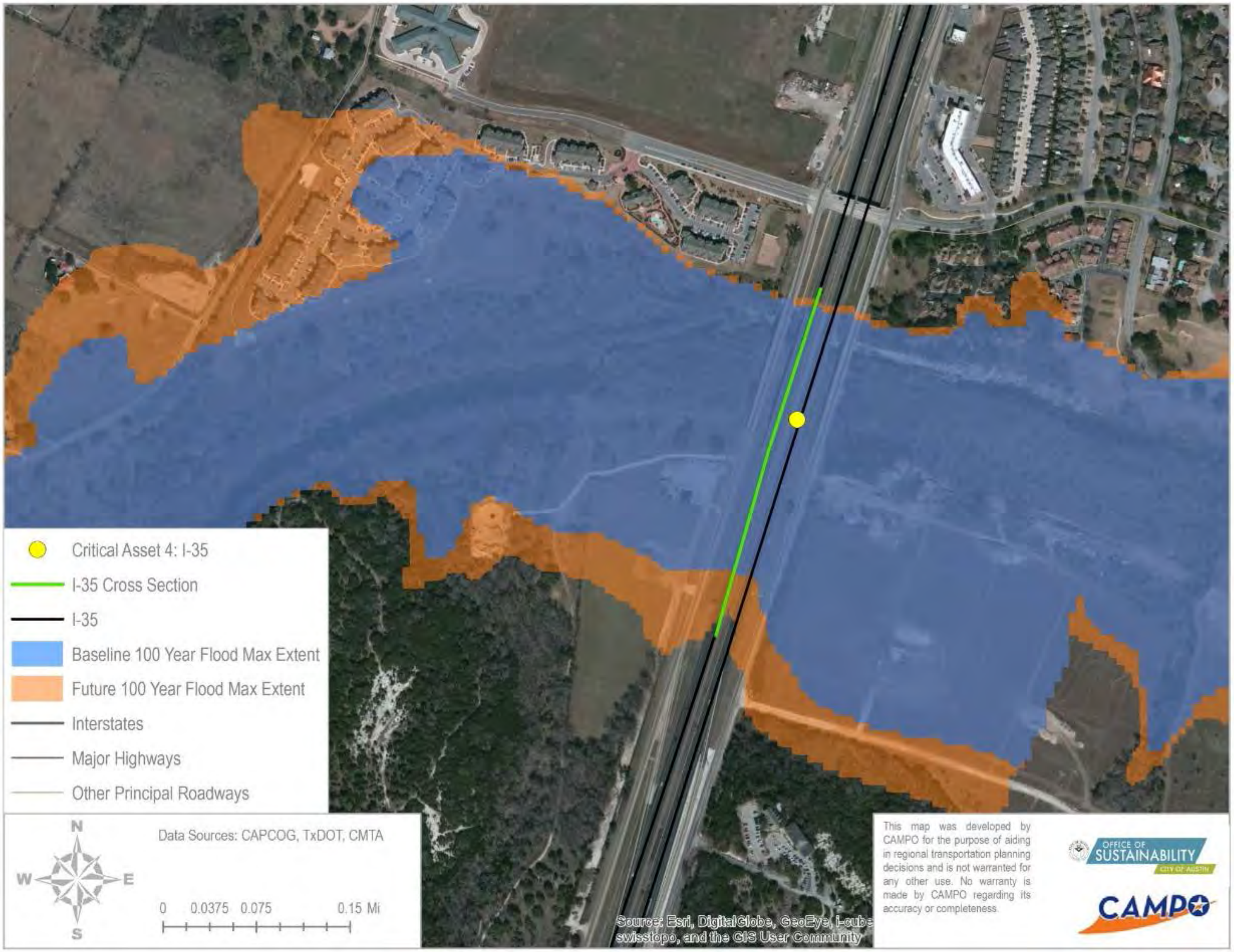
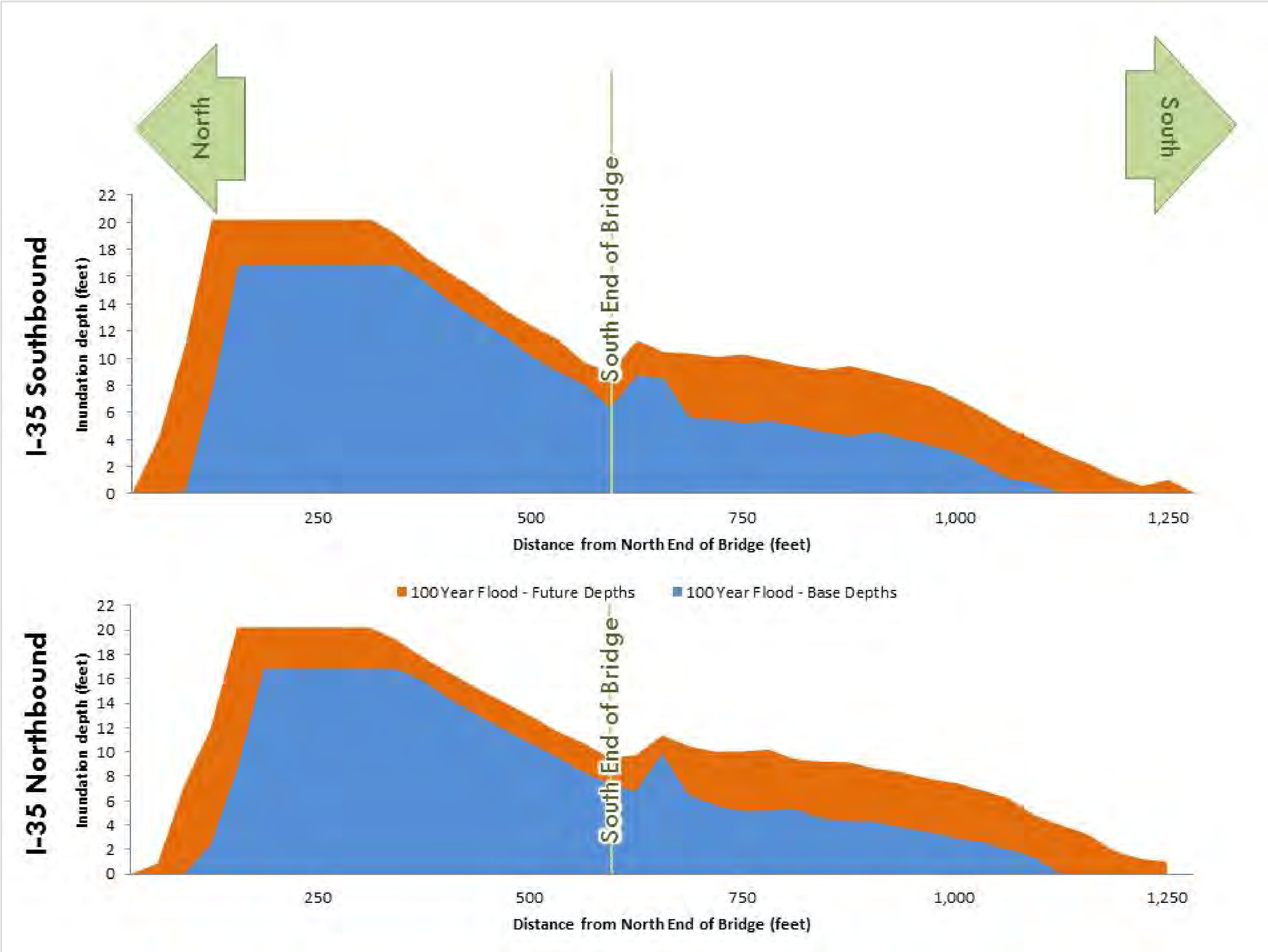


Figure D-7 100 Year Flood Depths, I-35 Bridge at Onion Creek Cross-Section



Sensitivity

I-35 at Onion Creek is expected to have low sensitivity to flooding. Factors influencing this rating include:

- 24-hour precipitation design threshold of 8.87 inches (50 year event). As a major roadway, I-35 is designed to withstand at least the 50-year event (and estimates suggest that it may also withstand 100-year events); indicating low sensitivity.
- Bridge scour rating of 8 – A scour rating of 8 means the bridge has no scour issues, which indicates it is less susceptible to damage from floodwaters.
- Average inundation velocity of 6 feet/second – This velocity is right at the threshold where the risk of damage increases, according to TxDOT engineers, so this flood velocity could contribute to increased sensitivity.

Impact and Risk

The likelihood of impacts is considered very low. However, if flooding were to affect the bridge, it could disrupt up to 114,000 auto trips per day and thus have a substantial impact on the CAMPO region.

Overall, the risk of flooding—a function of the likelihood and consequences of flooding events—is **Low** for I-35. The asset is very unlikely to flood, although the consequences would be moderate disruption to a critical regional artery.

Drought

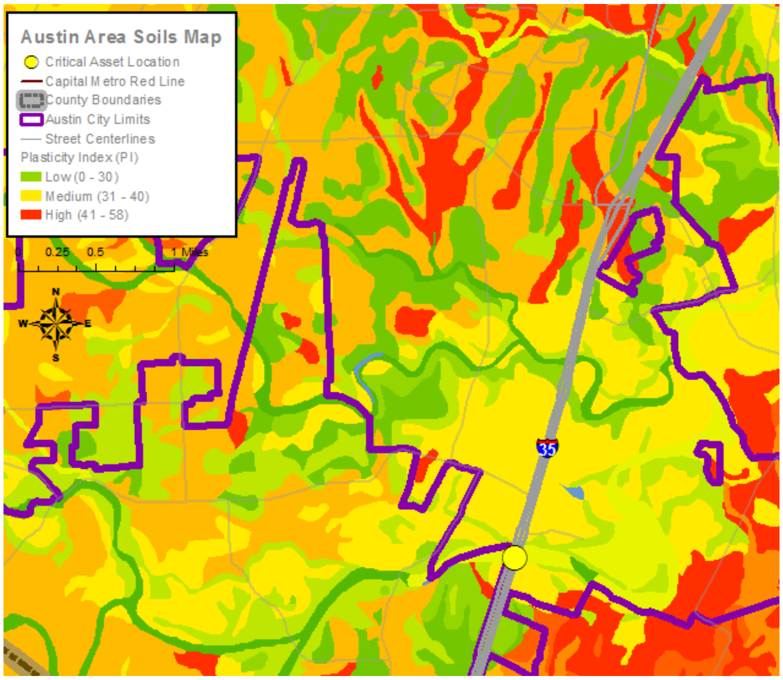
Exposure

I-35 at Onion Creek, like all infrastructure in the study area, is expected to have high exposure to drought. Drought is already a recurring issue in central Texas, and the climate model used in this study projects that summer soil moisture—an indicator of drought—may decrease by 4 to 10 percent by mid-century. These changes would exacerbate existing drought patterns and mean the region is very likely to experience drought in the future.

Sensitivity

I-35 at Onion Creek is not sensitive to drought. I-35 is built over low plasticity soils that are not likely to expand or contract dramatically with changes in soil moisture (see Figure D-8). Further, the highway and bridge footings are set into rock and with deep drill shafts, so soil expansion and contraction are not anticipated to affect the asset.

Figure D-8 City of Austin Soil Plasticity Index Map, I-35 at Onion Creek



Impact and Risk

I-35 is expected to experience no impacts from drought, since it is not sensitive to drought-related damage.

Therefore, the risk of drought to I-35 is **None** (negligible)**.** Although the likelihood of drought is high, the likelihood of impact is very low or nonexistent, given the asset's design.

Extreme Heat

Exposure

Like all assets, I-35 at Onion Creek is expected to have high exposure to extreme heat. The climate model used in this study projects that the region may experience 34 additional days per year above 100°F by mid-century, on average. In addition, average 7-day temperatures may increase by about 4°F by mid-century. These variables indicate that infrastructure in the CAMPO area is very likely to experience extreme heat events in the future.

Sensitivity

Although I-35 is expected to experience very hot conditions, the asset is not sensitive to heat-related damage. I-35 is designed to withstand high volumes of heavy truck traffic and extreme temperatures.

Impact and Risk

I-35 is expected to experience no impacts from extreme heat, since it is not sensitive to heat-related damage.

Therefore, the risk of extreme heat to I-35 is **None** (negligible). Although the likelihood of extreme heat is high, the likelihood of impact is very low or nonexistent, given the asset's design.

Wildfire

Exposure

I-35 at Onion Creek has moderate exposure to wildfire. The asset is currently located in an area of low-moderate Wildfire Threat (Figure 10),[31] and wildfire likelihood is expected to increase as summer soil moisture declines.

Sensitivity

I-35 has moderate sensitivity to wildfire. Wildfires cause temporary service disruptions for their duration, but do not generally cause much long-term physical damage to roadways.

Impact and Risk

Wildfire in the area could temporarily prevent traffic flow or destroy guardrail and sign posts along the highway. Temporary closure of the highway due to wildfire would have a large impact on the region, affecting up to 114,000 vehicle trips per day.

The risk of wildfire to I-35 is therefore **Moderate-High.** Although I-35 is unlikely to be damaged by wildfires, if it were to experience even minimal damage or temporary disruption the consequences would be high, given its criticality to the region.

Extreme Cold and Ice

Exposure

Like all assets, I-35 at Onion Creek is expected to have low exposure to extreme cold and icing events. In today's climate, icing events (days where temperatures are below freezing with non-trace precipitation) occur about twice per year, and they are projected to become even less frequent by mid-century, occurring about 1 day per year, on average.

[31] Wildfire Threat is defined by the Texas Wildfire Risk Assessment Portal (TxWRAP) as "the likelihood of a wildfire occurring or burning into an area."

Sensitivity

When icing days do occur, I-35 is susceptible to icing and temporary road closure may be necessary. The roadway is elevated and thus more likely to ice than non-elevated roadways. This translates to moderate sensitivity to this stressor. Though the roadway may ice when conditions are right and icing can cause severe traffic disruptions, these events last only for a few hours and do not cause long-term physical damage to the roadway.

Impact and Risk

Icing on I-35 can cause major traffic congestion and delays, or even prompt school and work closures because of unsafe driving conditions. For example, during an icing event on January 24, 2014, portions of I-35 were closed and traffic flows on adjacent roads moved at approximately five miles per hour. Disruptions related to icing are short-lived, but severe.

The risk of extreme cold to I-35—a function of the likelihood and consequences of cold events—is **Low-Moderate**. Although the likelihood of icing is unlikely, when it happens it can cause severe temporary disruptions.

D.4 ASSET #5. US 290W AND SH 71 – Y AT OAK HILL

Adaptive Capacity

This junction of two critical corridors (US 290 and SH 71) serves western communities. Few arterial roadways exist in the area to help carry traffic. The region's capacity to adapt to temporary disruption of this junction is moderate due to the following factors.

- The asset is a critical access route for an area with high population and employment density.
- The asset is a major undivided arterial; the loss of the asset could severely disrupt activity in a portion of the CAMPO region. However, with an AADT of 57,000 (relatively moderate compared to other roadways in the CAMPO area), the region may be able to cope temporarily with the loss of the asset.
- Its daily truck traffic volume of 2,050 indicates low freight traffic and thus higher adaptive capacity.
- The National Bridge Inventory suggests a very short detour length around this junction, indicating high redundancy serving the area. However, the available detour routes are not arterials and are not likely to have sufficient capacity to be truly redundant.

Flooding

Exposure

The Y at Oak Hill is expected to have moderate exposure to floods. Flood Early Warning System (FEWS) modeling of potential inundation from heavy rain events showed that the intersection could experience nearly 9 feet of inundation during 50-year rain events by mid-century. The bridge along US-290 over Williamson Creek may experience approximately seven feet of inundation during such events. The maximum flood extents for 50-year rain events are shown in Figure D-9, with the flood depths along the cross-section (green line) shown in Figure D-10.

However, stakeholders reviewing these preliminary, modeled results felt that the facility exhibits only modest potential for flooding exposure. Therefore, reflecting both inputs, the composite risk rating is moderate.

Figure D-9 FEWS 50 Year Maximum Flood Extents and Cross-section Location

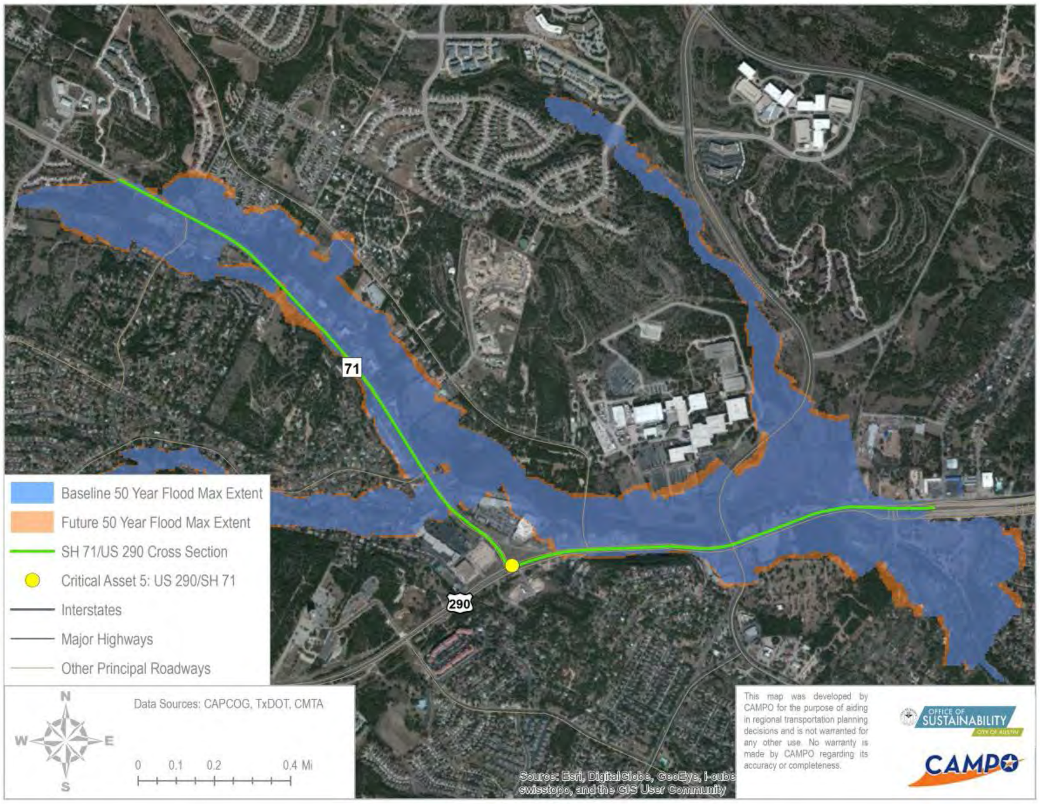
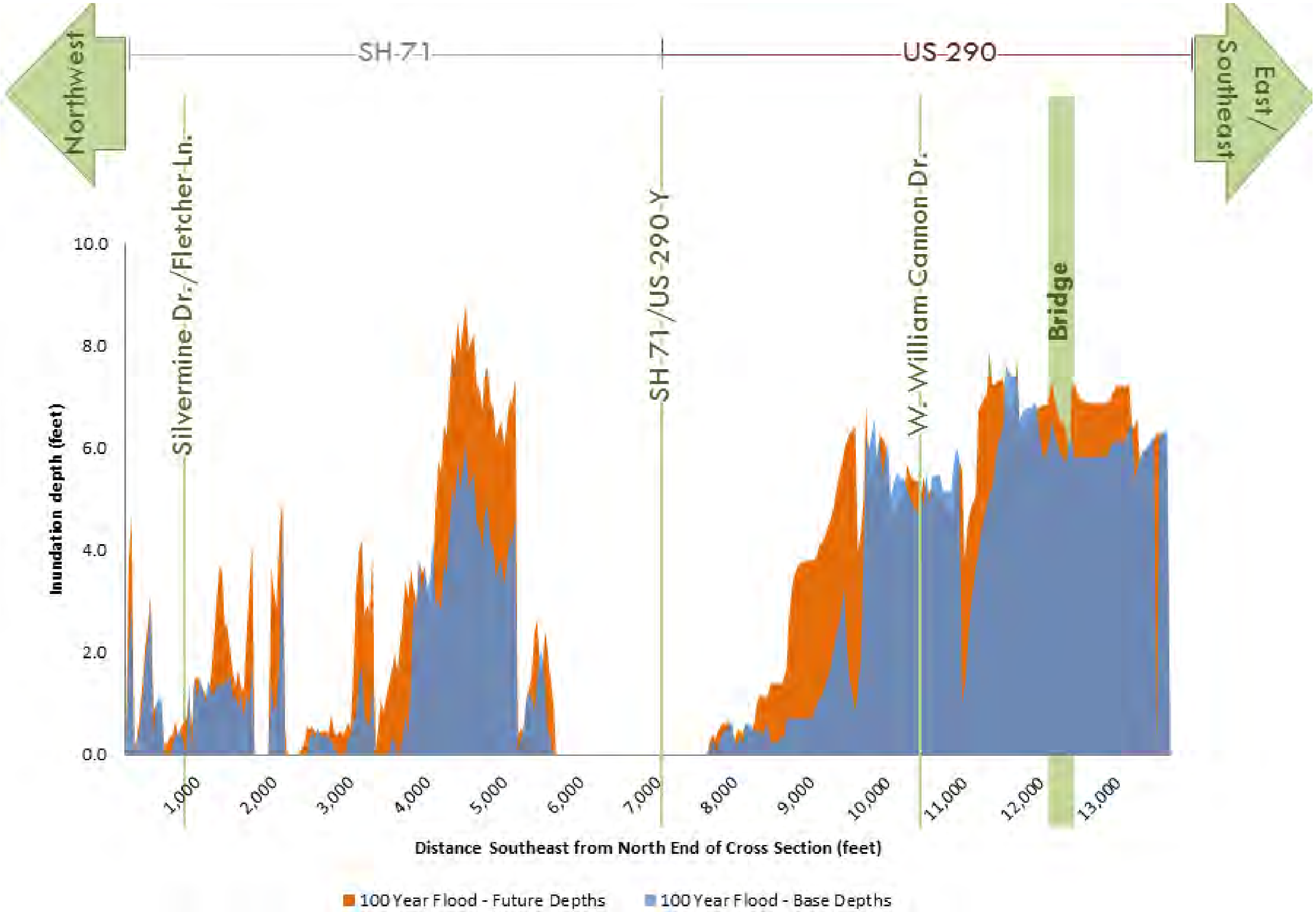


Figure D-10 50 Year Flood Depth Along SH 71 and US 290



Sensitivity

The intersection and surrounding roadway have low sensitivity to flooding. Factors influencing this rating include:

- 24-hour precipitation design threshold of 7.64 inches (25 year event) – This is a relatively low threshold compared to events the asset may experience.
- Bridge scour rating of 8 – A scour rating of 8 means the bridge has no scour issues, which indicates it is potentially less susceptible to damage from floodwaters.
- Average inundation velocity of 4.8 feet/second – This indicates that floodwaters at the asset may be relatively slow-moving and thus unlikely to cause structural damage (TxDOT engineers suggest that thresholds for damage start around 6 feet/second).
- Moderate Wildfire Threat – Flooding, debris, and erosion can be much worse in the aftermath of a fire, so the asset's moderate risk of wildfire indicates moderate sensitivity to flood-related damage influenced by wildfire.

Impact and Risk

SH 71/US 290 – Y at Oak Hill could experience moderate impacts from flooding. If flooding occurs, which stakeholders suggest is unlikely, then flooding is prone to be slow-moving and cause only temporary road closures or operational disruptions until floodwaters recede. Flooding at this intersection could disrupt approximately 57,000 auto trips per day.

The risk of flooding—a function of the likelihood and consequences of flooding events—is **Moderate** for this asset. The asset may be susceptible to 50-year rainfall events, but the consequences of flooding are only anticipated to be temporary service disruptions.

Drought

Exposure

SH 71/US 290 – Y at Oak Hill, like all infrastructure in the study area, is expected to have high exposure to drought. Drought is already a recurring issue in central Texas, and the climate model used in this study projects that summer soil moisture—an indicator of drought—may decrease by 4 to 10 percent by mid-century. These changes would exacerbate existing drought patterns and mean the region is very likely to experience drought in the future.

Sensitivity

Surface soil maps indicate the Y at Oak Hill is built over moderate-to-high plasticity soils (plasticity index of 38 on a scale of 0 to 58). High plasticity soils are prone to shrink and swell as soil moisture changes, which can degrade pavement, causing longitudinal cracking and edge drop-off.

The available data on soil plasticity therefore suggests this intersection is moderately sensitive to damage from drought. However, more detailed site-specific soil analysis would be needed to confirm these findings, particularly since the available dataset does not factor in the depth of the clay surface soils.

Impact and Risk

Drought may cause increased annual maintenance costs for this asset due to an increase in pavement cracking.

The risk of drought for this asset is **Moderate**. The likelihood of drought is high, and the medium plasticity soils suggest drought could yield moderate consequences for the intersection.

Extreme Heat

Exposure

Like all assets, SH 71/US 290 – Y at Oak Hill is expected to have high exposure to extreme heat. The climate model used for this study projects that the region may experience 34 additional days per year above 100°F by mid-century, on average. In addition, average 7-day temperatures may increase by about 4°F by mid-century. These variables indicate that infrastructure in the CAMPO area is very likely to experience extreme heat events in the future.

Sensitivity

This intersection is not sensitive to heat-related damage. The roadway is designed to accommodate the extreme heat of central Texas. The pavement binder used for the asset (PG 64-22, according to design guidelines) is designed to withstand extended temperatures of 108°F, which is still higher than the projected mid-century average 7-day maximum temperatures of about 101°F. Further, the asset has relatively low truck traffic volume (2,050 trucks per day), so truck traffic is not expected to exacerbate heat-related damage. Finally, local experts indicated that even if heat-related pavement damage like rutting or shoving were to occur at the intersection, is not likely to disrupt traffic.

Impact and Risk

SH 71/US 290 – Y at Oak Hill is expected to experience minimal or no impact from extreme heat. Despite being highly exposed to hot temperatures, the roadway is designed to withstand those extremes.

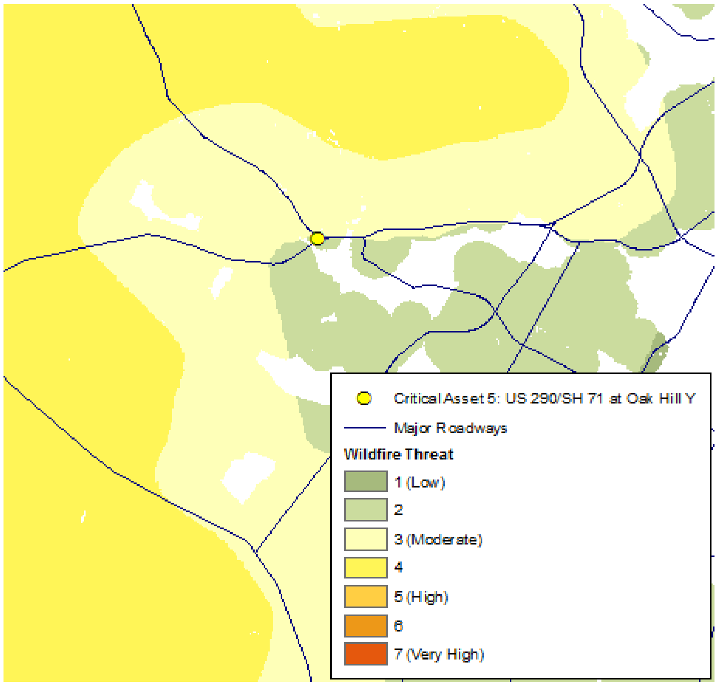
Therefore, the risk of extreme heat to this asset is **None** (negligible). Although the likelihood of extreme heat is high, the likelihood of impact is very low or nonexistent, given the asset's design.

Wildfire

Exposure

SH 71/US 290 – Y at Oak Hill is expected to have high exposure to wildfire. The asset is currently located in an area of moderate Wildfire Threat and adjacent to an area with high Wildfire Threat (Figure D-11). In addition, wildfire likelihood is expected to increase as summer soil moisture declines.

Figure D-11 Wildfire Threat, SH 71/US 290 – Y at Oak Hill



Source: Texas Wildfire Risk Assessment Portal, Wildfire Threat layer

Sensitivity

The Y at Oak Hill may be particularly sensitive to impacts from wildfire. SH 71 and US 290 both serve as evacuation options for residents west of the intersection, where wildfire likelihood is high. If this intersections were to be damaged or disrupted by wildfire (or by any cause during a wildfire event to the west), stakeholders believe it has the potential to be a dangerous "choke point" that impedes the evacuation process. This concern is supported by data showing a high "Values Response Index"[32] at the intersection, referring to the potential impact of wildfire in that location. Wildfire is not expected to cause much long-

32 Values Response Index (VRI) is a field from the Texas Wildfire Risk Assessment Portal (TxWRAP). According to TxWRAP, VRI "reflects a rating of the potential impact of wildfire on values or assets," which incorporates Wildland Urban Interface (WUI) and housing density.

term physical damage to the roadway, but could have a severe impact on human health and safety in this area.

Impact and Risk

Wildfire at or west of the Y at Oak Hill presents a risk to the nearby population. Wildfire hazards are high in the area west of the intersection, and it could serve as a "choke point" in west-east wildfire evacuations.

The risk of wildfire to the intersection—a function of the likelihood and consequences of wildfire events—is thus **High**. Wildfires have high likelihood in the area of the Oak Hill Y, and could result in major disruptions and/or life safety issues.

Extreme Cold and Ice

Exposure

Like all assets, SH 71/US 290 – Y at Oak Hill is expected to have low exposure to extreme cold and icing events. In today's climate, icing events (days where temperatures are below freezing with non-trace precipitation) occur about twice per year, and they are projected to become even less frequent by mid-century, occurring about 1 day per year, on average.

Sensitivity

This asset has low sensitivity to extreme cold. Though it is not as likely to ice as elevated roadway segments or bridges, the roadway may ice when conditions are right. Icy conditions cause severe traffic disruptions, though these conditions last only for a few hours and do not cause long-term physical damage to the roadway.

Impact and Risk

Icing events can cause congestion and traffic disruptions, which typically last only a few hours.

The risk of extreme cold at SH 71/US 290—a function of the likelihood and consequences of cold events—is **Low**. Icing is unlikely with only moderate traffic disruption as an anticipated consequence.

D.5 ASSET #6. LOOP 360/RM 2222

Loop 360 at RM 2222 is a critical junction in the Austin area, located in Travis County.

Adaptive Capacity

The region possesses moderate capacity to adapt to temporary disruption of the asset. The moderate adaptive capacity rating is the result of several balancing factors, some indicating high and others indicating low adaptive capacity:

- The asset is a critical access route in that it serves an area with high population and employment density—this indicates a high consequence of damage;
- Loop 360 is an expressway, which indicates that loss of the asset could severely disrupt activity in a portion of the CAMPO region. RM 2222 is more likely to be impacted by flooding, and the loss of this asset could also have regional repercussions;
- RM 2222's AADT of 23,000 is relatively low compared to major roadways in the CAMPO area, which indicates the region may be able to cope with the loss of the asset temporarily;
- RM 2222's daily truck traffic volume of 1,350 indicates relatively low truck traffic and thus higher adaptive capacity; and
- A very low projected detour length (from the National Bridge Inventory) indicates ample redundancy, which equates to relatively higher adaptive capacity.

Flooding

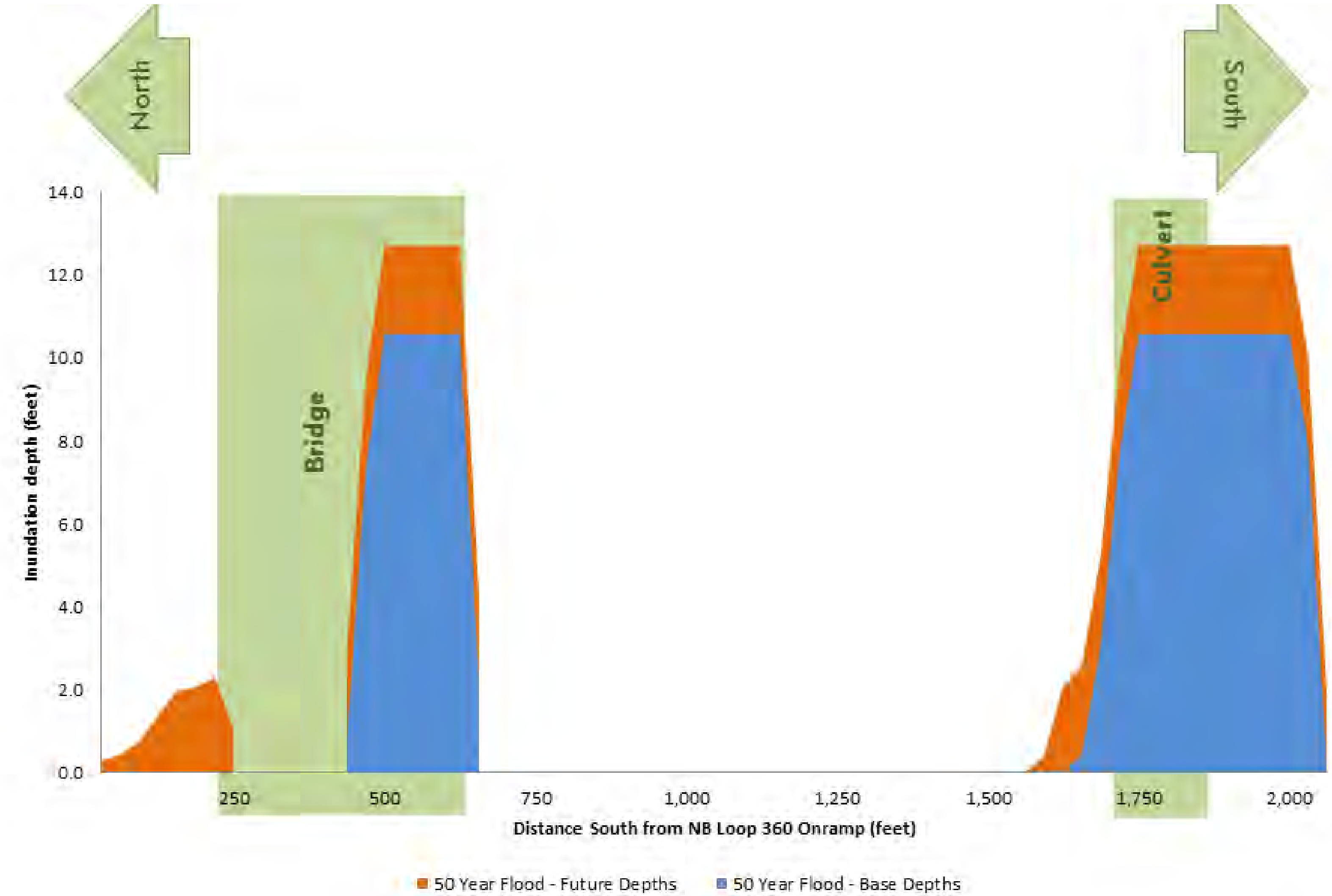
Exposure

Loop 360/RM 2222 is expected to have high exposure to floods. RM 2222 in particular, runs along and crosses Bull Creek approaching the interchange. Bull Creek has a history of overrunning its banks after heavy rainfall, and could rise up to 12 feet as result of a future 50-year rain event based on modeled results from the City of Austin Flood Early Warning System (FEWS) (compared to 10 feet in today's 50-year rain event). Future 50-year rainfall could cause the Bull Creek bridge to experience up to two feet of inundation (relative to bridge deck level, estimated).

The projected maximum flood extents for 50-year rainfall events are shown in Figure D-12, with flood depths along the green cross-section shown in Figure D-13.

Figure D-12 Projected 50-Year Maximum Flood Extents and Cross-section Location, Loop 360/RM 2222

Figure D-13 Projected 50-Year Flood Depths Along RM 2222



Sensitivity

RM 2222 was severely damaged during Tropical Storm Hermine in 2010 (see Figure D-14) and was rebuilt and re-resigned to prevent future flood damage. As a result, this asset is estimated to have low sensitivity to flood damage.

Figure D-14 Damage to RM 2222 at the Bull Creek Crossing Due to Overnight Flooding September 7-8, 2010 (Tropical Storm Hermine)

The roadway was highly sensitive to damage in 2010, but has since been re-designed to reduce flooding sensitivity. Photo source: Austin American-Statesman

The initial VAST assessment suggested high sensitivity based on factors like the default 24-hour precipitation design standard for assets of this functional class, a history of scour damage, and relatively high average inundation velocities (6.4 feet/second) at the asset. However, stakeholders suggest that these sensitivity indicators have been addressed by the re-design.

Impact and Risk

Given the redesign of RM 2222, flooding (which is more likely at RM 2222 than at Loop 360) is not expected to cause structural damage, as experienced in the wake of Hermine. Flooding could still overtop the roadway, however, and cause temporary traffic disruptions, affecting up to 23,000 auto trips per day. If RM 2222 closes, this could lead to traffic delays on Loop 360.

The overall risk of flooding for Loop 360/RM 2222—a function of the likelihood and consequences of flooding events—is **Moderate**. Flooding is likely, but the recent redesign of RM 2222 is expected to limit the consequences of that flooding.

Drought

Exposure

Loop 360/RM 2222, like all infrastructure in the study area, is expected to have high exposure to drought. Drought is already a recurring issue in central Texas, and the climate model used in this study projects that summer soil moisture—an indicator of drought—may decrease by 4 to 10 percent by mid-century. These changes would exacerbate existing drought patterns and mean the region is very likely to experience drought in the future.

Sensitivity

Surface soil maps indicate that the Loop 360/RM 2222 interchange is built over medium plasticity soils (plasticity index of 32 on a scale of 0 to 58). High plasticity soils are prone to shrink and swell as soil moisture changes, which can degrade pavement, causing longitudinal cracking and edge drop-off.

The available data on soil plasticity therefore suggests this intersection is moderately sensitive to damage from drought. However, more detailed site-specific soil analysis would be needed to confirm these findings, particularly since the available dataset does not factor in the depth of the clay surface soils.

Impact and Risk

Drought could cause increased annual maintenance costs due to an increase in pavement cracking and edge failures.

The risk of drought for this asset is **Moderate**. The likelihood of drought is high, and the medium plasticity soils suggest drought could also mean moderate consequences for the intersection.

Extreme Heat

Exposure

Like all assets, Loop 360/RM 2222 is expected to have high exposure to extreme heat. The climate model used for this study projects that the region may experience an additional 34 days per year above 100°F by mid-century, on average. In addition, average 7-day temperatures may increase by about 4°F by mid-century. These variables indicate that infrastructure in the CAMPO area is very likely to experience extreme heat events in the future.

Sensitivity

Although the Loop 360/RM 2222 interchange is expected to experience very hot conditions, the asset is not sensitive to heat-related damage. Factors influencing this rating include pavement binder used and volume of truck traffic. The pavement binder used for the asset (PG 64-22, according to design guidelines) is designed to withstand extended temperatures of 108°F, which is still higher than the projected mid-century average 7-day maximum temperatures of about 101°F. Further, the asset has relatively low truck traffic volume (1,350 trucks per day), so truck traffic is not expected to exacerbate heat-related damage. Finally, local experts indicated that because the interchange is a major roadway in terms of functional classification, it is designed to withstand even more extreme conditions—in terms of both heat and heavy traffic—than available data suggests (i.e., it may use a pavement binder that can withstand a higher temperature than 108°F).

Impact and Risk

Loop 360/RM 2222 is expected to experience minimal or no impact from extreme heat. Despite being highly exposed to hot temperatures, the roadway is designed to withstand those extremes.

Therefore, the risk of extreme heat to this asset is **None** (negligible). Although the likelihood of extreme heat is high, the likelihood of impact is very low or nonexistent, given the asset's design.

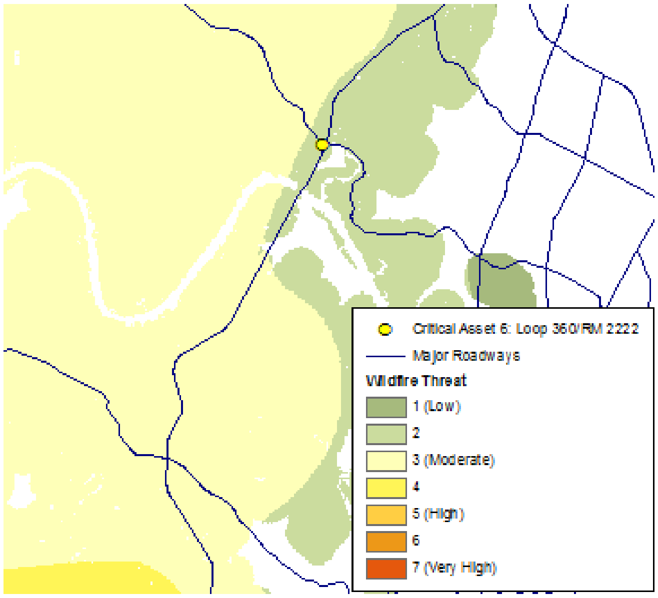
Wildfire

Exposure

Loop 360/RM 2222 is expected to have high exposure to wildfire. Although the asset is located in an area defined by TxWRAP to have "low-moderate" Wildfire Threat (Figure D-15),[33] local experts indicated that the data on past fire ignition—one of the key drivers of the Wildfire Threat rating—is incomplete for this location. The number of actual historical fire starts in the area is higher than the quantity reflected in TxWRAP and wildfire likelihood is expected to increase as summer soil moisture declines. Therefore, the asset received a high wildfire exposure rating.

[33] Wildfire Threat is defined by the Texas Wildfire Risk Assessment Portal (TxWRAP) as "the likelihood of a wildfire occurring or burning into an area."

Figure D-15 Wildfire Threat, Loop 360/RM 2222



Source: Texas Wildfire Risk Assessment Portal, Wildfire Threat layer

Sensitivity

Loop 360/RM 2222, like all assets studied, was initially rated as having moderate sensitivity to wildfire. However, vulnerability assessment focus group participants indicated that wildfires could have a larger impact on this asset (and the population it serves). Loop 360 and RM 2222 both serve as evacuation options for residents west of the interchange, where wildfire likelihood is high. The intersection, were it to be damaged or disrupted by wildfire or during a wildfire event, could become a dangerous "choke point," impeding the evacuation process. This feedback is also supported by data showing a high "Values Response Index"[34] at the intersection, referring to the potential impact of wildfire in that location. Wildfire is not expected to cause much long-term physical damage to the roadway, but could have a severe impact on human health and safety in this location.

Impact and Risk

Wildfire at or west of the Loop 360/RM 2222 interchange presents a risk to the nearby population. Wildfires are likely in the area, and the intersection could serve as a "choke point" in wildfire evacuations.

[34] Values Response Index (VRI) is a field from the Texas Wildfire Risk Assessment Portal (TxWRAP). According to TxWRAP, VRI "reflects a rating of the potential impact of wildfire on values or assets," which incorporates Wildland Urban Interface (WUI) and housing density.

The risk of wildfire—a function of the likelihood and consequences of wildfire events—to this asset is **High**. Wildfires likelihood is high in the area of the interchange, and could result in major disruptions.

Extreme Cold and Ice

Exposure

Like all assets, Loop 360/RM 2222 is expected to have low exposure to extreme cold and icing events. In today's climate, icing events (days where temperatures are below freezing with non-trace precipitation) occur about twice per year, and they are projected to become even less frequent by mid-century, occurring about 1 day per year, on average.

Sensitivity

When icing days do occur, however, the interchange is susceptible to icing, which can temporarily close the roadway. The asset interchange has moderate sensitivity to icing because it is elevated, making it more likely to ice than non-elevated roadways. Though the roadway may ice when conditions are right and icy conditions cause severe traffic disruptions, these conditions last only for a few hours and do not cause long-term physical damage to the roadway.

Impact and Risk

Anticipated impacts from icing at Loop 360/RM 2222 include congestion because of slow traffic for the duration of the icing event. Icing events tend to last a few hours.

The risk of extreme cold—a function of the likelihood and consequences of cold events—to this asset is **Low-Moderate**. Icing days are infrequent, while the consequences are likely to be moderate disruption.

D.6 Asset #7. FM 1431 at Brushy Creek/Spanish Oak Creek

Adaptive Capacity

The region possesses moderate capacity to adapt to temporary disruptions to this asset. The rating takes the following into account:

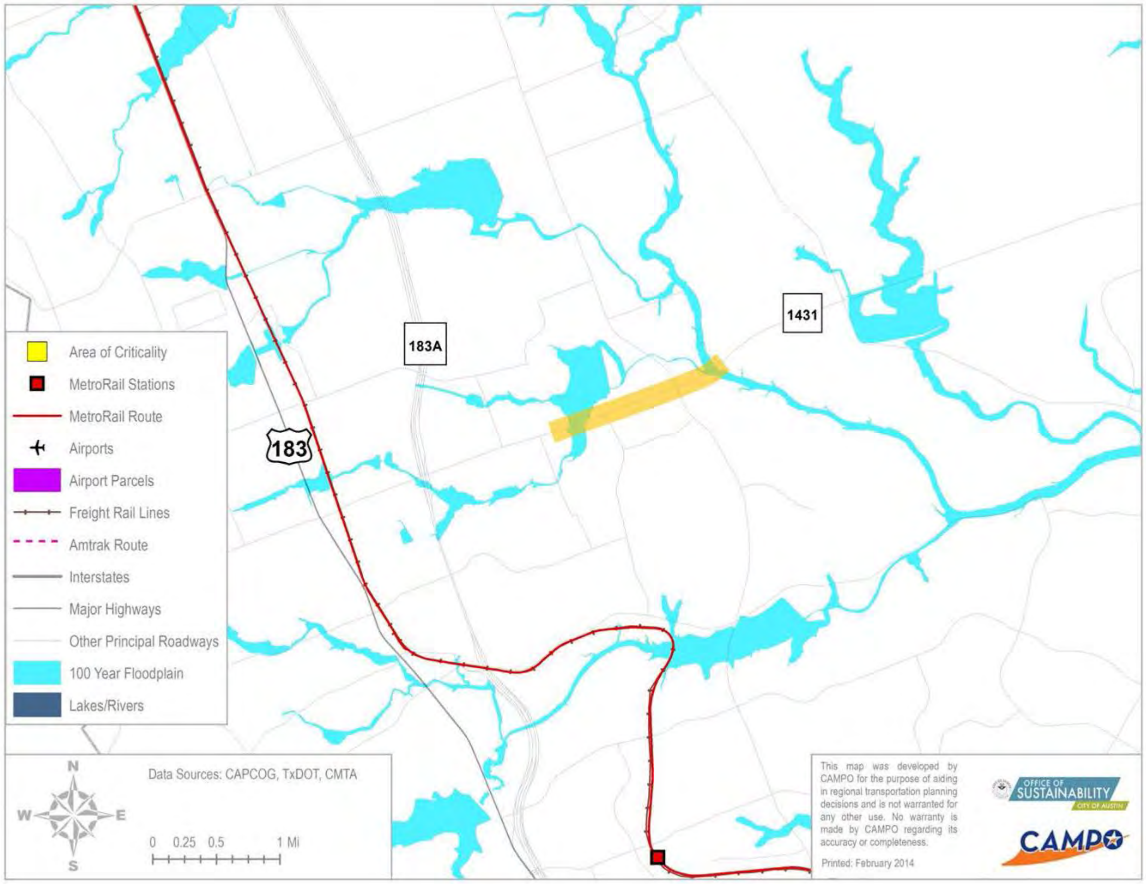
- The facility provides an important east-west connection between two of the region's major north-south freeways (I-35 and US 183);
- The asset, a Farm to Market road, is not a designated evacuation route;
- The AADT of this location (30,000) is moderate relative to other roadways in the CAMPO area, which indicates that the asset plays an important role in regional mobility, but temporary functional redundancy may exist;
- Daily truck traffic volumes of just over 1,000 are comparatively low; and
- The detour length is unknown (associated bridge not listed in the National Bridge Inventory).

Flooding

Exposure

FM 1431 at Brushy Creek/Spanish Oak Creek is expected to have negligible flood exposure. Although the bridge is adjacent to the FEMA 100-year floodplain, it is situated approximately 10 feet above the floodplain and thus not expected to be overtopped even during heavy rain events. The location of this asset relative to the 100-year floodplain is shown in Figure D-16.

Figure D-16 Proximity to 100-Year Floodplain, FM 1431 at Brushy Creek/Spanish Oak Creek



Sensitivity

Because the bridge is not expected to be exposed, the sensitivity of the bridge to flooding is not relevant to the risk rating.

Impact and Risk

FM 1431 at Brushy Creek/Spanish Oak Creek is not expected to experience flooding expects, except under extremely severe conditions. If it were to occur, flooding could render the roadway impassable for the duration of the flood, affecting up to 30,000 auto trips and 1,050 trucks per day.

The risk of flooding—a function of the likelihood and consequences of flooding events—is projected to be **None** for this facility.

Drought

Exposure

Like all assets, FM 1431 at Brushy Creek/Spanish Oak Creek is expected to have high exposure to droughts. Drought is already a recurring issue in central Texas. At least one climate model projects that summer soil moisture—an indicator of drought—may decrease by 4 to 10 percent by mid-century. These changes would exacerbate existing drought patterns and mean the region is very likely to experience drought in the future.

Sensitivity

Surface soil maps indicate that FM 1431 at Brushy Creek/Spanish Oak Creek is built over medium plasticity soils (plasticity index of 35 on a scale of 0 to 58). High plasticity soils are prone to shrink and swell as soil moisture changes, which can degrade pavement, causing longitudinal cracking and edge drop-off.

The available data on soil plasticity therefore suggests this asset is moderately sensitive to damage from drought. However, more detailed site-specific soil analysis would be needed to confirm these findings, particularly since the available dataset does not factor in the depth of soils.

Impact and Risk

Drought can cause increased annual maintenance costs due to an increase in pavement cracking.

The risk of drought to this asset is projected to be **Moderate**. The likelihood of drought is high, and the medium plasticity soils suggest drought could also mean moderate consequences (related primarily to deterioration) for the intersection.

Extreme Heat

Exposure

Like all assets, FM 1431 at Brushy Creek/Spanish Oak Creek is expected to have high exposure to extreme heat. Climate models are in general agreement that the region will experience more extremely hot days in the future, with one model projecting that the region may experience an additional 34 days per year above 100°F by mid-century, on average. In addition, average 7-day maximum temperatures (a key pavement mix factor) may increase by about 4°F by mid-century.

Sensitivity

Although FM 1431 at Brushy Creek/Spanish Oak Creek is expected to experience very hot conditions, the asset is rated as having low sensitivity to heat, meaning heat is not likely to damage the roadway. Factors influencing this rating include pavement binder used and volume of truck traffic. The pavement binder used for the asset (PG 64-22, according to design guidelines) is designed to withstand extended temperatures of 108°F, which is still higher than the projected mid-century average 7-day maximum temperatures of about 101°F. Further, the asset has relatively low truck traffic volume (1,050 trucks per day), so truck traffic is not expected to exacerbate heat-related damage.

Impact and Risk

FM 1431 at Brushy Creek/Spanish Oak Creek is expected to experience minimal or no impact from extreme heat. Despite being highly exposed to hot temperatures, the roadway is designed to withstand those extremes.

The risk posed by extreme heat to this asset is projected to be **Low**. Although the likelihood of extreme temperatures is high, the consequences are expected to be minimal.

Wildfire

Exposure

FM 1431 at Brushy Creek/Spanish Oak Creek is expected to have moderate exposure to wildfire. The asset is currently located in an area of low-moderate Wildfire Threat,[35] and wildfire likelihood is expected to increase as summer soil moisture declines.

Sensitivity

FM 1431 at Brushy Creek/Spanish Oak Creek, like all assets studied, was initially rated as having moderate sensitivity to wildfire. However, vulnerability assessment focus group participants indicated that wildfires could have a larger impact on this asset (and the population it serves). Because the area near Round Rock is growing rapidly, stakeholders anticipate this location could become a future choke point for north-west and east-west travel. This, in turn, could increase the risk posed by wildfire, since it could compromise evacuation. As a result, the asset received a high sensitivity rating.

Impact and Risk

Wildfire around FM 1431 at Brushy Creek/Spanish Oak Creek presents a risk to the nearby population. Wildfires are likely in the area, and the intersection could serve as a future "choke point" in wildfire evacuations.

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[35] Wildfire Threat is defined by the Texas Wildfire Risk Assessment Portal (TxWRAP) as "the likelihood of a wildfire occurring or burning into an area."

Although the risk of wildfire to the intersection—a function of the likelihood and consequences of wildfire events—is moderate today, that risk is projected to increase over time as population density increases in the area. Risk may also increase as the region experiences more extreme heat and drought, and an increased chance of wildfire ignition. This asset is therefore considered to have a **Moderate-High** risk from wildfires.

Extreme Cold and Ice

Exposure

Like all assets, FM 1431 at Brushy Creek/Spanish Oak Creek is expected to have low exposure to extreme cold and icing events. In today's climate, icing events (days where temperatures are below freezing with non-trace precipitation) occur about twice per year, and they are projected to become even less frequent by mid-century, potentially occurring about 1 day per year, on average.

Sensitivity

This asset has low sensitivity to icing events. Though it is not as likely to ice as elevated roadway segments or bridges, the roadway may ice when conditions are right. Icy conditions cause severe traffic disruptions. These conditions last only for a few hours, however, and do not cause long-term physical damage to the roadway.

Impact and Risk

Overall expected impacts from icing on FM 1431 at Brushy Creek/Spanish Oak Creek are low. Anticipated impacts include congestion because of slow traffic for the duration of the icing event. Icing events tend to last a few hours.

The risk of extreme cold to this asset is **Low**. The likelihood of icing is low, while the consequences are low-moderate disruption.

D.7 Asset #8. Intersection of US 281 and SH 29 (Burnet County)

Adaptive Capacity

The region's capacity to adapt to temporary disruption of the intersection of US 281 and SH 29 in Burnet County is moderate. This rating takes the following into account:

- The asset is a critical access route that provides intra-regional connectivity.
- The asset is a major undivided arterial; loss of the asset could severely disrupt activity in a portion of the CAMPO region.
- The average detour length[36] when the intersection is impassable is 35 miles (indicating low redundancy serving the area and, thus, lower adaptive capacity).
- Traffic volumes are low (although specific data on AADT and truck traffic volumes were not available), indicating higher adaptive capacity since fewer trips would be disrupted or rerouted.

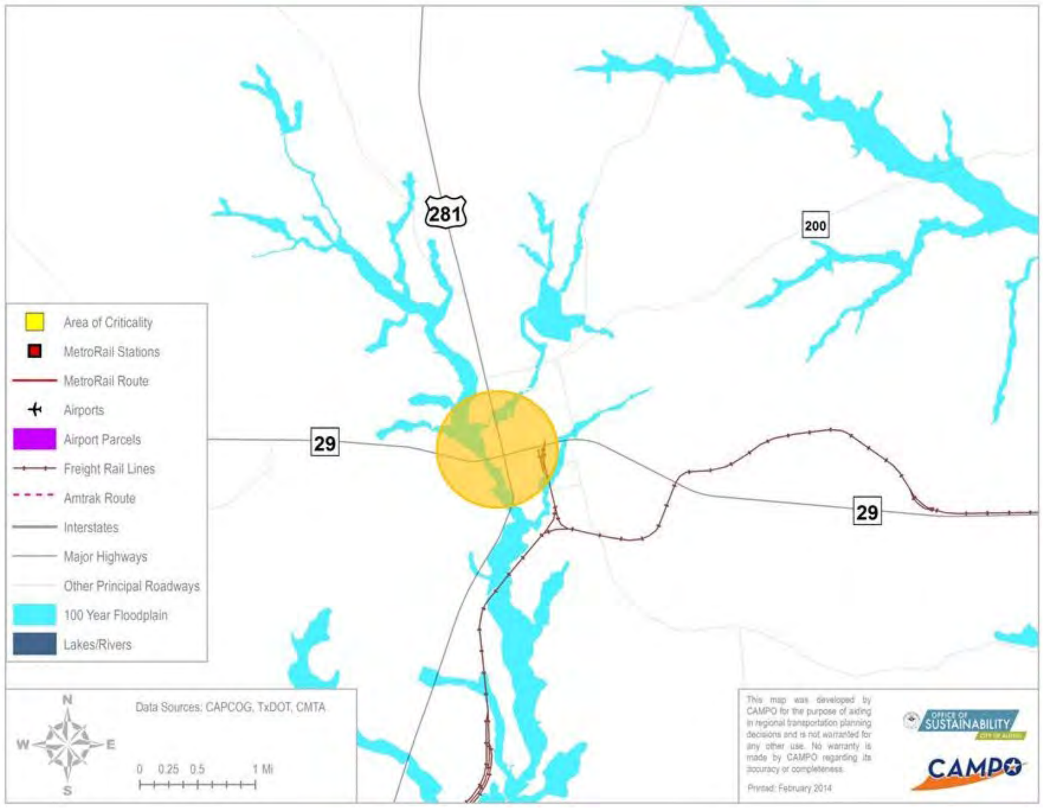
Flooding

Exposure

Limited information is available about flooding exposure at the intersection of US 281 and SH 29 in Burnet County. As shown in Figure D-17, all four approaches to the intersection cross the 100-year FEMA floodplain. The vertical proximity of the approaches to the floodplain is unknown. Therefore, the exposure rating is based on anecdotal evidence of flood risk. Vulnerability assessment focus group participants noted that the intersection floods "semi-regularly" and during rains of about 3-4 inches. When compared to the likelihood of flooding for other assets studied, this would equate to high exposure.

[36] Detour length was not available for this intersection from the National Bridge Inventory, so a supplementary analysis was conducted to estimate redundancy. The estimated average detour length of 35 miles is the average of four scenarios that would normally take a traveler through the intersection: approaching from the west (85 miles), approaching from the north (25 miles), approaching from the east (6 miles), and approaching from the south (24 miles).

Figure D-17 Proximity to 100-Year Floodplain, US 281 and SH 29 in Burnet County



Sensitivity

The intersection of US 281 and SH 29 in Burnet County is expected to have high sensitivity to flooding. The asset could experience major disruptions (on the order of days) or moderate damage during a flood event. This rating is based on the asset's 24-hour precipitation design threshold of 7.64 inches (25-year event). This is a relatively low threshold compared to events the asset may experience, and suggests potentially high sensitivity.

Data on other flooding sensitivity indicators, such as scour rating and inundation velocity, were not available for this asset.

Impact and Risk

Flooding at this intersection could cut off a major access route to Burnet County from Austin (and vice versa). A severe, fast-moving flood could also washout the roadway and require longer-term repairs.

Based on the available information, the risk of flooding—a function of the likelihood and consequences of flooding events—is **Moderate-High** for the intersection. Flooding is possible at the intersection, and the consequences of flooding are projected to be moderate disruptions or minor damage.

Drought

Exposure

The intersection of US 281 and SH 29 in Burnet County, like all infrastructure in the study area, is expected to have high exposure to drought. Drought is already a recurring issue in central Texas, and the climate model used in this study projects that summer soil moisture—an indicator of drought—may decrease by 4 to 10 percent by mid-century. These changes would exacerbate existing drought patterns and mean the region is very likely to experience drought in the future.

Sensitivity

Though the CAMPO area may experience drought, the intersection is rated as having low sensitivity to drought (meaning drought is not likely to affect the asset). This rating is based on the expected plasticity of the soil around the asset. Though precise information on soil plasticity was not available, the intersection is located west of the Balcones Fault, which means it is unlikely to have the highly expansive clay soils found elsewhere in the region. Soils with low plasticity are not likely to expand or contract dramatically with changes in soil moisture.

Impact and Risk

The intersection of US 281 and SH 29 has low sensitivity to drought.

The risk of drought to this asset is projected to be **Low**. Although the likelihood of drought is high, the anticipated consequences would be minimal.

Extreme Heat

Exposure

Like all assets, the intersection of US 281 and SH 29 in Burnet County is expected to have high exposure to extreme heat. The climate model used in this study projects that the region may experience 34 additional days per year above 100°F by mid-century, on average. In addition, average 7-day temperatures may increase by about 4°F by mid-century. These variables indicate that infrastructure in the CAMPO area is very likely to experience extreme heat events in the future.

Sensitivity

Although the intersection is expected to experience very hot conditions, the asset is rated as having low sensitivity to heat, meaning heat is not likely to damage the roadway. Factors influencing this rating include the typical pavement binder used and volume of truck traffic. The pavement binder usually used for this class of asset (PG 64-22) is designed to withstand extended temperatures of 108°F, which is higher than the projected mid-century 7-day average maximum temperatures of 101°F. Further, while a precise figure for truck traffic volume was not available for the asset, local experts indicate the asset has relatively low truck traffic volume. Truck traffic is, thus, not expected to exacerbate heat-related damage.

Impact and Risk

The intersection has low sensitivity to extreme heat and, thus, is expected to experience only minimal impacts. When extreme heat does affect infrastructure, it can accelerate pavement deterioration and increase maintenance costs.

The risk of extreme heat to the intersection is **Low**. Though the likelihood of extreme heat is high, the consequences are expected to be minimal.

Wildfire

Exposure

The intersection of US 281 and SH 29 in Burnet County has moderate exposure to wildfire. The asset is currently located in an area of low-moderate Wildfire Threat,[37] and wildfire likelihood is expected to increase as summer soil moisture declines.

Sensitivity

This intersection was rated as having moderate sensitivity to wildfire. Wildfires cause temporary service disruptions for their duration, but do not generally cause significant long-term physical damage to roadways.

Impact and Risk

Wildfire could cause temporary disruption, and the destruction of guardrail and sign posts for this asset.

The risk of wildfire to the intersection is **Moderate**. Although the asset is not particularly exposed to wildfire, the potential consequence would be moderate disruption of service on the asset.

Extreme Cold and Ice

Exposure

Like all assets, the intersection of US 281 and SH 29 in Burnet County is expected to have low exposure to extreme cold and icing events. In today's climate, icing events (days where temperatures are below freezing with non-trace

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[37] Wildfire Threat is defined by the Texas Wildfire Risk Assessment Portal (TxWRAP) as "the likelihood of a wildfire occurring or burning into an area."

precipitation) occur about twice per year, and they are projected to become even less frequent by mid-century, occurring about 1 day per year, on average.

Sensitivity

This intersection is expected to have low sensitivity to extreme cold. Though it is not as likely to ice as elevated roadway segments or bridges, the roadway may ice when conditions are right. Icy conditions cause traffic disruptions, though these conditions last only for a few hours and do not cause long-term physical damage to the roadway.

Impact and Risk

Infrequent icing events could impact the intersection of US 281 and SH 29 by temporarily creating traffic congestion and hazardous driving conditions.

The risk of extreme cold—a function of the likelihood and consequences of cold events—to this asset is **Low**. Although the likelihood of icing is low, when it happens it can cause moderate disruption.

D.8 ASSET #9. US 183 NORTH OF LOCKHART

Adaptive Capacity

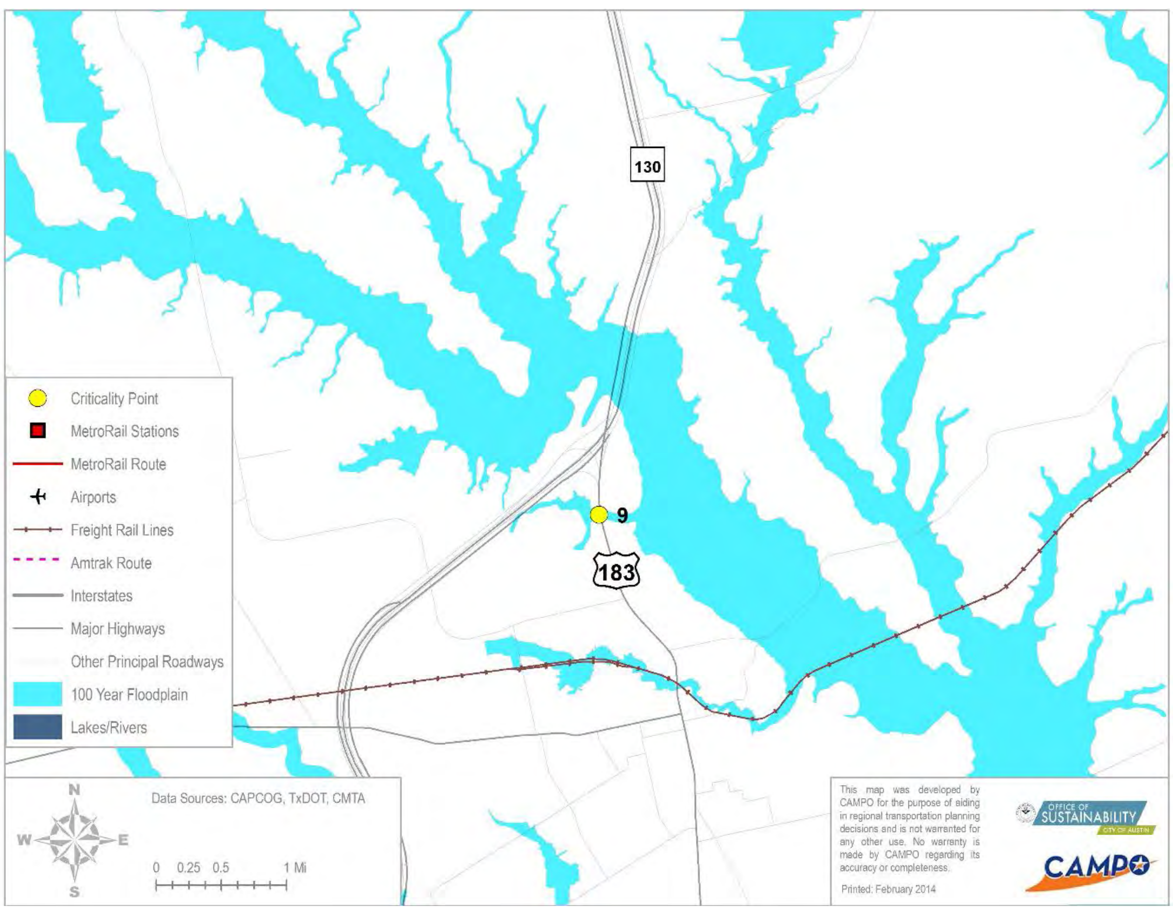
The CAMPO region's capacity to adapt to temporary disruption of the asset is low. The primary factor driving this rating is the road's function as an evacuation route. Damage to an evacuation route could have higher consequences for the region if the roadway is damaged or otherwise rendered unusable while needed for an evacuation.

Flooding

Exposure

US 183 north of Lockhart is expected to have very low exposure to floods. Although the segment is located within the horizontal extent of the FEMA 100-year floodplain (Figure D-18), it is elevated about two feet above 100-year flood depths. Thus, although flooding is possible at the segment, it likely would be rare.

Figure D-18 Proximity to 100 Year Floodplain, US 183 North of Lockhart



Sensitivity

If flooded, this segment of US 183 could be highly sensitive to damage. The segment is classified as a Minor Arterial. Assuming it was designed to TxDOT standards for its functional class, the segment was built to withstand about six inches of rain in 24 hours (the present-day 10-year event). This is a relatively low design standard compared to other assets studied, and suggests that flooding could cause damage if it were to occur. Further, the segment is located in an area of moderate Wildfire Threat. Flooding, debris, and erosion can be much worse in the aftermath of a fire.

Impact and Risk

If flooding were to occur at this segment of US 183, it could disrupt traffic (up to 13,200 auto trips and 1,922 trucks per day). More severe flooding could cause erosion or wash out the roadway.

The risk of flooding—a function of the likelihood and consequences of flooding events—is **Low-Moderate** for this asset. The likelihood of flooding is very low, but the consequences could be high given the high sensitivity and low adaptive capacity of the asset.

Drought

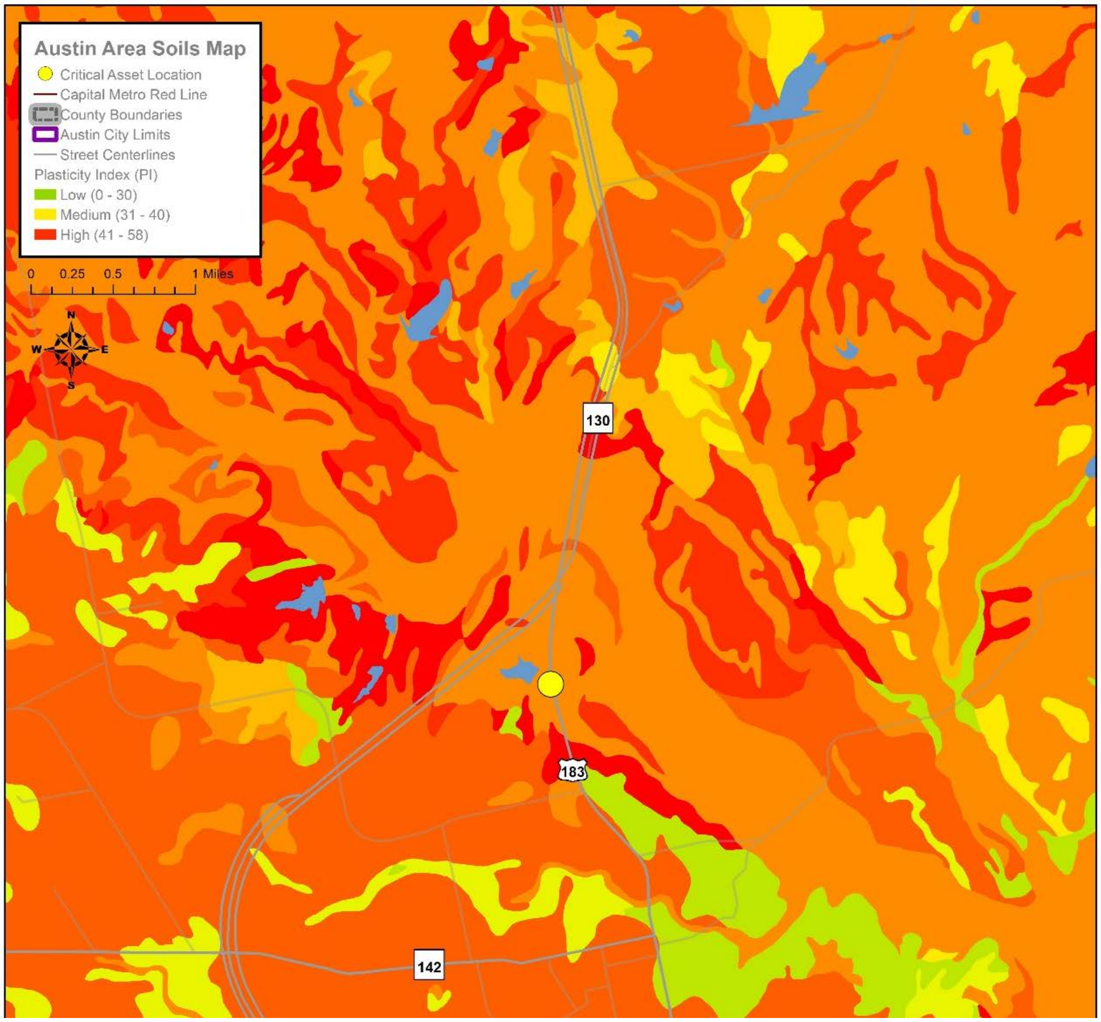
Exposure

US 183 north of Lockhart is expected to have a high exposure to drought. Drought is already a recurring issue in central Texas, and the climate model used for this study projects that summer soil moisture—an indicator of drought—may decrease by 4 to 10 percent by mid-century. These changes would exacerbate existing drought patterns and mean the region is very likely to experience drought in the future.

Sensitivity

This asset is estimated to have high sensitivity to drought. This rating is based on the high soil plasticity at this location (plasticity index of 44, on a scale of 0 to 58) (see Figure). High plasticity soils are more prone to expansion and contraction with changes in soil moisture, and thus infrastructure built on these soils may be more likely to be damaged during droughts.

Figure D-19 City of Austin Soil Plasticity Index Map, US 183 North of Lockhart



Impact and Risk

Roads built over high plasticity soils can experience longitudinal cracking and pavement degradation because of drought. Pavement damage tends to be particularly pronounced along the pavement edge. This type of damage is problematic for an evacuation route, which may rely on the shoulder to provide an additional traffic lane during an evacuation. Drought-related pavement damage can increase annual maintenance costs to repair damaged pavement.

The risk of drought to US 183 north of Lockhart is **High**. The likelihood of drought is high, and the consequences could also be high (due to the possibility of pavement damage on an evacuation route).

Extreme Heat

Exposure

Like all assets, US 183 north of Lockhart is expected to have high exposure to extreme heat. The climate model used for this study projects that the region may experience 34 additional days per year above 100°F by mid-century, on average. In addition, average 7-day maximum temperatures may increase by about 4°F by mid-century. These variables indicate that infrastructure in the CAMPO area is very likely to experience extreme heat events in the future.

Sensitivity

Available information suggests this asset would have low sensitivity to extreme heat. The pavement binder used (PG 64-22, according to design guidelines) is designed to withstand extended (average 7-day maximum) temperatures of approximately 108°F—a threshold projected to be exceeded rarely (perhaps once during the asphalt lifecycle). Further, the roadway carries relatively low truck traffic volumes (about 1,922 trucks per day); truck traffic is, thus, not likely to exacerbate heat-related damage.

Impact and Risk

Because US 183 north of Lockhart is not expected to be sensitive to extreme heat, anticipated impacts are minimal. Heat-related damage, if it were to occur, could include pavement rutting and cracking. This damage does not disrupt traffic, but could increase costs or reduce the useful life of the pavement.

The risk of extreme heat—a function of the likelihood and consequences of extreme heat events—to this asset is **Low-Moderate,** a rating heavily influenced by the low degree of adaptive capacity (due to the facility's status as an evacuation route). The likelihood of extreme heat is high, but the anticipated consequences are minimal. Therefore, the risk is present, but might be considered negligible at this time.

Wildfire

Exposure

US 183 north of Lockhart is expected to have high exposure to wildfire. The asset is currently located in an area of moderate Wildfire Threat,[38] and wildfire likelihood is expected to increase if summer soil moisture declines.

[38] Wildfire Threat is defined by the Texas Wildfire Risk Assessment Portal (TxWRAP) as "the likelihood of a wildfire occurring or burning into an area."

Sensitivity

US 183 north of Lockhart was rated as having relatively low sensitivity to wildfire. Wildfires cause temporary service disruptions for their duration, but do not generally cause much long-term physical damage to roadways. In addition, the road segment is located in an area with a Values Response Index[39] of 0, meaning that there is virtually no potential impact on assets (a rating based primarily on nearby housing density).

Impact and Risk

Nearby wildfire could temporarily prevent use of the roadway, and could even destroy guardrail and sign posts for this asset.

Overall, the risk of wildfire to this segment of US 183 north of Lockhart is estimated as **Moderate-High**. Wildfires are relatively likely in the area. Although the roadway itself is considered minimally sensitive to wildfire, consequences could be high if a wildfire occurred when the route was needed for evacuation.

Extreme Cold and Ice

Exposure

Like all assets, US 183 north of Lockhart is expected to have low exposure to extreme cold and icing events. In today's climate, icing events (days where temperatures are below freezing with non-trace precipitation) occur about twice per year, and they are projected to become even less frequent by mid-century, occurring about 1 day per year, on average.

Sensitivity

This asset has low sensitivity to icing events. Though it is not as likely to ice as elevated roadway segments or bridges, the roadway may ice when conditions are right. Icy conditions could cause severe traffic disruptions, though these conditions last only for a few hours and do not cause long-term physical damage to the roadway.

Impact and Risk

Overall, minor impacts are expected for extreme cold. Icing events are rare, and their effects are temporary.

The overall risk of extreme cold for US 183 north of Lockhart is Low-Moderate. Although the likelihood of icing is low, the consequences could be higher if an icing event occurred when the route was needed for evacuation.

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[39] Values Response Index is defined by TxWRAP as "the potential impact of a wildfire on values or assets."

D.9 Asset #10. SH 80 (San Marcos Highway) at the Blanco River

Adaptive Capacity

The region's capacity to adapt to temporary disruption of this segment of San Marcos Highway is estimated to be relatively high. This rating is based on the following:

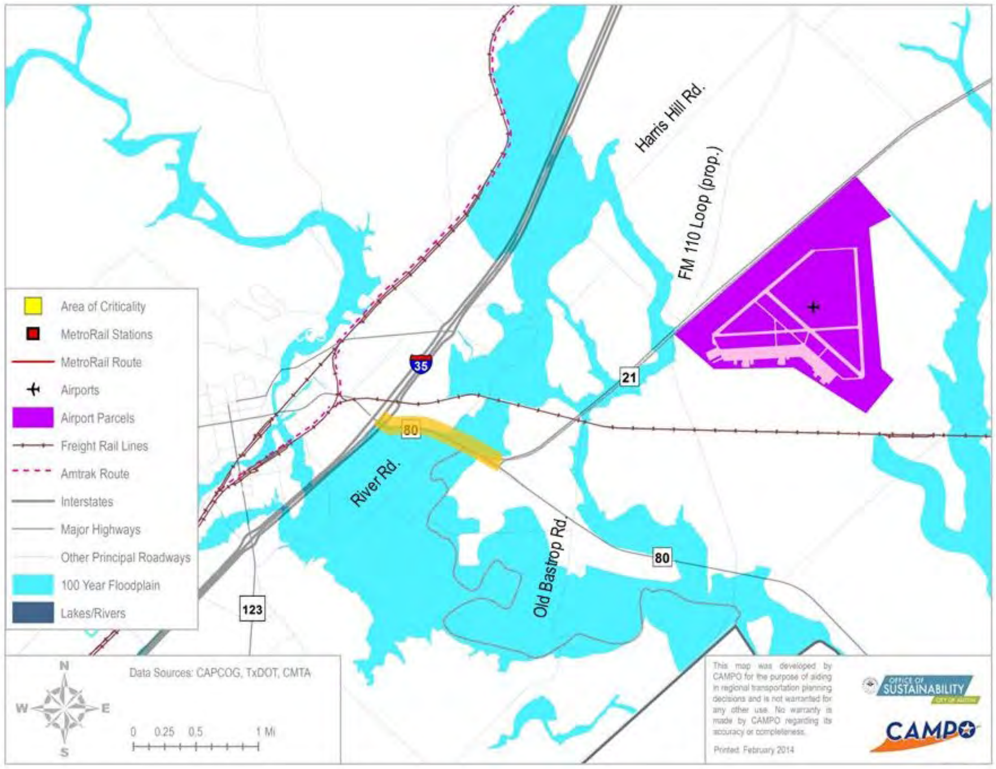
- The asset is classified as a major undivided arterial, which indicates that loss of the asset could severely disrupt activity in the immediate area (indicating low adaptive capacity).
- The roadway's primary function is to provide access to San Marcos Airport, a secondary airport in the CAMPO area (indicating moderate adaptive capacity.
- The AADT of 9,500 is relatively low compared to other roadways in the CAMPO area (indicating higher adaptive capacity, since fewer trips would be disrupted).
- Daily truck traffic volume of 1,112 (indicating higher adaptive capacity due to low freight traffic).
- Detour length of 6.84 miles indicates moderate redundancy, which improves the capacity of the region to adapt to disruption of the asset.

Flooding

Exposure

San Marcos Highway is estimated to have moderate exposure to floods. Flooding exposure was estimated based on the asset's vertical proximity to the 100-year floodplain. San Marcos Highway lies approximately one foot *below* the 100-year floodplain. If today's 100-year rain event were to occur more frequently in the future, the asset could be inundated more often. Figure D-20 shows the position of the asset relative to the FEMA 100-year floodplain (horizontal extent).

Figure D-20 Proximity to 100-Year Floodplain, San Marcos Highway at Blanco River



Sensitivity

San Marcos Highway is estimated to be moderately sensitive to flooding. Flooding could cause traffic disruptions on the order of hours or minor structural damage to the roadway. This rating is based on two factors:

- The default 24-hour precipitation design threshold for this functional class is 7.64 inches (the 25-year event), a relatively low threshold (compared to the 100-year event, for example). This suggests potentially high sensitivity, especially as heavy rain events could become more intense in the future.
- The bridge has no scour issues (bridge scour rating is 8), which indicates it may not experience damage from floodwaters. This factor lowers the overall sensitivity rating.

Impact and Risk

The impacts of flooding on San Marcos Highway could range from temporary roadway inundation (preventing traffic flow and access to the San Marcos Airport) to more significant flooding damage (e.g., washouts). Flooding of this asset could disrupt up to 9,500 auto trips per day (based on current traffic volumes).

The risk of flooding at San Marcos Highway—a function of the likelihood and consequences of flooding events—is **Moderate**. The likelihood of flooding is moderate given its location, while the consequences of flooding could include temporary disruptions to airport access.

Drought

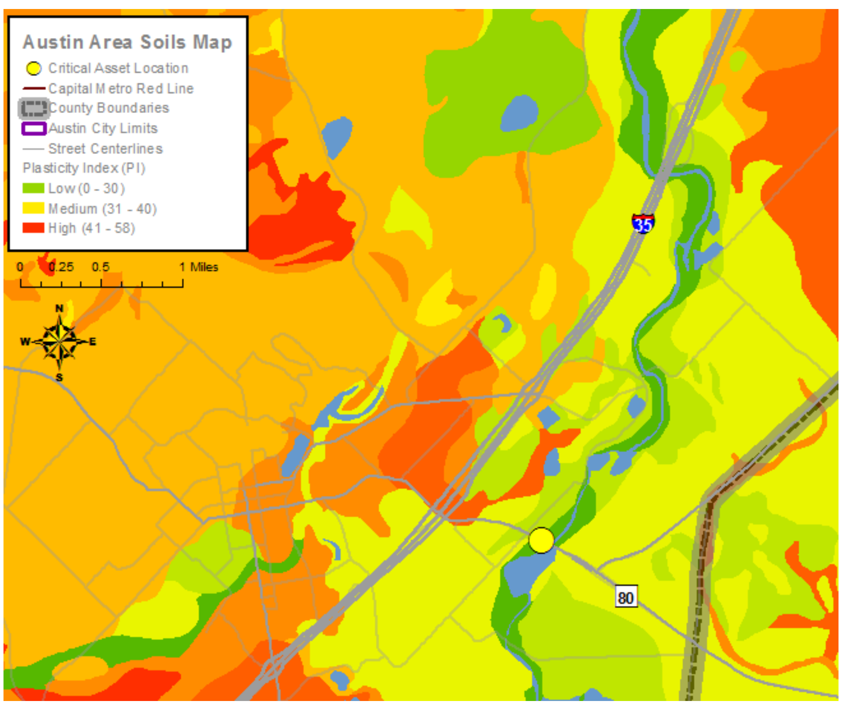
Exposure

San Marcos Highway, like all infrastructure in the study area, is expected to have high exposure to drought. Drought is already a recurring issue in central Texas, and the climate model used in this study projects that summer soil moisture—an indicator of drought—may decrease by 4 to 10 percent by mid-century. These changes would exacerbate existing drought patterns and mean the region is very likely to experience drought in the future.

Sensitivity

Though the CAMPO area may experience drought, San Marcos Highway is estimated to have very low sensitivity to drought (i.e., drought is not likely to affect the asset). This rating is based on the plasticity of soils in the vicinity of the asset. The plasticity index of 4 (on a scale of 0 to 58) means the soils have very low plasticity, and thus are not likely to expand or contract dramatically with changes in soil moisture (see Figure D-21).

Figure D-21 City of Austin Soil Plasticity Index Map, San Marcos Highway



Impact and Risk

This segment of San Marcos Highway is estimated to have low sensitivity to drought.

The risk of drought to this asset is **Low**. Although the likelihood of drought is high, the anticipated consequences would be minimal.

Extreme Heat

Exposure

Like all assets, San Marcos Highway is expected to have high exposure to extreme heat. The climate model used in this study projects that the region may experience an additional 34 days per year above 100°F by mid-century, on average. In addition, average 7-day maximum temperatures could increase by about 4°F by mid-century. These variables indicate that infrastructure in the CAMPO area is very likely to experience extreme heat events in the future.

Sensitivity

Although San Marcos Highway is expected to experience very hot conditions, the asset is rated as having low sensitivity to heat, meaning heat is not likely to damage the asset. Factors influencing this rating include pavement binder used and volume of truck traffic. The pavement binder used for the asset (PG 64-22, according to design guidelines) is designed to withstand extended temperatures of 108°F, which is still higher than the projected mid-century average 7-day maximum temperatures of about 101°F. Further, the asset has relatively low truck traffic volume (1,112 trucks per day), so truck traffic is not expected to exacerbate heat-related damage.

Impact and Risk

The roadway has low sensitivity to extreme heat and therefore is expected to experience only minimal impacts when it is exposed. When extreme heat does affect infrastructure, it can accelerate pavement deterioration and increase maintenance costs.

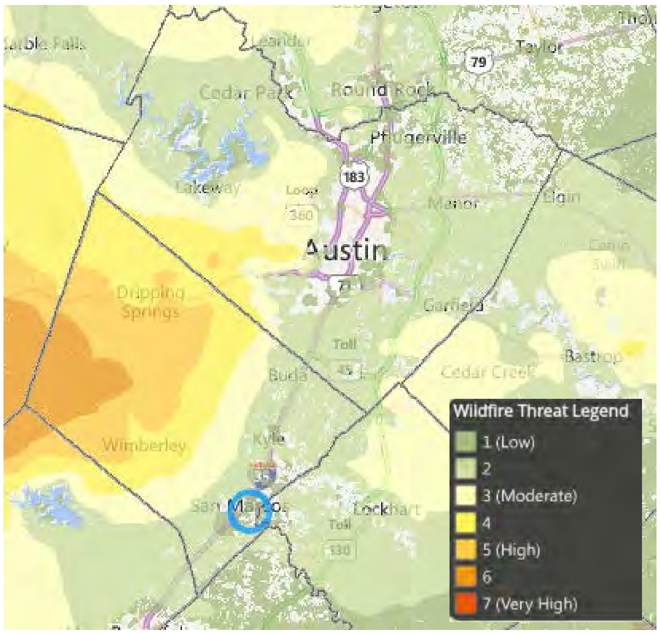
The risk of extreme heat to San Marcos Highway is **Low**. Though the likelihood of extreme heat is high, the consequences are expected to be minimal.

Wildfire

Exposure

San Marcos Highway has moderate exposure to wildfire. The asset is currently located in an area of low Wildfire Threat (Figure D-22),[40] and wildfire likelihood is expected to increase as summer soil moisture declines.

Figure D-22 Wildfire Threat, San Marcos Highway at Blanco River



Source: Texas Wildfire Risk Assessment Portal, Wildfire Threat layer

Sensitivity

San Marcos Highway is estimated to have relatively moderate sensitivity to wildfire. Wildfires cause temporary service disruptions for their duration, but do not generally cause much long-term physical damage to roadways. The road segment is located in an area with a Values Response Index[41] of -4, meaning that there is a relatively high potential impact on assets (a rating based primarily on nearby housing density).

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[40] Wildfire Threat is defined by the Texas Wildfire Risk Assessment Portal (TxWRAP) as "the likelihood of a wildfire occurring or burning into an area."

[41] Values Response Index is defined by TxWRAP as "the potential impact of a wildfire on values or assets."

Impact and Risk

Nearby wildfire could temporarily prevent use of the roadway, and could even destroy guardrail and sign posts for this asset.

Overall, the risk of wildfire to San Marcos Highway is **Moderate**. Wildfires are possible near the asset and could cause temporary disruptions of service on the roadway.

Extreme Cold

Exposure

Like all assets, San Marcos Highway is expected to have low exposure to extreme cold and icing events. In today's climate, icing events (days where temperatures are below freezing with non-trace precipitation) occur about twice per year, and they are projected to become even less frequent by mid-century, occurring about 1 day per year, on average.

Sensitivity

When icing days do occur, however, San Marcos Highway is susceptible to icing, which can temporarily close the roadway. This segment of the roadway is elevated, and thus more likely to ice than non-elevated roadways. This feature indicates the segment is likely to be moderately sensitive to icing. Though the roadway may ice when conditions are right and icy conditions cause severe traffic disruptions, these conditions last only for a few hours and do not cause long-term physical damage to the roadway.

Impact and Risk

Infrequent icing events could impact San Marcos Highway by temporarily creating traffic congestion and hazardous driving conditions.

The risk of extreme cold—a function of the likelihood and consequences of cold events—to this asset is **Low**. Although icing is unlikely, when it happens it can cause moderate, although temporary, disruption.

E. Appendix: VAST Indicator and Scoring Information

E.1 Exposure Indicators

Table E-1 Exposure Indicator Details

Stressor	Indicator	Data Source	Indicator Value*	Score	Rationale	Weight**
Flooding	Modeled available freeboard for future 50-year storm	CS analysis of Vieux VFlo model results	> 2 ft	0.5	The less freeboard between the bridge and floodwaters under the 50-year flooding scenario, the more likely the asset is to flood. 50-year storm used because data are available for all assets studied using the VFlo model.	100% (only one indicator used per asset, depending on data available)
			1 – 2 ft	1		
			0 – 1 ft	2		
			-5 – 0 ft	3		
			-10 – -5 ft	4		
	Vertical proximity to the 100-year floodplain	FEMA SFHAs and Digital Elevation Model	> 2 ft	NE	Proxy for available freeboard if VFlo modeling not available. Scores for bins shifted to reflect difference between 50- and 100-year rain events.	
			1 – 2 ft	0.5		
			0 – 1 ft	1		
			-5 – 0 ft	2		
			-10 – -5 ft	3		
	Demonstrated past exposure (anectotal)	Workshop and focus group participants	Floods "semi regularly" (Asset #8)	3	Assets that have flooded repeatedly in the past have demonstrated their exposure to this stressor. [Note, this indicator is only used for assets with no data for the other indicators].	
			Subject to flooding in the past (Asset #3)	3		
Drought	Projected change in average summer soil moisture	Dr. Kerry Cook, based on National Center for Atmospheric Research (NCAR) Weather Research and Forecasting Model	-4%	3	Assume baseline drought exposure is relatively high based on past experience with drought, and change in soil moisture exacerbates this.	100%
			-10%	4		
Extreme Heat	Projected change in number of days per year ≥ 100°F	Dr. Kerry Cook, based on NCAR Weather Research and Forecasting Model	0-7	1	Assume each week of days above 100°F represents an additional level of exposure (long-term average number of days per year > 100°F is 12, from 1898-present)	50%
			7-14	2		
			14-21	3		
			≥21	4		

Stressor	Indicator	Data Source	Indicator Value*	Score	Rationale	Weight**
	Change in average 7-day maximum temperature (for pavements)	Dr. Kerry Cook, based on NCAR Weather Research and Forecasting Model	0-1 °F	1	These changes are large relative to the long-term average and the difference in pavement design thresholds (binders are separated by about 5.6 degrees)	50%
			1-2 °F	2		
			2-3 °F	3		
			≥ 3 °F	4		
Wildfire	Wildfire Threat	Texas Wildfire Risk Assessment Portal (TxWRAP)	0	NE	Wildfire Threat is defined as the likelihood of a wildfire occurring or burning into an area.	50%
			1 (Low)	1		
			2 (Low/Moderate)	1		
			3 (Moderate)	2		
			4 (Moderate/High)	2		
			5 (High)	3		
			6 (High/Very High)	4		
			7 (Very High)	4		
	Projected change in average summer soil moisture	Dr. Kerry Cook, based on NCAR Weather Research and Forecasting Model	-4%	3	Reductions in soil moisture exacerbate existing wildfire threat	50%
			-10%	4		
Extreme Cold (Icing)	Projected change in number of "ice days" (days with both freezing temperatures and non-trace precipitation) per year	Dr. Kerry Cook, based on NCAR Weather Research and Forecasting Model	1	1	Ice days may become less common in the future as temperature warm. They are rare, with 2 days per year in the baseline time period, projected to become just 1 day per year.	100%
			2	1		

* Exposure indicators were scored on a scale of 0 (not exposed) to 4 (highest exposure). The indicators were broken down into the most appropriate number of scoring bins possible given the available dataset. For example, some indicators are divided into only two bins because there were only two data values.

** If data are not available for any indicator, its weight gets distributed to remaining indicators proportionally.

E.2 Sensitivity Indicators

Table E-2 Highway Sensitivity Indicator Details

Stressor	Indicators	Data Source	Indicator Value*	Score	Rationale	Weight**
Flooding	24-hour precipitation design threshold	TxDOT Hydraulics Design Manual, Table 4-2 (based on Functional Classification and structure type)	10.2" (100-yr)	1	Roadways or bridges designed to lower standards are more likely to suffer damage.	25%
			8.9" (50-yr)	2		
			7.6" (25-yr)	3		
			< 25-yr	4		
	Scour Criticality	National Bridge Inventory (NBI), Item 113	8 (no scour issues)	1	Bridges with past scour may be more prone to future scour, though sensitivity is currently low.	25%
			7 (formerly scour critical, but fixed)	2		
	Average inundation velocity in future 50-year rain event	Vieux VFlo model results	0-5 ft/sec	1	The faster floodwaters flow, the more likely they are to cause damage. TxDOT staff indicated floodwaters start to cause damage around 5 ft/second.	25%
			5-10 ft/sec	2.5		
			≥ 10 ft/sec	4		
	Wildfire Threat	TxWRAP	1 (Low)	N/A	Flooding, debris, and erosion can be much worse in the aftermath of a fire. Therefore, areas prone to wildfires may be more sensitive to damage from flooding. This indicator is only included if Wildfire Threat increases flooding sensitivity. This indicator is not included for assets with low Wildfire Threat.	25%
			2 (Low/Moderate)	N/A		
			3 (Moderate)	2		
			4 (Moderate/High)	2		
			5 (High)	3		
			6 (High/Very High)	4		
			7 (Very High)	4		
Drought	Soil Plasticity Index	City of Austin	0-30 (Low)	1	Assets located on high plasticity soils are more likely to suffer damage during droughts. Soil plasticity index bins provided by City of Austin Street and Bridge Operations.	100%
			31-40 (Medium)	2		
			41-58 (High)	4		

Stressor	Indicators	Data Source	Indicator Value*	Score	Rationale	Weight**
Extreme Heat	Pavement binder used	TxDOT	PG 64-22	1	Pavements using less heat-tolerant binders are more likely to experience rutting during heat waves. Temperature-related damage causes pavement rutting and cracking.	25%
			PG 70-22	1		
			PG 76-22	1		
	Truck traffic volume	TxDOT	0-1,000	0.5	Heavy traffic increases the likelihood of pavement damage during heat waves. Scoring thresholds set based on the range of freight traffic within the CAMPO study area. Scoring ranges applied only if asset is not an interstate. For interstate assets, assign sensitivity score of 1.	75%
			1,001-5,000	1		
			5,001-10,000	1.5		
			≥ 10,001	2		
			Interstate	1		
Wildfire	Wildfire sensitivity rating	Workshop and focus group participants	Temporary disruption	2	Most roads are sensitive to wildfire, but only temporarily. Service is completely disrupted for the duration of the wildfire, but roads typically do not suffer long-term damage. However, stakeholders also noted that certain roads in the study area have potential to cause pinch points in evacuations, representing higher sensitivity.	50%
			Moderate-High sensitivity, pinch point potential	3		
			High sensitivity, pinch point potential	4		
	Values Response Index	TxWRAP	1 (positive impact)	0	Values Response Index is “the potential impact of a wildfire on values or assets.” This indicator is a reflection of the service the asset provides and the likelihood of disruption if a wildfire were to occur.	50%
			0	1		
			-1 – -3	2		
			-4 – -6	3		
			-7 – -9	4		
Cold Temperatures (icing)	Whether roadway is elevated	Visual inspection	No	1.5	Elevated roadways are more susceptible to icing. On all roadways, when icing occurs, traffic is slowed or disrupted, for a matter of hours until the ice melts.	100%
			Yes	2		

* Sensitivity indicators were scored on a scale of 0 (not sensitive) to 4 (highest sensitivity). The indicators were broken down into the most appropriate number of scoring bins possible given the available dataset. For example, some indicators are divided into only two bins because there were only two data values.

** If data are not available or applicable for any indicator, its weight gets distributed to remaining indicators proportionally.

Table E-3 Rail Sensitivity Indicator Details

Stressor	Indicators	Data Source	Indicator Value*	Score	Rationale	Weight**
Flooding	Rail flooding sensitivity rating	Workshop and focus group participants	Rail experiences washouts, scour damage	3	The MetroRail at Boggy Creek experiences washouts and scour damage during floods, causing 1-2 days' worth of delays.	100%
Drought	Soil Plasticity Index	City of Austin	0-30 (Low)	1	Same as Highways drought sensitivity. Assets located on high plasticity soils are more likely to suffer damage during droughts. Soil plasticity index bins provided by City of Austin Street and Bridge Operations.	100%
			31-40 (Medium)	2		
			41-58 (High)	4		
Extreme Heat	Rail Neutral Temperature	TxDOT	115°F	1	When temperatures approach or exceed the rail neutral temperature, risk of thermal misalignments increases and rail operators must issue slow orders.	75%
			107.5°F	2		
			100°F	3		
	Freight traffic density	Capital Metro	0	1	Lines with heavy rail traffic are more sensitive to thermal misalignments.	25%
Wildfire	Rail wildfire sensitivity rating	Workshop and focus group participants	Temporary disruption	2	Same as highways. Rail service would completely disrupted for the duration of the wildfire.	50%
			Moderate-High sensitivity, pinch point potential	3		
			High sensitivity, pinch point potential	4		
	Values Response Index	TxWRAP	1 (positive impact)	0	Values Response Index is "the potential impact of a wildfire on values or assets." This indicator is a reflection of the service the asset provides and the likelihood of disruption if a wildfire were to occur.	50%
			0	1		
			-1 – -3	2		
			-4 – -6	3		
			-7 – -9	4		

Stressor	Indicators	Data Source	Indicator Value*	Score	Rationale	Weight**
Cold Temperatures (icing)	Rail icing sensitivity rating	Workshop and focus group participants	Icing likely to occur	2	Rails cannot operate if >1/16th inch of ice on rails. Therefore, assume rails are automatically sensitive when icing occurs, but that sensitivity is limited to a few hours during the day when there is ice. Ice does not cause long-term damage.	100%

* Sensitivity indicators were scored on a scale of 0 (not sensitive) to 4 (highest sensitivity). The indicators were broken down into the most appropriate number of scoring bins possible given the available dataset. For example, some indicators are divided into only two bins because there were only two data values.

** If data are not available or applicable for any indicator, its weight gets distributed to remaining indicators proportionally.

E.3 Adaptive Capacity Indicators

Table E-4 Highway Adaptive Capacity Indicator Details

Indicators	Data Source	Indicator Value*	Score	Rationale	Weight**
Whether asset is an evacuation route	TxDOT	Yes	4	If an evacuation route is damaged or otherwise out of service when needed for an evacuation, the consequences could be great.	60%
		No	N/A		
Asset criticality	Workshop and focus group participants	Provides inter-regional connectivity (connects outlying counties)	2	Assets that play a larger role in the functioning of the overall region will have a greater consequence if damaged or disrupted.	8%
		Provides intermodal connections (i.e., airport)	3		
		Serves area with high population and employment density	3		
Annual Average Daily Traffic (existing)	CAMPO	9,500 – 35,648	1	Roadways with higher traffic volumes would affect more drivers/traffic and cause a greater disruption if damaged. Scoring bins determined by dividing range of AADTs across all assets studied into evenly sized bins.	8%
		35,648 – 61,795	2		
		61,795 – 87,943	3		
		87,943 – 114,090	4		
Truck traffic volume	TxDOT	0 – 5,000	1	Roadways with higher truck traffic volumes would affect more freight traffic and cause a greater disruption to commerce if damaged. Scoring thresholds set based on the range of freight traffic within the CAMPO study area.	8%
		5,001 – 10,000	2		
		≥ 10,001	3		

Indicators	Data Source	Indicator Value*	Score	Rationale	Weight**
Functional Class	CAMPO	Minor Arterial Divided (TxDOT FC = 6)	2	Functional class is another indicator of the level of service provided by the roadway. Major roads would cause a greater system effect if they are taken out of service.	8%
		Major Arterial Undivided (TxDOT FC = 5)	3		
		Major Arterial Divided (TxDOT FC = 4)	3		
		Expressway (TxDOT FC = 3)	4		
		Freeway (TxDOT FC = 2)	4		
		Interstate (TxDOT FC = 1)	4		
Detour length	NBI, Item 19	0-5 mi	1	Longer detour lengths indicate the lack of redundancy serving an area and thus greater consequences if an asset is out of service.	8%
		5-10 mi	2		
		10-15 mi	3		
		> 15 mi	4		

* Adaptive capacity indicators were scored on a scale of 1 (highest adaptive capacity) to 4 (lowest adaptive capacity). The indicators were broken down into the most appropriate number of scoring bins possible given the available dataset. For example, some indicators are divided into only two bins because there were only two data values.

** If data are not available or applicable for any indicator, its weight gets distributed to remaining indicators proportionally.

Table E-5 Rail Adaptive Capacity Indicator Details

Indicators	Data Source	Indicator Value*	Score	Rationale	Weight**
Asset criticality	Workshop and focus group participants	Provides inter-regional connectivity (connects outlying counties)	2	Assets that play a larger role in the functioning of the overall region will have a greater consequence if damaged or disrupted.	50%
		Provides intermodal connections (i.e., airport)	3		
		Serves area with high population and employment density	3		
Average daily ridership	Capital Metro	9,500 – 35,648	1	Rail lines with higher ridership would affect more people/traffic and cause a greater disruption if damaged. Scoring bins set to equal those used to rate AADT for highways.	50%
		35,648 – 61,795	2		
		61,795 – 87,943	3		
		87,943 – 114,090	4		

* Adaptive capacity indicators were scored on a scale of 1 (highest adaptive capacity) to 4 (lowest adaptive capacity). The indicators were broken down into the most appropriate number of scoring bins possible given the available dataset. For example, some indicators are divided into only two bins because there were only two data values.

** If data are not available or applicable for any indicator, its weight gets distributed to remaining indicators proportionally.

F. Appendix: CAMPO-Area Extreme Weather Events and Their Effects

F.1 OVERVIEW

The following sections summarize the impacts of four recent extreme weather events that have occurred in the study area:

- Tropical Storm Hermine (2010);
- 2013/2014 ice events;
- 2011 drought/heat event; and
- Bastrop wildfire (2011).

Because each of these events had a specific set of meteorological conditions, each affected the Central Texas region in a different way. For example, Tropical Storm Hermine's heavy rainfall during a short period caused the bulk of the storm's impacts. The ice events of Winter 2013/2014, as well as the Bastrop wildfire, caused little in terms physical damage to transportation infrastructure, but seriously impacted system operations. The 2011 drought and heat event, on the other hand, created impacts to the transportation system that were spread over a fairly long time period and more difficult to pinpoint. The following sections describe both the meteorological background of each event as well as a selective assessment of the damage and disruption each caused to the transportation system.

F.2 TROPICAL STORM HERMINE

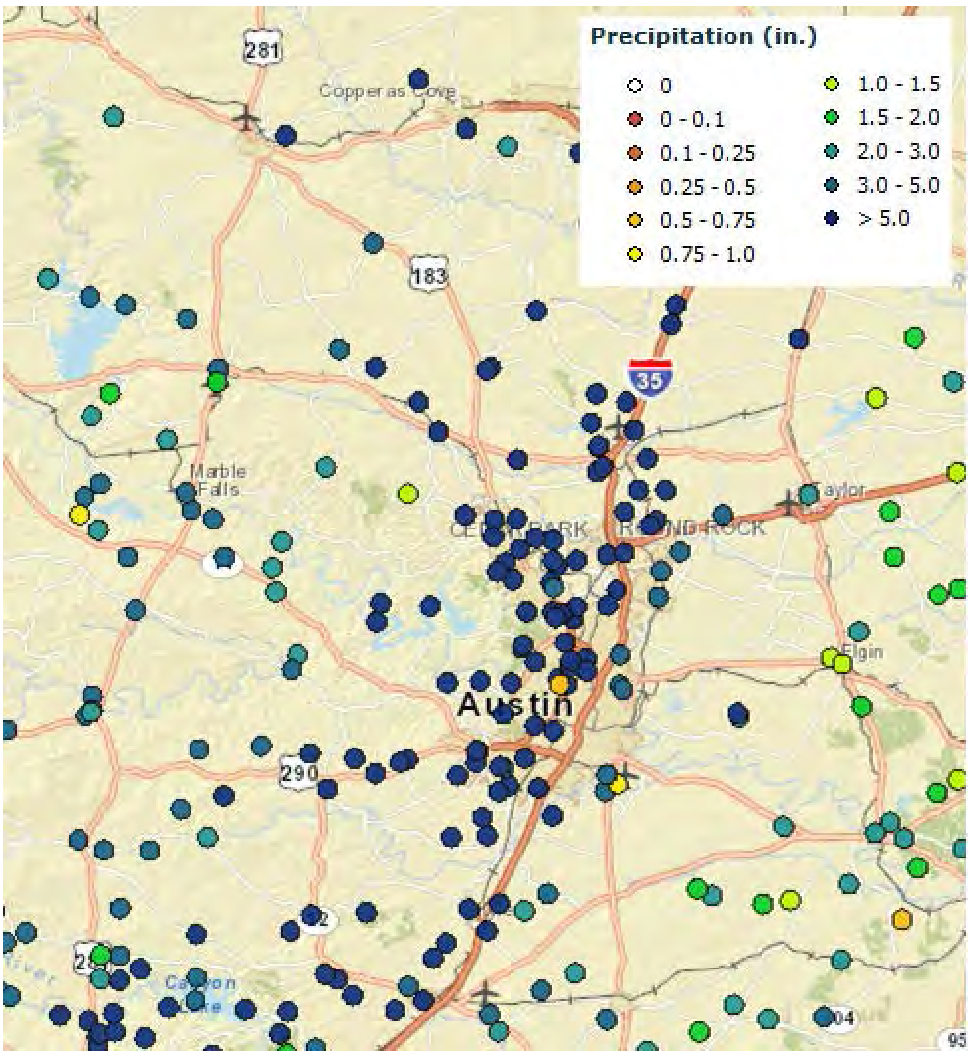
Tropical Storm Hermine highlighted the danger posed by tropical cyclones to areas well inland from the coast. The bulk of the storm's impacts to the transportation system came as a result of intense rainfall for an extended period of time, leading to elevated stream levels. Moreover, several individuals lost their lives due to the flash flooding. Two deaths occurred as vehicles were swept off the road at low water crossings. Three others died while swimming and kayaking in swollen waters well after the event was over.

Rainfall

Hermine made landfall on September 6th, 2010, approximately 25 miles south of Brownsville, Texas. By the early hours of September 8th, the storm's center of low pressure was located within the Capital Area Metropolitan Planning Organization (CAMPO) region (near Burnet). As the system passed along the western fringe of the six-county region, intense "feeder bands" of precipitation developed along the storm's eastern side. During this time, feeder band precipitation exhibited a meteorological phenomenon known as "training," whereby individual rain and thunderstorm cells within a band of precipitation repeatedly affect the same geographic area. The feeder bands associated with Hermine exhibited training, particularly in Travis and Williamson Counties.

The majority of precipitation in the study area fell during the overnight hours of September 7th/8th. Figure F-1 shows 24-hour rainfall totals taken on September 8th, with darker blue circles indicating stations that received five or more inches of rain. Areas along the I-35 corridor received the greatest amounts of precipitation. Many stations between Wimberley and Cedar Park received more than 10 inches of rain during that day. However, rainfall amounts were dramatically lower east of I-35.

Figure F-1 Tropical Storm Hermine Daily Rainfall Observations for September 8th, 2010

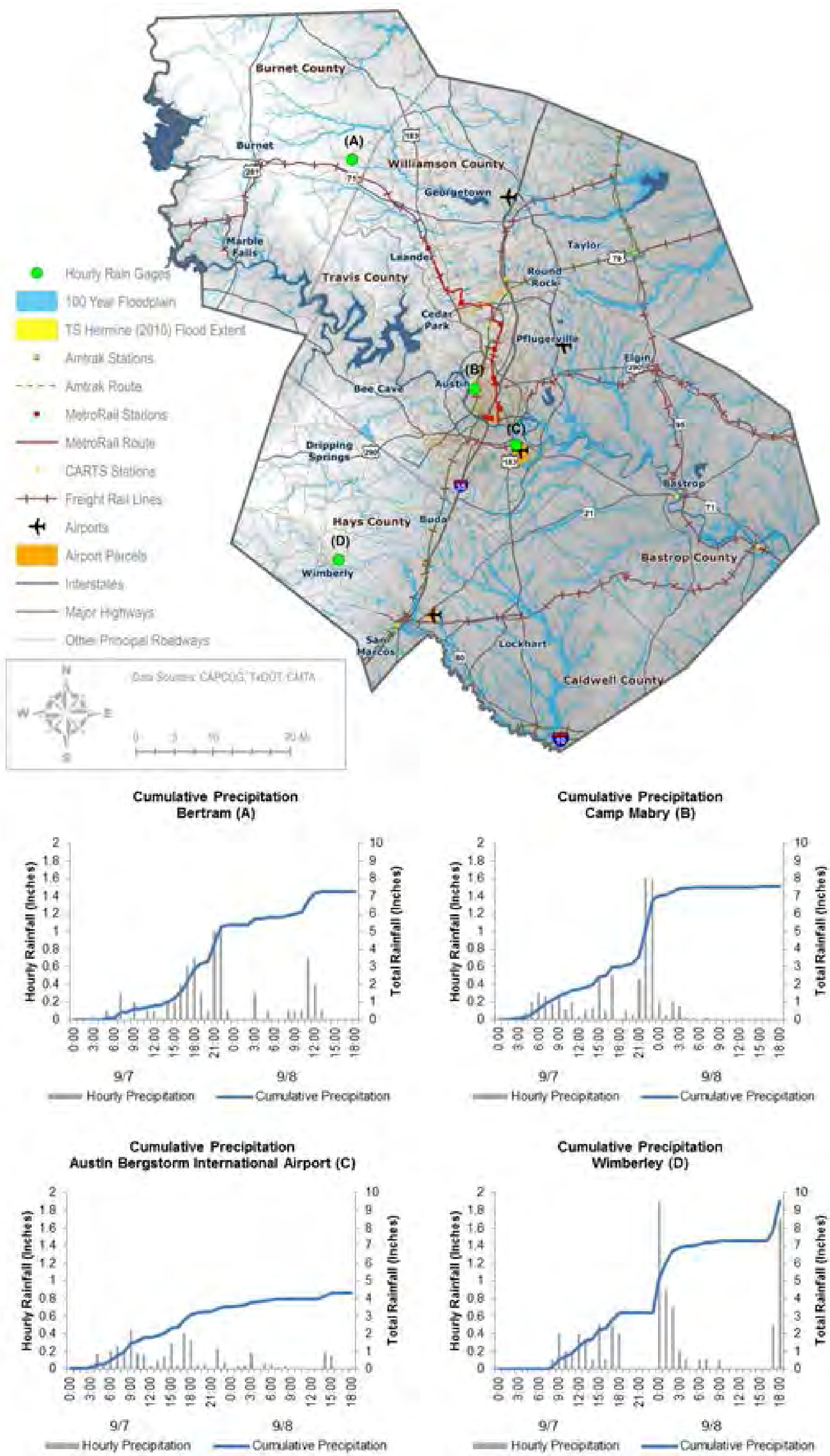


Source: Global Historical Climatology Network (GHCN)

Figure F-2 shows the hourly precipitation rates (gray) and cumulative precipitation (blue) during the period from 12:00 AM on September 7th through 6:00 PM on September 8th at the four weather stations within the study area for which hourly observations are available. Wimberley experienced both the greatest cumulative rainfall totals and the highest hourly rainfall rates among all the stations. This weather station saw 9.5 inches of total rainfall and precipitation rates peaking around 1.9 inches per hour (at midnight on September 8th). Precipitation rates peaked at all stations within the three hours before or after midnight, indicating an intense band of precipitation passing through the area during this time. Bertram and Camp Mabry both saw rainfall totals during this period of between seven and eight inches. The hourly weather station with the least precipitation was Austin Bergstrom International Airport (ABIA) with 4.32 inches. All data are from the National Oceanic and Atmospheric Administration's National Climatic Data Center.[42]

[42] Note that the Global Historical Climatology Network (GHCN), the data source for Figure F-1, is an integrated database of daily climate summaries from land surface stations across the globe, including official stations of the National Weather Service. The data are obtained from more than 20 sources and are subjected to a suite of quality assurance reviews.

Figure F-2 Tropical Storm Hermine Rainfall Observations



Flooding

The rainfall associated with Hermine caused significant flooding impacts within the six-county CAMPO region. An analysis of stream gage data from the United States Geological Survey (USGS) National Water Information System shows that many area streams and rivers experienced fairly dramatic increases in discharge rates and height as the storm passed through the area. Figure F-4 depicts discharge rates (green, cubic feet per second) for eight representative stream gages from throughout the study area shown in Figure F-3. Gage heights in feet (maroon) are also shown. Median discharge rates are indicated with green triangles, while median gage heights are given for stations where this information is available (maroon triangles).

Each gage reported a dramatic increase in discharge during the 72-hour time frame analyzed. Due to variations in basin geography, however, the magnitude and timing of this increase varied from site to site. Most gages showed the greatest increases in discharge as the heaviest rain fell during the late hours of September 7th and beginning of September 8th. Heavy rainfall in the hilly terrain west of Austin, noted above, translated into dramatic discharge rates and gage heights for areas downstream just after midnight. Notable examples are the Colorado River (E)—which saw gage heights increase from approximately 3 feet to 28 feet early on September 8th—and Onion Creek, where gage heights rapidly rose approximately five-fold (from about 3 feet to 15 feet) around midnight.

The rapid increases in gage height and discharge rates corresponded with flash flooding along many area streams and rivers. Figure 1.3 shows the maximum flood extent during Tropical Storm Hermine, in yellow. Many local streams and rivers with USGS stream gages also experienced flooding during the event. Flooding occurred along Lake Creek, Onion Creek, Shoal Creek, Walnut Creek, Williamson Creek, and Boggy Creek. Most areas that were inundated were located in Austin, Pflugerville, Cedar Park, and Round Rock.

Figure F-3   Tropical Storm Hermine Flooding Extent and Stream Gage Locations

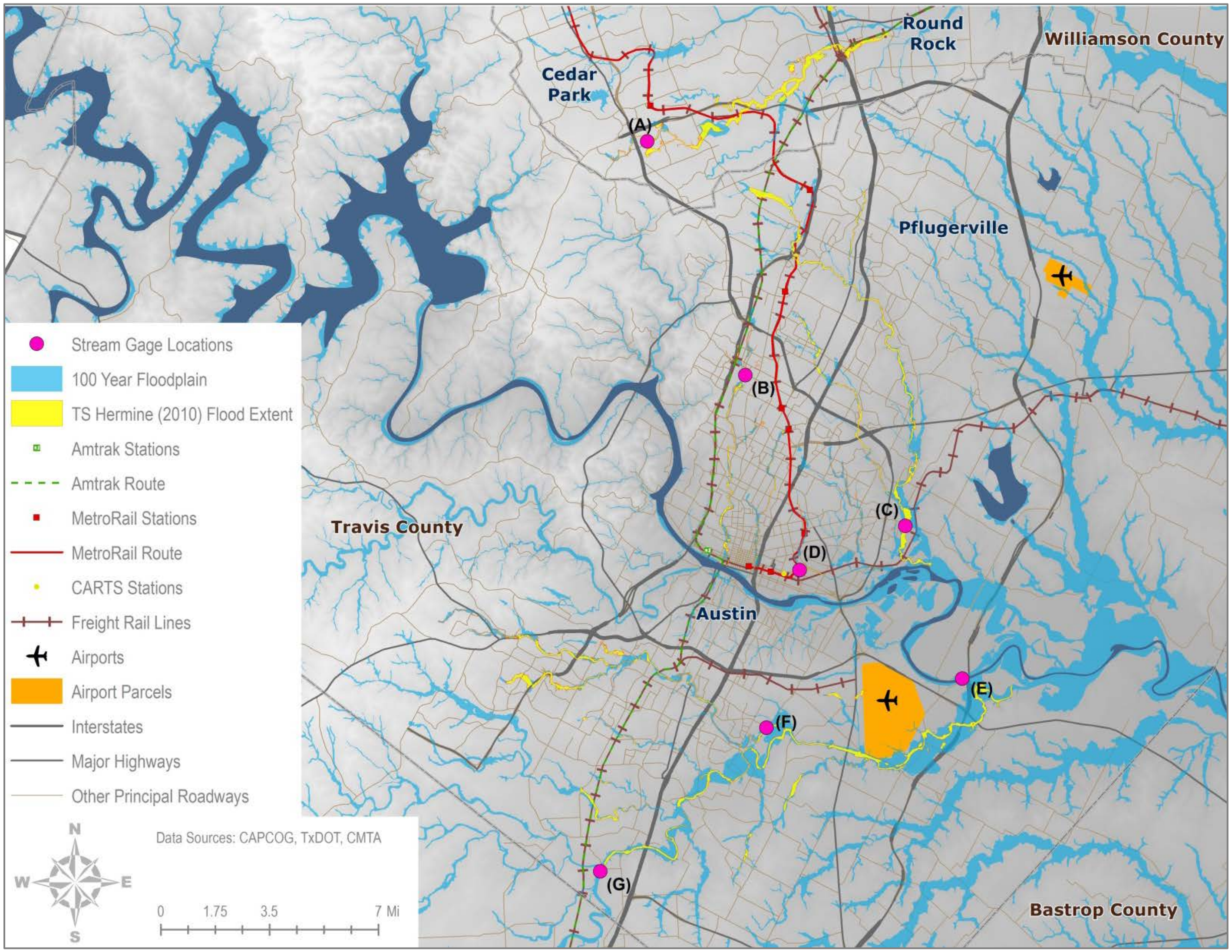
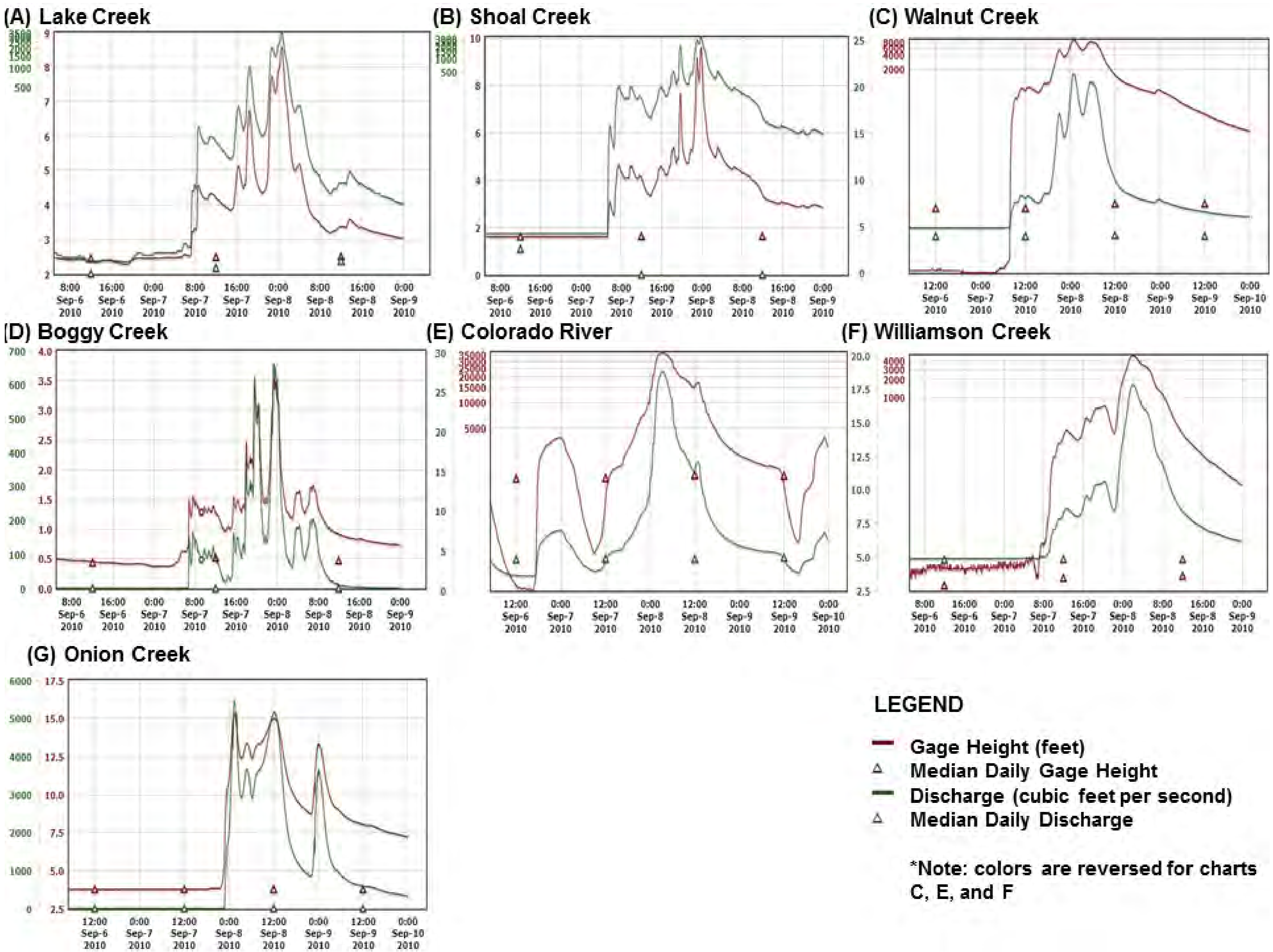


Figure F-4 Tropical Storm Hermine Stream Gage Observations



Damage

Tropical Storm Hermine produced an estimated $240 million in damage as it made its way across Texas and Oklahoma.[43] There were five confirmed deaths associated with the storm in Texas, three of which were reported in the CAMPO region. Governor Rick Perry activated search and rescue capabilities, which included 48 Texas Military Forces personnel, 10 high profile vehicles, two Texas Military Forces UH-60 Blackhawk helicopters, and four Texas Task Force 1 swift water rescue teams comprising 20 personnel.[44]

The Governor's report seeking Federal financial aid for Hermine indicates that 178 homes were destroyed and 298 suffered major damage across the state.[45] Examples of damage within the Central Texas region include:

- In Williamson County, floodwaters damaged 38 roads, requiring varying degrees of repair.[46] Cedar Park officials identified 80 homes with flood damage and Leander reported 15 flood damaged homes. In total, Williamson County flood damage was estimated at $1.1 million, affecting about 654 homes.[47, 48]
- Flooding on September 8 damaged parts of Capital Metro's Red Line track, requiring closure of the Leander station and suspension of service north of the Lakeline station for two days. Flooding in the area caused a broken rail tie subsidence. Debris and gravel washed onto the track at other areas, and floodwaters washed away ground coverings in several locations, exposing rail cables and signals.[49]

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43 Tropical Cyclone Report, Tropical Storm Hermine h*ttp://www.nhc.noaa.gov/pdf/TCR-AL102010_Hermine.pdf*

44 *Gov. Perry Issues Disaster Declaration for 40 Texas Counties*, 2010. http://governor.state.tx.us/news/press-release/15127/

45 Community Impact Newspaper, *Williamson County denied FEMA assistance for flooding*, Jen Rains and Rebecca LaFlure, December 10, 2010, *http://impactnews.com/austin-metro/leander-cedar-park/williamson-county-denied-fema-assistance-for-flooding/*

46 Community Impact Newspaper, *Updated numbers reveal more flood damage,* Victor O'Brien, September 14, 2010, *http://impactnews.com/austin-metro/leander-cedar-park/lcp-updated-numbers-reveal-more-flood-damage/*

47 Community Impact Newspaper, *Williamson County denied FEMA assistance for flooding*, Jen Rains and Rebecca LaFlure, December 10, 2010, *http://impactnews.com/austin-metro/leander-cedar-park/williamson-county-denied-fema-assistance-for-flooding/*

48 *Williamson County flood damage estimated at $1.1 million*, Andrea Lim, November 21, 2013, *http://insurancenewsnet.com/oarticle/2013/11/21/williamson-county-flood-damage-estimated-at-$11-million-a-426109.html#.Uzwj0IXYNTJ*

49 Community Impact Newspaper, *Flood damage shuts down Leander Metro Rail station,* Victor O'Brien, September 8, 2010, *http://impactnews.com/austin-metro/leander-cedar-park/flood-damage-shuts-down-leander-metro-rail-station/*

- In Travis County, several roads over Bull Creek sustained damage due to overnight flooding, including RM 2222 (Figure F-5) and a bridge on Spicewood Springs Road. The repairs to the washed out bridge on Spicewood Springs Road were estimated at $60,000 for construction materials, requiring four to six weeks to complete the repairs.[50]

Figure F-5 Damage to RM 2222 at the Bull Creek Crossing Due to Overnight Flooding

Source: Austin American-Statesman

Disruption

Tropical Storm Hermine also caused transportation system disruptions, including traffic delays and road closures at low water crossings, flooded roadways, and damaged bridges (Figure F-6 and Figure F-7). The intense rain band that developed along the I-35 corridor on the afternoon of Tuesday, September 7 stretched several hundred miles from Waco to south of San Antonio (Figure F-5). For a time, I-35 in Georgetown was shut down with witnesses reporting that water was as high as the center concrete barrier.[51]

[50] Community Impact Newspaper, *Road crews begin work to repair bridge on Spicewood Springs Road*, Beth Wade, September 15, 2010, *http://impactnews.com/austin-metro/northwest-austin/road-crews-begin-work-to-repair-bridge-on-spicewood-springs-road/*

[51] National Oceanic and Atmospheric Administration, *Tropical Storm Hermine Impacts South Central Texas*, 2010.

In Hutto, the Police Department began closing roads at approximately 11 a.m. on September 8th, with most reopening by 3 p.m. the following day. A reverse 911 call was sent out to warn residents of floodwaters that rose quickly Wednesday morning along FM 685, CR 135, and CR 137, affecting morning commutes and bus routes. Hutto schools were delayed by two hours Wednesday morning due to road closures.[52]

Figure F-6 Traffic Delays on Loop 360 Due to Road Closure at RM 2222

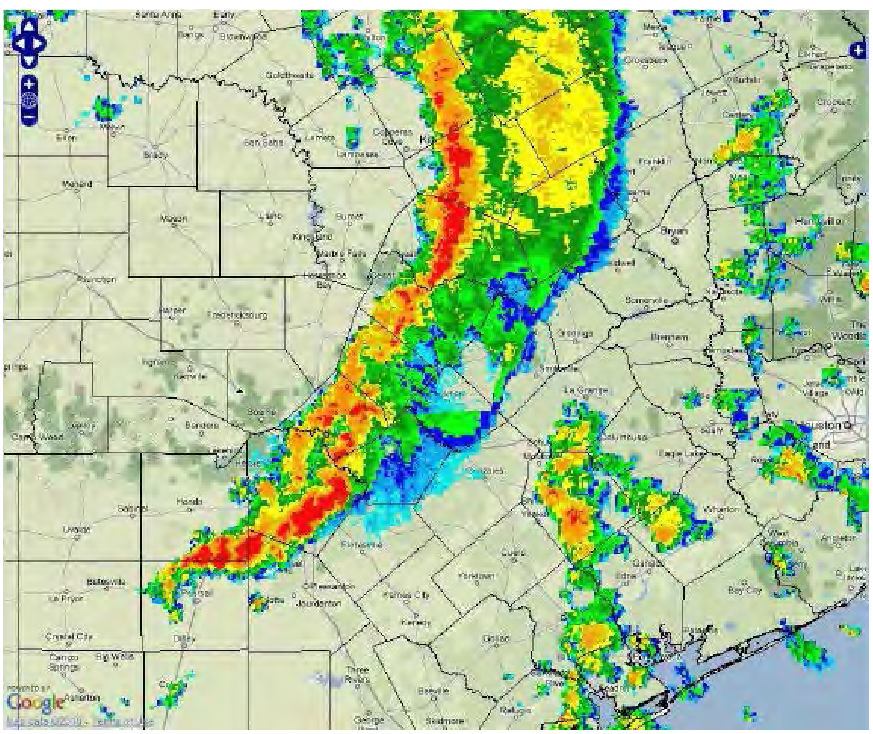
Source: Austin American-Statesman

[52] The Hutto News, *Floods leave county, Hutto a disaster*, September 15, 2010, *http://www.thehuttonews.com/news/article_6fb945c8-c117-11df-8e06-001cc4c002e0.html*

Figure F-7   Traffic Delays on Mopac During Morning Commute on Sept. 7

Source: Austin American-Statesman

Figure F-8   Radar Imagery Showing Intense Rainfall Activity Along the I-35 Corridor



Source: National Oceanic and Atmospheric Administration, *Tropical Storm Hermine Impacts South Central Texas*, 2010.

The heavy rainfall shut down several roads in Travis and Williamson Counties. In the City of Austin, at least 34 road sections were closed, including: RM 2222 at Loop 360, N. Lamar Boulevard between W. 9th and W. 12th streets, 2800 Bee Caves Road, 11500 Manchaca Road, 3100 William Cannon Drive, 5500-5600 Westgate Boulevard, and Spicewood Springs Road from loop 360 to Old Lampasas Trail.[53] Road closures in Williamson County included FH 1431 westbound at Vista Ridge Boulevard and eastbound at Spanish Oak Creek, all 6A gates on Toll 183A, and Brushy Creek Road from Great Oaks Drive to Round Rock city limits.

F.3 2013/2014 Ice Events

An unusually high number of ice events affected the Central Texas region during the 2013/2014 winter months. Precipitation in the study area occurred in the form of freezing rain on a number of occasions during this period, notably December 6th, 2013 and January 24th, January 28th, February 11th, and March 4th, 2014. These events highlighted the vulnerability of the Central Texas transportation system to such ice storms, however infrequent. The main culprit behind the storms was the combination of a shallow layer of cold air at the earth's surface with liquid precipitation that froze on contact. These conditions, and the impacts of the ice storms on the regional transportation system, are discussed below.

Ice Storm Meteorology

Ice storms occur when warm air overrides a relatively shallow layer of cold air at ground level, causing falling precipitation to melt into liquid until it makes contact with surfaces that are below freezing. Air temperatures at ground level must be below 32 degrees Fahrenheit for the precipitation to freeze upon contact with exposed surfaces, including pavements. Figure F-9 shows a cross-section of the atmosphere during rain, freezing rain, sleet, and snow events. Whereas precipitation stays frozen or re-freezes during sleet or snow events, during occurrences of freezing rain it must remain liquid until it contacts a cold surface, where it immediately freezes into a layer of ice. Areas of the southern United States—including the Central Texas region—are particularly prone to this type of precipitation. Winter weather events of this nature mainly occur from mid-to-late November through mid-February.

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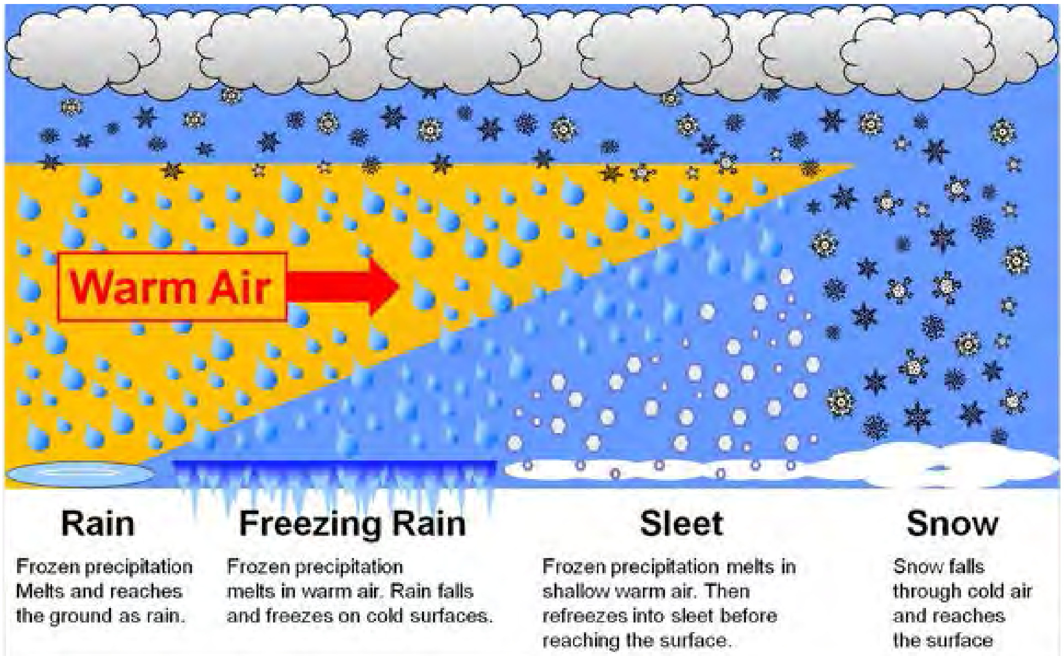
[53] Community Impact Newspaper, *Tropical Storm Hermine drenches Austin*, Bobby Longoria, September 8, 2010, *http://impactnews.com/austin-metro/southwest-austin/swa-tropical-storm-hermine-drenches-austin/*

Figure F-9 Atmospheric Cross-Section for Wintry Precipitation



Source: National Weather Service Weather Forecast Office, Huntsville, AL. http://www.srh.noaa.gov/hun/?n=winterwx_awarenessweek_2013

Precursor Events

A biannual report prepared by the Weather and Climate Resource Center at the University of Texas at Austin provides an overview of the ice events experienced in the recent past, through December 2011.[54] Beginning in May 1999 with the opening of ABIA, Austin had two official national weather service surface observation sites. Previously, only the site at Camp Mabry reported official surface observations. Between May 1999 and December 2011, there were reports of freezing rain or ice pellet accumulation during 13 events at either of the two sites—an average approximately one ice event per year during this period. Not every year experienced an ice event—2002 and 2007 saw no ice accumulation events.

2013/2014 Ice Events

During the winter of 2013/2014, the Central Texas region experienced a total of five accumulating ice events. This was much greater than the 1999-2011 annual average number of events, and more events than were observed in any of the preceding 25 years. These events occurred on December 6th, 2013; and January

[54] "Inclement/Severe Weather and Extreme Temperature/ Precipitation/ Wildfire/ Wind/ Pressure/ Fog/ Sunshine Climatology for the Greater Austin Metropolitan Area (Travis, Williamson and Hays Counties (5th Edition))

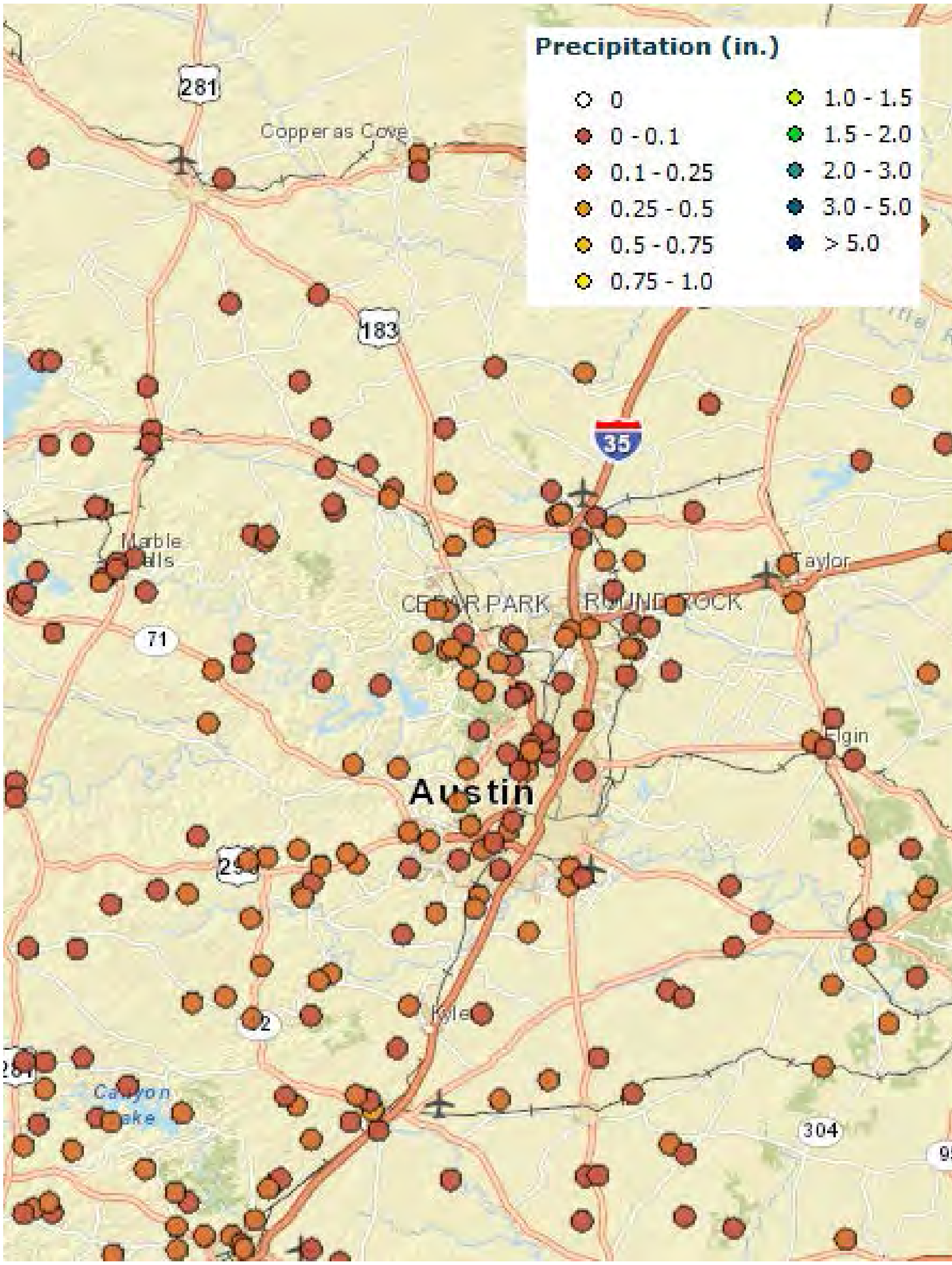
24th, January 28th, February 11th, and March 4th, 2014. The greatest amounts of freezing precipitation were observed on January 24th and March 4th, 2014.

Figure F-10 and Figure F-11 depict the daily precipitation amounts and hourly temperatures observed on January 24th, 2014, while Figure F-12 and Figure F-13 show the same information for March 4th, 2014. Because publicly available, official weather observations do not include total ice accumulation measurements, the combination of temperature and precipitation observations serve as a proxy for understanding the severity of each event. All data are from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center.

During the January 24th event, precipitation amounts were generally light—generally less than 0.25 inch (Figure 1.6). However, even accumulations this small can cause issues on roads. Ambient (air) temperatures were generally below freezing throughout the daylight hours before rising toward the end of the day (Figure 1.7). These low temperatures allowed ice to accumulate.

During the March 4th event, precipitation amounts were slightly less than those observed during the January 24th event, and generally under 0.25 inch. Temperature trends on this date were very similar to the preceding event, with observed temperatures below freezing until the evening hours.

Figure F-10 Daily Precipitation Observations for January 24th, 2014



Source: Global Historical Climatology Network

Figure F-11 Hourly Temperature Observations for January 24th, 2014

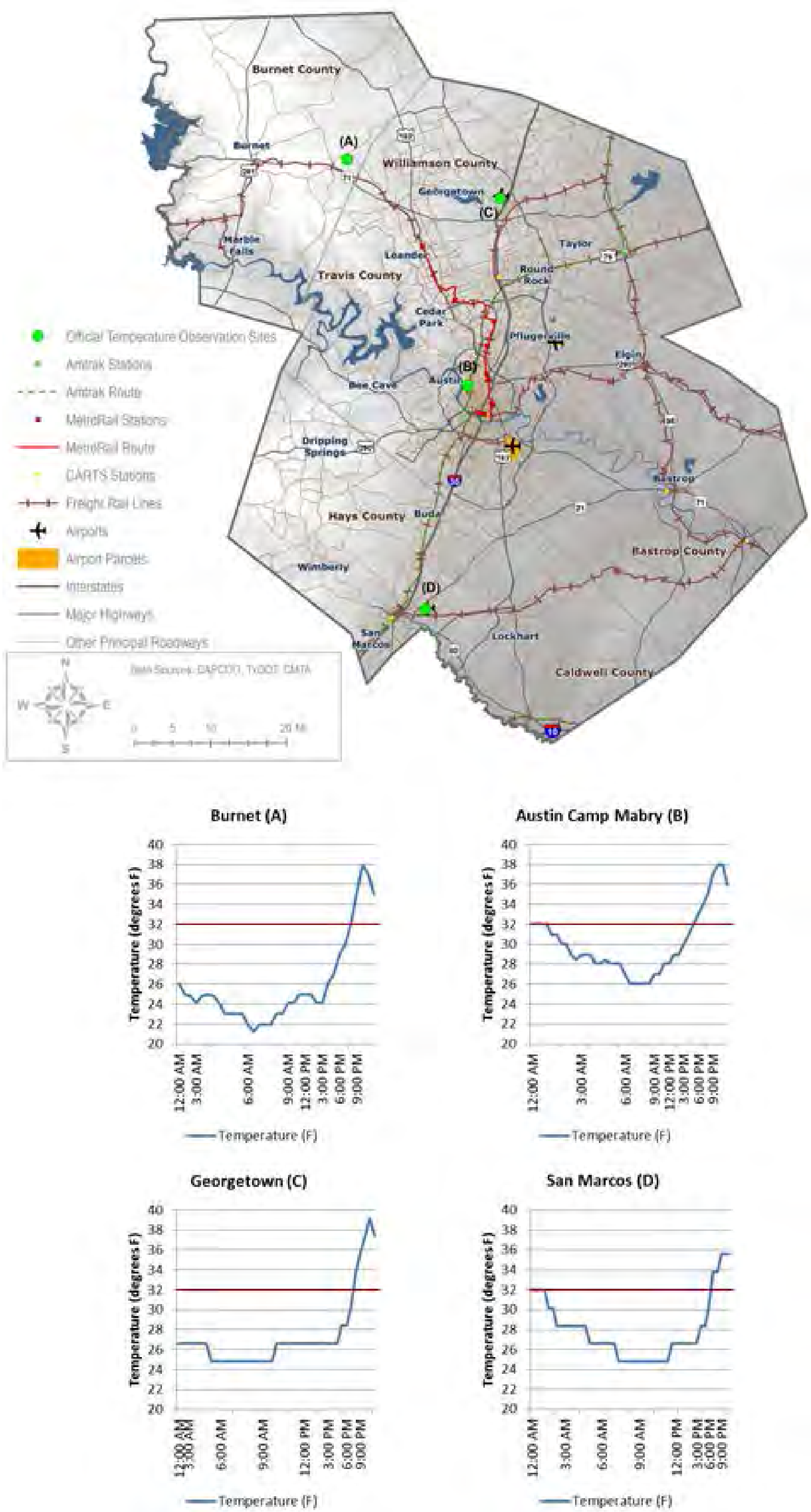
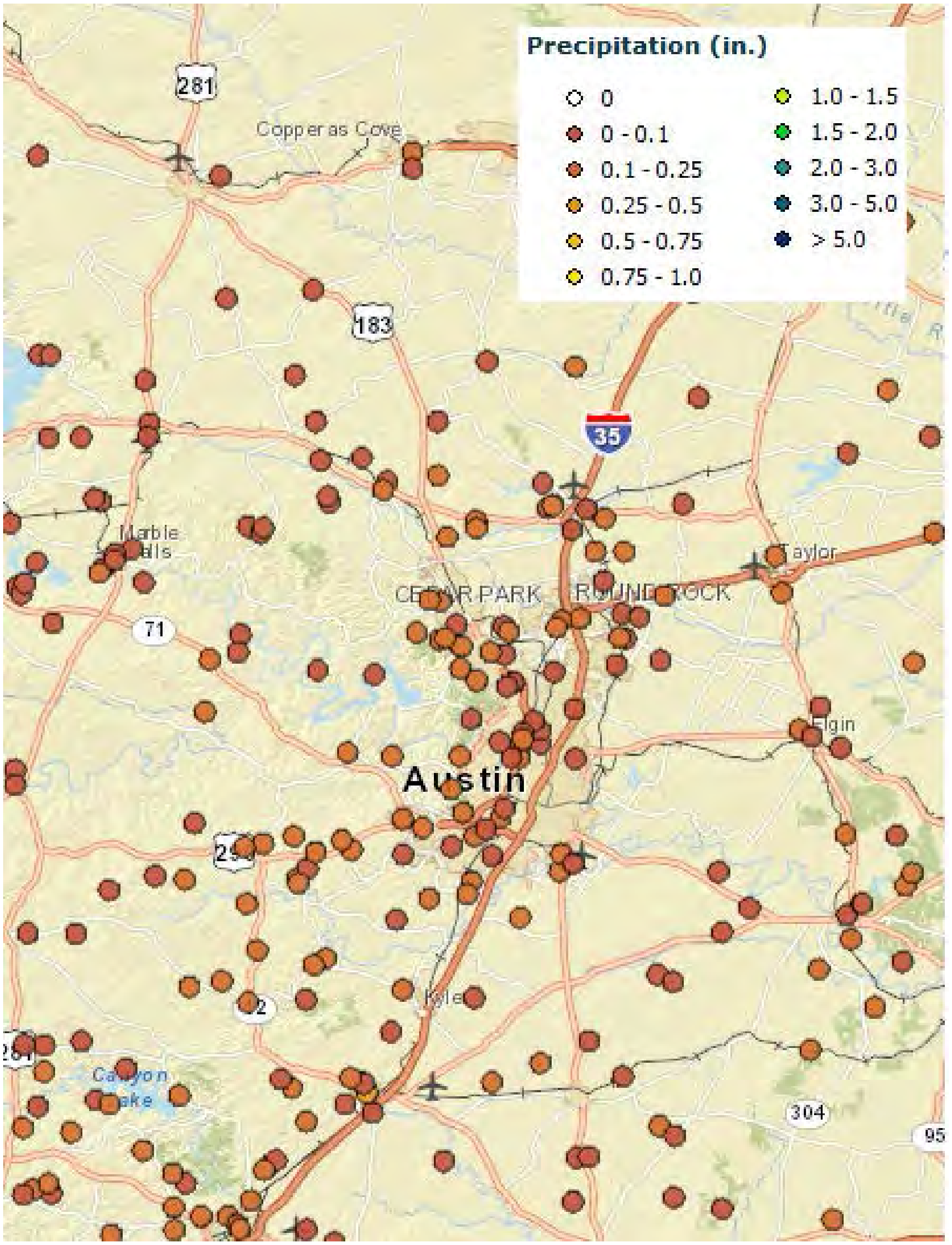
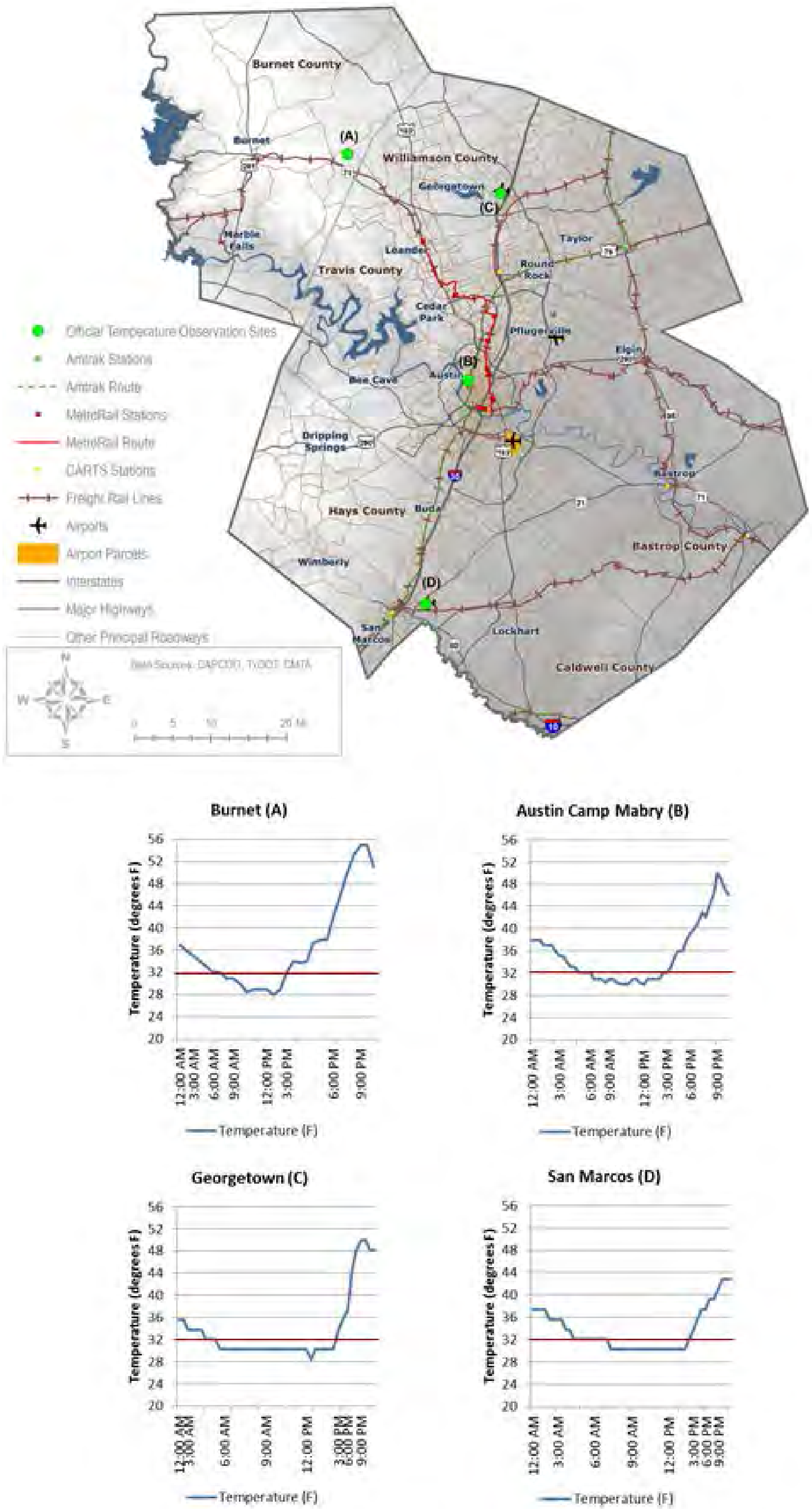


Figure F-12 Daily Precipitation Observations for March 4th, 2014



Source: Global Historical Climatology Network

Figure F-13 Hourly Temperature Observations for March 4th, 2014



Damage

The City of Austin uses carbon-based mineral dolomite on streets and roads during "major ice events." The city has between 4,000 to 5,000 cubic yards of dolomite at any given time during the winter, costing $64,000 and $80,000. This is enough to handle two days of icy weather, and the city had to replenish its stock after the January 28th ice event (the second event in the matter of a few days), when the City used about 1,200 cubic yards of deicer.[55]

TxDOT (Austin District) uses a deicing product called Meltdown-20, a granular substance containing magnesium chloride and red complex chloride (a slower melting agent). Meltdown-20 is applied reactively during icing events.

Disruption

The icing events created massive travel delays affecting the region's roadways and airports. Poor roadway conditions stranded hundreds of cars and trucks with numerous traffic accidents. Large trucks stranded on roadways created a shortage of diesel fuel.[56]

Nearly all sections of I-35 from San Antonio to Austin, a span of about 75 miles, were closed on the morning of Friday, January 24th. Traffic was moving at approximately five miles per hour around mid-day on adjacent access roads.[57] Area schools as well as City of Austin, Travis County, Texas Parks and Wildlife Austin offices were closed amid icy conditions.

Austin Police Department reported 245 collisions as of midday on the January 24th since 6:30 PM the night before. Capital Metro reduced service to Saturday service with no University of Texas shuttle buses. ABIA remained open, but 32 flights were cancelled.[58]

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55 City uses environmentally friendly dolomite on icy roads, February 13, 2014. *http://www.dailytexanonline.com/news/2014/02/13/city-uses-environmentally-friendly-dolomite-on-icy-roads*

56 Re: Appeal of Denial of Request for Disaster Declaration, *http://governor.state.tx.us/files/press-office/O-ObamaBarack201403130190.pdf*

57 Texas cold weather creates major highway closures, January 26, 2014. *http://en.wikinews.org/wiki/Texas_cold_weather_creates_major_highway_closures*

58 Ice Hits, Austin Stops, January 24, 2014. *http://www.austinchronicle.com/daily/news/2014-01-24/ice-hits-austin-stops/*

F.4 2011 Heat and Drought

The summer of 2011 was one of the hottest and driest on record in Central Texas. The drought was caused by La Niña conditions in the Pacific Ocean, and manifested itself with record low rainfalls in Central Texas and across the state. The lack of rainfall exacerbated already warm summer temperatures, resulting in record-breaking temperature extremes in the area. These conditions, in turn, increased evaporation and further worsened the drought. These extreme conditions caused the clay soils in area to contract in response to loss of moisture, damaging infrastructure.

Rainfall

The 2011 drought began in approximately October 2010, and was particularly severe by the summer of 2011. The Palmer Drought Severity Index (PDSI) registered 'Extreme Drought' in the South Central Texas climate division from July through December 2011.[59] As shown in Figure F-14, Austin (Camp Mabry) and the surrounding area received only trace amounts of precipitation from July through August, and no rainfall at all in August, following an equally dry spring. Precipitation observations in Austin show that the area received less than half its normal rainfall amount for the year. The drought was influenced by La Niña conditions in the Pacific Ocean, which tend to create drier than average fall-spring conditions in Texas.[60]

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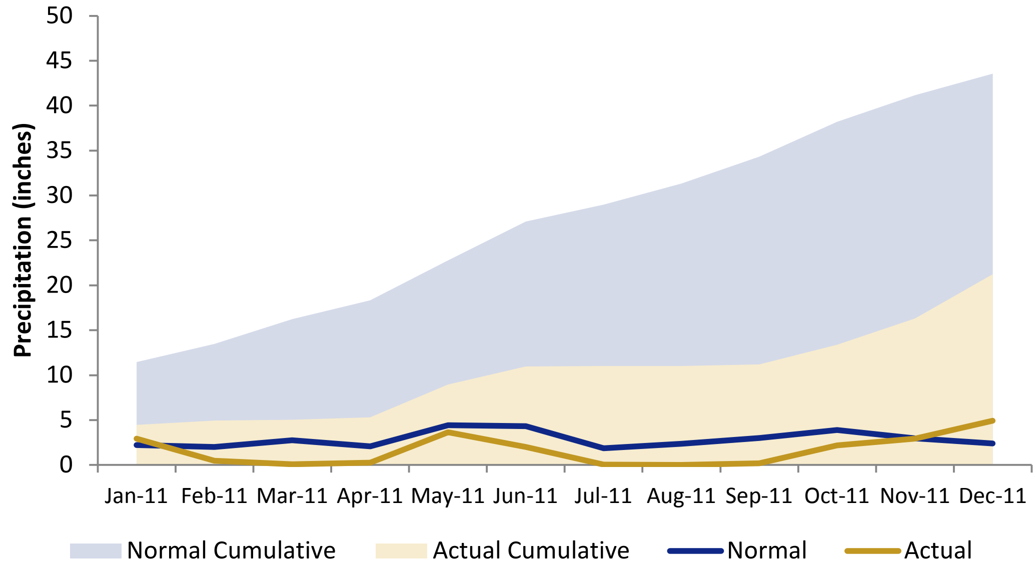
[59] National Climatic Data Center, 2014, Historical Palmer Drought Indices, NOAA National Climatic Data Center, http://www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmers.php?index.

[60] Nielsen-Gammon, John, 2011, The 2011 Texas Drought: A Briefing Packet for the Texas Legislature (October 31, 2011), The Office of the State Climatologist, http://climatexas.tamu.edu/files/2011_drought.pdf.

Figure F-14 2011 Monthly and Cumulative Rainfall versus Long-term Normal, Austin, TX



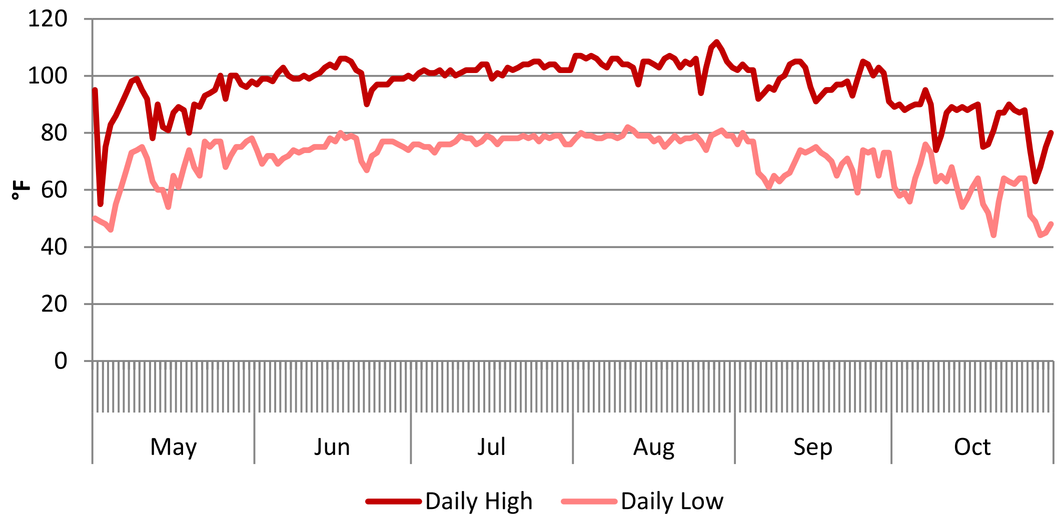
Source: NOAA National Climatic Data Center, Monthly Climatological Summary and Climate Normals (1981-2010), Austin Camp Mabry station (GHCND:USW00013958)

Temperature

The drought intensified Central Texas' usual summer heat, pushing it to record-breaking levels. August of 2011 was the warmest month of all time in the area, with an average temperature of 91.6°F at Austin Mabry.[61] That summer had 90 days with temperatures exceeding 100°F, 27 of which were *consecutive* (July 17 through August 12). Daily temperatures reached 100°F for nearly the entire summer (see Figure F-15). Average low temperatures in the summer were 77°F, indicating very little relief from the heat even at nighttime. On August 28, 2011, the heat peaked at an all-time high of 112°F.

[61] Kimmel, Troy M., 2012, Inclement/Severe Weather and Extreme Temperature/Precipitation/Wildfire/Wind/Pressure/Fog/Sunshine Climatology for the Greater Austin Metropolitan Area.

Figure F-15 Daily Temperatures, May 1 – October 31, 2011, Austin, TX



Source: NOAA National Climatic Data Center, Global Historical Climate Network daily observations, Austin Camp Mabry station (GHCND:USW00013958)

Damage

By the end of September, 97 percent of Texas was in one of the top two most severe categories of drought, according to the U.S. Drought Monitor. This included all or part of all counties in Texas.

The drought and extreme heat dramatically reduced soil moisture in Central Texas. The clay soils found in the CAMPO study area, particularly east of I-35, are highly plastic and thus prone to swell and shrink as soil moisture changes (see Figure F-16). As water evaporated from the soils in the summer of 2011, soils in the area buckled, damaging foundations, roads, and other infrastructure.

The most prevalent form of roadway damage was cracks in asphalt pavement. Longitudinal cracks formed, running parallel to a road's center. The cracks began near the edge of the road, exacerbated by heavy dynamic loads associated with overweight trucks (outside wheel path), in particular, and then accelerated roadway damage, typically culminating in three or four cracks in the roadway. These cracks threaten roadway integrity and motorist safety and need to be repaired swiftly. The number and extent of cracks sustained in the summer of 2011 strained maintenance resources. Williamson County, for example, had 100 road and bridge employees working full-time to repair pavement cracks during the summer, and still could not keep up with needs.[62]

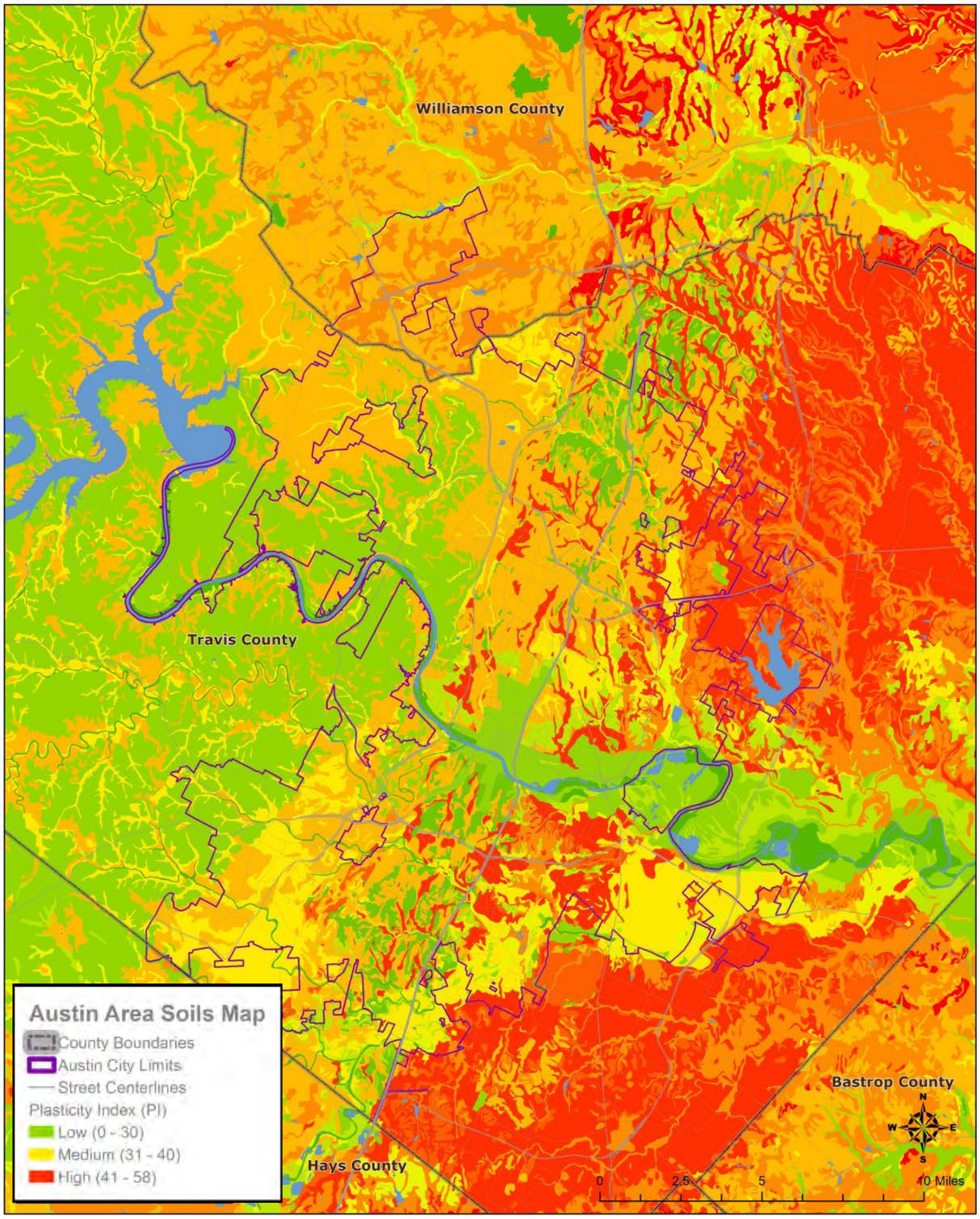
[62] Wear, Ben, 2011, "Parched soil takes toll on roads, slabs, pipes," *Austin American-Statesman*, October 18, 2011.

The photos below represent the types of longitudinal cracking damage that expansive soils cause in the Austin area. All of these pictures feature relatively new roads that have been damaged due, in part, to changes in soil moisture. Roads in the area experienced similar damage during the summer of 2011.

Left: Photo of pavement cracks in a new Austin subdivision in 2009. Right: Longitudinal cracking on Golden Falls Drive in Travis County in 2008. Photo credit: City of Austin.

Photo of a severe pavement crack on Hamann Lane in Travis County in 2005. Photo credit: City of Austin.

Figure F-16 Plasticity Index of Austin Area Soils



Source: City of Austin Street and Bridge Operations, October 2012

In addition, soil shrinkage resulted in gaps between roads and box culverts. Concrete box culverts, which often function as bridges, have different foundations and respond differently to drought conditions than adjoining roadways. This may result in misalignments between roads and culverts, which create dangerous ruts in the roadway.[63]

The extreme conditions even damaged brand new roads, including projects still under construction. The Texas State Highway (SH) 130 tollway, under construction in 2011 in Caldwell County, suffered an estimated $30 million in damage from cracks across several sections. In response, builders repaired cracks and also changed the substructure to create moisture barriers designed to mitigate soil moisture-related damage in the future.[64]

Deterioration

The drought and extreme heat conditions stressed pavements throughout the region. This stress affects assets' remaining service life, making them more susceptible to long-term damage or deterioration from heavy vehicle traffic and other stressors. For example, the City of Austin had to completely rebuild a roadway in northeast Austin after 12 years because of damage from contracting soils—dramatically sooner than the anticipated service life of approximately 50 years (and ideally, even longer). Anecdotally, City of Austin staff cite instances of roadways failing after less than one year of service because of changes in soil moisture.

Disruption

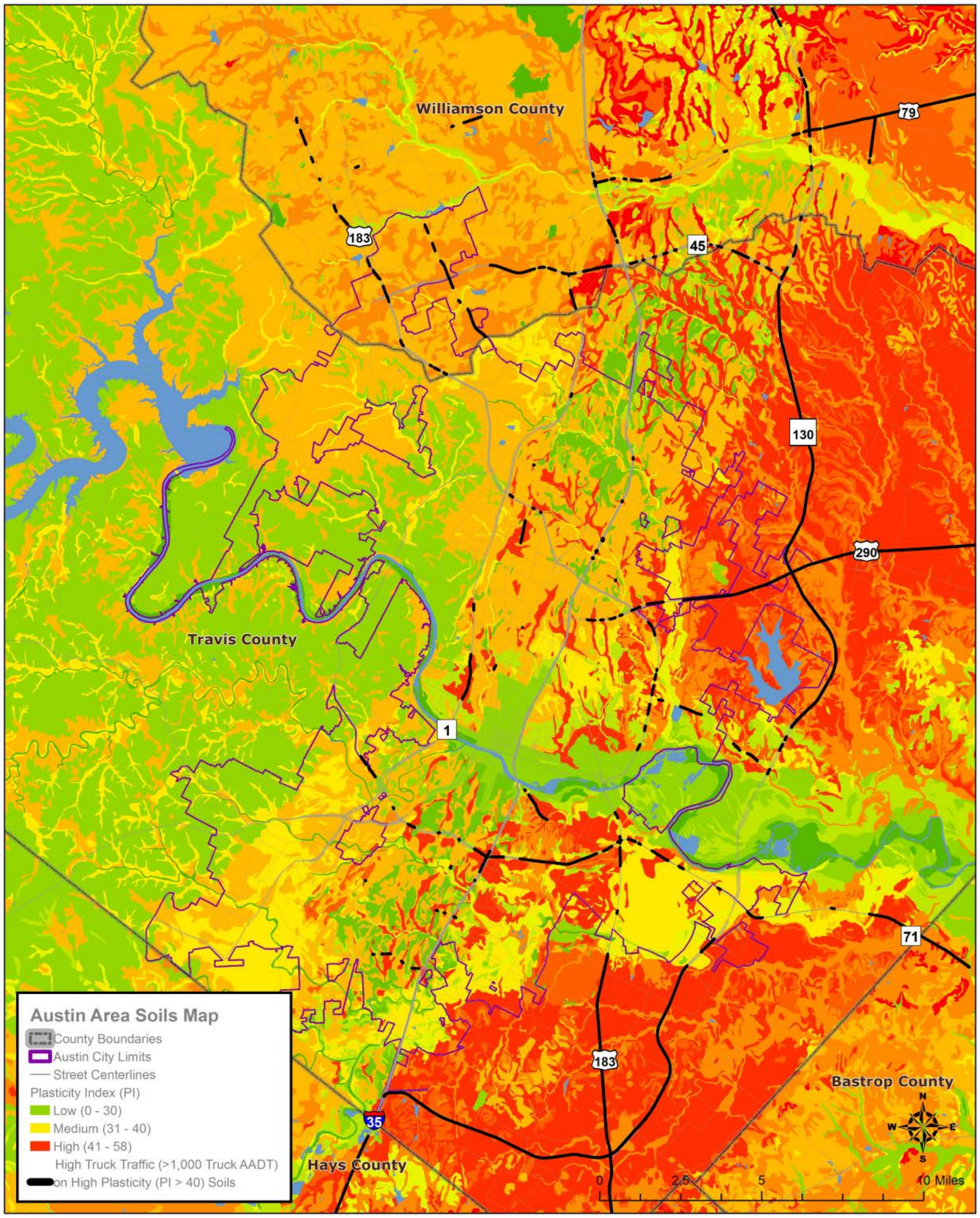
When pavement degradation becomes widespread, as it does in the CAMPO area during droughts, roadways become rough and crack, and reduce safe travel speeds and weight capacities. Roadway owners may not be able to keep pace with the damage given constrained maintenance resources. The repairs to remedy damage and deterioration caused by soil expansion and contraction can create traffic delays, road closures, or other disruptions.

Further, when the roadway damage cannot be repaired immediately, drivers using the roads see more long-term damage to their vehicles and may need to slow down in order to use the roadways safely. Roadways with significant truck traffic are particularly vulnerable to deterioration caused by soil expansion. Figure F-17 shows roadway segments with greater than 1,000 trucks per day and soil plasticity (PI) of greater than 40, highlighting areas that may be more prone to such damage.

[63] Wear, 2011.

[64] Wear, Ben, 2012, "Drought causes $30 million in damage to Texas 130 tollway under construction," *Austin American-Statesman*, July 16, 2012.

Figure F-17 Roadways with High Truck Volumes and High Plasticity Soils



In addition to transportation system disruptions, the drought of 2011 had impacts throughout the entire state. On Tuesday, August 23rd, the Electric Reliability Council of Texas (ERCOT)) reported a stage-one energy emergency resulting from high-peak time usage.[65] In early November, nearly 1,000 Texas' 4,700 public water systems had imposed voluntary or mandatory water restrictions.[66]

F.5 Bastrop Complex Wildfire

By the end of September 2011, 97 percent of Texas was in one of the top two most severe categories of drought, according to the U.S. Drought Monitor. This included all or part of all counties in Texas. As a result of these conditions, Texas experienced its worst wildfire season on record.[67]

The Bastrop Complex Wildfire ignited on September 4, 2011, and quickly became one of the most destructive fires in Texas history, burning 33,120 acres (Figure F-18) and destroying 1,723 residential and commercial structures. The fire was not completely extinguished until October 9, 2011.

This section describes the meteorological conditions leading up to the wildfire and its impacts on the CAMPO transportation system.

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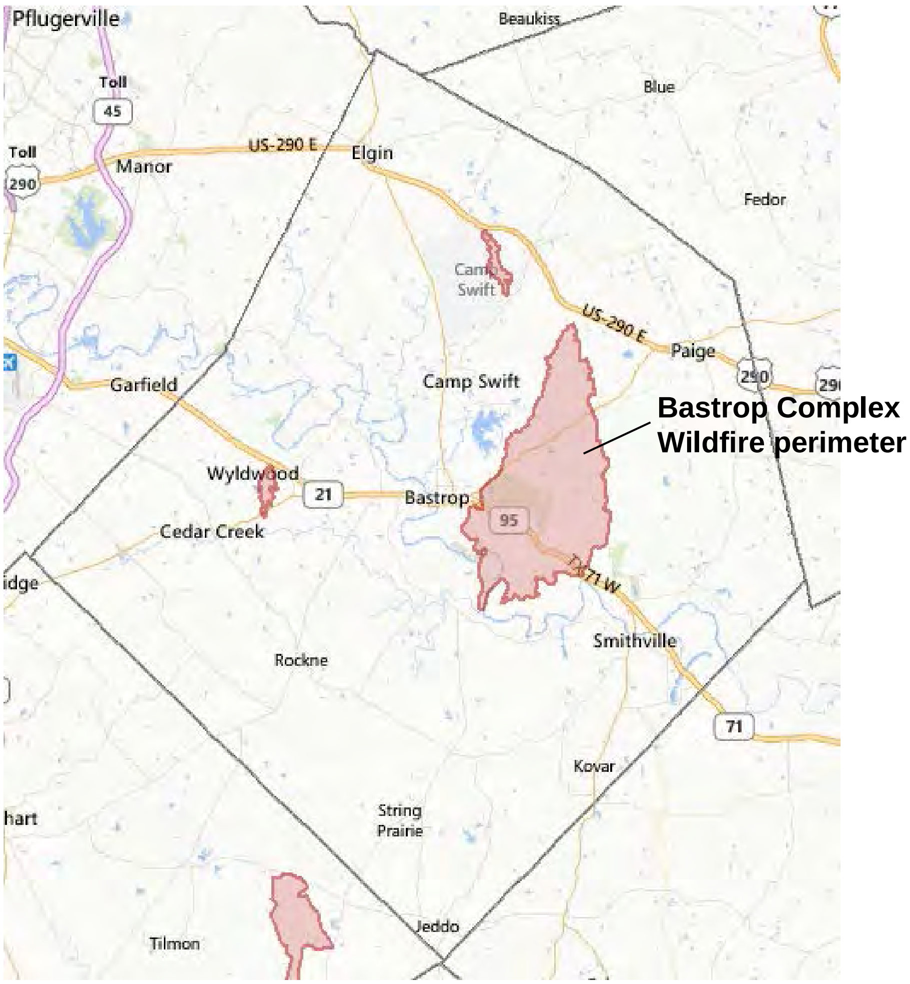
[65] http://www.ercot.com/news/press_releases/show/429

[66] *The Impact of the 2011 Drought and Beyond*, Susan Combs, Texas Comptroller of Public Account. http://www.window.state.tx.us/specialrpt/drought/pdf/96-1704-Drought.pdf

[67] http://www.climatecentral.org/library/climopedia/extreme-weather-and-climate-change-the-southwest

Figure F-18 Bastrop Complex Wildfire Perimeter



Source: Texas Wildfire Risk Assessment Portal, 2011 Large Fire Perimeters layer

Wildfire

The Bastrop Complex Wildfire was one of 57 wildfires to ignite in Texas on September 4, 2011.[68] Conditions were very hot and very dry due to the severe drought and intensely hot summer of 2011 (see section F.4). The drought contributed to very low soil moisture and reduced fuel (trees and brush) moisture content, creating conditions conducive to wildfire. Early afternoon temperatures on September 4 were around 100°F, with relative humidity around 20 percent. The average Keetch-Byram Drought Index (KBDI), which is used to

[68] Texas Forest Service, 2012, Bastrop Complex Wildfire Case Study.

measure forest fire potential based on daily water balance, was 789 (on a scale of 0 to 800) for Bastrop County on September 4.

In this hot, dry setting, Tropical Storm Lee passed through Central Louisiana, generating high winds in Bastrop County. Sustained winds were 12-14 mph, with gusts up to 31 mph. These winds helped both trigger and spread the wildfire.[69]

Once ignited, the wildfire spread quickly because of the wind and drought conditions. A rainy period in 2010 had contributed to extensive vegetation growth that had been subsequently dried out by September 2011. The area was in the midst of an all-time historic low in both live and dead fuel moistures.[70] The conditions contributed to extreme fire behavior, such as high flame heights, extreme spotting (when the fire emits sparks or embers that travel by the wind and spread the fire), and long-term burning.

Meteorological Conditions Associated with the Bastrop Complex Wildfire – September 4, 2011

- Drought (KBDI of 789)
    - Fuel dryness ('extremely dry' Fuel Dryness Index)
    - Low soil moisture (160 mm below normal)
    - High energy release component* ('extreme', >97%)
- Heat (100°F)
- Low relative humidity (20%)
- Wind (gusts up to 31 mph)

*Energy release component relates to the total available energy available to burn per unit area

Damage

The Bastrop Complex Wildfire was the most destructive Wildland Urban Interface fire in Texas history. The fire destroyed 1,723 residential and commercial structures, with estimated losses of over $209 million.[71] Overall, it was the most expensive wildfire in Texas history.[72]

[69] Texas Forest Service, 2012, p. 32.

[70] Texas Forest Service, 2012, p. 44.

[71] Texas Forest Service, 2012, p. 12.

[72] http://www.climatecentral.org/library/climopedia/extreme-weather-and-climate-change-the-southwest

The Bastrop Complex Wildfires did not cause much direct damage to transportation infrastructure. The most immediate transportation-related recovery effort was clearing debris from roadways. According to reports from the Austin American Statesman, the Bastrop County fires also resulted in the loss of dozens of guardrails.[73]

The Bastrop Complex Fire burned through the Lost Pines forest. Within the forest, 76.26% of the burned acreage was private property, 19.9% was on Bastrop State Park and Park Road 1C, 3.6% was road rights-of-way, and the remaining 0.24% was county-owned tracts.[74]

By destroying copious amounts of vegetation, the wildfire reduced soil stability and increased the potential for erosion. Heavy rains on January 25, 2012 caused the unstablized soil to erode quickly, and several roads were washed out (see Figure F-19). The areas with the greatest risk of erosion in the fire's aftermath were heavily burned areas with slopes greater than 15 percent.[75] Another potential impact is that public and private property and public infrastructure, such as unpaved roads and culverts could be at an increased risk from erosion and sedimentation.

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[73] http://www.statesman.com/news/news/local/fire-notes-txdot-concerned-about-damage-to-roads-f/nRfF9/

[74] Bastrop County Complex Fire, Lost Pines Region, Resources Assessment and Response Report, November 10, 2011. *http://www.co.bastrop.tx.us/bcdisaster/pdf/LPRT_Recovery_Report_FINAL_11-10-11_reduced.pdf*

[75] Texas Forest Service, 2012, p. 75.

Figure F-19 Roadway Damage from January 2012 Rainfall – linked to Bastrop Complex Wildfire

Source: Texas Parks and Wildlife Department. Retrieved from Texas Forest Service, 2012, Bastrop Complex Wildfire Case Study.

Disruption

The transportation system plays a critical role in evacuating residents from wildfire danger. During this state of emergency, normal operations are disrupted. Over 5,000 people were forced to evacuate their homes during the Bastrop Complex Wildfire.[76] Firefighters also set up road closures to keep people out of dangerous areas. Road closures affected State Highways 71 and 21, the major route connecting Bastrop to the City of Austin. Affected neighborhoods were closed for re-entry through September 15, 11 days after the fire started.[77]

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[76] Peckham, Matt, 2011, "Disastrous Texas Wildfire Now Worst in State's History," *TIME Magazine*, September 6, 2011, http://newsfeed.time.com/2011/09/06/disastrous-texas-wildfire-now-worst-in-states-history.

[77] Texas Forest Service, 2012, p. 110.