Extreme Weather Vulnerability Assessment

Final Report

January 2015

U.S. Department of Transportation

Federal Highway Administration

ADOT

Technical Report Documentation Page
Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY	**2. REPORT DATE** January 2015	**3. REPORT TYPE AND DATES** Final Report
4. TITLE AND SUBTITLE Extreme Weather Vulnerability Assessment **6. AUTHOR(S)** Thor Anderson, Charles Beck, Kris Gade, Steven Olmsted		**5. PROJECT ID NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Cambridge Systematics 38 East 32nd Street, 7th Floor New York, NY 10016		**8.PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Arizona Department of Transportation 206 S. 17th Avenue, Phoenix, AZ 85007 Federal Highway Administration 1200 New Jersey Ave, SE, Washington, DC 20590		**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES		
12a. DISTRIBUTION/AVAILABILITY STATEMENT This document is available to the public on the FHWA website at www.fhwa.dot.gov/environment/climate/adaptation/2015pilots/		**12b. DISTRIBUTION CODE**
13. ABSTRACT (Maximum 200 words) This study, as part of the Federal Highway Administration (FHWA) Climate Change Resilience Pilot program, assessed the vulnerability of ADOT-managed transportation infrastructure to Arizona-specific extreme weather. ADOT elected to focus on the Interstate corridor connecting Nogales, Tucson, Phoenix, and Flagstaff (I-19, I-10, and I-17). This corridor includes a variety of urban areas, landscapes, biotic communities and climate zones, which present a range of weather conditions applicable to much of Arizona. The project team examined climate-related stressors including Extreme Heat, Freeze-Thaw, Extreme Precipitation, and Wildfire, considering the potential change in these risk factors as the century progresses. This assessment qualitatively addresses the complex, often uncertain interactions between climate and extreme weather, land cover types, and transportation facilities—with an ultimate focus on potential risks to infrastructure by District.		
14. SUBJECT TERMS climate change, adaptation		**15. NUMBER OF PAGES** **16. ACCOUNTING DATA**

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT**

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List of Acronyms

4FRI	U.S. Forest Service *Four Forest Restoration Initiative*
ADHS	Arizona Department of Health Services
ADEQ	Arizona Department of Environmental Quality
ADOT	Arizona Department of Transportation
ALRIS	Arizona Land Resource Information System
ADWR	Arizona Department of Water Resources
AZGFD	Arizona Game and Fish Department
AZGS	Arizona Geological Survey
BCSD	Bias Corrected and Spatial Disaggregation (or "Spatially Downscaled")
BLM	Bureau of Land Management
CAPLTER	Central Arizona-Phoenix Long-Term Ecological Research
CMIP	Coupled Model Intercomparison Project
CLIMAS	Climate Assessment for the Southwest
ENSO	El Niño Southern Oscillation
EPA	U.S. Environmental Protection Agency
ESRL	NOAA Earth System Research Laboratory
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FIS	Feature Inventory System
GCM	General Circulation Model
GEV	Generalized Extreme Value
GIS	Geographic Information System
HUC	Hydrologic Unit Code
MP	Milepost

MPO	Metropolitan Planning Organization
NAIP	National Agricultural Inventory Program
NBI	National Bridge Inventory
NCA	National Climate Assessment
NHD	USGS National Hydrography Dataset
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NWS	National Weather Service
PMP	Probable Maximum Precipitation
REA	Rapid Ecoregional Assessment
RCP	Representative Concentration Pathways
SFA	ADOT Strategic Focus Area
UA	University of Arizona
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
TAMP	Transportation Asset Management Plan

Disclaimer

This report was developed by the Arizona Department of Transportation (ADOT) in accordance with a grant from the Federal Highway Administration (FHWA). The statements, findings, conclusions and recommendations are those of the authors and do not necessarily reflect the views of FHWA or the U.S. Department of Transportation.

Acknowledgments

The Arizona Department of Transportation cannot express enough thanks to the many participants and stakeholders that participated in this climate and extreme weather vulnerability project. The completion of this project would not have possible without everyone's assistance. The project management team, Thor Anderson, Charles Beck, Kris Gade and Steven Olmsted, want to recognize Arizona Department of Transportation staff including the Flagstaff District, Phoenix District, Prescott District, and Tucson District, for helping to identify potentially vulnerable assets and impacts that could arise from potential changes in weather to their operations and the contributions of former project management team members Darcy Anderson and Kristen Busby.

We are grateful to the Federal Highway Administration (FHWA) who provided considerable support for this study. The study was partially funded by a FHWA grant and FHWA provided both technical resources and the assistance of knowledgeable staff who helped guide the study in a fruitful direction.

We benefitted greatly from the participation of many external stakeholders, as described throughout the report. In particular, Dr. Chris Castro of the University of Arizona provided invaluable assistance with selection of appropriate and transportation relevant climate models. Dr. Nancy Grim, Dr. Marcia Nation, and the State Climatologist, Dr. Nancy Selover of Arizona State University (ASU) provided valuable support for the project and the Scientific Stakeholder meeting.

Finally, we would like to acknowledge the efforts of Cambridge Systematics for their expertise, project management, and efforts to enhance the functionality of the U.S. Department of Transportation Climate Data Processing Tool allowing for the timely and efficient modeling of climate data over a large study area. An additional thank you goes to Cambridge's partners AECOM and Gunn Communications.

Executive Summary

This study, as part of the Federal Highway Administration (FHWA) Climate Change Resilience Pilot program, assessed the vulnerability of ADOT-managed transportation infrastructure to Arizona-specific extreme weather. Long term, Arizona DOT seeks to develop a multi-stakeholder decision-making framework – including planning, asset management, design, construction, maintenance, and operations – to cost-effectively enhance the resilience of Arizona's transportation system to extreme weather risks.

ADOT elected to focus on the Interstate corridor connecting Nogales, Tucson, Phoenix, and Flagstaff (I-19, I-10, and I-17), see Figure 1.1. This corridor includes a variety of urban areas, landscapes, biotic communities and climate zones, which present a range of weather conditions applicable to much of Arizona. The project team examined climate-related stressors including Extreme Heat, Freeze-Thaw, Extreme Precipitation, and Wildfire, considering the potential change in these risk factors as the century progresses.

As part of the Pilot program, the study leveraged the FHWA Vulnerability Assessment Framework (see Figure 2.1), customizing it to fit the study's needs. The project team gathered information on potential extreme weather impacts, collected datasets for transportation facilities and land cover characteristics (e.g., watersheds, vegetation), and integrated these datasets to perform a high-level assessment of potential infrastructure vulnerabilities. Each step of the process drew heavily on internal and external stakeholder input and feedback.

This assessment qualitatively addresses the complex, often uncertain interactions between climate and extreme weather, land cover types, and transportation facilities—with an ultimate focus on potential risks to infrastructure by District. Preliminary results were presented in focus groups, where ADOT regional staff provided feedback on the risk hypotheses developed through the desktop assessment. The results of the assessment are presented in Section 5.0, organized first by District, then by stressor, and then further delineated by land cover types (e.g., desert), which are considered qualitatively as potential factors that could either alleviate or aggravate the impacts of extreme weather phenomena.

Summary of Results

Flagstaff & North Prescott Districts

The Flagstaff/North Prescott District portion of the study corridor extends along I-17 approximately from milepost (MP) 260 to MP 340. Much of the aggregated Flagstaff/North Prescott District within the study area is Forest (60 percent), followed by Grassland (23 percent), Chaparral (16 percent), and a nominal amount of Desert/Urban land cover (2 percent). The combined study District is generally significantly cooler than Phoenix and Tucson; days exceeding 100°F are a relative rarity, but days below 32° F are common during winter months. Freeze-thaw and winter-related maintenance occur frequently. Generally, extreme precipitation magnitudes are greater than Phoenix and Tucson Districts, with particularly high intensities in mountainous areas. Due to the dominance of Forest, Grassland,

and Chaparral areas (containing higher concentrations of vegetation and associated fuel loading)—and the relatively minimal coverage of Desert and Urban areas—the Flagstaff District study corridor exhibits a relatively high wildfire risk, compared to southern districts.

Table ES.1 Summary of Results, Flagstaff District

Risk
Extreme Heat
Extreme heat likely increases, but the area remains relatively cooler than Phoenix and Tucson Districts.
Freezing Temperatures
Fewer opportunities for freeze-thaw and snow events likely translate to lower winter maintenance and operations costs.
Extreme Precipitation
Among the heaviest rainfall magnitudes in the study area, but minimal to modest increases are projected for much of the District.
Wildfire Risk
High wildfire risk today (heavily forested), long-term picture is uncertain.

Phoenix & South Prescott Districts

The Phoenix/South Prescott District portion of the study corridor extends approximately from I-10 MP 180 to MP 140 and along I-17 from MP 200 to MP 260. The aggregated Phoenix/South Prescott District within the study area is dominated by Desert and Urban land cover (79 percent)—which are the sole land covers found adjacent to the I-17 and I-10 corridor. About 13 percent of land cover is Chaparral, and 4 percent each for Grassland and Forest—a vast majority of which are located in Prescott District. Particularly in the Phoenix metro area, the District is prone to extreme heat, averaging greater than 73 days annually over 100°F in Desert areas, and significantly more in the vicinity of Phoenix, where summer temperatures exceeding 110° F are not uncommon. The area experiences freezing temperatures infrequently. Extreme precipitation magnitudes are relatively low, although pumps are necessary at depressed sections of Interstate. Due to the preponderance of Desert and Urban areas, wildfire risk is low or moderate along the corridor, although higher-risk land covers intersect I-17 just south of MP 260 (the northern border of the Phoenix District study area).

Table ES.2 Summary of Results, Phoenix District

Risk
Extreme Heat Extreme heat is projected to increase dramatically, with Desert areas projected to experience over 144 days above 100°F annually by 2080.
Freezing Temperatures Particularly south of I-17 MP 240, the corridor is projected to experience fewer than 5 days during which freezing temperatures occur, on average.
Extreme Precipitation 100-year rainfall estimates are relatively modest, particularly along the Interstate corridor, but extreme precipitation events will likely remain a concern at areas requiring pumping today. Generally, magnitudes are projected to decrease north of I-17 MP 230 and increase south of MP 230 (in the most urbanized portion of the study area).
Wildfire Risk Wildfire risk is relatively low today, particularly along the Interstate corridor, and there is little evidence that changes to climate will significantly influence future wildfire risk in Phoenix District; however, the spread of invasive Grassland into historically Desert landscape could increase this risk over time.

Tucson District

The Tucson District portion of the study corridor extends approximately from I-19 MP 0 to MP 60 and along I-10 from MP 260 to MP 180. Tucson District within the study area is characterized by Desert and urban land cover (58 percent) from the northern border of the District (approximately I-10 MP 180) to I-19 MP 40 (about 20 miles south of Tucson). Climatologically, this portion of the corridor bears close resemblance to the greater Phoenix area. From there, Grassland is dominant (32 percent), with some Forest areas near Nogales (9 percent). Chaparral constitutes only 1 percent of the Tucson study area, none of which is in proximity to the Interstate Corridor.

Particularly in Desert areas, the District is prone to extreme heat, averaging nearly 70 days annually over 100°F (Grassland, in contrast, averages less than 10 days annually). Although freezing temperatures can occur in higher elevation areas—particularly in the vicinity of Nogales—cold weather is not prevalent north of I-19 MP 20. Extreme precipitation magnitudes are relatively low throughout the corridor, rising slightly to the south. Wildfire risk is low or moderate along the corridor from the northern border to I-19 MP 40 (comprised of Desert or Urban areas) although Grassland, a high-risk land cover, is the dominant vegetation from I-19 MP 40 nearly until Nogales, where it is joined by Forest.

Table ES.3 Summary of Results, Tucson District

Risk
Extreme Heat Extreme heat is projected to increase dramatically, with Desert areas projected to experience over 146 days above 100°F annually by 2080.
Freezing Temperatures Particularly north of I-19 MP 20, the corridor is projected to experience between 1 and 20 days during which freezing temperatures occur, on average. Nogales may experience more than 50 days—still a significant reduction from the historical average.
Extreme Precipitation 100-year rainfall estimates are moderate in Desert areas, increasingly slightly approaching Nogales. However, modest increases are projected, particularly from Tucson to Nogales.
Wildfire Risk Wildfire risk is relatively low today in Desert and Urban areas, and high in Grassland and Forest areas south of I-19 MP 40. Long-term changes in risk are uncertain.

Next Steps

This FHWA extreme weather pilot study provided the opportunity to formalize extreme weather considerations at ADOT. Selected potential next steps for ADOT include:

- Seek partnerships and funding opportunities to further explore extreme weather risks and identify risk management opportunities.
- Continue to develop the partnerships established during this study.
- Continue to communicate and collaborate with ADOT planning, design, construction, maintenance and operation activities to mutually evolve ADOT's understanding of current and future extreme weather risks.
- Ensure that extreme weather risk management activities complement the agency's Strategic Focus Areas (SFA) and incorporate cost-effective adaptation strategies into ADOT's Transportation Asset Management Plan (TAMP).

Consistent with the objectives of the FHWA Pilot program, this study helped identify several potential avenues for further research and study, including:

- Expand the focus to encompass lower functional classification roadways which, in general, are likely to exhibit greater susceptibility to extreme weather events than Interstates.

- Further leverage, apply, and build on the work of academics and other agencies in Arizona and the southwestern region.
- Devote more in-depth consideration to potential shifts in biotic community composition and geographic distribution as the century progresses.
- Invest in more robust modeling of wildfire risk, including further research into wildfire precursors, including ignition sources, soil moisture, evapotranspiration, and potentially Keetch-Byram Drought Index. Also, collaborate with other wildfire risk modeling efforts across the State and region.
- Using precipitation projections, perform hydrologic modeling of runoff and flooding at a more granular geographic scale. Advanced research might also consider the potential impacts of post-wildfire debris. The United States Geological Survey Arizona Water Science Center is a strong potential partner for hydrological matters.
- Analyze Performance Control System (PeCos) data to better quantify the impacts of extreme weather in terms of costs and specific repairs and/or maintenance treatments. Leverage Traffic Operations Center data for information on the operational impacts of extreme weather events.
- Consider integrating climate into a scenario planning framework.

A combination—or all—of these activities could be integrated into a comprehensive transportation adaptation (risk management) plan, which would inform planning and decision-making across the State of Arizona in the face of a changing climate.

1.0 Introduction

The Arizona Department of Transportation (ADOT) led a study to assess the vulnerability of ADOT-managed transportation infrastructure to Arizona-specific extreme weather. This project was part of the Federal Highway Administration (FHWA) Climate Change Resilience Pilot program and builds upon ADOT's *Preliminary Study of Climate Adaptation for the Statewide Transportation System in Arizona* (*Preliminary Adaptation Study*), published in 2013. The study corridor crosses a diverse set of landscapes and is potentially vulnerable to a range of different extreme weather events and conditions.

1.1 Goals

Long term, ADOT seeks to develop a multi-stakeholder decision-making framework – including planning, asset management, design, construction, maintenance, and operations – to cost-effectively enhance the resilience of Arizona's transportation system to extreme weather risks. As a critical step in the progression toward this goal, the specific objectives of the Vulnerability Assessment were to:

- Qualitatively assess the risks of extreme weather on critical transportation infrastructure;
- Seek feedback from stakeholders to inform and enhance the assessment and propose a collaborative structure for future adaptation efforts; and
- Contribute to the ongoing development of FHWA's Vulnerability Assessment Framework[1].

1.2 Scope

This study focused on the Interstate corridor connecting Nogales, Tucson, Phoenix, and Flagstaff (I-19, I-10, and I-17), see Figure 1.1. This corridor includes a variety of urban areas, landscapes, biotic communities and climate zones, which present a range of weather conditions applicable to much of Arizona. The entire corridor was deemed critical, and therefore further efforts to identify and focus on critical assets within the corridor were not undertaken.

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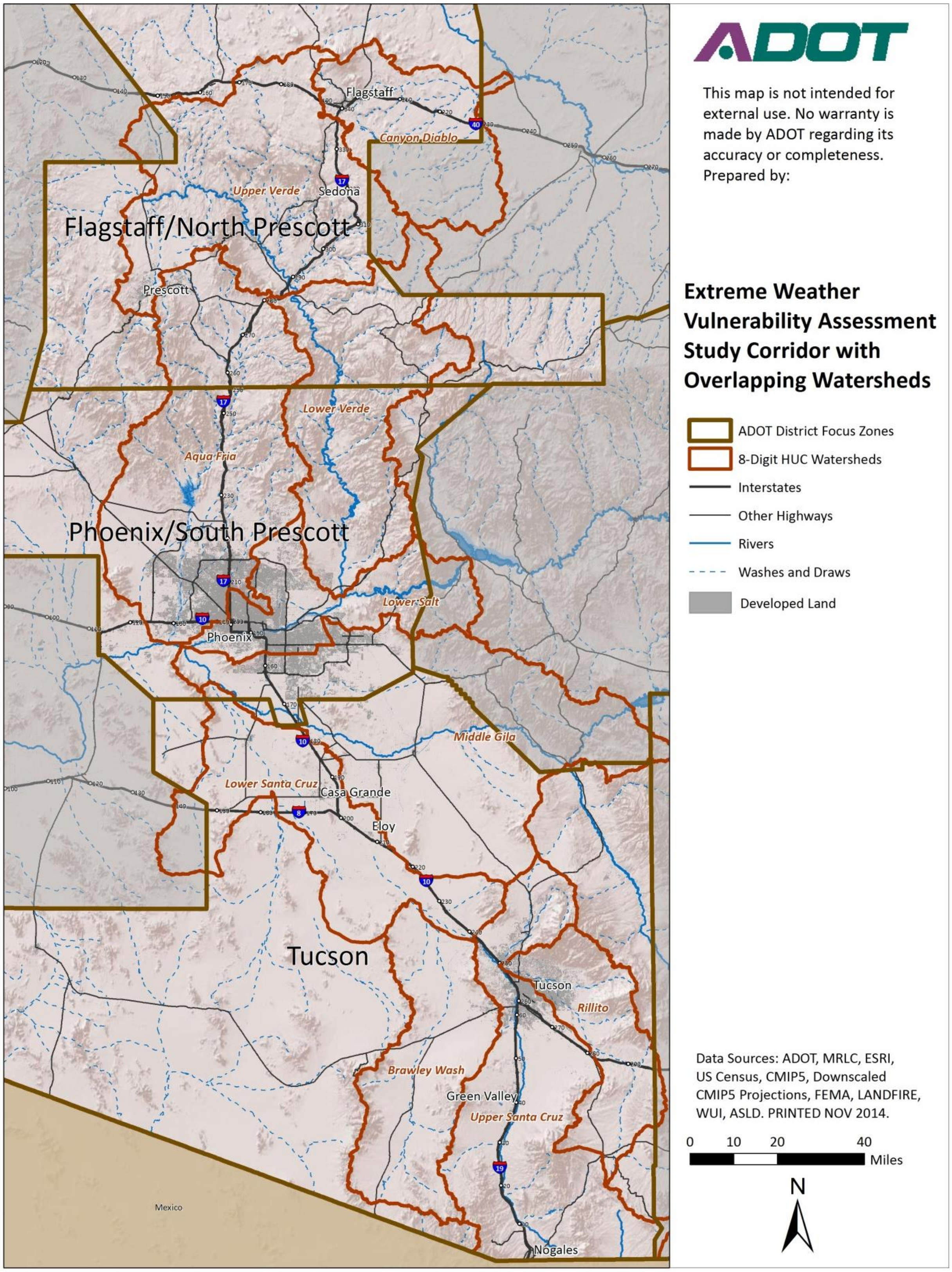
[1] www.fhwa.dot.gov/environment/climate_change/adaptation/publications_and_tools/vulnerability_assessment_framework/index.cfm.

Figure 1.1 Study Area: ADOT Districts and Watersheds



The project team examined climate-related stressors identified by ADOT, selected stakeholders, and by the *Preliminary Adaptation Study*, including:

- **Extreme Heat,** which can lead to pavement deformation and thermal expansion of bridges, limit summer construction windows, and act as a precursor to other extreme weather conditions, including dust storms and ***wildfire***. Dust Storms can create operational disruptions. Wildfire can also disrupt operations and additionally render an area more vulnerable to flooding and landslides by disturbing established vegetation patterns and creating debris that can clog drainage infrastructure.

- **Extreme Precipitation**, which can result in operational disruptions and cause flooding and landslides. ***Flooding*** also can damage infrastructure by causing washouts and scouring, for example.

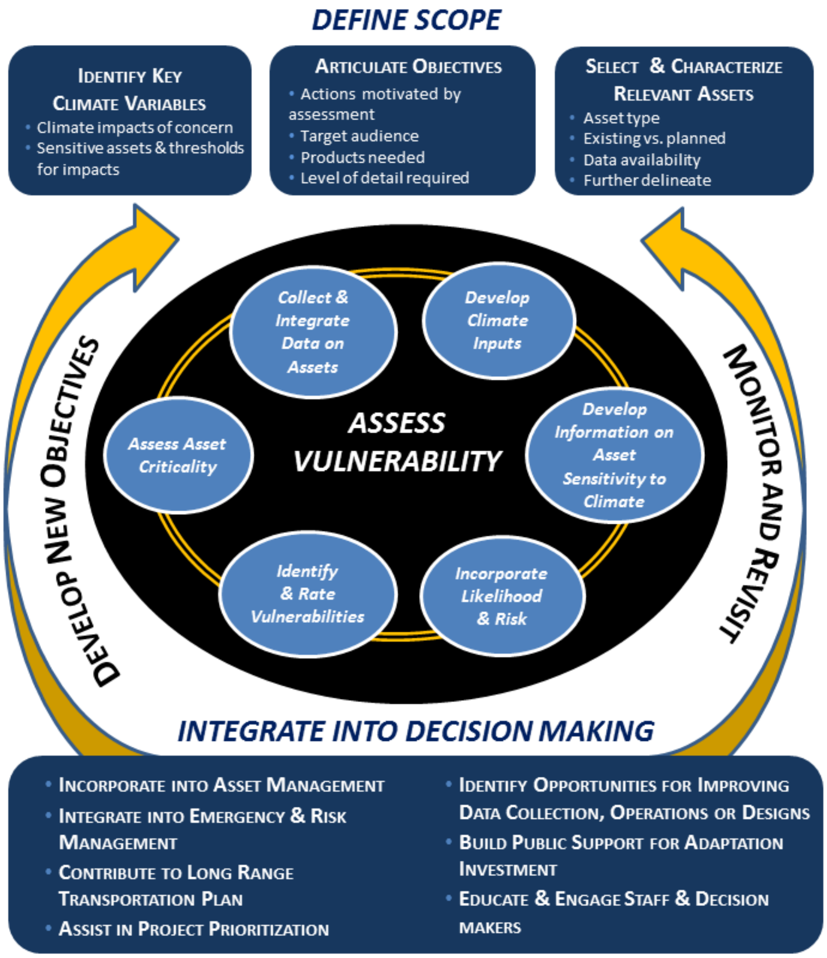
- Other issues, such as landslides, rockfall, and ***freeze-thaw***, were considered regionally, where relevant.

2.0 Methodology

2.1 FHWA Framework

The study leveraged the FHWA Vulnerability Assessment Framework (see Figure 2.1), customizing it to fit the study's needs. The project team gathered information on potential extreme weather impacts, collected datasets for transportation facilities and land cover characteristics (e.g., watersheds, vegetation), and integrated these datasets to perform a high-level assessment of potential infrastructure vulnerabilities. Each step of the process drew heavily on stakeholder input and feedback. More on the FHWA framework may be accessed on FHWA's web site[2].

Figure 2.1 FHWA Vulnerability Assessment Framework



Source: FHWA.

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[2] http://www.fhwa.dot.gov/environment/climate_change/adaptation/.

The project team gathered three categories of information for the assessment: climate data, transportation asset data, and land cover data. Focus Group meetings with internal and external stakeholders early in the study helped the project team develop an initial understanding of existing regional and statewide transportation vulnerabilities—as well as future concerns—from the practitioners who manage these challenges on a daily basis. This feedback helped the team focus on obtaining the most relevant data to efficiently assess vulnerability. The subsequent Scientific Stakeholder meeting helped establish appropriate assumptions for generating and processing climate stressor data.

The study examined baseline (historical) and potential future extreme weather conditions, focusing on temperature and precipitation variables. Two future analysis periods were selected: 2025 to 2055 (referred to subsequently as 2040, the median year), which reflects the time horizon of ongoing long-range planning efforts, and 2065 to 2095 (2080), roughly associated with the expected design lifespans of some critical infrastructure types, such as bridges[3]. To provide a long term baseline against which to compare the projections, the team also examined temperature and precipitation observations from 1950 through 1999.

After retrieving stressor projections, the team integrated these data into a Geographic Information System (GIS), and analyzed how projected changes in these risk factors might affect the susceptibility of Arizona transportation infrastructure to weather-related hazards. The assessment qualitatively addresses the complex, often uncertain interactions between climate and extreme weather, land cover types, and transportation facilities—with an ultimate focus on potential risks to infrastructure by District. Preliminary results were presented in Focus Groups, where ADOT regional staff provided feedback on hypotheses developed through the desktop assessment. The results of the assessment are presented in Section 5.0, organized first by District, then by stressor type (e.g., Extreme Precipitation). Stressor projections are further delineated by land cover types (e.g., Desert), which are considered qualitatively as potential risk “modifiers”—factors that could either alleviate or aggravate the impacts of extreme weather phenomena.

This process is detailed in the following sections:

- Study Corridor and Land Cover (Section 3.0);
- Climate Projections (Section 4.0); and
- Vulnerability Assessment (Section 5.0).

Lessons Learned, for both ADOT and FHWA are documented in Section 6.0, and potential Next Steps for ADOT are offered in Section 7.0.

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[3] The future analysis periods for extreme precipitation are 2000-2049 and 2050-2099.

2.2 Partners and Coordination

The project team engaged various internal and external stakeholders through several sets of meetings. Initial Focus Group meetings helped identify relevant extreme weather conditions, transportation system impacts, and resources. The Scientific Stakeholders workshop helped guide the use of climate data and other stressor information. The four ADOT District Vulnerability Focus Groups (one for each maintenance district along the study corridor) helped to refine and validate hypotheses generated through the desktop analysis, and identified specific potential vulnerabilities along the corridor.

Stakeholder meeting participants are shown in Table 2.1.

Table 2.1 Stakeholder Meeting Participants

Focus Groups

- ADOT
    - Budget Office
    - Maintenance Staff
    - District Environmental Coordinators
    - Design Managers
- Arizona Game and Fish
- Arizona Department of Environmental Quality
- Arizona Department of Health Services
- University of Arizona (UA) Climate Assessment for the Southwest (CLIMAS)
- Arizona State University
- Bureau of Land Management
- Sonoran Institute
- The Nature Conservancy
- Federal Highway Administration

Scientific Stakeholders

- Arizona Game and Fish Department
- Arizona State Land Department
- Arizona State University
- University of Arizona
- Central Arizona-Phoenix Long-Term Ecological Research (CAPLTER) program
- Flood Control District of Maricopa County
- National Weather Service (Phoenix)
- The Nature Conservancy
- Sonoran Institute
- U.S. Geological Survey's Arizona Water Science Center

District Focus Groups

- Flagstaff District
- Phoenix District
- Prescott District
- Tucson District

Summaries and findings from these gatherings are incorporated throughout the report. Summaries of the Focus Groups and Scientific Stakeholders workshop are included in the appendix.

3.0 Study Corridor and Land Cover

This chapter describes the study corridor and summarizes the four main land cover types found in the study area.

3.1 Study Corridor Selection

This study focused on the Interstate corridor connecting Nogales, Tucson, Phoenix, and Flagstaff (I-19, I-10, and I-17), sections of which are managed by ADOT's Tucson, Phoenix, Prescott and Flagstaff Districts. This corridor includes a variety of urban areas, landscapes, biotic communities and climate zones, which present a range of weather conditions applicable to much of Arizona. To evaluate the range of extreme weather conditions and impacts across these diverse conditions, environmental factors beyond the immediate right-of-way (ROW) were considered. Therefore, the boundaries of the watersheds[4] that cross the corridor were selected to define the study area (see Figure 1.1).

The project team examined weather-related risks identified by ADOT and selected stakeholders and by the *Preliminary Adaptation Study*, including:

- **Extreme Heat**, which can lead to pavement deformation and thermal expansion of bridges, limit summer construction windows, and act as a precursor to other extreme weather conditions, including dust storms and wildfire.

- **Freeze-Thaw Cycles**, which can cause frost heaving and other deterioration due to frequent thermal expansion and contraction.

- **Flooding** and other precipitation-related phenomena like washouts, erosion, scour, and mudslides, which can create operational disruptions and damage infrastructure. Flooding was examined primarily through the lens of extreme precipitation, a significant risk factor.

- **Wildfire**, which can disrupt operations and render an area more vulnerable to flooding and landslides by disturbing established vegetation patterns, changing runoff coefficients and creating debris that can affect stream flow and drainage.

Other climate-related phenomena—dust storms and rockfall/landslides—also were considered, but due to data deficiencies and/or lack of information on causal relationships, they were not considered in the District assessments. Instead, selected information on these hazards is included in Appendix B.

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[4] At the 8-digit Hydrologic Unit Code (HUC) scale (USGS 1987).

3.2 Land Cover

3.2.1 Land Cover Data

Land cover and dominant vegetation type (e.g., Forest, Grassland) can significantly influence the impact of weather-related hazards on transportation infrastructure, and therefore land cover is an important aspect of this study. The project team identified relevant land cover datasets through literature review, the Focus Group meetings, the Scientific Stakeholders workshop, internal conversations at ADOT, and the *Preliminary Adaptation Study* (see Table 3.1).

The study corridor crosses through a range of land cover types, broadly characterized as Urbanized areas and Deserts, Chaparral, Grasslands, and Forests. Brown and Lowe's *Biotic Communities of the Southwest* (based on the map by Brown and Lowe [1982; The Nature Conservancy 2006] and the descriptions in Brown [1994]) were used to classify the vegetative land cover types in the study corridor. Biotic communities were selected as the appropriate landscape classification type due to the fine resolution of the classification scheme and availability of data.

Table 3.1 Selected Land Cover Datasets

Feature Name(s)	Source(s)
Biotic Communities	Brown and Lowe (1982); data layer developed by The Nature Conservancy of Arizona (2006)
Rivers, creeks, streams, and washes	Arizona Land Resource Information System (ALRIS 1993)[a]
Watersheds (8-Digit Hydrologic Unit Code [HUC])	ALRIS (2008), based on USGS National Hydrography Dataset (1987)[b]
Floodplain and Flood Risk Levels	FEMA National Flood Hazard Layer
Digital Elevation Model	USGS National Elevation Dataset
Levees	FEMA National Flood Hazard Layer
Historical Wildfire Risk	Arizona Geological Survey (AZGS)
Historical Wildfire Perimeters	USGS Wildland Fire Decision Support System

[a] Arizona State Land Department, Arizona Land Resource Information System (ALRIS), 1993, Streams – Ephemeral and Perennial (Vector digital data file), available on-line at: https://azgeo.az.gov/azgeo/datasets/streams-ephemeral-and-perennial.

[b] Arizona State Land Department, Arizona Land Resource Information System (ALRIS), 2008, Subbasin (8-digit HUC) Boundaries – NHD (Vector digital data file), available on-line at: https://azgeo.az.gov/azgeo/datasets/subbasin-8-digit-huc-boundaries-nhd.

3.2.2 Land Cover Analysis

According to Brown and Lowe (1982), eight main biotic communities are present in the study area; the study corridor itself crosses six biotic communities, while two additional biotic communities occur in the surrounding watersheds. The biotic communities were consolidated into four distinct groupings or land cover types: Desert and Urbanized Areas, Chaparral, Grassland, and Forest (Table 3.2). Figure 3.1 shows where these consolidated land cover types occur in relation to the study corridor and ADOT Districts. Appendix B describes the land cover types and biotic communities in greater detail.

Table 3.2 Grouping of Biotic Communities into Land Cover Types

Biotic Community (Brown and Lowe 1982)	Land Cover Type	ADOT Districts
Interior Chaparral	Chaparral	Prescott, Flagstaff
Arizona Upland Sonoran Desertscrub	Desert[a]	Tucson, Phoenix, Prescott
Lower Colorado River Sonoran Desertscrub		
Chihuahuan Desertscrub[b]		
Great Basin Desertscrub[b]		
Great Basin Conifer Woodland	Forest	Tucson, Prescott, Flagstaff
Madrean Evergreen Woodland		
Petran Montane Conifer Forest		
Plains and Great Basin Grassland	Grassland	Tucson, Prescott, Flagstaff[b]
Semidesert Grassland		

[a] The larger urban areas in the study area are located within the Desert land cover type.

[b] Limited presence in study area or district.

- **Chaparral** is a dense evergreen shrubland that is summer drought tolerant and is shaped by wildfire, typically crown fires.
- **Desert** is a general term used to define an arid landscape that receives limited precipitation and is dominated by shrubs. Arizona deserts have highly variable temperatures, routinely exceeding 100°F in summers, potentially with relatively cooler nighttime temperatures.
- **Forest** is defined in this study as a landscape that is dominated by conifer (cone-bearing) trees, often occurring at higher elevations with cooler temperatures.
- **Grassland** is a landscape that is dominated by grasses[5].

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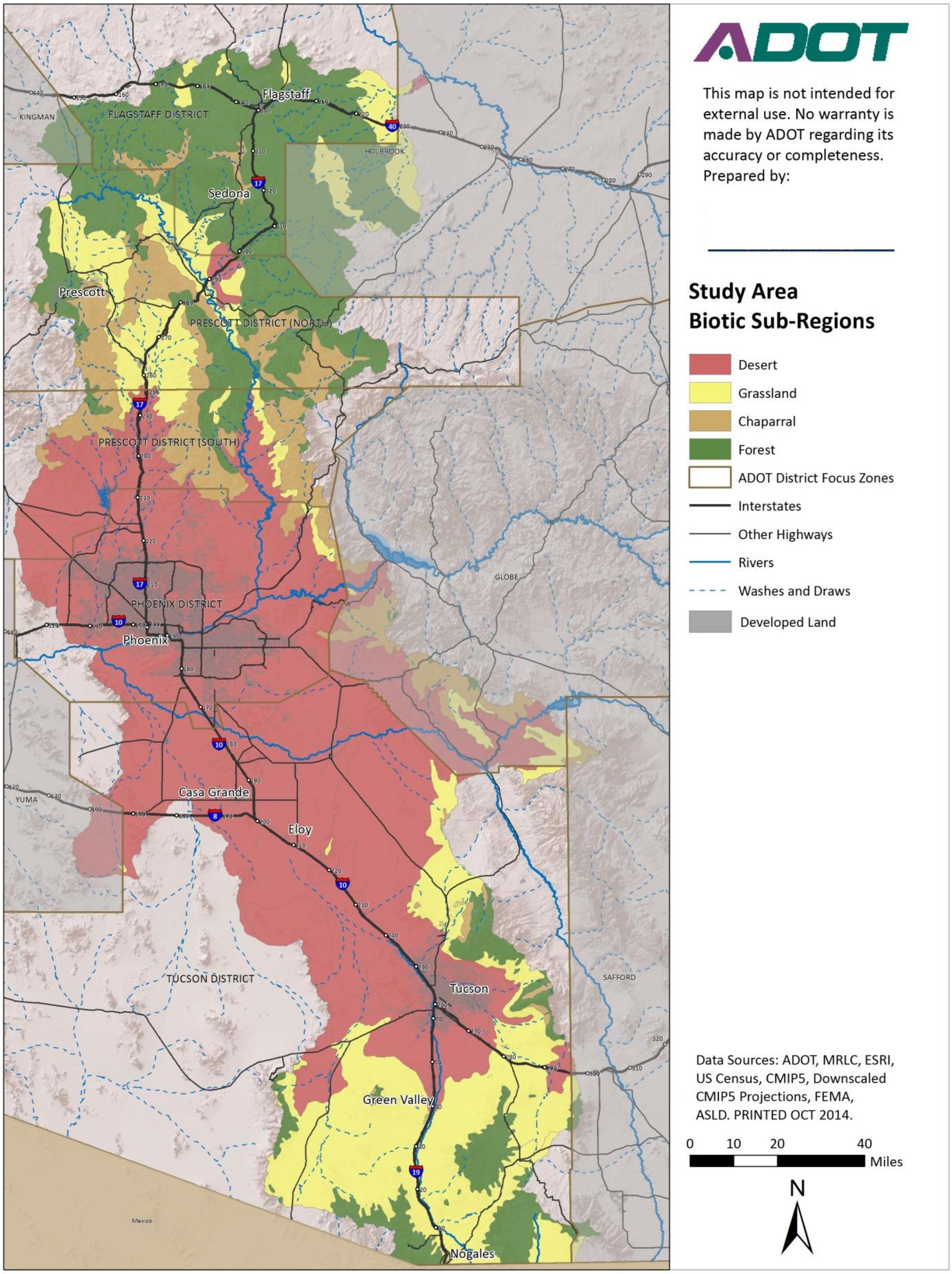
[5] In many areas in Arizona, native grasses have been replaced by nonnative grassland species. Nonnative invasive grasses also have spread to other native land cover types, including deserts.

Figure 3.1 Study Area Land Cover Groupings



Biologists from ADOT and the project team collaborated to consider how these land cover types might modify (e.g., alleviate or aggravate) the risk of various extreme weather phenomena posed to transportation infrastructure within the study corridor, with an emphasis on wildfire risk (see below). Although projected shifts in climate could affect the composition and spatial distribution of these biotic communities in the future, the nature and timing of these changes constitute an area of emerging inquiry, beyond the scope of this study. Therefore, although biotic community types and distributions are held static for the purposes of this assessment, they should be considered dynamic and subject to change in the long term.

3.2.3 Wildfire Risk

The National Climate Assessment (NCA) states that wildfire models estimate increased wildfire incidence due to projected changes in climate in the southwestern U.S. (Garfin et al., 2014). However, more specific, localized information is needed to assess the vulnerability of particular transportation assets.

Wildfire season in Arizona generally peaks in June when fine fuel vegetation is at its maximum and before monsoon rains have commenced (Westerling et al., 2003). Dynamics operating at multiple scales across both time and geographic space affect the number and extent of wildfires that occur in the western United States each year. Both natural and human-influenced factors drive the wildfire regime, including fuel structure and composition; climatic factors such as temperature and precipitation which influence humidity, soil moisture content, and drought stress; wind; lightning strikes; and human-influenced ignition sources which tend to increase in proximity to roads and developed areas.

Projections of key wildfire risk indicators, such as the Keetch-Byram Drought Index (KBDI) or soil moisture, were beyond the scope of this study, although the CMIP Processing Tool produces temperature and precipitation variables that, as proxies, may provide potential clues about future wildfire risk trends. For example, changes in seasonal average rainfall and average temperature may augment the risk of wildfires and/or of post-wildfire flooding, particularly if spring conditions foster the growth of wildfire-prone vegetation (fuel), late spring/early summer conditions are hot and dry (affecting dead fuel moisture), and the mid- to late-summer monsoon thunderstorms are particularly severe, leading to debris-laden flooding. However, in most instances, climate data generated for this study lacks sufficient temporal granularity (e.g., at the scale of a week or month) or certainty on issues of sequencing (e.g., whether early summer drought is likely to be followed by intense monsoon rainfalls).

The project team also reviewed available fire risk assessments conducted by land managers in the study area. This included the *Statewide Strategy for Restoring Arizona's Forests* (Governor's Forest Health Councils, 2007), Bureau of Land Management (BLM) *Sonoran Desert Rapid Ecoregional Assessment Report* (Strittholt et al., 2012), and documents from the U.S. Forest Service (USFS), including the *Four Forest Restoration Initiative (4FRI) Final Environmental Impact Statement for Coconino and Kaibab Forests* (USFS, 2014). Summaries and relevant maps from these reports are included in Appendix B.

Table 3.3 shows estimated wildfire burn risk levels by land cover type and biotic community. They are general, qualitative approximations of present day risk. Further information on these risk ratings, as well as analyses conducted by the Governor's Forest Health Councils, BLM and the U.S. Forest Service 4FRI project, is included in Appendix B.

Table 3.3 Wildfire Burn Risk by Biotic Community

Grouping	Burn Risk	Biotic Community	Summary
Chaparral	High	Interior Chaparral	Fires are infrequent; however, when fires occur they are hot and intense due to the shrub density, and are typically crown fires. The fuel loads have increased due to fire suppression and influx of nonnative grasses such as red brome. Plants are fire-adapted and resprout quickly following fire.[a]
Desert	Moderate/Low	Sonoran Desertscrub – Arizona Upland/Lower Colorado River Subdivisions	Historically, fires were infrequent, of small areal extent, and low intensity due to bare interspaces between plants. Both an influx of nonnative grass cover and proximity to human activities are increasing the frequency, spread and temperature of fires, leading to permanent changes in plant composition and loss of cacti.[b]
Forest	Unmanaged Fuels – High; Managed Fuels – Moderate	Great Basin Conifer Woodland; Petran Montane Conifer Forest	Managed forest with limited understory fuel burns with lower intensity at a higher frequency. Unmanaged forest with high fuel loading and infrequent burning leads to high intensity fires.[c]
		Madrean Evergreen Woodland	Increases in woody vegetation and fuels, overgrazing, and a decline in herbaceous resources leads to increases in large wildfires.[d]
Grassland	High	Plains and Great Basin Grassland; Semidesert Grassland	Grass fires burn with high intensity across the landscape. Frequent hot fires help restrict woody plant establishment; grasses resprout quickly and often recover within 3 years. Grazing reduces fuels and fire frequency, allowing more woody vegetation to grow; however, nonnative grass species produce more fine fuel than native species and may lead to more extensive fires.[e]

Sources: [a] Schalau and Twaronite, 2010; [b] Esque and Schwalbe, 2002; [c] Strittholt et al., 2012; [d] Lata, 2014; [d] O'Connor et al., 2014; and [e] McPherson, 1995.

As the climate changes, wildfire regimes in Arizona are projected to change as well; however, the reasons for the changes vary across land cover types. In forested areas, fires may become more frequent and more severe as a result of increased fuel loads due to long-term fire suppression and generally drier conditions. Conversely, desert areas that are not affected by invasion of nonnative species may have a decreased risk of a large wildfire as a result of increases in the area of bare interspaces between plants (Westerling et al. 2003). Desert areas along the study corridor are being invaded by nonnative grasses and plants including buffelgrass (*Pennisetum ciliare*) and Sahara mustard (*Brassica tournefortii*), as well as more common roadside weeds such as tumbleweed (*Salsola* spp.). The presence of these plants results in an increase in fine fuels in areas that previously were characterized by bare interspaces between plants, leading to more frequent fires that carry over larger areas (Esque et al., 2006). The native desert vegetation is not fire-adapted; it recovers slowly after a fire (Esque and Schwalbe, 2002) and may be replaced by grassland.

Appendix B contains summaries and maps derived from other agencies' assessments of fire regimes and fire potential within the study area. Coordination with the surrounding land owners and managers will be vital to reducing the vulnerability of ADOT's infrastructure to risks associated with wildfire and aftereffects related to post-fire stormwater runoff.

4.0 Climate Data

Chapter 4 summarizes the climate data retrieval process. District-scale stressor projections have been integrated into the Vulnerability Assessment (Section 5.0), while corridor-scale projections are included in Appendix A.

4.1 Climate Data Collection and Processing

Atmosphere-Ocean General Circulation Models (climate models) simulate climate processes at a global scale, ranging in resolution from about 75 to 250 square miles[6]. The process of generating climate data at a more granular scale is called "downscaling." This study uses statistically downscaled climate data. Statistical downscaling employs observed climate data to help adjust model projections based on localized conditions.

ADOT convened a workshop of Scientific Stakeholders to help the project team select and apply the most relevant and robust models, emissions scenarios, and downscaling techniques (Table 4.1 lists the Scientific Stakeholders). Table 4.1 presents the climate data parameters employed in this study, based on conversations with members of Arizona's climate science community.[7] See Appendix A for further detail.

Table 4.1 Climate Data Parameters

Parameter	Selection for Assessment
Projections and Historical Data Source	CMIP5 Bias Corrected – Spatially Disaggregated (BCSD) daily projections and historical data [a]
Emissions Pathway	Representative Concentration Pathway 8.5
Downscaled General Circulation Models (GCM)	NorESM1-M, HadGEM2-ES, CSIRO-MK3.6, CanESM2, MPI-ESM-LR, MPI-ESM-P, GFDL-ESM2M
Horizontal Spatial Resolution	1/8° (~7.5 mile or ~12 km)
Temporal Resolution	Daily for 1950-2000 (backcastings from models in addition to historical data), 2025-2055, and 2065-2095

[a] The team acknowledges the World Climate Research Programme's Working Group on Coupled Modeling, which is responsible for CMIP; and we thank the respective climate modeling groups for producing and making available their model output. Downscaled CMIP5 projections and accompanying historical observations may be downloaded from the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" archive at gdo-dcp.ucllnl.org.

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[6] *Climate Change 2007: Working Group I: The Physical Science Basis (*Intergovernmental Panel on Climate Change, 2007).

[7] The project team used the assessments in a Journal of Climate paper, *North American Climate in CMIP5 Experiments* (Sheffield et al.), to identify climate models based on bias in 1) precipitation and 2) bias in Pacific sea surface temperature (i.e., El Nino Southern Oscillation, or ENSO). The project team is particularly grateful for guidance from Dr. Chris Castro of the University of Arizona, although all errors remain ours alone.

To retrieve downscaled climate data, the team leveraged the U.S. DOT *CMIP Climate Data Processing Tool* (2014). In order to automate the downscaling process—a necessity given the approximately 450 CMIP grid cells covering the study area (multiplied by as many as seven climate models, three time periods, and 13 climate variables)—the team enhanced the Tool to facilitate batch processing and to derive a wider range of variables (such as the projected 100-year 24-hour rainfall magnitude)[8]. See Appendix A for further detail on the modified Tool.

Table 4.2 Climate Data Fields Summary

Field Name(s)	**Temporal Period(s)**
Maximum 1-Day Precipitation Event (by time period)	1950-1999 (backcasting[a] and historical), 2000-2049, 2050-2099
100-/200-Year Maximum Precipitation Event[b]	
Minimum Annual Precipitation	1950-1999 (backcasting and historical), 2025-2055, 2065-2095
Average Annual Precipitation	
Average Number of Days Per Year in which Precipitation Exceeds Baseline Period's 99th-Percentile Precipitation Event	
Average May-June-July-August Precipitation	
Average Daily Maximum Temperature	
Average Number of Days Per Year in which Temperature equals or exceeds 100 degrees	
Average Number of Days Per Year in which Temperature equals or exceeds 110 degrees	
Average Number of Days Per Year in which Temperature falls below or is equal to 32 degrees	
Average Daily Minimum Temperature	

[a] In this context, the term "backcasting" (also called "hind-casting") refers to the simulation of past climate conditions (effectively, the opposite of a "forecast," which simulates future conditions). Comparing backcasted values with actual historical values is an important step in validating climate models.

[b] Added feature. Estimated by fitting Generalized Extreme Value (GEV) distribution to annual precipitation maxima. 2000 to 2049 and 2050 to 2099 are the future analysis periods for GEV-generated projections.

4.2 Summary of Climate Projections

Within a given grid cell, projections vary depending on which climate model is referenced (and would vary further if alternative emissions scenarios were considered). Across the study corridor, projections vary spatially depending on factors such as latitude, topography, urbanization, and land cover. Generally, there is greater agreement (a smaller projection

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[8] Not all variables were directly useful for the assessment. Therefore, only a selection of the most relevant projections are included in this report.

range) across models on temperature variables (averages and extremes) versus precipitation variables (projection ranges are shown in Appendix A), and confidence in the models' ability to estimate actual weather patterns is higher for temperature than for precipitation.[9] More detailed, spatially-explicit projections and accompanying narratives are found in Section 5.0 (Vulnerability Assessment), organized by ADOT District study areas, as well as in Appendix A.

Temperature

Substantial increases in average daily maximum temperatures are projected by each climate model, generally 7° to 9°F throughout the study corridor, regardless of land cover type. The average number of days exceeding 100°F is also expected to increase significantly across models and land cover types. Backcasted (modeled historical) values accord closely with observed values (see "T1 Historical," represented as a box, compared to "T1 Backcast," represented as a purple dot, in Figure 4.1). Particularly for Desert areas, there is a high degree of agreement among the climate models used for this study, even out to 2065 to 2095 (indicated by the relatively small spread of the dark blue line).

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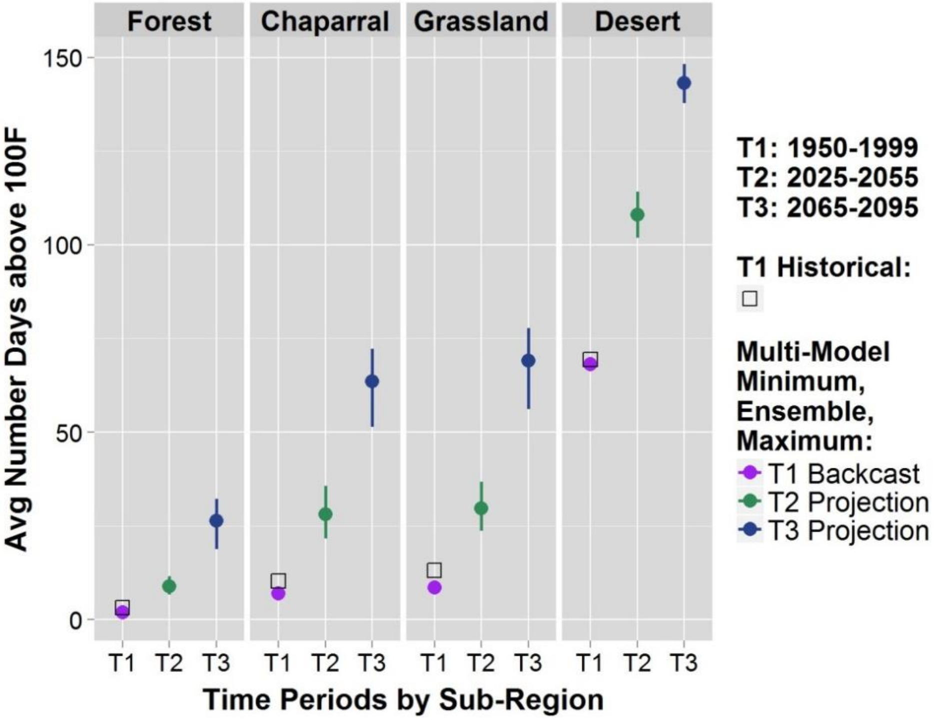
[9] Randall, D. A., R. A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R. J. Stouffer, A. Sumi, and K. E. Taylor, 2007: Climate Models and their Evaluation. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the 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, New York, USA.

Figure 4.1 Average Number of Days above 100°F (Land Cover Type[a])



[a] Values represent blended averages by land cover type over the entire study area.

Precipitation

The model ensembles (the average of all model outputs) project modest increases in the magnitude of rainfall associated with the 100-year (1 percent chance) event. However, the spread of projections is generally very broad—indicating significant disagreement among models—ranging from negligible decreases to significant increases by 2050 to 2099. The ensemble backcasted (modeled historical) values diverge significantly from observed values (see "T1 Historical," represented as a box, compared to "T1 Backcasted," represented as a purple line, in Figure 4.2)—meaning that, generally, CMIP5 data significantly under-predict 1 percent chance rainfall magnitudes in the study corridor. This result reflects the guidance of the Scientific Stakeholders, which counseled that CMIP extreme precipitation data should be considered cautiously in Arizona. Because the upper bound CMIP modeled output more closely maps to historical data[10] and to NOAA's Atlas 14[11] estimates, model maxima are used for the extreme precipitation projection tables in Section 5.0 (all other stressor projections represent model averages).

The ensembles also tend to show slight increases in average annual precipitation across land cover types. There is close concurrence between backcasted and historical values, but a

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[10] Also sourced from CMIP.

[11] http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=az.

widening range of model projections as the century progresses, with substantial disagreement by the 2065 to 2095 timeframe. See Appendix A for more details.

Figure 4.2 100-Year Precipitation Magnitudes (Land Cover Type)

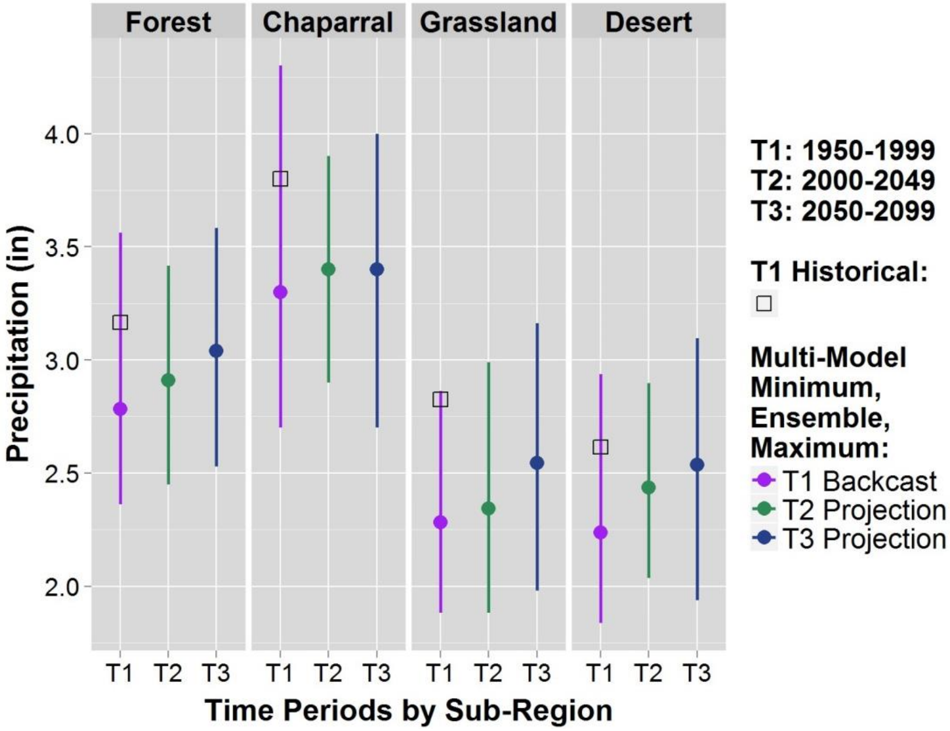
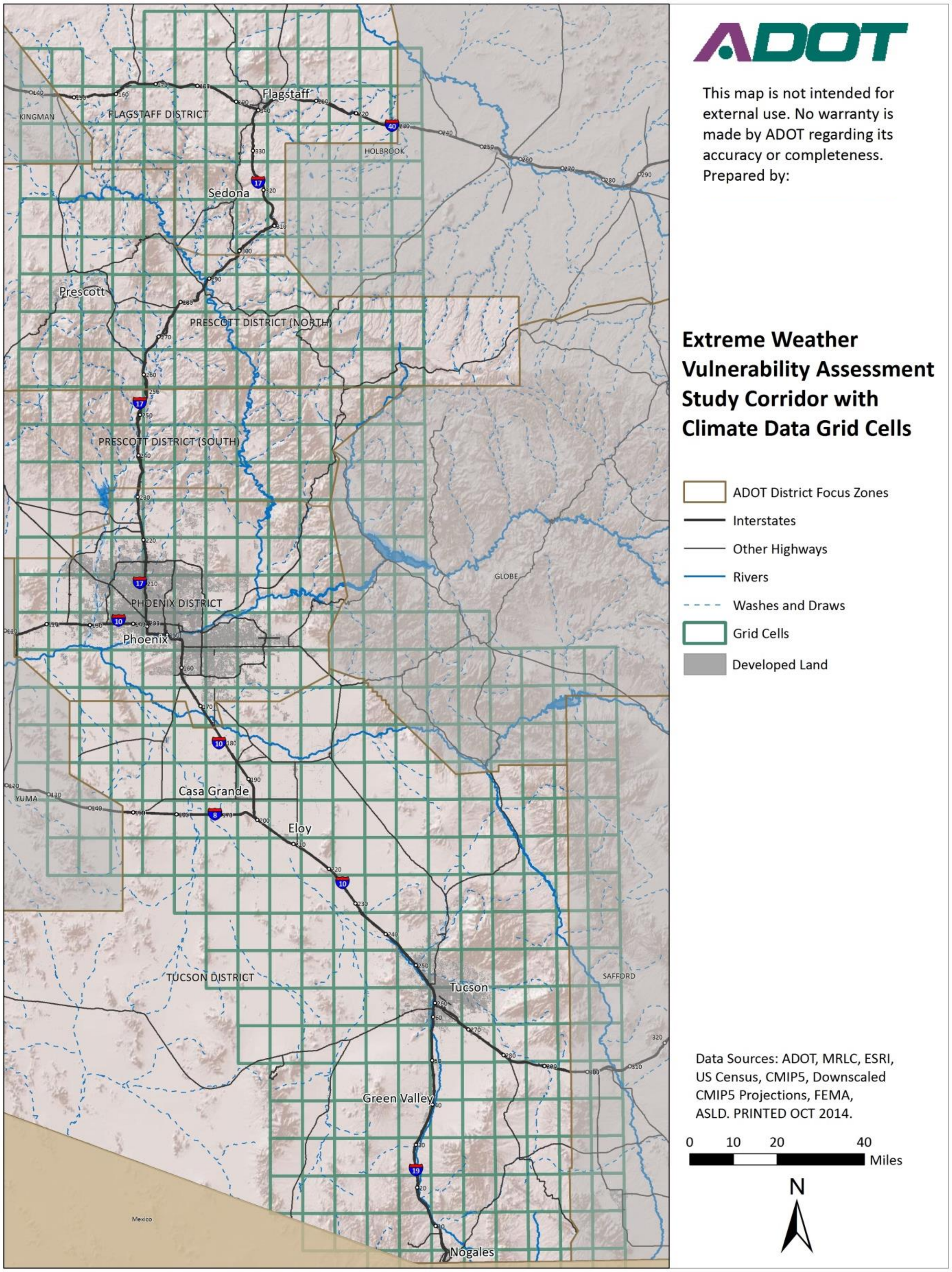


Figure 4.3 Climate Data Grid Cells



This map is not intended for external use. No warranty is made by ADOT regarding its accuracy or completeness. Prepared by:

Data Sources: ADOT, MRLC, ESRI, US Census, CMIP5, Downscaled CMIP5 Projections, FEMA, ASLD. PRINTED OCT 2014.

5.0 Vulnerability Assessment

5.1 Approach

In this section, climate and extreme weather projections (and baseline data) are considered in concert with current land cover data to develop hypotheses of how existing transportation-related vulnerabilities might change as the century progresses.

Because the elements that comprise climate risk are numerous, and the chain of causality cannot, in many instances, be responsibly modeled at this level of analysis, climate variables are treated as factors that influence risk, and land cover is considered as a risk "modifier"—potentially alleviating or aggravating the impact of a given climate event or pattern on transportation facilities and/or operations. For example, the threat of roadway washouts is significantly influenced by precipitation intensity, but the picture of risk is incomplete until precipitation is factored into localized hydrology—of which land cover is an important component—and specific drainage infrastructure is considered. Given the scale of this assessment—a corridor of greater than 300 miles in length—site-specific characteristics like hydrology were not considered, so downscaled projection values and land cover data are considered at the District level to provide a big picture regional projection of risk. This information can be leveraged to support subsequent, localized assessments of vulnerability.

Subsequently, climate projections and land cover data are summarized by District. Due to strong similarities in climate characteristics and land cover types, the northern portion of Prescott District is grouped with Flagstaff District (referred to, in shorthand, as the "Flagstaff District" study area), and the southern portion of Prescott District is grouped with Phoenix District ("Phoenix District" study area).

The assessments commence with a high-level Summary of Results, which distills the major themes relevant to each District grouping. Embedded in the Summary is a table relaying the expected changes, broadly speaking, in impacts associated with Extreme Heat, Freezing Temperatures (Flagstaff and Tucson only), Extreme Precipitation, and Wildfires (Flagstaff and Tucson only). These qualitative rankings are based on the expected interplay between indicative climate variables and dominant land cover types—all else being equal—and do not consider complex phenomena (e.g., change in biotic community characteristics) or localized factors (e.g., hydrology, infrastructure materials or conditions, usage, etc.). The symbols used to represent these rankings are shown in Table 5.1.

The District assessments are organized by stressor type (Extreme Heat, Freezing Temperatures, Extreme Precipitation, and Wildfires). Each stressor is introduced with a table of impacts associated with that stressor (e.g., for precipitation, flooding or scour), paired with potential climate risk indicators (variables that correspond to potential failure thresholds) and a summary of how land cover might affect the manifestation of the stressor on transportation infrastructure (these tables are replicated for each District). District-level maps are provided for selected indicators, as are tables that show the share of each land cover type by District (within the study area) and a blended average projection of that variable for each land cover type (again, within the District study area) for the past (backcastings for 1950 to 1999), mid century (2000-2049 for extreme precipitation, 2025-2055 for all other variables) and end of century (2050-2099 for extreme precipitation, 2065-2095 for all other variables). Finally, summary-level, District-specific Risk Hypotheses are offered for each stressor.

Table 5.1 Explanation of Assessment Symbology

Symbol	Meaning
🟥	**Negative** All else being equal, the impacts of this stressor may worsen as the century progresses.
⬌	**Neutral/Not Relevant** The change signal is weak (no significant movement from baseline conditions) OR the stressor does not significantly affect the District, generally.
⬌ ⬌	**Uncertain** The change signal is murky (e.g., a wide range among model projections), but appears to have a positive (green tinted) or negative (red tinted) valence.
✚	**Positive** All else being equal, the impacts of this stressor may lessen as the century progresses.

5.2 Findings: Flagstaff/North Prescott Districts ("Flagstaff District")

5.2.1 Summary of Results

Much of the aggregated Flagstaff/North Prescott District (approximately I-17 MP 340 to 255) within the study area is Forest (60 percent), followed by Grassland (23 percent), Chaparral (16 percent), and a nominal amount of Desert/Urban land cover (2 percent). The District is generally significantly cooler than Phoenix and Tucson; days exceeding 100°F are a relative rarity, but days below 32°F are common during winter months. Freeze-thaw and winter-related maintenance occur frequently. Generally, extreme precipitation magnitudes are greater than Phoenix and Tucson Districts, with particularly high intensities in mountainous areas. Due to the dominance of Forest, Grassland, and Chaparral areas (containing higher concentrations of vegetation and associated fuel loading)—and the relatively minimal coverage of Desert and Urban areas—the Flagstaff District study corridor exhibits a relatively high wildfire risk, compared to southern districts.

Table 5.2 Summary of Results, Flagstaff District

Expected Change	Climate Risk
↔	**Extreme Heat** Extreme heat likely increases, but remains relatively cooler than Phoenix and Tucson Districts.
✚	**Freezing Temperatures** Fewer opportunities for freeze-thaw and snow events likely translate to lower winter maintenance and operations costs.
↔	**Extreme Precipitation** Among the heaviest rainfall magnitudes in the study area, but minimal to modest increases are projected for much of the District.
↔	**Wildfire Risk** High wildfire risk today (heavily forested), long-term picture is uncertain.

5.2.2 Extreme Temperature

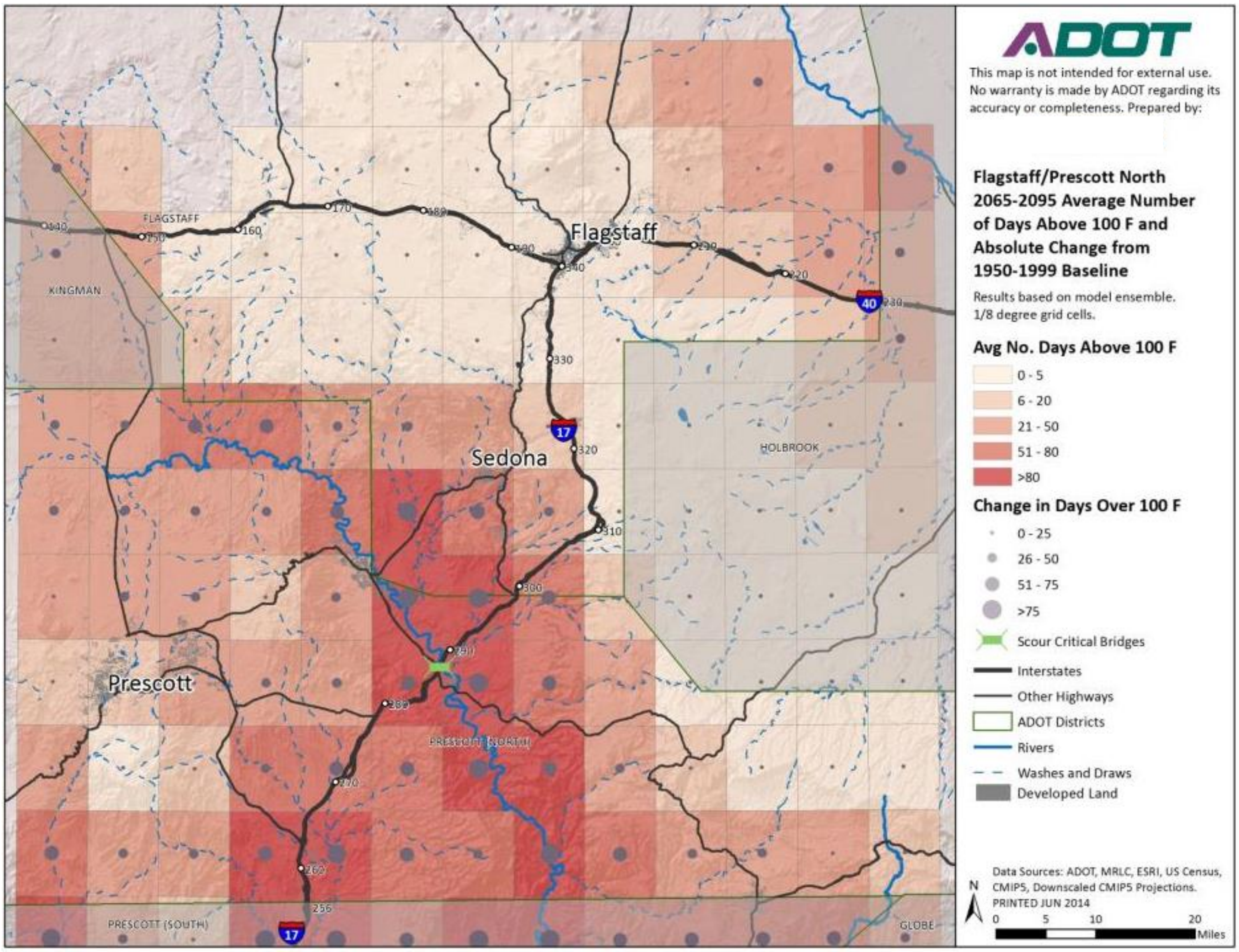
The District is generally significantly cooler than Phoenix and Tucson Districts; days exceeding 100°F are a relative rarity—especially in the vicinity of the City of Flagstaff—averaging 1.5 days annually for Forest areas and 6.1 for Grassland areas. Ensemble projections for 2080 show significant increases in heat events, with Forest areas projected to experience an average of 24 days annually of 100°F or greater, and Grassland areas over 58 days annually.

Average daily maximum temperatures follow the same upward trend. The backcasted average daily maximum for Forest areas is about 67°F, with 2080 projections showing nearly 76°F. Values for Grassland areas are approximately 73°F (backcasted) and 81°F (2080 projections).

Table 5.3 Extreme Heat Impacts and Key Risk Factors

	Risk Factors	
Associated Impacts	**Climate Risk Indicators**	**Land Cover**
Pavement deformation	Days ≥ 100°F	Large urban areas generally augment temperatures (heat island effect)
Thermal expansion	Days ≥ 110°F	
Worker safety		
Shortened construction windows	Average Daily Maximum (Summer)	
	Average Daily Maximum (Annual)	

Figure 5.1 Projected Average Annual Days ≥ 100° (2065 to 2095), Flagstaff District



The projections for average annual number of days exceeding 100°F are especially pronounced south of milepost 310 on I-17, where Forest areas give way to a small pocket of Desert (which roughly maps to the hottest projections, in dark red) and swaths of Grassland and Chaparral.

Table 5.4 shows the average annual days greater than or equal to 100°F in the Flagstaff District. Desert is projected to have the greatest increase in number of extreme heat days; however, it only comprises 2 percent of the landscape. Grassland is also projected to have a large increase in the number of extreme heat days. Average maximum daily temperature (Table 5.5) is projected to increase over time across all land cover types.

Table 5.4 Average Annual Days ≥ 100°F, Flagstaff District

Average Annual Days ≥100°F	% Area	Climate Variables		
		Past[a]	2040	2080
		1950-1999	2025-2055	2065-2095
Chaparral	16%	2.4	13.2	40.3
Desert	2%	23.7	62.6	103.5
Forest	60%	1.5	7.7	24.0
Grassland	23%	6.1	24.9	58.3

[a] Past values represent model backcastings.

Table 5.5 Average Daily Maximum Temperature (F), Flagstaff District

Average Daily Maximum Temperature (°F)	% Area	Climate Variables		
		Past[a]	2040	2080
		1950-1999	2025-2055	2065-2095
Chaparral	16%	71.0	75.2	79.6
Desert	2%	78.1	82.2	86.5
Forest	60%	67.4	71.5	75.8
Grassland	23%	72.8	76.9	81.3

[a] Past values represent model backcastings.

↔

Risk Hypotheses: Extreme Heat, Flagstaff District

Neutral. Despite projections for relatively large percentage increases in extremely hot temperatures, the District is still expected to experience significantly fewer days over the critical heat thresholds of 100°F and 110°F than Phoenix and Tucson Districts, and notably lower average maximums.

- **Pavement Deformation/Thermal Expansion.** Particularly in the transition zone around milepost 310 on I-17, guidelines and specifications for pavement mixes and structural elements may require updating—potentially to resemble those already in place in Phoenix and Tucson Districts.

- **Construction Windows.** Construction windows (periods of the year during which conditions are neither too hot nor cold for work) may shrink during the summer due to increased hot days and higher average temperatures, but may expand with milder weather during the spring and fall (see Freezing Temperatures).

- **Safety.** Heat-related fatigue and illness may become an increasing concern as the century progresses, particularly south of MP 310. Worker safety protocols now more common to Phoenix and Tucson Districts may be required.

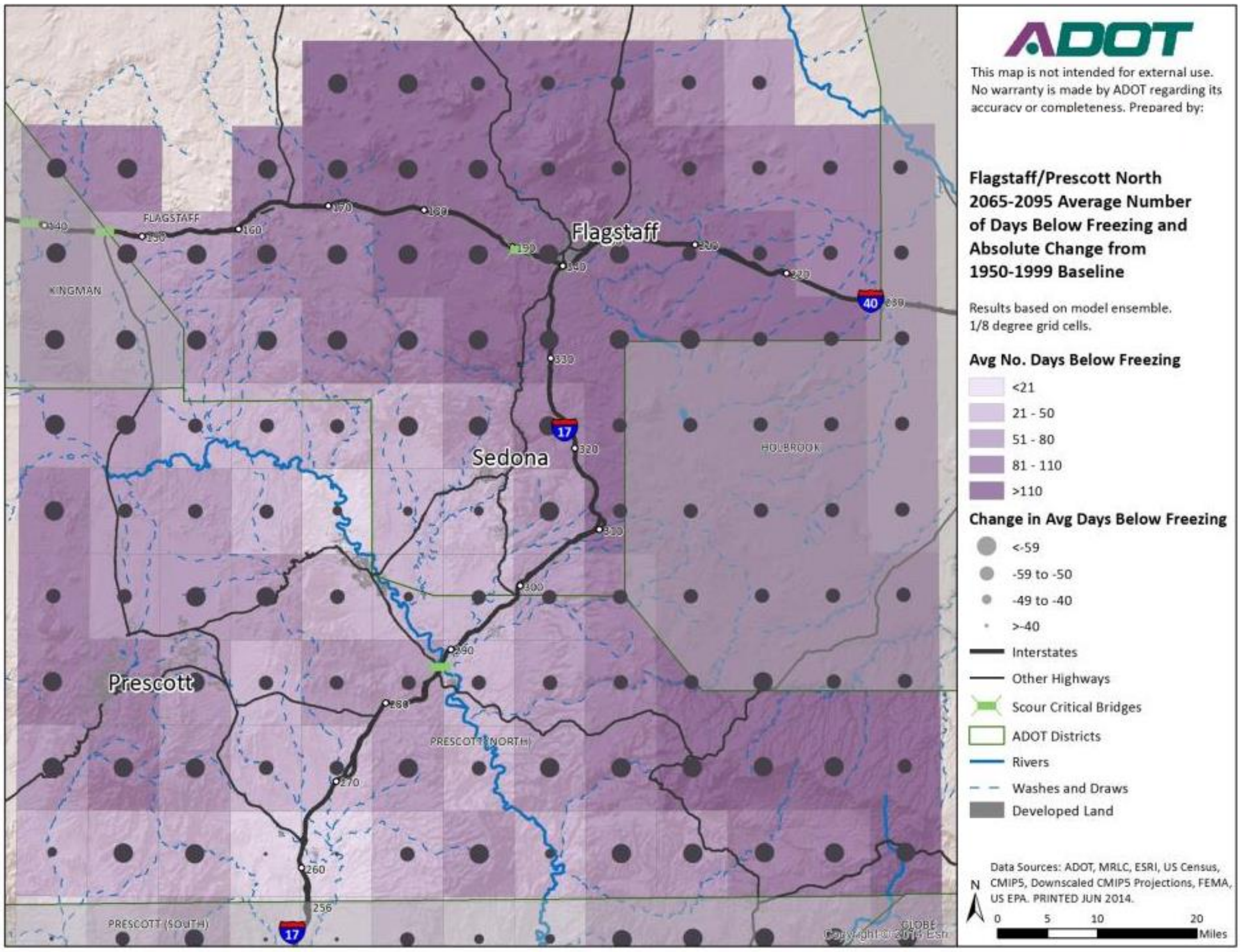
5.2.3 Freezing Temperatures

Flagstaff is prone to freeze-thaw events (fluctuations between freezing and nonfreezing temperatures) and other winter weather phenomena. Forest areas, common to the higher elevation areas of the District, have experienced over 157 days, on average, during which the temperature has fallen below 32°F (thereby creating the opportunity for a freeze-thaw or snow event), and Grassland areas have experienced an average of nearly 107 days during which freezing temperatures occur. Opportunities for freeze-thaw, snow, and other winter weather events are projected to decrease as the century progresses, down to an average of approximately 97 days annually for Forest areas, and 54 days annually for Grassland areas.

Table 5.6 Freezing Temperatures Impacts and Key Risk Factors

	Risk Factors	
Associated Impacts	**Climate Risk Indicators**	**Land Cover**
Frost heaves	Days ≤ 32° F	Higher elevations, associated with Forest areas, are generally more prone to freezing temperatures
Winter maintenance		
Construction windows		

Figure 5.2 Projected Average Annual Days ≤ 32°F (2065 to 2095), Flagstaff District



Projections uniformly show decreases in the average annual number of days at or below freezing across the District. Absolute decreases are relatively more modest in areas that currently experience fewer freezing days, most notably south of MP 310. The corridor immediately south of Flagstaff is projected to experience the greatest number of freezing days, but also realize the most significant reductions—greater than 59 days—versus the historical average. Table 5.7 shows a projected reduction across all land cover types.

Table 5.7 Average Annual Days ≤ 32° F, Flagstaff District

		Climate Variables		
		Past*	2040	2080
Average Annual Days ≤ 32° F	% Area	1950-1999	2025-2055	2065-2095
Chaparral	16%	121.7	93.1	61.7
Desert	2%	93.7	69.8	43.5
Forest	60%	157.1	128.9	97.2
Grassland	23%	106.5	80.7	54.1

[a] Past values represent model backcastings.

Risk Hypotheses: Freezing Temperatures, Flagstaff District

Positive. Although freeze-thaw, snowfall, and other winter weather will continue to affect the Flagstaff District (particularly in higher-elevation Forested areas), a projected reduction in average annual days during which freezing temperatures occur is expected to reduce these phenomena.

- **Frost Heaves.** A reduction in average annual days at or below freezing likely correlates with fewer freeze-thaw events (in Forest areas, this equates to approximately 60 fewer days during which frost-heave conditions are possible, annually).
- **Winter Maintenance.** The incidence of plowing, salting, and other winter-related operations and maintenance activities may diminish as conditions necessary for snow and ice formation occur with less frequency.
- **Construction Windows.** Construction activities requiring warmer minimum temperatures (paving, for example) might be possible earlier in the spring or later in the fall (although monthly projections for freezing temperatures were not downscaled in this study).

5.2.4 Extreme Precipitation

According to NOAA Atlas 14[12], the current estimated magnitude of 100-year precipitation is 4.65 inches at the Flagstaff Airport weather station, 4.54 inches at the Sedona Ranger Station, and 4.86 inches at the Prescott station. Estimates for the area to the northeast of Flagstaff are significantly lower; 2.24 inches at Cameron, for example.

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[12] http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=az.

The downscaled CMIP5 ensemble data, to which the team applied a GEV function, do not closely correspond with NOAA's Point Precipitation Frequency Estimates[13], although the CMIP5 ensemble grids (shown) roughly reflect the geographic distribution of relative rainfall intensities shown by NOAA. Therefore, the upper-bound CMIP5 data, the backcasted values of which more closely resemble the NOAA estimates, are provided.

Based on CMIP5 backcasted data, the estimated magnitude of the current 100-year, 24-hour rainfall event ranges from an average of about 3.3 to 3.4 inches in Grassland and Desert areas (25 percent of the Flagstaff District study area) to around 3.7 inches in Forest areas (60 percent) and 4.2 inches in Chaparral areas (16 percent). Projections show negligible change—both increases and decreases, depending on the land cover type and model—along the corridor as the century progresses. The signal of change for extreme precipitation is, therefore, uncertain.

Table 5.8 Extreme Precipitation Impacts and Key Risk Factors

	Risk Factors	
Associated Impacts	**Climate Risk Indicators**	**Land Cover**
Flooding/Inundation	100-Year (1% chance) rainfall	Heavily vegetated land cover generally mitigates runoff, but may also result in higher debris volumes after wildfire events (which can exacerbate flooding)
Washouts/Erosion		
Bridge Scour		
Mudslides		

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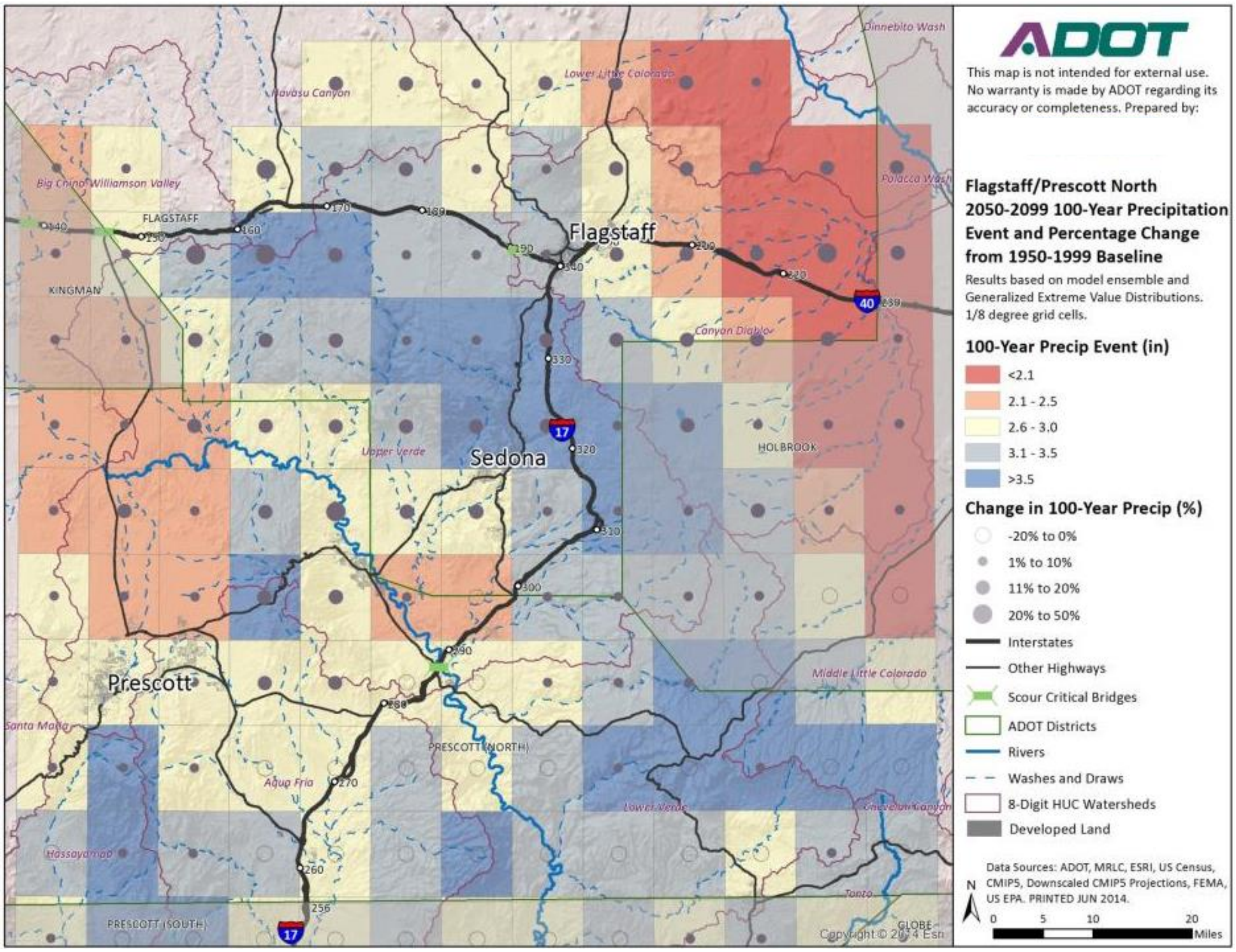
[13] This result reflects the guidance of the Scientific Stakeholders, which counseled that CMIP extreme precipitation data should be considered cautiously in Arizona.

Figure 5.3 Projected 100-Year (1-Percent Chance) Rainfall (2050 to 2099), Flagstaff District



Consistent with NOAA Atlas 14[14], the elevated areas south of Flagstaff (such as Oak Creek Canyon) and, to a lesser extent, south of Prescott (such as Groom Creek), are projected to experience relatively greater extreme rainfall volumes. However, the ensemble projections (model averages) depicted in Figure 5.3 generally show increases in magnitude north of MP 300 and decreases south of MP 300.

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[14] See the ADWR (2013) *Probable Maximum Precipitation Study for Arizona*, Figure 2.2, for a map of NOAA Atlas 14 precipitation estimates for the 100-year, 24-hour event. http://www.azwater.gov/AzDWR/SurfaceWater/DamSafety/documents/ArizonaPMPStudyFinalReport.pdf.

Table 5.9 100-year (1-Percent Chance) Rainfall Event[a], Flagstaff District

		Climate Variables		
		Past[b]	2025	2075
100-Year Rainfall Event (Inches)	% Area	1950-1999	2000-2049	2050-2099
Chaparral	16%	4.2	3.6	3.6
Desert	2%	3.3	3.2	3.0
Forest	60%	3.7	3.5	3.6
Grassland	23%	3.4	3.0	3.2

[a] Table shows the highest modeled value, which better reflects the NOAA Atlas 14 estimates.

[b] Past values represent model backcastings. Future values are model maxima.

Figure 5.4 FEMA Flood Risk (Existing), Flagstaff District

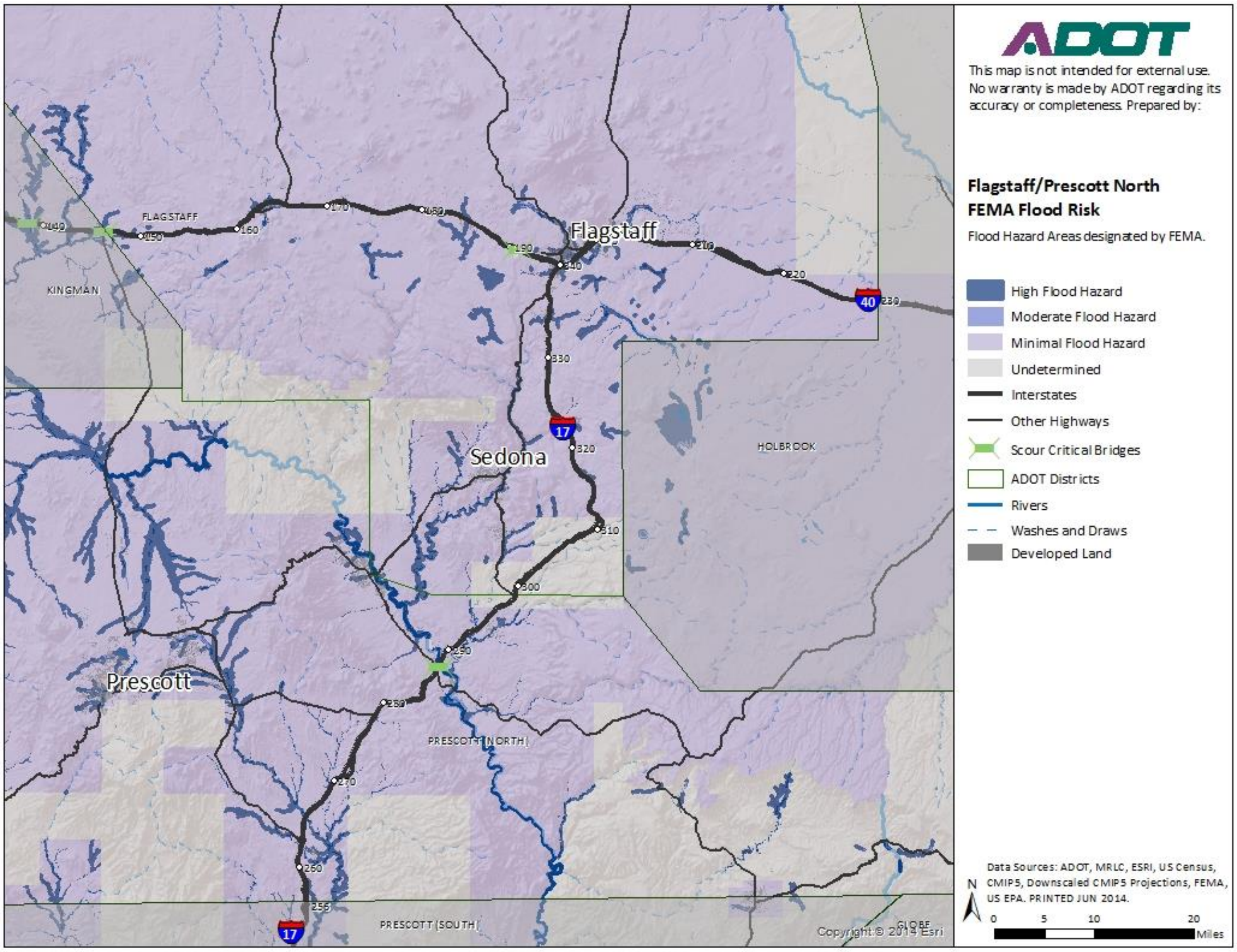


Figure 5.4 shows current FEMA-defined flood risk areas intersected by the corridor.

↔

Risk Hypotheses: Extreme Precipitation, Flagstaff District

Uncertain. The signal of change for extreme precipitation projections is murky. Although discernible trends emerge toward precipitation magnitude increases north of MP 290 and decreases south of MP 290, changes are modest and there is notable disagreement among models.

- **Flooding/Inundation.** The contribution of extreme precipitation to localized flooding cannot be ascertained at this time. Changes in land cover characteristics may have more influence on future flooding risk.
- **Washouts/Erosion.** This portion of the Interstate corridor is not currently prone to washouts. Future washout risk may be driven by land cover changes.
- **Bridge Scour.** According to the National Bridge Inventory, the I-17 corridor currently has one bridge (both northbound and southbound spans) considered scour critical, between MP 290 and 280 over the Verde River. Future scour risk may be driven by land cover changes.
- **Mudslides.** Although portions of the Interstate corridor run adjacent to steep slopes, rockfall is of greater concern.

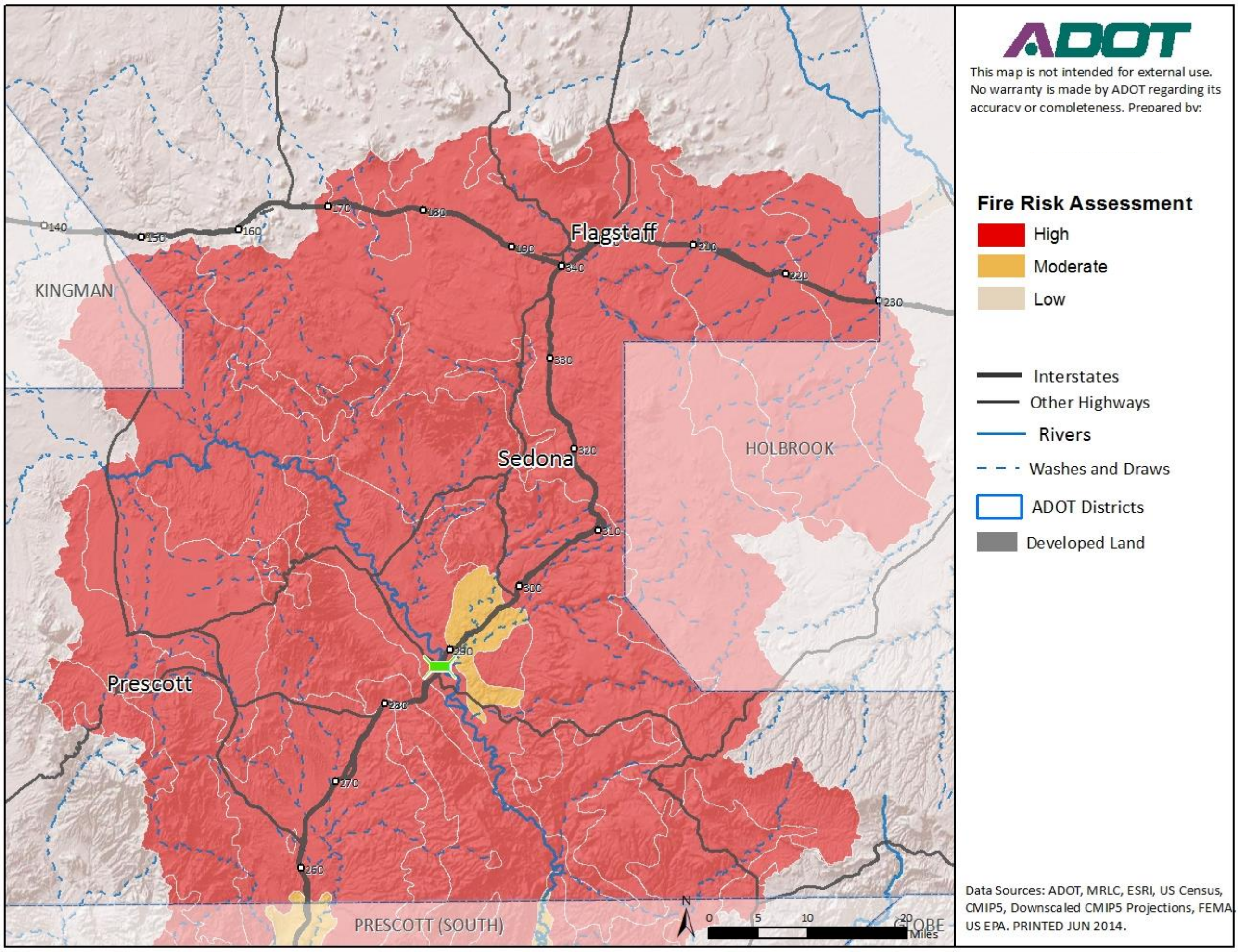
5.2.5 Wildfire

Due to the relative dominance of Forest, Grassland, and Chaparral areas in the Flagstaff District (about 98 percent of land area), wildfire risk is generally high across the District and along the corridor. Desert areas, which exhibit a relatively lower fire risk, comprise only about 2 percent of land area. However, of the 80 miles of I-17 included in this aggregated District, about 10 miles intersect Desert areas. Changes in seasonal average rainfall and average temperature may augment the risk of wildfires and/or of post-wildfire flooding, particularly if spring conditions foster the growth of wildfire-prone vegetation (fuel), late spring/early summer conditions are hot and dry (affecting dead fuel moisture), and the mid- to late-summer monsoon thunderstorms are particularly severe, leading to debris-laden flooding. Projections of key wildfire risk indicators, such as the Keetch-Byram Drought Index (KBDI), fell beyond the scope of this study, although the CMIP Processing Tool produces temperature and precipitation variables that, as proxies, may provide potential clues about future wildfire risk trends.

Table 5.10 Wildfire Impacts and Key Risk Factors

	Risk Factors	
Associated Impacts	**Climate Risk Indicators**	**Land Cover**
Flooding, mudslides, scour (reduced vegetative cover, increased debris)	Average seasonal precipitation Average annual maximum temperature 100-Year (1% chance) rainfall (post-wildfire flooding)	Unmanaged Forests, Grassland, and Chaparral areas all exhibit high wildfire risk—particularly adjacent to highways, where ignition risk is greater. Managed Forest areas and, increasingly, Desert areas exhibit moderate wildfire risk.
Operational disruptions		
Minor damage to guiderail, pavements		

Figure 5.5 Wildfire Risk by Current Land Cover Type, Flagstaff District



With the exception of a limited stretch of I-17 that runs through Desert areas (approximately MP 300-290, as well as a miniscule segment at the southern District border), the entire aggregated Flagstaff study area exhibits a high risk to wildfire—although active wildfire management in Forest areas could reduce risk levels.

Average daily maximum temperatures are projected to increase by approximately 7° to nearly 9°F across the District and across all land cover types. Although the direct effect on wildfire risk cannot be ascertained, a change of this magnitude could, over time, affect the composition and geographic distribution of biotic communities themselves (see, for example, the USDA's *Risk of Human Induced Desertification* map[15], which shows moderate to very high risk for this region).

Average annual rainfall projections for the District show little change from baseline conditions as the century progresses, although average summer rainfall (May-August) is more pronounced, showing 11 to 20 percent increases along the I-17 corridor. The temporal distribution of rainfall over the summer season, which was not examined by this study, will influence the effect of precipitation on wildfire. Extreme rainfall, particularly during the monsoon, could exacerbate wildfire-related flooding, scour, and mudslides, for example. As noted previously, projections for extreme rainfall are clouded by uncertainty.

Table 5.11 Average Annual Precipitation, Flagstaff District

		Climate Variables		
		Past [a]	**2040**	**2080**
Average Annual Precipitation (Inches)	**% Area**	**1950-1999**	**2025-2055**	**2065-2095**
Chaparral	16%	20.2	20.7	20.6
Desert	2%	15.0	15.4	15.5
Forest	60%	21.3	21.9	21.9
Grassland	23%	16.4	16.9	16.9

[a] Past values represent model backcastings.

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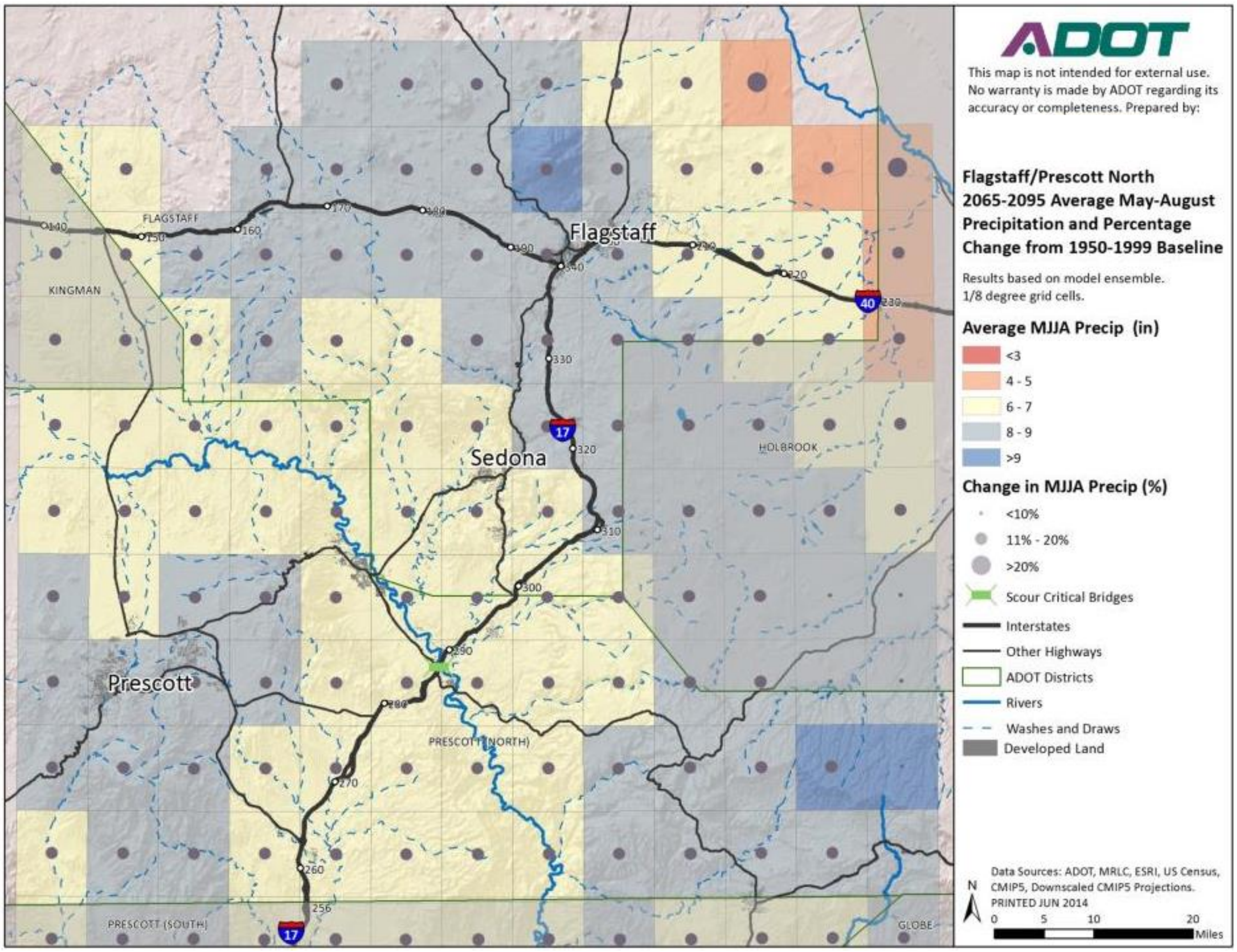
[15] Desertification map, USDA-NRCS, Soil Survey Division, World Soil Resources, Washington, D.C. Population density map, Tobler, W., V. Deichmann, J. Gottsegen, and K. Maloy, 1995, http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/?cid=nrcs142p2_054004.

Figure 5.6 Average June to August Precipitation (2065 to 2095), Flagstaff District



Risk Hypotheses: Wildfire, Flagstaff District

Uncertain. A vast majority of the Flagstaff District study area is comprised of land cover types exhibiting a high wildfire risk. Higher average maximum temperatures could exacerbate existing risks, but also could influence land cover composition and distribution as the century progresses.

- **Flooding/Scour/Mudslides.** Under the right conditions, the after effects of wildfire can influence the severity of flooding, scour, and mudslides—both by increasing runoff rates where vegetation has been destroyed and increasing debris flows. However, both future wildfire risk and projections for extreme precipitation are uncertain.

- **Operational Disruptions.** Wildfire can cause significant traffic delays while in progress, and traffic itself is a major source of wildfire ignition, but future trends for roadway-adjacent wildfire risk are uncertain.

- **Minor Damage.** Wildfire can destroy guiderail and even pavement, but future trends for roadway-adjacent wildfire risk are uncertain.

5.3 Findings: Phoenix/South Prescott Districts ("Phoenix District")

5.3.1 Summary of Results

The aggregated Phoenix/South Prescott District (approximately I-17 MP 255 to I-10 MP 175) within the study area is dominated by Desert and Urban land cover (79 percent)—which are the sole land covers found adjacent to the I-17 and I-10 corridor in this area. About 13 percent of land cover is Chaparral, and 4 percent each for Grassland and Forest—a vast majority of which are located in Prescott District. Particularly in the Phoenix metro area, the District is prone to extreme heat, averaging greater than 73 days annually over 100°F in Desert areas, and significantly more in the vicinity of Phoenix, where summer temperatures exceeding 110°F are not uncommon (an average of nearly 13 days annually at Sky Harbor from 1982-2010, ranging from 2 days in 1999 to 24 days in 2007).

The area experiences freezing temperatures infrequently, particularly south of I-17 MP 240/250. Extreme precipitation magnitudes are relatively low (NOAA Atlas 14 estimates the 100-year, 24-hour precipitation event at Phoenix Sky Harbor International Airport to be 2.9 to 3.66 inches), although pumps are necessary at depressed sections of Interstate. Due to the preponderance of Desert and Urban areas, wildfire risk is low or moderate along the corridor, although higher-risk land covers begin to converge north of I-17 MP 240, and intersect I-17 just south of MP 260 (the border of the combined Phoenix District study area).

Table 5.12 Summary of Results, Phoenix District

Expected Change	Climate Risk
🟥	**Extreme Heat** Extreme heat increases dramatically, with Desert areas projected to experience over 144 days above 100°F annually by 2080.
↔	**Freezing Temperatures** Particularly south of I-17 MP 240, the corridor is projected to experience fewer than 5 days during which freezing temperatures occur, on average.
↔	**Extreme Precipitation** 100-year rainfall estimates are relatively modest, particularly along the Interstate corridor, but extreme precipitation events will likely remain a concern at areas requiring pumping today. Generally, magnitudes are projected to decrease north of I-17 MP 230 and increase south of MP 230 (in the most urbanized portion of the study area).
↔	**Wildfire Risk** Wildfire risk is relatively low today, particularly along the Interstate corridor, and there is little evidence that changes to climate will significantly influence future wildfire risk in Phoenix District; however, the spread of invasive Grassland into historically Desert landscapes could increase this risk over time.

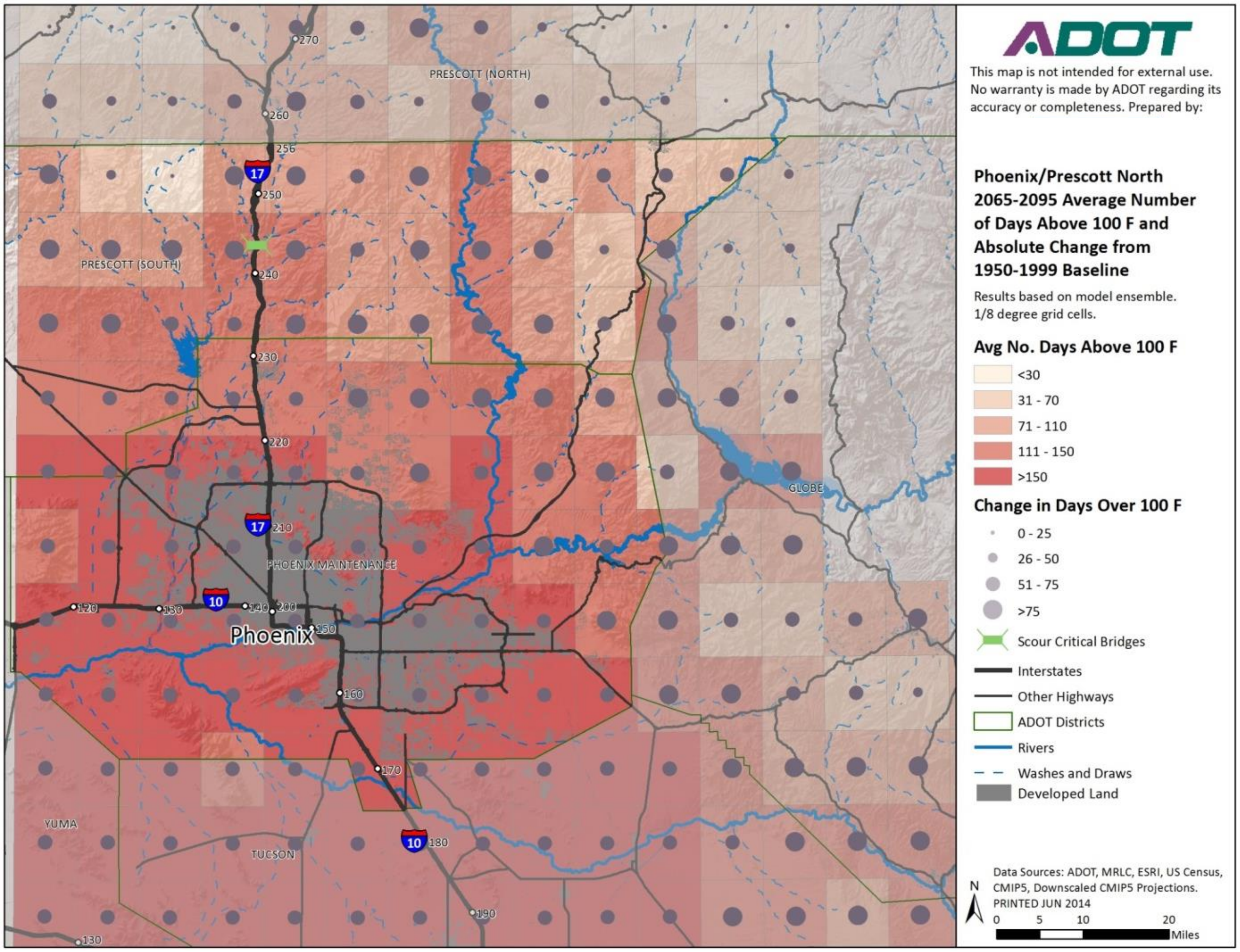
5.3.2 Extreme Temperature

Phoenix District is characterized by extreme heat, particularly south of I-17 MP 240. Currently, the dominant Desert/urban land cover types experience an average of more than 73 days per year exceeding 100°F. Districtwide (factoring in generally cooler Forest, Grassland, and Chaparral areas), the District study area has seen an average of about 60 days annually above 100°F, and about 4 days exceeding 110°F. Districtwide projections for the period of 2065 to 2095 show an average of 129 days annually exceeding 100°F (over 150 annually for Phoenix metro), and nearly 50 days exceeding 110°F.

Table 5.13 Extreme Heat Impacts and Key Risk Factors

	Risk Factors	Land Cover
Associated Impacts	**Climate Risk Indicators**	
Pavement deformation	Days ≥ 100° F	Large urban areas (e.g., Phoenix) generally augment temperatures (heat island effect)
Thermal expansion	Days ≥ 110° F	
Worker Safety		
Shortened construction windows	Average Daily Maximum (Summer) Average Daily Maximum (Annual)	

Figure 5.7 Projected Average Annual Days ≥ 100° (2065 to 2095), Phoenix District



Extreme heat projections for greater Phoenix, particularly south of I-17 MP 220, show greater than 150 days exceeding 100°F, on average. Desert and Urban areas comprise nearly 80 percent of the land cover in this area. Average annual days greater than 100°F are projected to increase across all habitat types, with Deserts having the greatest increase in number of extreme heat days and overall average daily maximum temperature.

Table 5.14 Average Annual Days ≥ 100° F, Phoenix District

Average Annual Days ≥100°F	**% Area**	**Climate Variables**		
		Past[a]	**2040**	**2080**
		1950-1999	**2025-2055**	**2065-2095**
Chaparral	13%	11.9	42.8	83.9
Desert	79%	73.5	112.4	144.5
Forest	4%	12.2	42.7	82.6
Grassland	4%	16.8	54.3	97.2

[a] Past values represent model backcastings.

Table 5.15 Average Daily Maximum Temperature (F), Phoenix District

Average Daily Maximum Temperature (°F)	**% Area**	**Climate Variables**		
		Past[a]	**2040**	**2080**
		1950-1999	**2025-2055**	**2065-2095**
Chaparral	13%	76.0	80.0	84.4
Desert	79%	83.9	87.7	92.0
Forest	4%	75.7	79.8	84.2
Grassland	4%	77.3	81.4	85.8

[a] Past values represent model backcastings.

Risk Hypotheses: Phoenix, Extreme Heat

Negative. Particularly around the greater Phoenix area, extreme heat is projected to occur even more frequently (in Phoenix, an average of 150 days—or over 5 months, in total—annually over 100° F), and average daily maximum temperatures are projected to increase correspondingly.

- **Pavement Deformation/Thermal Expansion.** Although Phoenix District's design guidelines and specifications already call for heat-resistant pavement mixes, these standards may need to be reevaluated as temperatures of 110°F (and above) become more common and potentially last longer.

- **Construction Windows.** Construction, which is already often confined to nighttime hours in Phoenix District (both due to temperature and traffic volumes), may be further curtailed due to higher average annual maximum temperatures (Tmax)—projected to average over

93°F by the 2065 to 2095 timeframe. Although nighttime summer temperatures were not projected as part of this study, based on other temperature projections they are very likely to rise correspondingly.

- **Safety.** Heat-related fatigue and illness, which become a factor as temperatures exceed 90°F, may become an increasing concern as the century progresses, particularly south of I-17 MP 240. Worker safety protocols may require updating as 100°F, 110°F, and even greater temperatures become more common. The incidence of shredded truck tires, known as "alligators," generally increases in very hot weather, affecting motorist and worker safety.

5.3.3 Freezing Temperatures

Although Phoenix District (especially the southern portion of Prescott District) does experience freezing temperatures, especially in higher elevation areas, the phenomenon is not prevalent along the study corridor, and therefore is not considered in this analysis (see the Flagstaff District section for information on the impacts of freezing temperatures).

5.3.4 Extreme Precipitation

According to NOAA Atlas 14[16], the estimated magnitude of 100-year precipitation is 3.31 inches at the Phoenix Sky Harbor weather station (90 percent confidence intervals of 2.9 to 3.66 inches). Estimates are relatively uniform (in the range of 3 to 4 inches) from I-17 MP 220 and south (estimates for the corridor in northern portions of Maricopa County generally exceed 4 inches, with estimates of above 5 inches in mountainous areas).

The downscaled CMIP5 ensemble data, to which the team applied a GEV function, do not closely correspond with NOAA's Point Precipitation Frequency Estimates[17], although the CMIP5 ensemble grids (shown) roughly reflect the geographic distribution of relative rainfall intensities shown by NOAA. Therefore, the upper-bound CMIP5 data, the backcasted values of which more closely resemble the NOAA estimates, are provided.

Based on CMIP5 backcasted data, the estimated magnitude of the 100-year, 24-hour rainfall event ranges from an average of about 3.3 inches in Desert and urban areas (79 percent of the Phoenix District study area) to around 4.6 to 4.8 inches in other land cover types. Projections show the potential for modest increases[18] in Desert areas, particular south of MP 230, and decreases north of MP 230 (where Chaparral in particular becomes more prevalent) as the century progresses. Although these projections lack a high degree of

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[16] http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=az.

[17] This result reflects the guidance of the Scientific Stakeholders, which counseled that CMIP extreme precipitation data should be considered cautiously in Arizona.

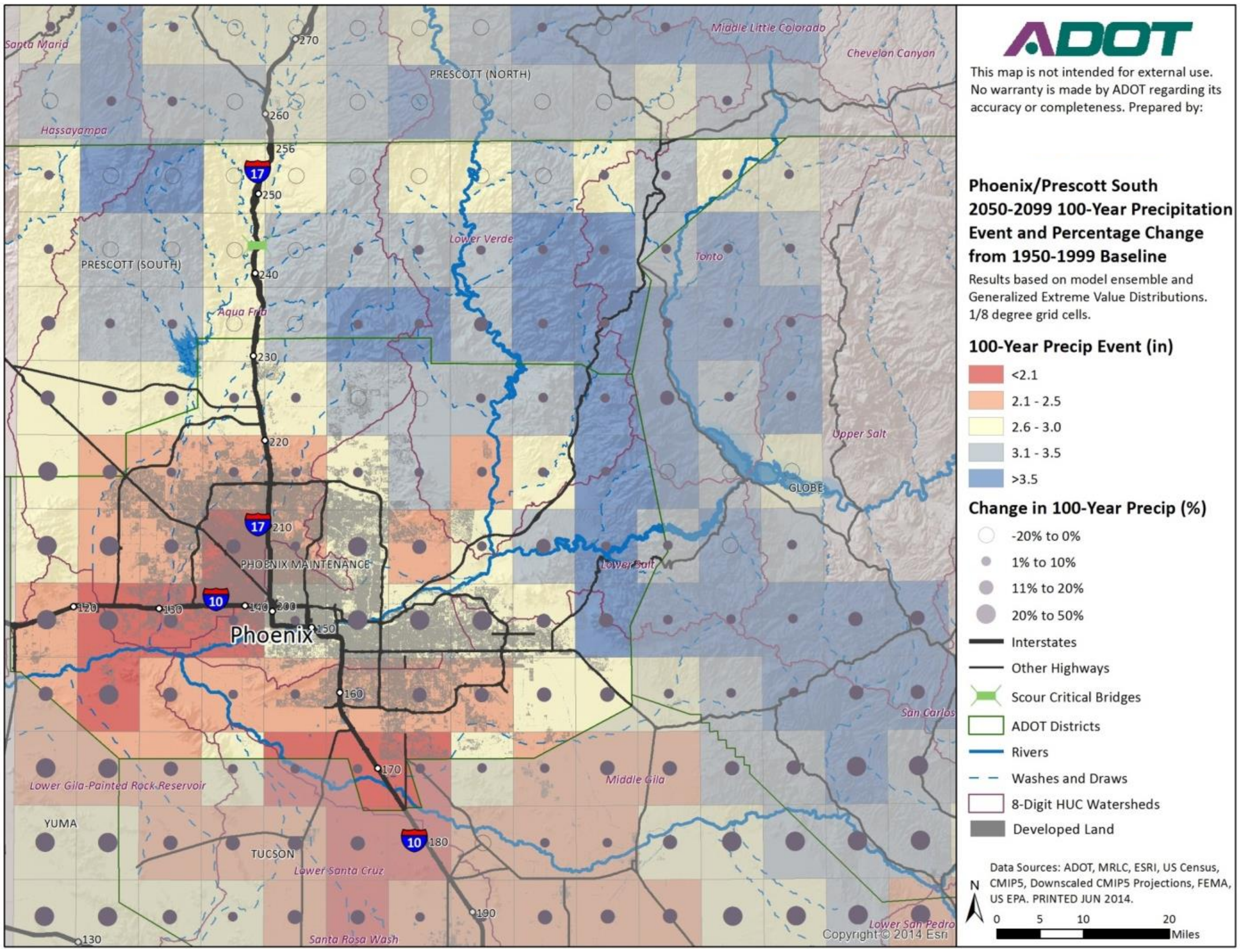
[18] Increases are generally low in terms of absolute magnitude, but more significant in terms of percentage, due to relatively low baseline values. These increases only appear in the model ensembles, not the model maxima shown in Table 5.18).

certainty, they may indicate that the contribution of extreme precipitation events to the inundation of low-lying areas in greater Phoenix (including currently susceptible depressed freeways), may increase marginally as the century progresses.

Table 5.16 Extreme Precipitation Impacts and Key Risk Factors

Associated Impacts	Risk Factors Climate Risk Indicators	Land Cover
Flooding/Inundation	100-Year (1% chance) rainfall	Heavily vegetated land cover generally mitigates runoff, but may also result in higher debris volumes after wildfire events (which can exacerbate flooding)
Washouts/Erosion		
Bridge Scour		
Mudslides		

Figure 5.8 Projected 100-year (1-Percent Chance) Rainfall (2050 to 2099), Phoenix District



Marginal increases in the magnitude of extreme precipitation are projected in the more urbanized area south of MP 230 (approximately), while more pronounced—but still modest—decreases are projected north of MP 230.

Table 5.17 100-year (1-Percent Chance) Rainfall Event, Phoenix District

		Climate Variables		
		Past[a]	2025	2075
100-Year Rainfall Event (Inches)	% Area	1950-1999	2000-2049	2050-2099
Chaparral	13%	4.8	3.9	4.3
Desert	79%	3.3	3.1	3.3
Forest	4%	4.6	3.8	3.7
Grassland	4%	4.6	3.8	4.1

[a] Past values represent model backcastings. Future values are model maxima.

Figure 5.9 FEMA Flood Risk (existing), Phoenix District

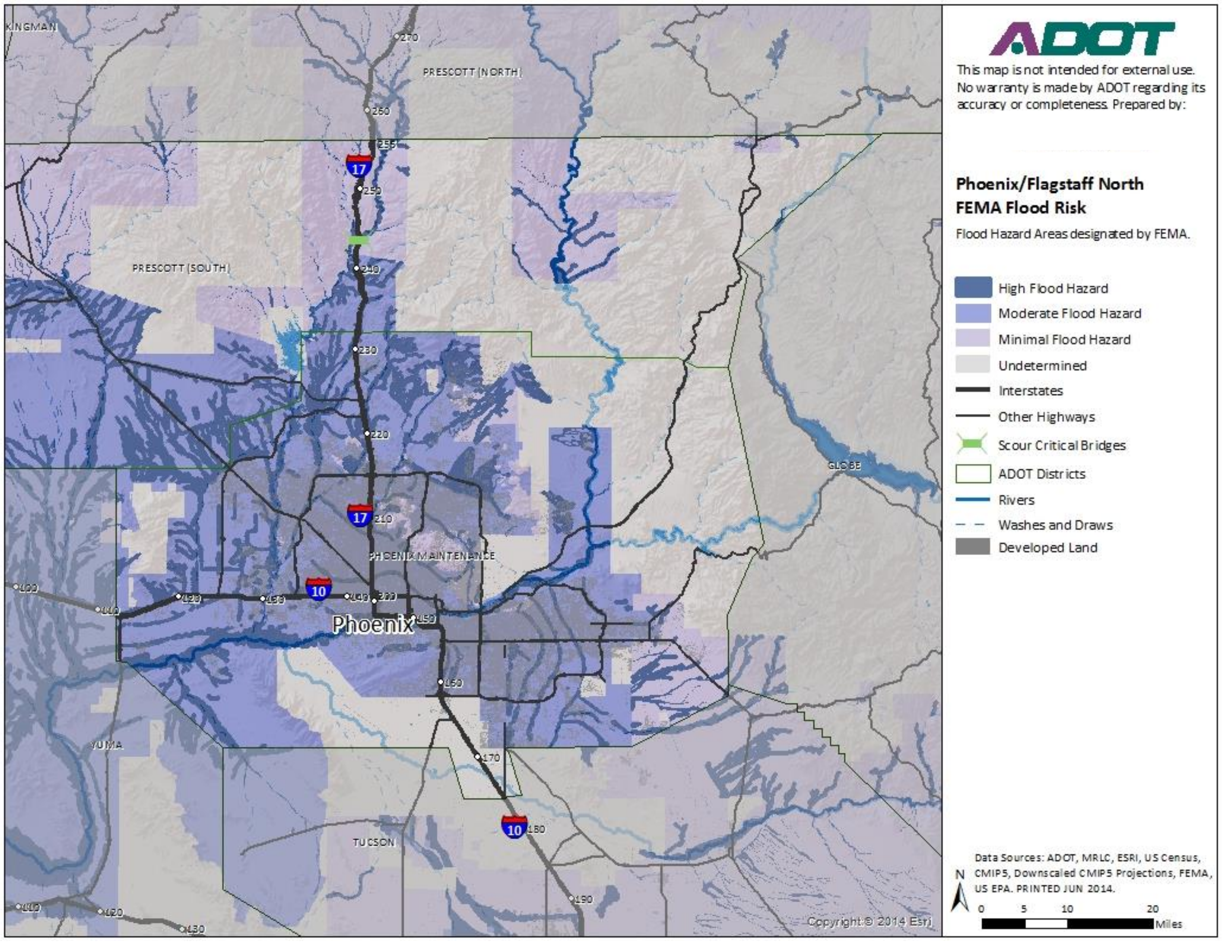


Figure 5.9 shows current FEMA-defined flood risk areas intersected by the corridor.

Risk Hypotheses: Extreme Precipitation, Phoenix District

Uncertain. Projections for extreme precipitation in Desert and Urban areas show no to marginal increases in magnitude in the latter part of the century.[19] Projections for areas north of MP 230 show modest decreases, particularly for Forest areas.

- **Flooding/Inundation.** The contribution of extreme precipitation to localized flooding may increase marginally around the Phoenix metro area, posing a particular threat to depressed freeways and other low-lying areas.

- **Washouts/Erosion.** This portion of the Interstate corridor is not currently prone to washouts.

- **Bridge Scour.** According to the National Bridge Inventory, the I-17 corridor currently has one bridge considered scour critical, crossing the Agua Fria River northbound between MP 240 and 250. NBI indicates that scour countermeasures have been installed for the southbound span.

- **Mudslides.** Particularly in the environs of Phoenix, mudslides are not considered a key risk.

5.3.5 Wildfire

Although areas of the combined Phoenix District (especially the southern portion of Prescott District) exhibit high wildfire risk, particularly in higher elevation areas, there are no high wildfire risk areas bordering the Interstate corridor[20] (see Figure 5.10). See the Flagstaff District section for information on the impacts of wildfires.

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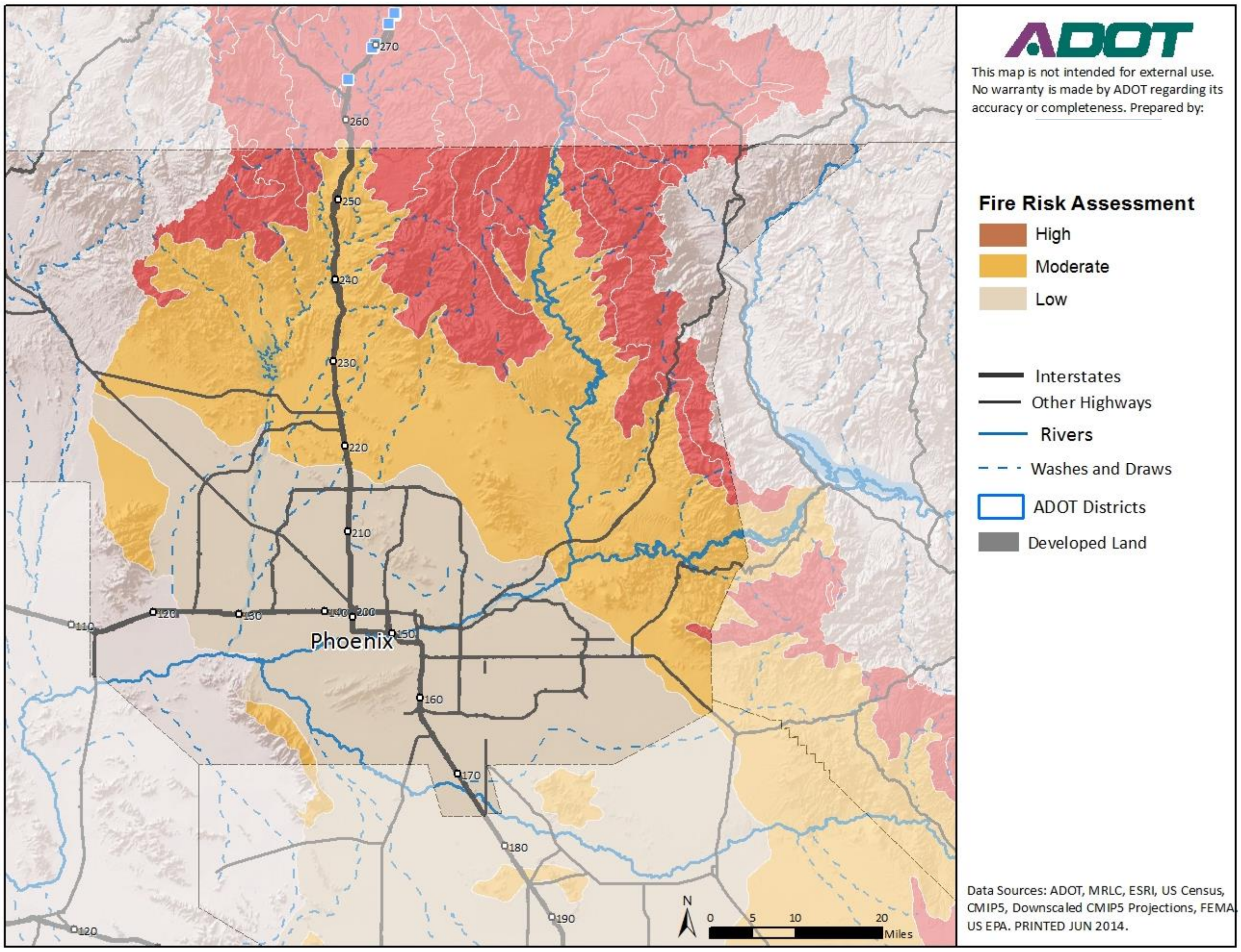
[19] Although model maxima show a modest dip in the 2000-2049 timeframe for all land cover types. All extreme precipitation projections are associated with significant uncertainty.

[20] Repeated grassfires have occurred in the vicinity of the Sunset Point rest area, however.

Figure 5.10 Wildfire Risk by Current Land Cover Type, Phoenix District



5.4 Findings: Tucson District

5.4.1 Summary of Results

Tucson District within the study area (approximately I-10 MP 175 to I-19 MP 0) is characterized by Desert and Urban land cover (58 percent) from the northern border of the District (approximately I-10 MP 180) to I-19 MP 40 (about 20 miles south of Tucson). Climatologically, this portion of the corridor bears close resemblance to the greater Phoenix area. From there, Grassland is dominant (32 percent), with some Forest areas near Nogales (9 percent). Chaparral constitutes only 1 percent of the Tucson study area, none of which is in proximity to the Interstate Corridor.

Particularly in Desert areas, the District is prone to extreme heat, averaging nearly 70 days annually over 100°F (Grassland, in contrast, averages less than 10 days annually). Although freezing temperatures can occur in higher elevation areas—particularly in the vicinity of Nogales—cold weather is not prevalent north of I-19 MP 20. Extreme precipitation magnitudes are relatively low throughout the corridor; NOAA Atlas 14 estimates the 100-year, 24-hour precipitation event Tucson to be 3.79 inches (National Weather Service office), rising slightly to the south (e.g., 4.45 inches at Nogales). Wildfire risk is low or moderate along the corridor from the northern border to I-19 MP 40 (comprised of Desert or Urban areas) although Grassland, a high-risk land cover is the dominant vegetation from I-19 MP 40 nearly until Nogales, where it is joined by Forest.

Table 5.18 Summary of Results, Tucson District

Expected Change	**Climate Risk**
▬	**Extreme Heat** Extreme heat increases dramatically, with Desert areas projected to experience over 146 days above 100°F annually by 2080, on average.
✚	**Freezing Temperatures** Particularly north of I-19 MP 20, the corridor is projected to experience between 1 and 20 days during which freezing temperatures occur, on average. Nogales may experience greater than 50—still a significant reduction from the historical average.
⬌	**Extreme Precipitation** 100-year rainfall estimates are moderate in Desert areas, increasing slightly approaching Nogales. However, modest increases are projected, particularly from Tucson to Nogales.
⬌	**Wildfire Risk** Wildfire risk is relatively low today in Desert and Urban areas, and high in Grassland and Forest areas south of I-19 MP 40. Long-term changes in risk are uncertain.

5.4.2 Extreme Temperature

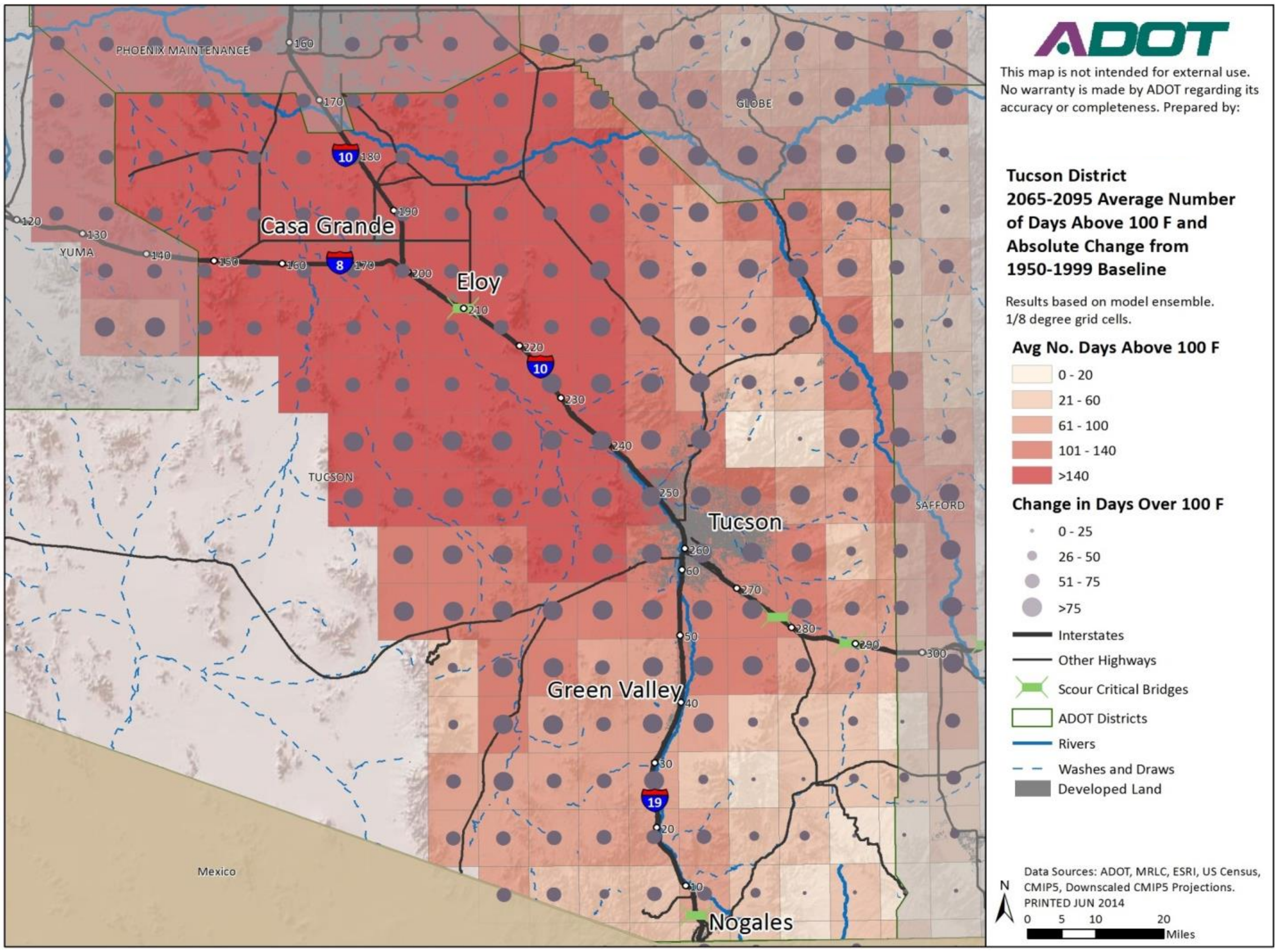
Desert and Urban areas are characterized by extreme heat. Currently, these land cover types experience an average of almost 70 days per year exceeding 100°F. Temperatures south of I-19 MP 40 (mostly Grassland and Forest) are generally significantly cooler; days exceeding 100°F average 9.5 days annually for Grassland areas and 2.9 for Forest areas. Projections for 2080 show significant increases in heat events, with Desert areas projected to experience an average of nearly 147 days annually of 100°F or greater, and Grassland areas over 75 days annually (nearly 41 days annually for Forest areas). Districtwide, days above 110°F have historically occurred an average of 3 times annually (across all land cover types); mid-century projections show about 10 days, and end-of-century projections show nearly 34 days annually.

Average daily maximum temperatures follow the same upward trend. The historical average daily maximum for Desert areas is about 85°F, with 2080 projections showing nearly 93°F. Values for Grassland areas are approximately 78°F (historical) and 87°F in 2080—hotter than today's Desert areas.

Table 5.19 Extreme Heat Impacts and Key Risk Factors

	Risk Factors	
Associated Impacts	**Climate Risk Indicators**	**Land Cover**
Pavement deformation	Days ≥ 100° F Days ≥ 110° F	Large urban areas generally augment temperatures (heat island effect)
Thermal expansion		
Worker Safety		
Shortened construction windows	Average Daily Maximum (Summer) Average Daily Maximum (Annual)	

Figure 5.11 Projected Average Annual Days ≥ 100° (2065 to 2095), Tucson District



The Desert-dominated northwest portion of the Tucson study area has historically experienced the greatest number of annual days exceeding 100° F, but projections show a significant increase in very hot days across the District, including historically cooler areas near Nogales. Desert areas are projected to experience the greatest increase in number of annual days exceeding 100°F. Average daily maximum temperatures are projected to increase commensurately across all land cover types

Table 5.20 Average Annual Days ≥ 100° F, Tucson District

		Climate Variables		
		Past [a]	2040	2080
Average Annual Days ≥100°F	**% Area**	**1950-1999**	**2025-2055**	**2065-2095**
Chaparral	1%	2.7	14.0	44.6
Desert	58%	69.8	109.9	146.5
Forest	9%	2.9	13.2	40.7
Grassland	32%	9.5	31.7	75.3

[a] Past values represent model backcastings.

Table 5.21 Average Daily Maximum Temperature (F), Tucson District

		Climate Variables		
		Past [a]	2040	2080
Average Daily Maximum Temperature °F	**% Area**	**1950-1999**	**2025-2055**	**2065-2095**
Chaparral	1%	74.3	78.0	82.3
Desert	58%	84.5	88.2	92.5
Forest	9%	75.4	79.0	83.3
Grassland	32%	78.7	82.3	86.5

[a] Past values represent model backcastings.

Risk Hypotheses: Extreme Heat, Tucson District

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Negative. From I-10 MP 180 to the greater Tucson area, extreme heat is projected to occur, on average, more than 140 days per year (greater than 75 days above the historical average around Tucson). South of Tucson, particularly south of I-19 MP 40, 60 to 100 days above 100°F are projected.

- **Pavement Deformation/Thermal Expansion.** Although Tucson District's design guidelines and specifications already call for heat-resistant pavement mixes, these standards may need to be reevaluated as temperatures of 110°F (and above) become more common and potentially last longer.

- **Construction Windows.** Construction windows may be affected due to higher average annual maximum temperatures (Tmax)—projected to average over 89°F by the 2065 to 2095 timeframe. Areas north of Tucson on I-10 may experience a Tmax of greater than 93°F. Projected Tmax for the area surrounding Nogales is between 81° and 84° F.

- **Safety.** Heat-related fatigue and illness, which become factors as temperatures exceed 90°F, may become an increasing concern as the century progresses, particularly north of I-19 MP 40. Worker safety protocols may require updating as 100°F, 110°F, and even greater temperatures become more common. The incidence of shredded truck tires, known as "alligators," generally increases in very hot weather, affecting motorist and worker safety.

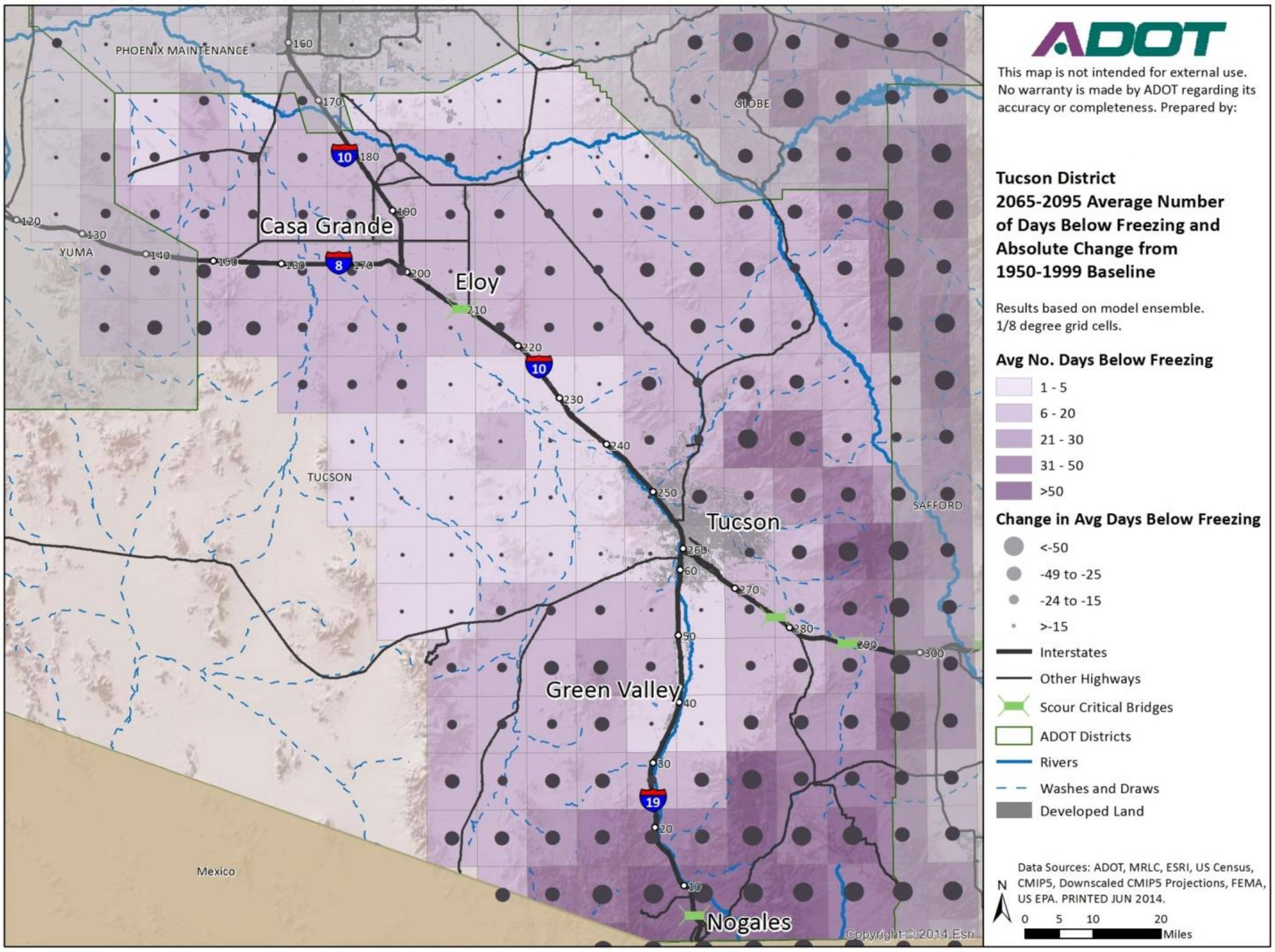
5.4.3 Freezing Temperatures

Although Tucson District does experience freezing temperatures, especially in the mountainous areas near Nogales, the phenomenon is not prevalent along most of the study corridor. Therefore, this analysis considers the segment of I-19 south of MP 20 (approximately).

Table 5.22 Freezing Temperatures Impacts and Key Risk Factors

	Risk Factors	
Associated Impacts	**Climate Risk Indicators**	**Land Cover**
Frost heaves	Days ≤ 32° F	Higher elevations, associated with Forest areas, are generally more prone to freezing temperatures
Winter maintenance		
Construction windows		

Figure 5.12 Projected Average Annual Days ≤ 32°F (2065 to 2095), Tucson District



Projections show decreases in the average annual number of days at or below freezing across the District and across all land cover types. Because freezing is only prevalent south of about I-19 MP 20, reductions around Nogales are most significant (over 50 days fewer in some areas, on average).

Table 5.23 Average Annual Days ≤ 32° F, Tucson District

		Climate Variables		
		Past*	2040	2080
Average Annual Days ≤ 32°F	% Area	1950-1999	2025-2055	2065-2095
Chaparral	1%	68.8	47.4	26.7
Desert	58%	15.8	8.7	3.6
Forest	9%	79.8	55.5	31.6
Grassland	32%	56.7	36.4	18.2

[a] Past values represent model backcastings.

Risk Hypotheses: Freezing Temperatures, Tucson District

Positive. Although freeze-thaw, snowfall, and other winter weather will continue to affect Santa Cruz County, a projected reduction in average annual days during which freezing temperatures occur is expected to reduce these phenomena.

- **Frost Heaves.** A reduction in average annual days at or below freezing likely correlates with fewer freeze-thaw events. In Grassland areas, this equates to nearly 40 fewer days during which frost-heave conditions are possible, annually (a reduction of almost 50 days annually for Forest areas).

- **Winter Maintenance.** The incidence of plowing, salting, and other winter-related operations and maintenance activities may diminish as conditions necessary for snow and ice formation occur with less frequency.

- **Construction Windows.** Construction activities requiring warmer minimum temperatures (paving, for example) might be possible earlier in the spring or later in the fall (although monthly projections for freezing temperatures were not downscaled in this study).

5.4.4 *Extreme Precipitation*

According to NOAA Atlas 14[21], the estimated magnitude of 100-year precipitation is 3.79 inches at the Tucson NWS weather station, rising slightly to the south (e.g., 4.45 at Nogales), particularly in the mountainous areas in Santa Cruz county.

The downscaled CMIP5 ensemble data, to which the team applied a GEV function, do not closely correspond with NOAA's Point Precipitation Frequency Estimates[22], although the CMIP5

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[21] http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=az

ensemble grids (shown) roughly reflect the geographic distribution of relative rainfall intensities shown by NOAA. Therefore, the upper-bound CMIP5 data, the backcasted values of which more closely resemble the NOAA estimates, are provided.

Based on CMIP5 data, the estimated magnitude of the 100-year, 24-hour rainfall event ranges from an average of about 2.6 inches in Desert and Grassland areas (58 percent and 32 percent of the Tucson District study area, respectively). As the century progresses, projections show a slight increase in Desert areas (up to 2.8 inches) and modest, but more significant increases in Grassland areas (up 0.5 to 3.1 inches) and Forest areas (up 0.7 to 3.4 inches). However, there is significant uncertainty among models, and CMIP5 backcastings accord poorly with historical observations.

Table 5.24 Extreme Precipitation Impacts and Key Risk Factors

	Risk Factors	
Associated Impacts	**Climate Risk Indicators**	**Land Cover**
Flooding/Inundation	100-Year (1% chance) rainfall	Heavily vegetated land cover generally mitigates runoff, but may also result in higher debris volumes after wildfire events (which can exacerbate flooding)
Washouts/Erosion		
Bridge Scour		
Mudslides		

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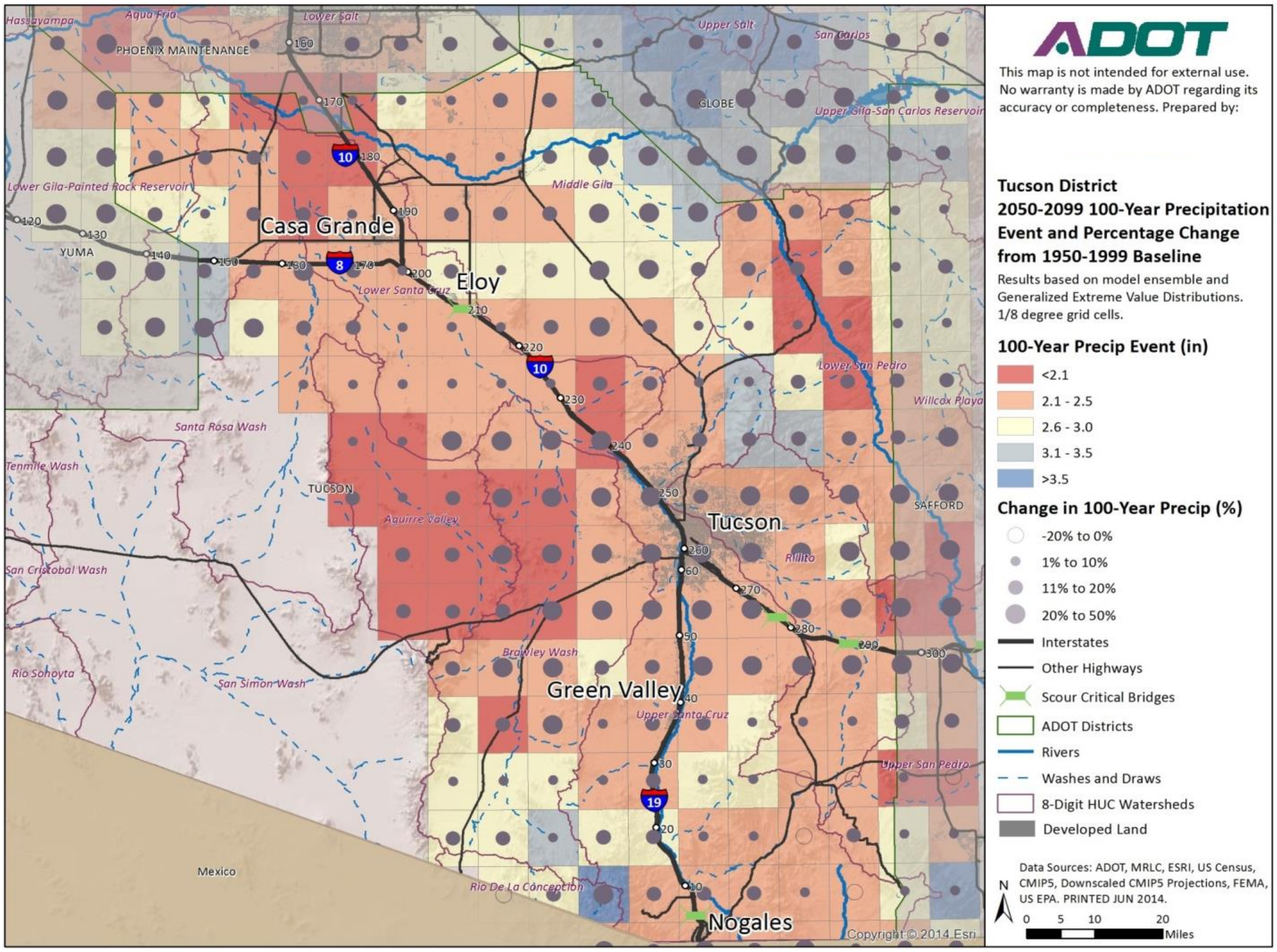
[22] This result reflects the guidance of the Scientific Stakeholders, which counseled that CMIP extreme precipitation data should be considered cautiously in Arizona.

Figure 5.13 Projected 100-Year (1-Percent Chance) Rainfall (2050 to 2099), Tucson District



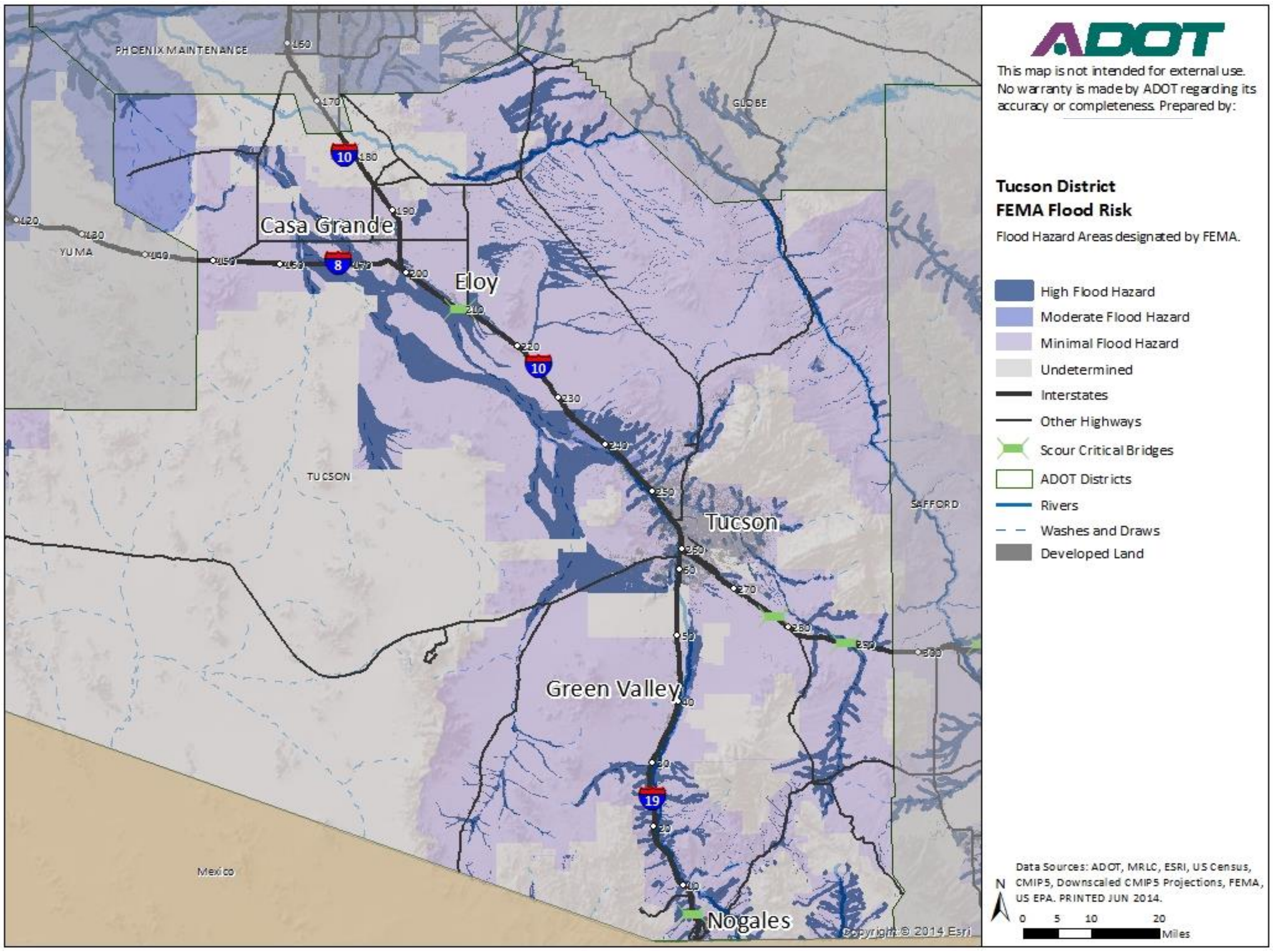
Percentage increases in the Desert and Urban areas surrounding Tucson are relatively greater than elsewhere in the District, although baseline magnitudes are relatively low. In terms of absolute magnitude, 100-year rainfall events in Desert areas (58 percent of the land cover) are projected to remain relatively stable—with slight increases possible toward the end of the century—while all other land cover types are projected to increase modestly (from ½ inch to nearly 1 inch) as the century progresses.

Table 5.25 100-year (1-Percent Chance) Rainfall Event, Tucson District

		Climate Variables		
		Past [a]	2025	2075
100-Year Rainfall Event, inches	**% Area**	**1950-1999**	**2000-2049**	**2050-2099**
Chaparral	1%	2.7	3.3	3.6
Desert	58%	2.6	2.5	2.8
Forest	9%	2.7	3.1	3.4
Grassland	32%	2.6	2.9	3.1

[a] Past values represent model backcastings. Future values are model maxima.

Figure 5.14 FEMA Flood Risk (Existing), Tucson District



This map shows current FEMA-defined flood risk areas intersected by the corridor.

↔

Risk Hypotheses: Extreme Precipitation, Tucson District

Uncertain. Projections for extreme precipitation in Desert and Urban areas show slight increases in magnitude in the latter part of the century.[23] Projections for Grassland and Forest areas show greater increases in magnitude.

- **Flooding/Inundation.** The contribution of extreme precipitation to localized flooding may increase throughout the corridor.
- **Washouts/Erosion.** This portion of the Interstate corridor is not currently prone to washouts.
- **Bridge Scour.** According to the National Bridge Inventory, the I-10 corridor in Tucson District currently has one bridge considered scour critical over the Gila River, although scour countermeasures have since been installed. NBI also reports that I-19 has one scour critical bridge (NB and SB spans) in the vicinity of MP 5, crossing Country Club Drive.
- **Mudslides.** Particularly in the environs of Tucson, mudslides are not considered a key risk.

5.4.5 Wildfire

The northern portion of Tucson District (I-19 MP 40 and north, approximately), wildfire risk is low to moderate. South of MP 40, the corridor intersects Grassland areas and runs adjacent to Forest areas near Nogales, both of which are considered high risk land covers. Active wildfire management in Forest areas could reduce risk levels, although wildfires affecting the area have, in the past, originated in Mexico and crossed the border.

Changes in seasonal average rainfall and average temperature may augment the risk of wildfires and/or of post-wildfire flooding, particularly if spring conditions foster the growth of wildfire-prone vegetation (fuel), late spring/early summer conditions are hot and dry (affecting dead fuel moisture), and the mid- to late-summer monsoon thunderstorms are particularly severe—leading to debris-laden flooding. Projections of key wildfire risk indicators, such as the Keetch-Byram Drought Index (KBDI), fell beyond the scope of this study, although the CMIP Processing Tool produces temperature and precipitation variables that, as proxies, may provide potential clues about future wildfire risk trends.

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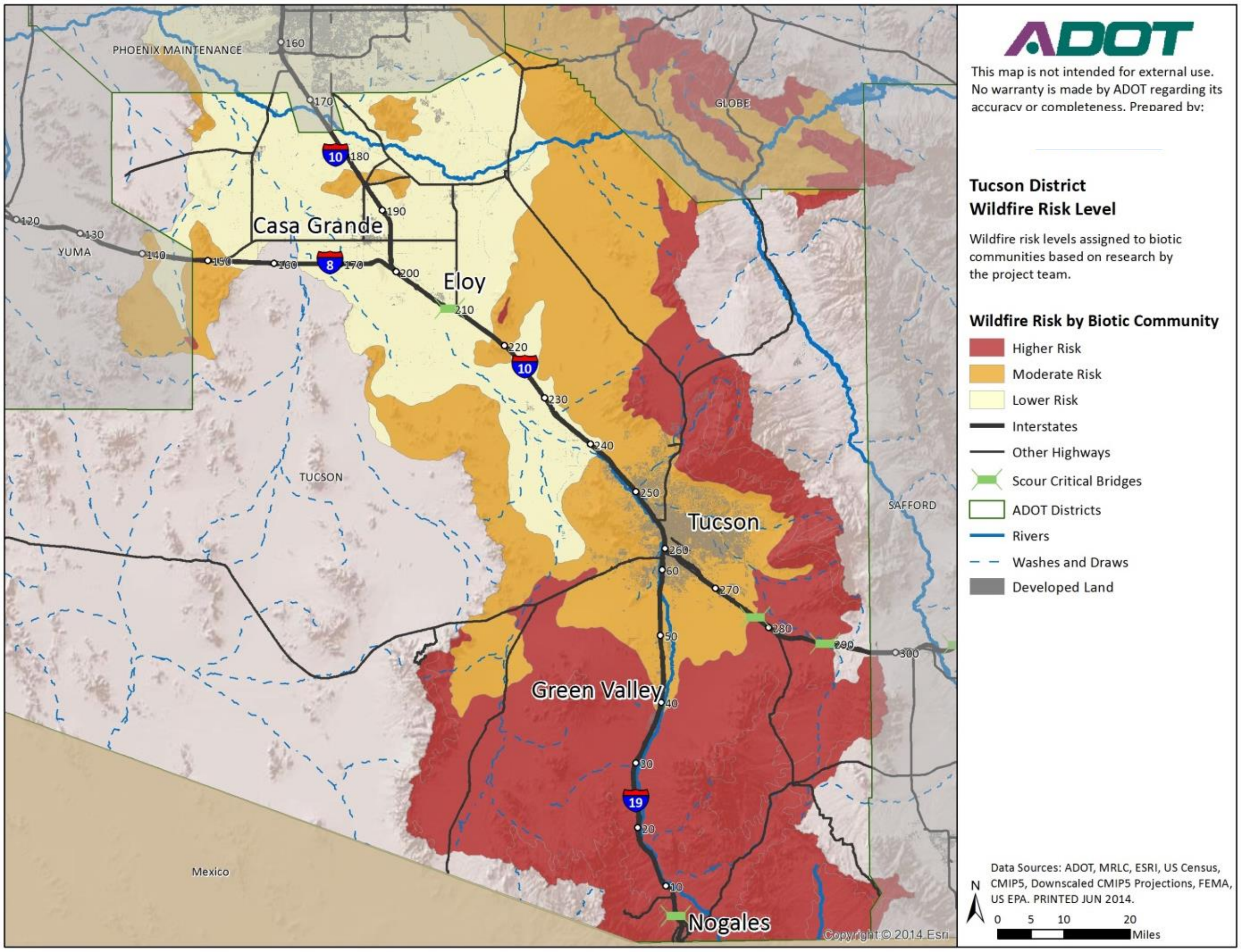
[23] Model maxima show a modest dip in the 2000-2049 timeframe for all land cover types. All extreme precipitation projections are associated with significant uncertainty.

Table 5.26 Wildfire Impacts and Key Risk Factors

	Risk Factors	
Associated Impacts	**Climate Risk Indicators**	**Land Cover**
Flooding, mudslides, scour (reduced vegetative cover, increased debris)	Average seasonal precipitation Average annual maximum temperature 100-Year (1% chance) rainfall (post-wildfire flooding)	Unmanaged Forests, Grassland, and Chaparral areas all exhibit high wildfire risk—particularly adjacent to highways, where ignition risk is greater. Managed Forest areas and, increasingly, Desert areas exhibit moderate wildfire risk.
Operational disruptions		
Minor damage to guiderail, pavements		

Figure 5.15 Wildfire Risk by Current Land Cover Type, Tucson District



Average daily maximum temperatures are projected to increase by approximately 8°F across the District. Although the direct affect on wildfire risk cannot be ascertained, a change of this magnitude could, over time, affect the composition and geographic distribution of biotic communities themselves (see, for example, the USDA's *Risk of Human Induced Desertification* map[24], which shows high to very high risk for much of Santa Cruz county).

Average annual and summer seasonal rainfall projections for the corridor south of I-19 MP 40 show little change from baseline conditions as the century progresses, although this area typically receives relatively more rainfall than areas north of MP 40. Average daily maximum temperature is projected to increase across all habitat types, while average annual rainfall is projected to remain relatively constant.

The temporal distribution of rainfall over the summer season, which was not examined by this study, will influence the effect of precipitation on wildfire. Extreme rainfall, particularly during the monsoon, could exacerbate wildfire-related flooding, scour, and mudslides, for example. As noted previously, projections for extreme rainfall are clouded by uncertainty.

Table 5.27 Average Annual Precipitation, Tucson District

		Climate Variables		
		Past [a]	**2040**	**2080**
Average Annual Precipitation (Inches)	**% Area**	**1950-1999**	**2025-2055**	**2065-2095**
Chaparral	1%	19.3	19.9	19.7
Desert	58%	11.4	11.6	11.9
Forest	9%	18.6	19.1	18.9
Grassland	32%	16.7	17.2	17.1

[a] Past values represent model backcastings.

↔

Risk Hypotheses: Wildfire, Tucson District

Uncertain. The Tucson District study area south of I-19 MP 40 is comprised of land cover types exhibiting a high wildfire risk. Higher average maximum temperatures could exacerbate existing risks, but also could influence land cover composition and distribution as the century progresses.

- **Flooding/Scour/Mudslides.** Under the right conditions, the after effects of wildfire can influence the severity of flooding, scour, and mudslides—both by increasing runoff rates

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[24] Desertification map, USDA-NRCS, Soil Survey Division, World Soil Resources, Washington, D.C. Population density map, Tobler, W., V. Deichmann, J. Gottsegen, and K. Maloy, 1995, http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/?cid=nrcs142p2_054004.

where vegetation has been destroyed and increasing debris flows. However, both future wildfire risk and projections for extreme precipitation are uncertain.

- **Operational Disruptions.** Wildfire can cause significant traffic delays while in progress, and traffic itself is a major source of wildfire ignition, but future trends for roadway-adjacent wildfire risk are uncertain.
- **Minor Damage.** Wildfire can destroy guiderail and even pavement, but future trends for roadway-adjacent wildfire risk are uncertain.

6.0 Lessons Learned

6.1 Challenges Addressed

6.1.1 Climate Data Processing

Given the relatively large and geographically diverse study area and desired high spatial resolution of climate data, the team faced a data acquisition and processing challenge. The FHWA CMIP Processing Tool produces data for four cells simultaneously, but did not provide for batch processing. In order to retrieve data from multiple models for over a dozen variables over three time periods (baseline, mid-century, and end-of-century) for approximately 450 grid cells, the team enhanced the Processing Tool to process all cells in a single run. In the course of developing the batch processing script, the team also added extreme rainfall (100- and 200-year rainfall events) variables by applying a Generalized Extreme Value (GEV) function (Appendix A).

6.1.2 Quantifying Asset Vulnerability

The Scientific Stakeholders emphasized the inherent uncertainty of climate projections, particularly pertaining to extreme precipitation. Secondary stressors, such as wildfire and flooding, which are influenced by a variety of climate and non-climate factors, compound that uncertainty for localized analyses. Rather than attempting to assign definitive vulnerabilities, the study team aimed to characterize current extreme weather vulnerabilities and highlight potential future changes in key risk factors—if possible—often through the lens of land cover (i.e., biotic communities). Without greater focus on a specific region or stressor, uncertainty characterized many of the climate impacts considered.

6.1.3 Study Resources versus Scope

The study area comprises a multitude of extreme weather vulnerabilities, from extreme heat to flooding to wildfire to dust storms to freeze-thaw cycles. Most of these conditions have a complex array of causal factors, and robust modeling (e.g., hydrology or wildfire behavior) of these relationships was outside of the scope and resources of the study. Future research could isolate specific stressors and/or geographies to potentially obtain more detailed results.

6.1.4 Study Corridor

In order to capture the wide diversity of land cover types and topographies in Arizona, the study area covered over 300 miles of Interstate corridor, and was buffered by intersecting watersheds (HUC-8). The entire corridor was deemed critical, and therefore further efforts to identify and focus on critical assets were not undertaken. Generally, Interstates are the most resilient roadway functional classification, with more robust design guidelines, specifications, and maintenance regimes. Interstates (and Interstate bridges, drainage, and other appurtenances) can reasonably be expected to be more resilient to current extreme weather impacts with fewer negative effects than proximate lower functional classification roadways.

Future research could focus on, for example, recognizing particular high risk areas and assessing the vulnerability of Interstate assets or less robust road classifications, such as arterials in those areas.

6.2 Recommendations for Changes or Additions to FHWA Vulnerability Assessment Framework

6.2.1 Land Cover

Incorporating land cover types (biotic communities) into the vulnerability assessment helped the project team differentiate and summarize potential risks over the extensive study area. FHWA could incorporate land cover/biotic communities as an optional module of the Framework, particularly for geographically diverse regions similar to the Nogales-Flagstaff corridor.

6.2.2 Stakeholders

While the current Framework already advocates stakeholder input, the ADOT project team found stakeholder feedback invaluable in conducting the assessment. As expected, practitioners within ADOT, especially at the District level, offered observations about current conditions that improved the quality of the assessment immensely—although the groups would have benefitted from the presence of natural resource managers. In particular, the Scientific Stakeholder group's input guided the project in identifying the appropriate assumptions, models, and datasets for climate data processing, and helped ensure that uncertainty was appropriately reflected in the results. The team recommends that future vulnerability assessments include ample feedback from the scientific community, perhaps through a similar structure of regional academics, nonprofits, and State and federal agency personnel.

7.0 Next Steps

ADOT has responsibility for 30,000 maintenance lane miles, which provide key connections to all of the state's 140,000 maintenance lane miles and 7,800 bridges. Maintaining optimum health and performance of this infrastructure is critical to Arizona's economic vitality, quality of life, and natural and built environments. Assessment of the potential impacts of extreme weather events—some of which may increase in severity and/or frequency as the century progresses—on Arizona roadway infrastructure is an important risk management exercise (and fully consistent with Federal guidance and activities).

This FHWA extreme weather pilot study provided the opportunity to formalize extreme weather considerations at ADOT and identified a host of potential next steps for the agency, including (in no particular order):

- Seek continued support from ADOT executive management for further assessment of the statewide highway system and potential implementation of adaptation strategies, leveraging FHWA and other funding sources, as appropriate.

- Systematically integrate extreme weather risks into long-range asset management planning to better identify opportunities to cost-effectively address risks while achieving broader performance goals.

- Support the FHWA Climate Change Team and allied offices, such as Asset Management, in the continued development of frameworks for extreme weather risk management and, as requested, in the application of extreme weather risk information to support asset management and infrastructure health initiatives.

- Support the FHWA Office of Operations in the development of an extreme weather transportation systems management and operations guidebook (as requested).

- Advance ADOT/USGS collaboration to address project planning, design, and delivery relating to flooding incidents, hydraulic-related failures, and extreme weather events.

- Incorporate cost-effective adaptation strategies into ADOT's Transportation Asset Management Plan (TAMP)—the Federal guidance for which calls for risk-based approaches—with a particular focus on developing broadly applicable risk-based models. As of December 2014, the ADOT Transportation Asset Management Plan (TAMP) is underway and may benefit from (and possibly support) consideration of extreme weather risks.

- Continue to develop the partnerships established during this study. Several other jurisdictions and stakeholders in the State and region have begun their own efforts to plan for extreme weather and climate change. ADOT can play a pivotal part as a key stakeholder in these efforts.

- Seek partnerships and funding opportunities, such as the FHWA Pilot program, to further explore extreme weather risks and identify risk management strategies, as appropriate.

- Continue to communicate and collaborate with ADOT planning, design, construction, maintenance and operations activities to mutually evolve ADOT's understanding of current and future extreme weather risks.

- Ensure that extreme weather risk management activities complement the agency's Strategic Focus Areas (SFA) and further strengthen linkages to SFAs through the development of risk-based approaches and continuous process improvements to enhance agency performance. In relation to the agency's Workforce Development SFA, communicate long-term internal technical capacity requirements due to extreme weather risks.

- Re-evaluate climate stressor projections periodically (perhaps corresponding to the National Climate Assessment updates) and, as applicable, update construction and maintenance strategies and resource allocations. Revisit agency guidance pertaining to high heat and heat windows for worker safety.

- Leverage the findings of this report to further inform ADOT's dust storm studies and communication efforts.

- Evaluate and, as necessary, update controlled access highway exit plans and incorporate safety and weather data to identify areas of concern, with a particular focus on frontage roads.

Consistent with the objectives of the FHWA Pilot program, this study helped identify several potential avenues for further research and study, including:

- Expand the focus to encompass lower functional classification roadways (perhaps within a single ADOT maintenance district), which, in general, are likely to exhibit greater susceptibility to extreme weather events than Interstates. Prioritize particular flooding/wildfire risk areas along Interstates for targeted assessments.

- Further leverage, apply, and build on the work of academics and other agencies in Arizona and the southwestern region, including research on urbanization-induced landscape change (see, for example, the work of Matei Georgescu of Arizona State University) and recent updates to probable maximum precipitation estimates by the Arizona Department of Water Resources.

- More in-depth consideration of potential shifts in biotic community composition and geographic distribution as the century progresses due to climate and non-climate phenomena.

- More robust modeling of wildfire risk, including further research into wildfire ignition factors and precursors, including soil moisture, evapotranspiration, and potentially the Keetch-Byram Drought Index. ADOT could partner with Federal and local land managers to further explore data on historic fire incidence and, ultimately, to help the agency better manage fire risk in the vicinity of highly critical transportation facilities.

- Using precipitation projections, pursue hydrologic modeling of runoff and flooding at a more granular geographic scale, incorporating specific information on slopes, runoff coefficients, drainage infrastructure. Advanced research might also consider the potential impacts of post-wildfire debris. The United States Geological Survey Arizona Water Science Center is a strong potential partner for hydrological matters.

- Analyze Performance Control System (PeCos) data to better quantify the impacts of extreme weather in terms of costs and specific repairs and/or maintenance treatments. Leverage Traffic Operations Center data for information on the operational impacts of extreme weather events.

- Similar to the Volpe-led Central New Mexico Climate Change Scenario Planning Project[25], consider integrating climate into a scenario planning framework.

A combination—or all—of these activities could be integrated into a comprehensive transportation adaptation (risk management) plan, which would inform planning and decision-making across the State of Arizona in the face of a changing climate.

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[25] http://www.volpe.dot.gov/transportation-planning/public-lands/central-new-mexico-climate-change-scenario-planning-project.

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Appendix A. Climate Data Selection and Processing

The Scientific Stakeholders recommended using downscaled Coupled Model Intercomparison Project (CMIP) data to obtain climate projections and historical observations. Table A.1 presents the climate data parameters, based on conversations with members of Arizona's climate science community.

Table A.1 Temperature and Precipitation Data Parameters Summary

Parameter	Selection for Assessment
Projections and Historical Data Source	Downscaled CMIP5 Bias Corrected and Spatially Disaggregated (BCSD) daily projections with accompanying historical data
Emissions Pathway	Representative Concentration Pathway 8.5
Downscaled General Circulation Models (GCM)	NorESM1-M, HadGEM2-ES, CSIRO-MK3.6, CanESM2, MPI-ESM-LR, MPI-ESM-P, GFDL-ESM2M
Horizontal Spatial Resolution	1/8° (~7.5 mile or ~12km)
Temporal Resolution	Daily for 1950-2000 (backcastings from models in addition to historical data), 2025-2055, and 2065-2095
Model Outputs	Temperature (daily maximum and minimum) and precipitation (daily total)

The project team used the assessments in a Journal of Climate paper, *North American Climate in CMIP5 Experiments* (Sheffield et al.), to identify climate models based on bias in 1) precipitation and 2) bias in Pacific sea surface temperature (i.e., El Nino Southern Oscillation, or ENSO)[26].

Accordingly, the project team identified four models based on precipitation bias: NorESM1-M, HadGEM2-ES, CSIRO-MK3.6, and CanESM2. The research showed these models to have relatively low bias in predicting December/January/February (DJF) and June/July/August (JJA) precipitation in Western North America.

The team identified five models – HadGEM2-ES (repeat), NorESM1-M (repeat), MPI-ESM-LR, MPI-ESM-P, and GFDL-ESM2M – that attain relatively high correlations with actual ENSO patterns for both the Central Pacific and Eastern Pacific.

Two of the seven unique models identified using these two criteria were unavailable from the CMIP downscaling web site at the time of collection (HadGEM2-ES and MPI-ESM-P); hence the remaining five were used.

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[26] The project team is grateful for guidance from Dr. Chris Castro from the University of Arizona.

The Scientific Stakeholders emphasized the uncertainty involved in using climate projections; and encouraged grounding projections with historical data, particularly for precipitation.

Table A.2 Selected Climate Models

Model	Modeling Center (or Group)
NorESM1-M	Norwegian Climate Centre
CSIRO-MK3.6	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence
CanESM2	Canadian Centre for Climate Modeling and Analysis
MPI-ESM-LR	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)
GFDL-ESM2M	National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory

Note: Downscaled CMIP5 projections and accompanying historical observations downloaded from the “Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections” archive at gdo-dcp.ucllnl.org.

Processing Tool

To retrieve downscaled climate data, the team leveraged the U.S. DOT CMIP Climate Data Processing Tool (2014). In order to automate the downscaling process, a necessity given the approximately 450 CMIP grid cells covering the study area (multiplied by as many as five climate models, three time periods, and 13 climate variables), the team enhanced the Tool to facilitate batch processing and to derive a wider range of variables (such as the projected 100-year 24-hour rainfall magnitude). The updated code, in R (programming language), was delivered to ADOT for future use.

Table A.1 lists the transportation-relevant metrics and other fields computed by the Tool for each grid cell (this represents a subset of the variables calculated by the FHWA Tool, in addition to 100- and 200-year estimated precipitation events, using Generalized Extreme Value distributions).

Selected projections for the latter part of the 21st century are mapped below, some of which are accompanied by modified box and whisker charts to show the range of projections across models and timeframes, displayed as blended averages by land cover type. Analysis of the implications of these potential changes to Arizona transportation infrastructure and operations is included in Section 5.0 (Vulnerability Assessment) for each District study area.

Table A.3 Climate Data Fields Summary

Field Name(s)	Temporal Period(s)
Latitudes, longitudes, and well-known text field to draw polygons	–
Maximum 1-Day Precipitation Event (i.e., 50-Year Event)	1950-1999 (backcasting and historical), 2000-2049, 2050-2099
100-/200-Year Maximum Precipitation Event, estimated by fitting Generalized Extreme Value (GEV) distribution to annual precipitation maxima	1950-1999 (backcasting and historical), 2000-2049, 2050-2099
Minimum Annual Precipitation	1950-1999 (backcasting and historical), 2025-2055, 2065-2095
Average Annual Precipitation	1950-1999 (backcasting and historical), 2025-2055, 2065-2095
Average Number of Days Per Year in which Precipitation Exceeds Baseline Period's 99th Percentile Precipitation Event	1950-1999 (backcasting and historical), 2025-2055, 2065-2095
Average Annual May-June-July-August Precipitation	1950-1999 (backcasting and historical), 2025-2055, 2065-2095
Average Daily Maximum Temperature	1950-1999 (backcasting and historical), 2025-2055, 2065-2095
Maximum Temperature	1950-1999 (backcasting and historical), 2025-2055, 2065-2095
Average Number of Days Per Year in which Temperature exceeds 100 degrees	1950-1999 (backcasting and historical), 2025-2055, 2065-2095
Average Number of Days Per Year in which Temperature exceeds 110 degrees	1950-1999 (backcasting and historical), 2025-2055, 2065-2095
Average Number of Days Per Year in which Temperature falls below or is equal to 32 degrees	1950-1999 (backcasting and historical), 2025-2055, 2065-2095
Average Daily Minimum Temperature	1950-1999 (backcasting and historical), 2025-2055, 2065-2095

A.1 Summary of Climate Projections

Within a given grid cell, projections vary depending on which climate model is referenced (and would vary further if alternative emissions scenarios were considered). Across the study corridor, projections vary spatially depending on factors such as latitude, topography, urbanization, and land cover. Generally, there is greater agreement (a smaller projection range) across models on temperature variables (averages and extremes) versus precipitation variables (projection ranges are shown below); and confidence of the models' ability to estimate actual weather patterns is higher for temperature than for precipitation.

Figure A.1 2065 to 2095 Average Daily Maximum Temperature (Projections)

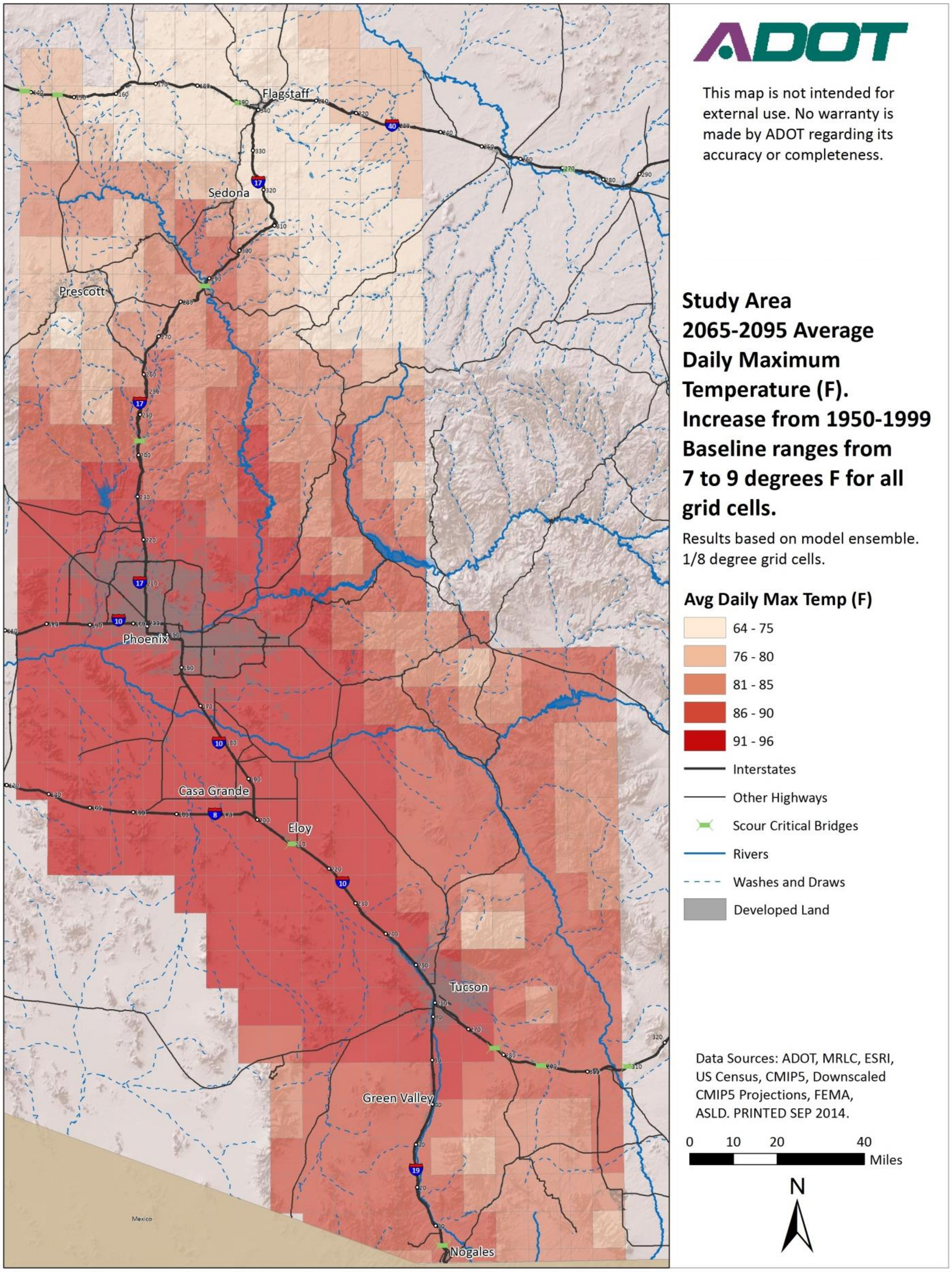


Figure A.2 Average Daily Maximum Temperature (Land Cover Type)

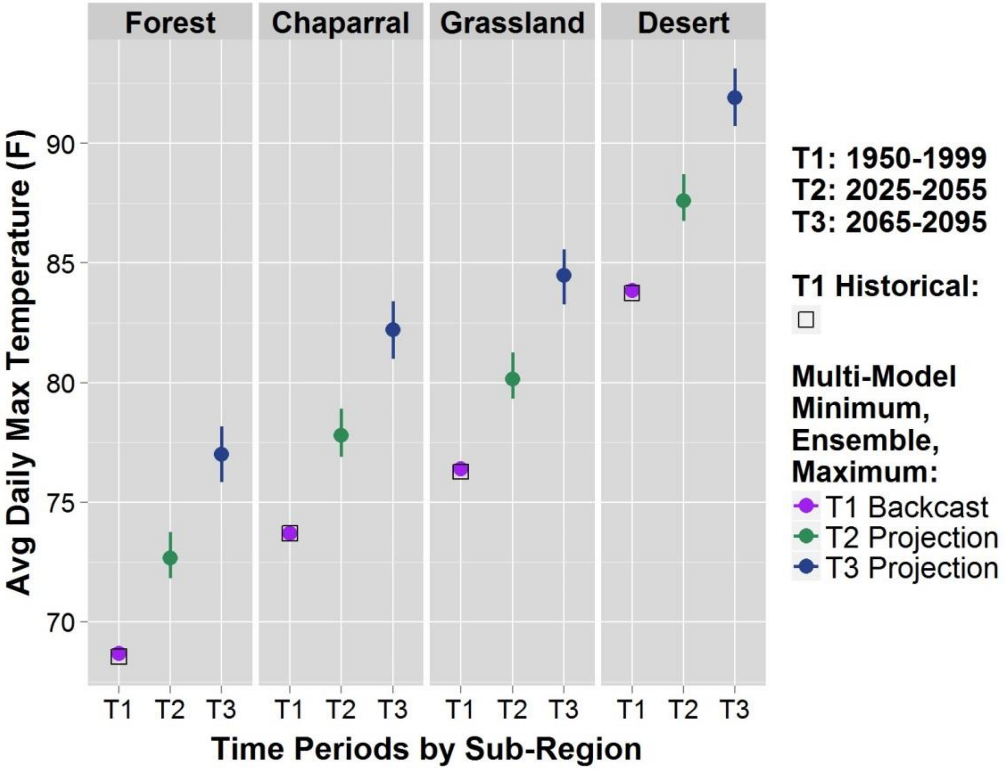


Figure A.3 Average Number of Days above 100°F (Land Cover Type)

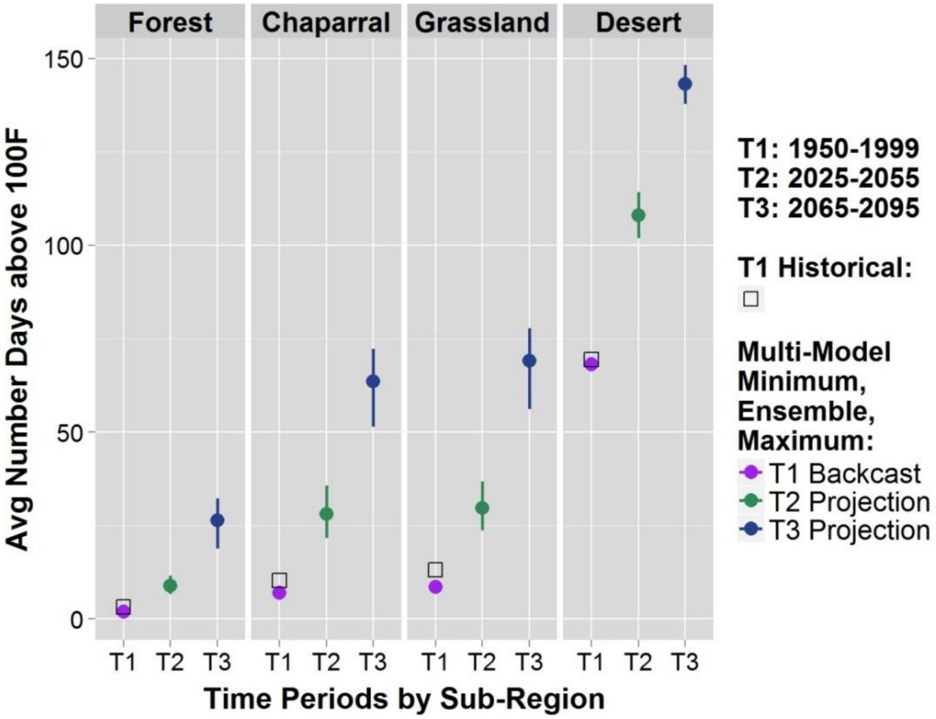


Figure A.4 2065 to 2095 Average Number of Days above 100°F (Projections)

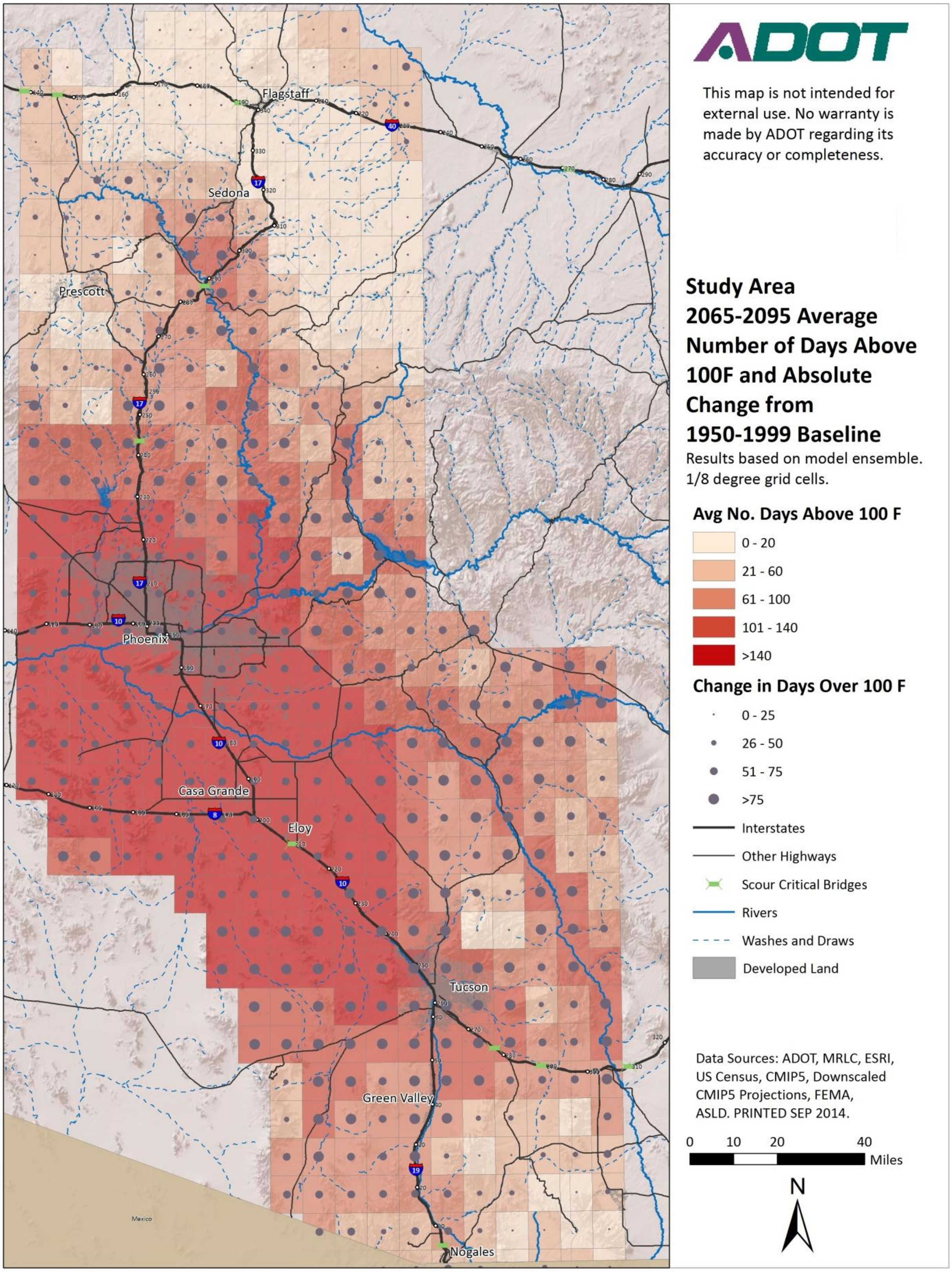
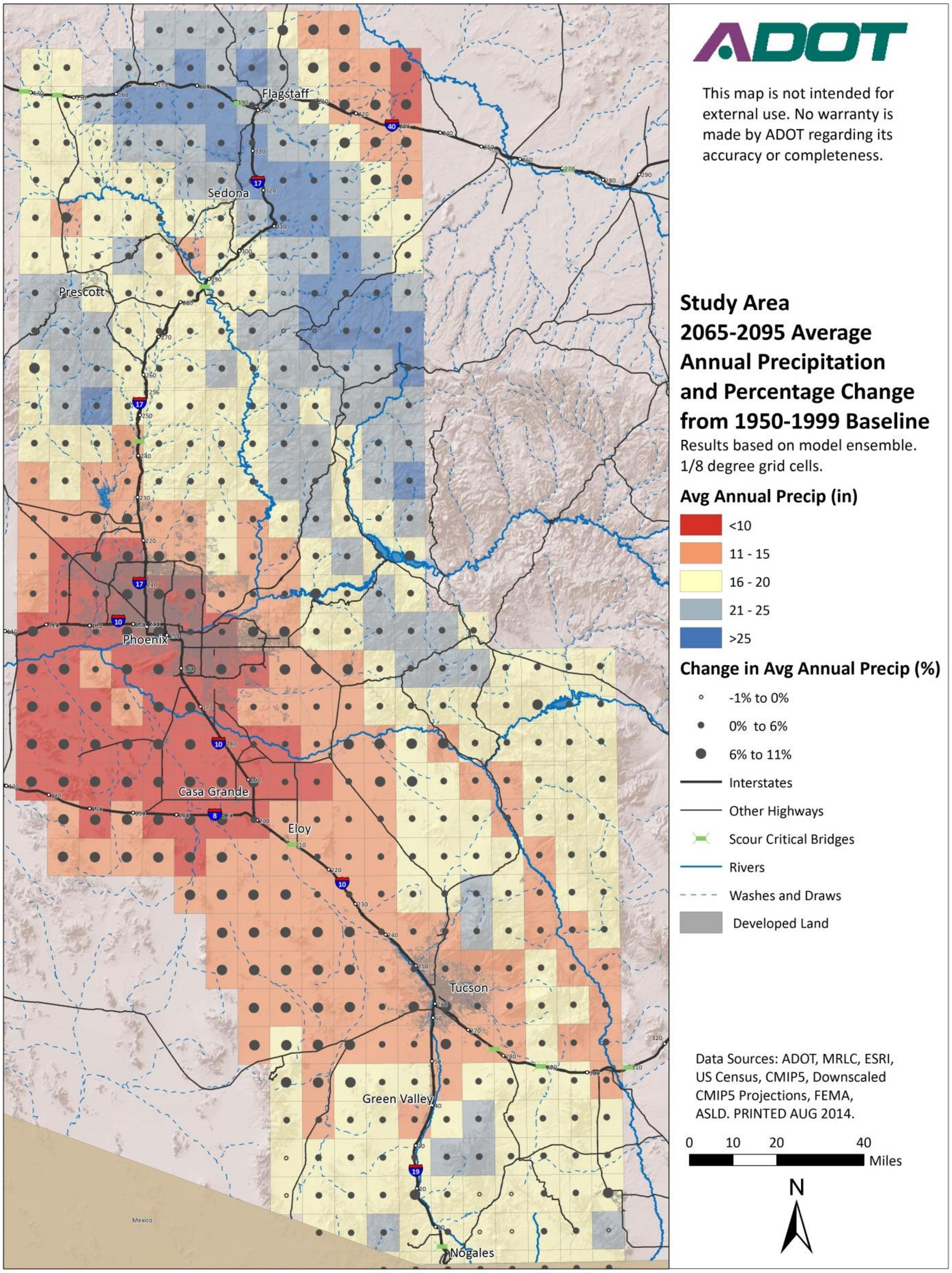


Figure A.5 2065 to 2095 Average Annual Rainfall (Projections)



This map is not intended for external use. No warranty is made by ADOT regarding its accuracy or completeness.

Study Area 2065-2095 Average Annual Precipitation and Percentage Change from 1950-1999 Baseline

Results based on model ensemble. 1/8 degree grid cells.

Data Sources: ADOT, MRLC, ESRI, US Census, CMIP5, Downscaled CMIP5 Projections, FEMA, ASLD. PRINTED AUG 2014.

Figure A.6 Average Annual Rainfall (Land Cover Type)

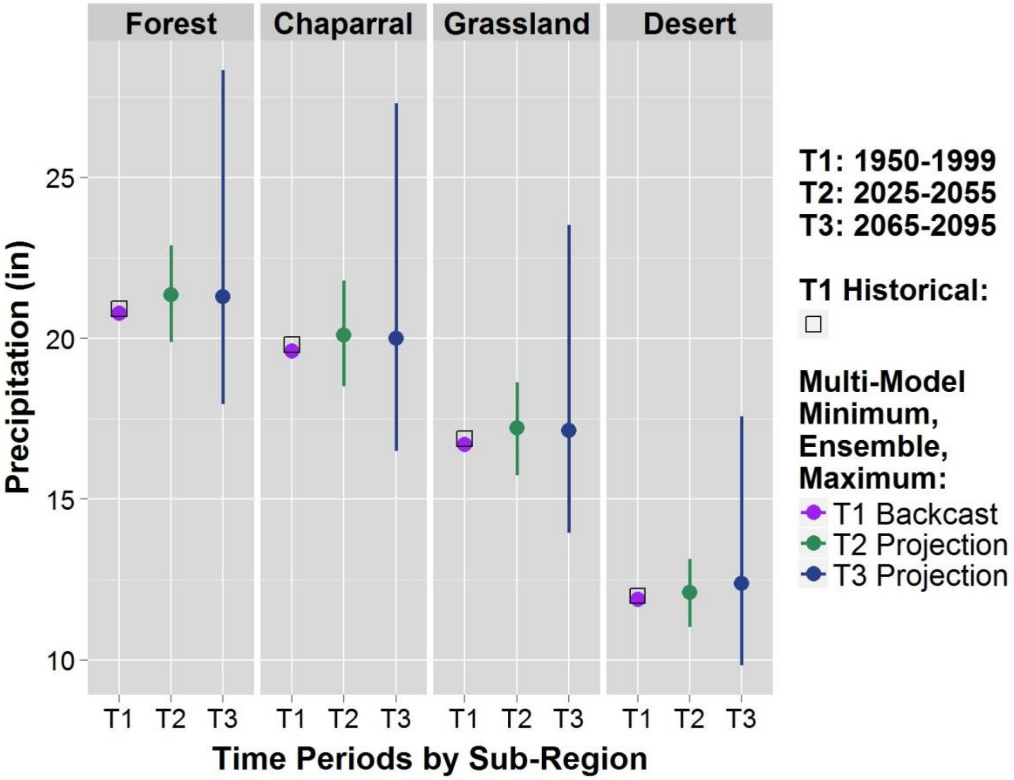


Figure A.7 100-Year Rainfall Day (Land Cover Type)

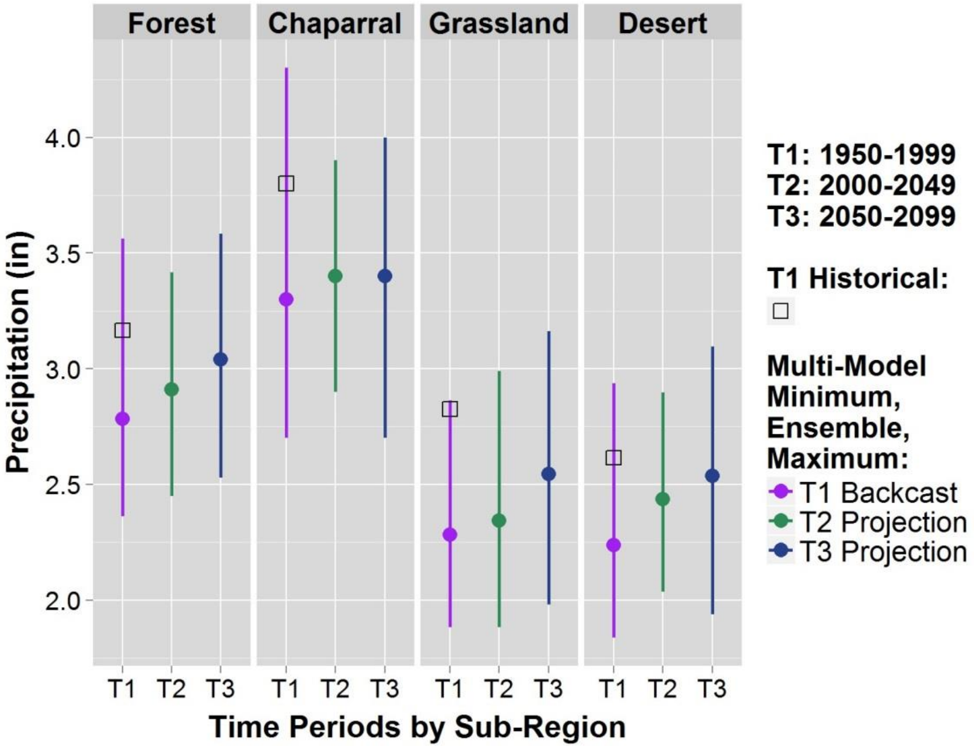
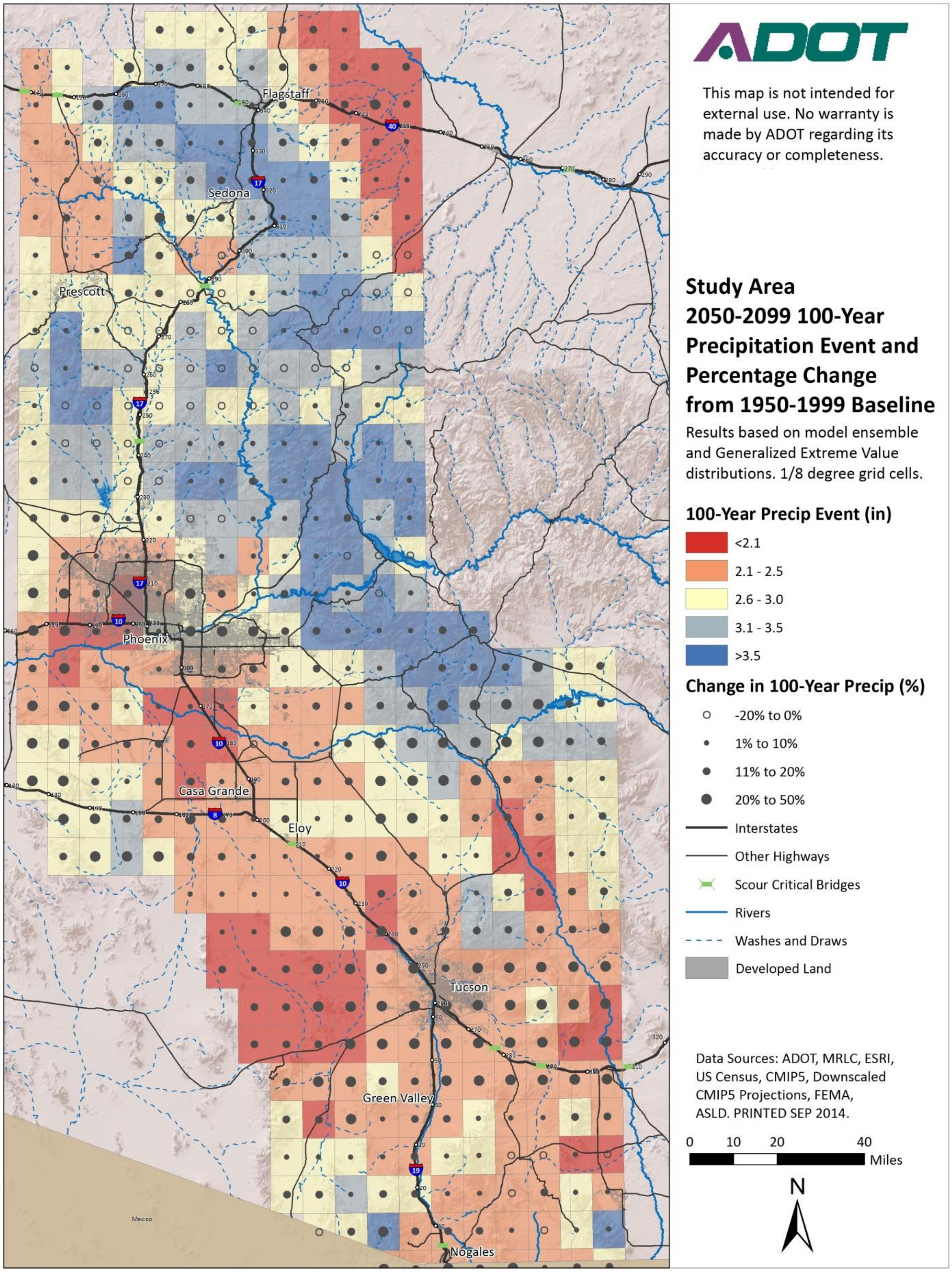


Figure A.8 2065 to 2095 100-Year Rainfall Event (Projections)



Appendix B. Land Cover/Biotic Communities Analysis

The study examined extreme weather vulnerabilities by grouping similar biotic communities into four main land cover types, in order to account for the variation in vegetation types in the study corridor. Biotic communities are groups of living organisms that occur together and are adapted to the local moisture and temperature conditions in a particular region (Brown and Lowe 1982; Brown 1994). ADOT utilizes biotic community boundaries to select seed mixes for revegetation efforts throughout the state. Biotic communities were selected as the appropriate landscape classification system due to the fine resolution of the classification scheme, availability of data, and ADOT's existing familiarity with this classification scheme.

B.1 Biotic Communities within the Study Area

As described in Section 3.1, the study area was defined by overlaying 8-digit Hydrologic Unit Code (HUC) watershed boundaries onto the ADOT interstate system map to designate the study area perimeter. Watersheds were selected as naturally occurring boundaries in the landscape useful in analyzing stormwater flows.

The biotic community classification developed by Brown and Lowe (1982; GIS layer file developed by The Nature Conservancy of Arizona in 2006) was used for this study. This file was overlaid with the study area perimeter to determine the biotic communities present in the study area. Figure 2.3 shows the distribution and extent of the biotic communities in the study area.

A total of 10 biotic communities occur in the study area: 6 biotic communities intersect the interstates and 4 additional biotic communities occur in the broader study area corridor (marked with an asterisk in Table B.1).

Due to the limited occurrence of Chihuahuan Desertscrub in the study area, this biotic community type was excluded from further analysis. Petran Montane Conifer Forest and Madrean Evergreen Woodland were considered as one vegetation type for the purposes of this analysis, for a total of eight main biotic communities, as described in Section 3.1. Brief descriptions of the biotic communities in the study area are provided below.

Table B.1 Biotic Communities within the Study Area

Biotic Community	**Land Cover Type**	**Occurs in these ADOT Districts**
Sonoran Desert Scrub – Arizona Upland Subdivision	Desert	Flagstaff, Phoenix, Tucson
Sonoran Desert Scrub – Lower Colorado Subdivision	Desert	Phoenix, Tucson
Chihuahuan Desertscrub[a]	Desert	Tucson[a]
Great Basin Desertscrub[a]	Desert	Flagstaff[a]
Interior Chaparral	Chaparral	Flagstaff, Phoenix[a], Tucson[a]
Semidesert Grassland	Grassland	Flagstaff, Phoenix[a], Tucson
Plains and Great Basin Grassland[a]	Grassland	Flagstaff*, Tucson[a]
Great Basin Conifer Woodland	Forest/Woodland	Flagstaff, Phoenix[a]
Biotic Community	Land Cover Type	Occurs in these ADOT Districts
Petran Montane Conifer Forest	Forest/Woodland	Flagstaff, Phoenix[a], Tucson[a]
Madrean Evergreen Woodland[a]	Forest/Woodland	Tucson

[a] Biotic communities found within the study area but not crossed by the interstates.

Figure B.1 shows images of the main biotic communities in the study area. Biotic community descriptions summarized from Brown (1994) are presented in Table B.2.

Table B.2 Biotic Community Descriptions

Biotic Community	Elevation	Average Annual Precipitation	Dominant Plants
Sonoran Desert Scrub – Arizona Upland Subdivision	300 to 1,000 m (~1,000 – 3,300 ft)	300 – 400 mm (~11.8 – 15.7 in)	Pincushion, hedgehog, barrel, prickly pear and saguaro cacti; cholla; palo verde, ironwood, and mesquite trees; creosote bush, white bursage, brittlebush and saltbush
Sonoran Desert Scrub – Lower Colorado River Subdivision	300 to 1,000 m (~1,000 – 3,300 ft)	40 mm (~1.6 in)	Mesquite, ironwood, palo verde, and smoketree along washes; more arid parts are covered by a single layer of tightly packed pebbles and are commonly devoid of perennial plants, typically have sparse seasonal cover of ephemerals such as wooly plantain
Great Basin Desertscrub[a]	1,200 to 2,200 m (~3,900 – 7,200 ft)	typically less than 250 mm (~9.8 in)	Sagebrushes, saltbrushes, winterfat, rabbitbrush, blackbrush, hopsage, and horsebrush; a few cacti are present, including chollas, prickly pears, and hedgehog
Interior Chaparral	320 to 610 m (~1,000 – 2,000 ft)	380 to 635 mm (~15.0 – 25.0 in)	Dominated by shrub live oak, commonly accompanied by birchleaf mountain-mahogany, skunkbush sumac, silktassels, and desert ceanothus
Semidesert Grassland	1,100 to 1,700 m (~3,600 – 5,800 ft)	250 to 450 mm (~9.8 – 17.7 in)	Summer-active perennial grasses (Black Grama, Tobosa grass), forbs and weeds (filarees, lupines), bear grasses, agaves, yuccas and cacti
Plains and Great Basin Grassland[a]	1,200 to 2,300 m (~3,900 – 7,500 ft)	300 to 460 mm (~11.8 – 18.1 in)	Tall grass, prairie grass and/or short-grassland; other species present in areas where grazing has not been too severe include: bluestems, shinnery, midget oak, Indian grass and sideoats grass
Great Basin Conifer Woodland	1,500 to 2,150 m (~5,000 – 7,000 ft)	250 to 500 mm (~9.8 – 19.7 in)	Dominated by two types pf conifer: pinyon and juniper, particularly Rocky Mountain juniper, Utah juniper, one-seed juniper and Rocky Mountain pinyon
Petran Montane Conifer Forest and Madrean Evergreen Woodland[a]	2,000 to 3,050 m (~6,500 – 10,000 ft) Found on high plateaus and mountains	460 to 760 mm (~18.1 – 29.9 in)	Two major communities: Ponderosa Pine forest at lower elevations and mixed conifer Douglas-fir, white fir, limber pine, and aspen at higher elevations

Source: Brown, 1994.

[a] Biotic communities found within the study area but not crossed by the interstates.

Figure B.1 Main Biotic Communities in Study Area

Top row (L-R): Sonoran Desertscrub – Arizona Upland Subdivision, Sonoran Desertscrub – Lower Colorado Subdivision, Madrean Evergreen Woodland. Middle row (L-R): Petran Montane Conifer Forest, Great Basin Conifer Woodland, Interior Chaparral. Bottom row (L-R): Semidesert Grassland, Plains and Great Basin Grassland.

Sources: Wild Sonora: www.wildsonora.com; G. L. Olmsted; Glendale Community College: www.gccaz.edu; Tom Brennan; Jeff Servos; Mark Dimmitt; Reptiles of Arizona: www.reptilesofaz.org; T. R. Vandevender; and the Arizona-Sonora Desert Museum: www.www.desertmuseum.org.

B.2 Wildfire

Fire assessments from three sources are reviewed in this section.

1. BLM Sonoran Desert Rapid Ecoregional Assessment (REA) (Strittholt et al. 2012)
2. Statewide Strategy for Restoring Arizona's Forests (Governor's Forest Health Councils 2007)
3. U.S. Forest Service Four Forest Restoration Initiative, Environmental Impact Statement for Kaibab and Coconino Forests (USFS 2014)

B.2.1 BLM Sonoran Desert REA

REAs are large landscape-scale assessments that synthesize existing information to more fully understand ecological conditions and trends; natural and human influences; and opportunities for resource conservation, restoration, and development, and are typically completed in under 18 months (BLM 2014[27]).

Figure B-2 shows the location of the BLM REAs that have been completed or are in progress throughout the United States.

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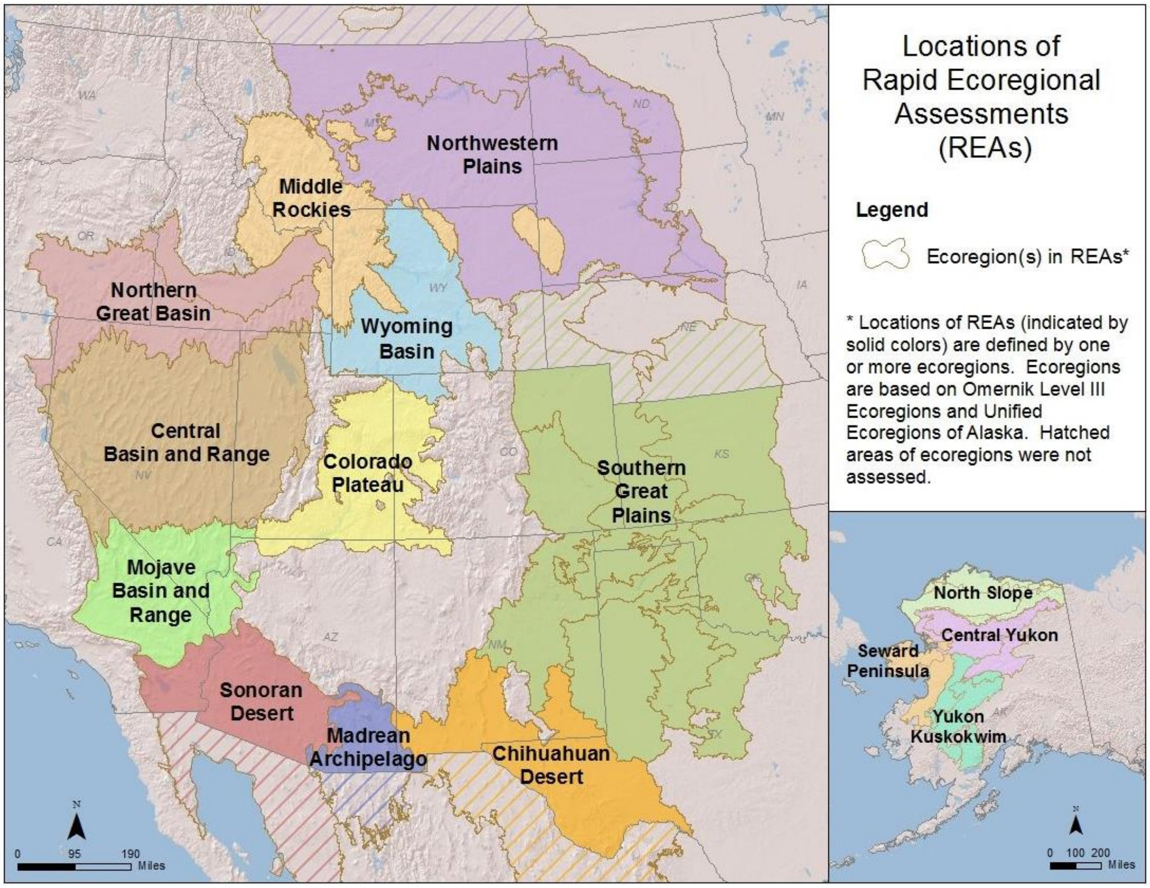
[27] 2014 BLM. Rapid Ecoregional Assessments (REAs). Accessed from: http://www.blm.gov/wo/st/en/prog/more/Landscape_Approach/reas.html. Last updated 11-14-2014.

Figure B.2 BLM Rapid Ecoregional Assessments



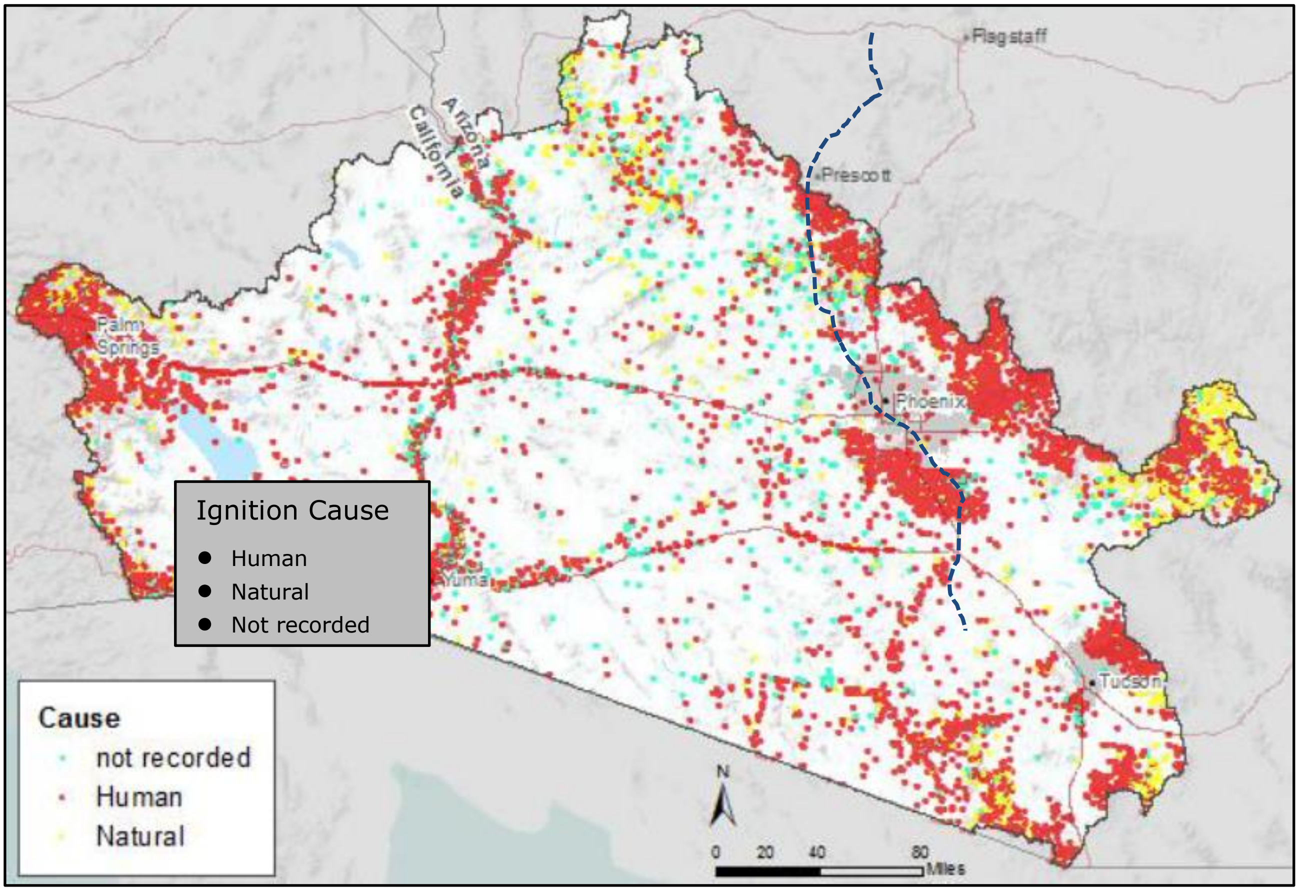
* Locations of REAs (indicated by solid colors) are defined by one or more ecoregions. Ecoregions are based on Omernik Level III Ecoregions and Unified Ecoregions of Alaska. Hatched areas of ecoregions were not assessed.

Source: http://www.blm.gov/wo/st/en/prog/more/Landscape_Approach/reas.html.

The BLM completed the Sonoran Desert REA in 2012; an REA for the Madrean Archipelago, which includes the Sky Island forested areas east of I-19 is in progress but has not been released as of December 2014.

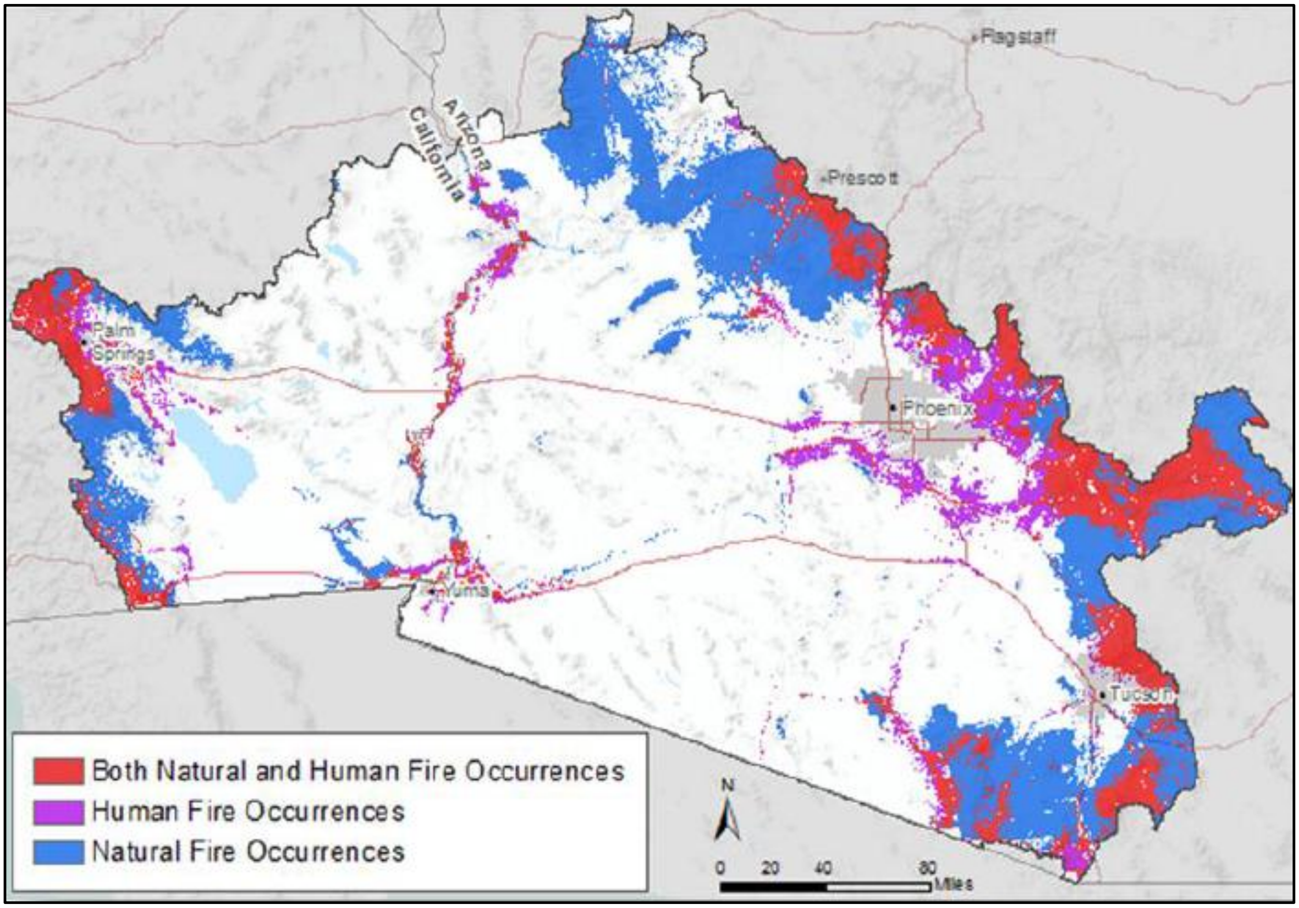
The REA contained maps showing the fire occurrences within the assessment area between 1980 and 2010 according to the cause of ignition (Figure B-3) and the areas with the greatest potential for change as a result of fire from either natural causes, human causes or both (Figure B.4).

Figure B.3 Fire Occurrences in the Sonoran Desert REA Area between 1980 and 2010 According to Cause of Ignition



Source: Figure 3-9 in Strittholt et al., 2012.

Figure B.4 Potential Fire Occurrence from Human and Natural Sources for the Sonoran Desert Ecoregion

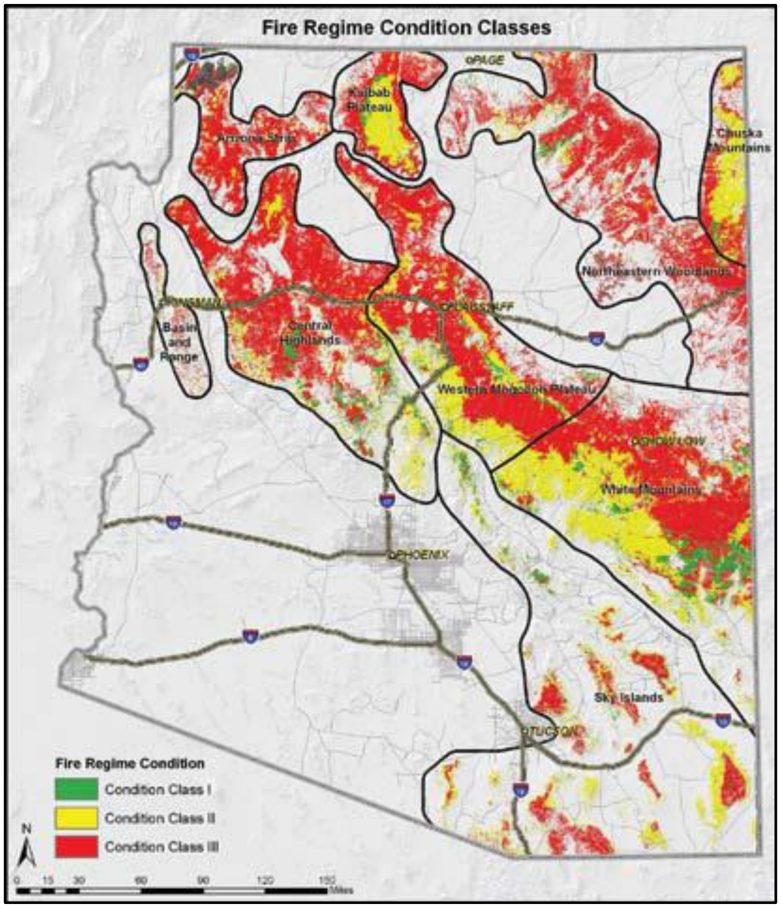


Source: Figure 4-29 in Strittholt et al. (2012)

B.2.2 Arizona State Forest Health Strategy 2007

In 2005, the Governor's Forest Health Advisory and Oversight Councils created a subcommittee to develop a strategy for restoration of Arizona's Forests. The Strategy was published in June 2007. Figure B.5 shows the fire regime condition classes assigned to forested areas across Arizona. The areas in Condition Class III (shown in red) have diverged significantly from their natural fire regimes and unnaturally severe fires in these areas are likely to cause significant damage.

Figure B.5 Fire Regime Condition Characteristics of Forests across the State

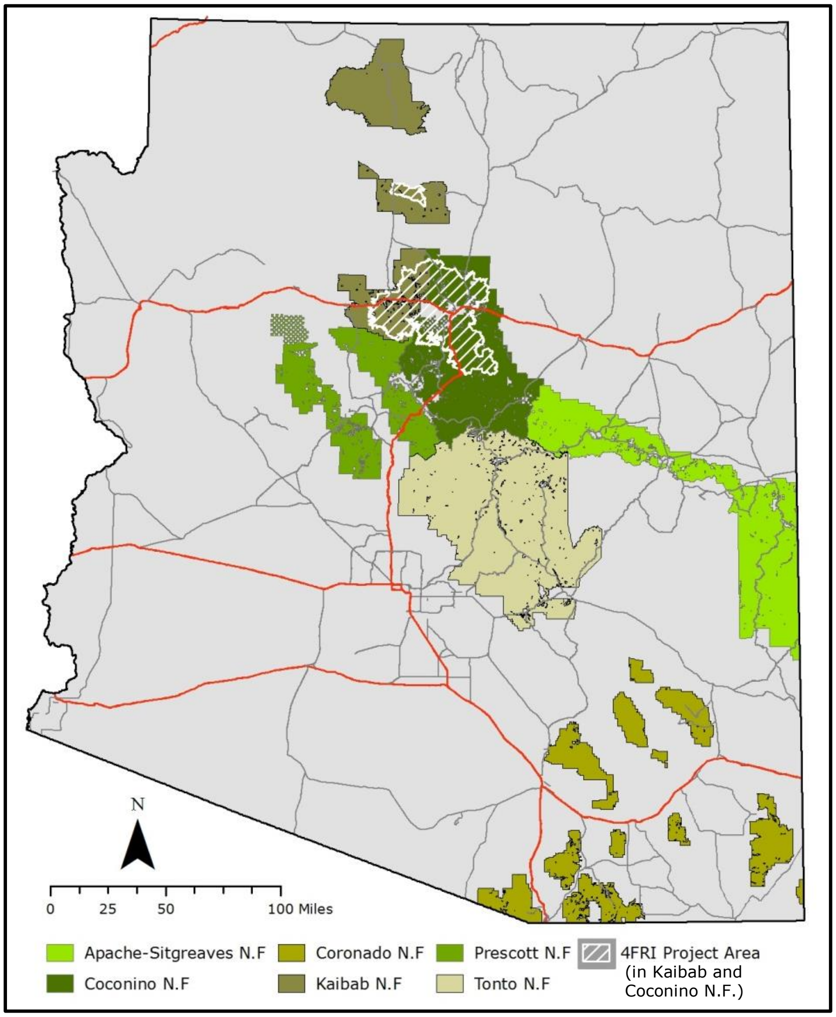


Source: Executive Summary, Governor's Forest Health Councils, 2007.

B.2.3 U.S. Forest Service Four Forest Restoration Initiative (4FRI) – Environmental Impact Statement for Treatments in Kaibab and Coconino Forests

Forest Service land covers approximately 15 percent of the state of Arizona. Figure B.6 shows the location and extent of National Forests in Arizona and of the area included in a multi-forest initiative to treat fuels for wildfire reduction referred to as the Four Forest Restoration Initiative (4FRI).

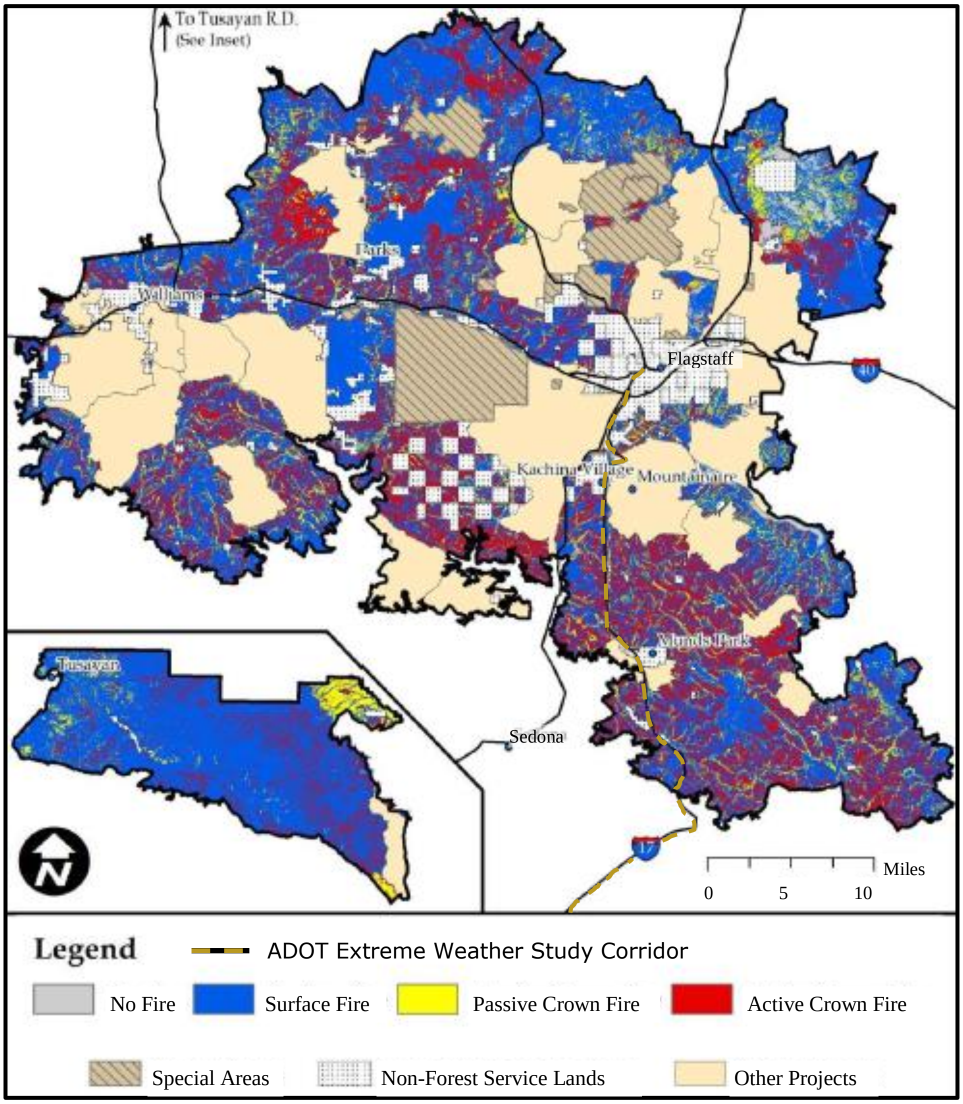
Figure B.6 Arizona National Forests and the 4FRI Project Area



The 4FRI effort began in 2009, although regional planning efforts had begun in the late 1990s. The Final Environmental Impact Statement (FEIS) evaluating planned fuel treatments in the Coconino and Kaibab National Forests was released in December 2014.

The project team reviewed the documents supporting the FEIS including the Fire Ecology, Fuels and Air Quality Specialist Reports (Lata 2014). Figure B.7 presents the results of a model from that report predicting the type of fire that would occur under the existing conditions. The tan areas in Figure B.7 are parts of other projects and were not included in the model. The model shows a mix of ground surface fire (blue) and tree crown fire (yellow and red) is predicted to occur along the study corridor. The portion of I-17 in the pilot study corridor was used as the dividing line between two restoration units. In the unit to the east of I-17 (Restoration Unit 1), the model for the existing conditions predicts that 42 percent of the vegetation in the unit has the potential for crown fires to occur (Lata 2014). The desired condition specified in the FEIS is to have less than 10 percent potential for crown fire.

Figure B.7 Predicted Fire Type for Existing Conditions (4FRI Fire Model)



Source: Figure 6 in Lata, 2014.

B.2.4 Wildfire Summary

Efforts are underway across Arizona to better understand, predict and reduce the risk of large scale wildfires. As ADOT develops an internal assessment of the vulnerability of critical infrastructure, continued coordination with land managers adjacent to transportation infrastructure will be important. With joint planning, actions for fuels management and forest restoration may be able to incorporate or prioritize areas important for protecting vital transportation infrastructure.

Dust Storms

Temperature increases and precipitation decreases can amplify the impacts of dust storms on transportation infrastructure. Decreases in precipitation can lead to increases in dust storms, as soils are much drier and more prone to wind uptake. Furthermore, precipitation decreases can lead to increases in plant mortality across all landscapes. Plant root structures maintain soil stability. When plants die, conditions conducive to erosion occur. Erosion, in combination with wind and other environmental conditions that are not fully understood, can result in dust storms. Alternatively, an increase in precipitation could lead to higher soil stability in certain cases, as root growth increases and leads to better soil holding capacity and less erosion.

Table B.3 shows qualitative dust storm risk levels assigned by the project team to the land cover groupings. Dust storms are of particular concern in the Desert subregion.

Table B.3 Dust Storm Risk Level by Land Cover Grouping

Grouping	Dust Storm Risk Level	Causal Factors
Chaparral	Moderate to Low	Unknown. Chaparral in Arizona tends to have grasses and forbs in the shrub understory, reducing bare ground areas. Chaparral is found in varied topography which is atypical for dust storm areas.
Desert	High	Lack of vegetation, bare ground, and fine/loose soil in habitat. Open landscapes.
Forest	Low	Dominant vegetation type maintains soil stability. Typically in topographically diverse area.
Grassland	Low	Dominant vegetation type maintains soil stability. Typically in topographically diverse area.

Landslides

Table B.4 shows landslide risk levels assigned by the project team to the land cover groupings. These risk levels are general, qualitative approximations for present day conditions.

Although the presence of steep slopes is a significant risk factor for landslides, climate-driven factors like temperature, precipitation, and ground cover are also notable risk factors. As explained in the Dust Storms subsection, plant root systems that stabilize soil could be compromised in a hotter and drier climate. Wildfire can also lead to soil destabilization and increased potential for landslide events. This is particularly relevant when soil destabilization is followed by large scale precipitation events (Robichaud et al., 2000).

Similarly, changes in the precipitation regime and intense storms can lead to localized or regional flooding and therefore increased landslides, regardless of habitat type. Seasonality and precipitation timing are important factors. In addition, a warmer climate, which would lead to more precipitation falling as rain rather than snow in the mountains, could also lead to an increase in landslide impacts. However, with warmer temperature come decreasing opportunities for freeze-thaw events, which can exacerbated landslide risk because they are characterized by rapid thermal expansion and contraction.

Table B.4 Landslide Risk Level by Land Cover Grouping

Grouping	Biotic Community	Landslide Risk Level	Causal Factors
Chaparral	Interior Chaparral	Moderate	Woody chaparral has moderate to deep roots and an extensive root structure that reduces the risk of landslide. However, high fire temperatures can increase water repellency of the soil leading to high postfire erosion.
Desert	Sonoran Desertscrub – Arizona Upland and Lower Colorado River Subdivisions	Moderate	Soil slope stability reduced by loss of native perennial species and increase in nonnative shallow rooted annual grasses.
Forest	Great Basin Conifer Woodland	High	Accelerated precipitation runoff and soil erosion common, leading to significant, permanent losses of site productivity and erosive watershed conditions. Major vegetative changes include decreases in cool-season grasses, and increases in grazing-resistant plants, such as snakeweed and big sagebrush (CP-LHUNA Grahame et al., 2002).
Forest	Madrean Evergreen Woodland	Moderate	Slope stability increased by woodland tree species.
Forest	Petran Montane Conifer Forest	Moderate	Slope stability increased by conifer species.
Grassland	Plains and Great Basin Grassland	Moderate	Soil slope stability reduced by loss of native perennial species and increase in nonnative shallow rooted annual grasses.
Grassland	Semidesert Grassland	Moderate	Soil slope stability reduced by loss of native perennial species and increase in nonnative shallow rooted annual grasses.
Chaparral	Interior Chaparral	Moderate	Woody chaparral has moderate to deep roots and an extensive root structure that reduces the risk of landslide. However, high fire temperatures can increase water repellency of the soil leading to high postfire erosion.

Appendix C. Focus Group Meeting Notes

Major themes discussed in the focus group meetings included:

- Effective adaptation will depend on productive communication between stakeholders, including coordination among ADOT business units and external stakeholders.
- Given the high levels of uncertainty associated with climate projections, particularly in the case of climate extremes (as opposed to averages), the applicability of downscaled climate data to specific infrastructure should be viewed cautiously. Scenario based analysis might be useful in managing climate-related uncertainty.
- An effective study will both identify adaptation strategies and determine how they may be incorporated into existing planning and decision-making processes and tools. (For example, building future climate scenarios into bridge and road design guidelines, specifications, and management systems).
- The study area covers several different ecosystem types/biomes. The potential for variation in extreme weather impacts on the different ecoregions found throughout the study corridor is an important aspect of this project.

C.1 Meeting Summaries

C.1.1 Arizona State University (ASU)

1. A variety of datasets and sources were suggested for the project. Subject areas covered included:
    a. Dust Storms: National Weather Service (NWS), ASU.
    b. Land Cover/Use: National Agricultural Inventory Program (NAIP), Matei Georgescu, metropolitan planning organizations (MPOs) (for regional growth projections).
    c. Extreme Weather: National Climate Assessment, Scripps.
    d. Hydrology: Enrique Vivoni (runoff modeling), USGS office in Tucson, Flood Control Districts, Arizona Flood Warning System.

C.1.2 ADOT Design Managers

1. There are set design standards for bridges and roadways, which provide some flexibility to manage weather-related hazards. To adjust these standards to respond to a potential climate related condition, designers need specific information (such as hydrology and slope analysis).

2. Asset vulnerability issues are addressed on a project-by-project basis, which does not lead to standard hazard mitigation/management strategies across the agency.
    a. The ADOT Transportation Asset Management Plan (TAMP) is in the early stages and may benefit from, and possibly support, adaptation analysis related to the extreme weather assessment.

C.1.3 ADOT Budget Office

1. The ADOT Budget Office is working to link budgets to outcomes and benefits, and is already considering weather-related/environmental hazards (snow, precipitation, dust). The Budget Office is using a maintenance budgeting system developed by Cambridge Systematics to help clarify potential relationships between expenditures and outcomes.

2. The Budget Office is looking to integrate data from across traditionally "siloed" divisions and departments at ADOT, which requires considerable resources and cooperation.

C.1.4 University of Arizona (UA) Climate Assessment for the Southwest (CLIMAS)Project

1. Daniel Ferguson, CLIMAS Program Director, described the interdisciplinary program, which is one of 11 regional NOAA-funded assessments. CLIMAS houses climate data for Arizona and New Mexico.

2. Useful resources will include the upcoming CLIMAS vulnerability/adaptation report, a VOLPE research center project in New Mexico, and NOAA ESRL downscaling for the southwest.

3. Mr. Ferguson emphasized the difficulty in overlaying a climate model and a roadway network to derive meaningful conclusions about potential vulnerability, especially for a geographically specific corridor (results would contain enough uncertainty to jeopardize credibility). A more general or regional focus may therefore be warranted.

4. Mr. Ferguson posited that the Scientific Stakeholder meeting should help the team to address issues of uncertainty and identify the most relevant existing climate models. He suggested several possible attendees that were incorporated into the Scientific Stakeholders participant list.

C.1.5 ADOT Maintenance Staff and District Environmental Coordinators

1. The maintenance staff identified the following issues:
    a. Dust Storms. Daniel Brilliant from ADOT Budget has maps of dust storm hot spots. Seeding immediately adjacent to the highway is an important aspect of prevention.
    b. Flooding is of particular concern in the Flagstaff district.

   c. Extreme low and high temperatures can damage pavement. In areas where shrinking and swelling is of particular concern, the void ratio (i.e., porosity) of concrete could be modified.

   d. Bridges are among the most vulnerable infrastructure types to extreme temperatures (expansion).

   e. Wildfires. Tree fall could be an issue, particularly on secondary roads where there is not a clear zone between the road and trees. Also, roadways are often susceptible to flooding after forest fires (which also leads to significant debris issues); secondary roads often do not have extra drainage capacity built in.

   f. Freeway management system integrity is a potential concern (e.g., electronic components vulnerable to extreme heat, signage fading due to sun).

   g. Slope failures, most of which occur due to freezing or thawing rock, are an issue in Flagstaff District, particularly.

   h. Drought, including the undesired movement of livestock near roadways seeking greener vegetation or shade, as well as dust-related issues, can also impact ADOT roadway facilities.

2. ADOT staff noted that longitudinal data on maintenance (available at ADOT) may be helpful in trend analysis.

C.1.6 ADOT Stakeholders

1. Stakeholders shared current activities with the team:

   a. Arizona Department of Health Services (ADHS) is creating a climate health profile of Arizona and focusing on wildfire, dust, drought, air quality, and airborne diseases.

   b. Bureau of Land Management (BLM) is conducting regional eco-assessments, which address invasive species, habitat, and wildfire.

   c. Sonoran Institute is working to develop climate scenarios.

   d. The Nature Conservancy published a report of climate change impacts in Arizona natural habitats. Marcos Robles noted the limitation of models and importance of scenario planning.

   e. Arizona Game and Fish has an understanding of large species movement that might be applicable.

   f. Arizona Department of Environmental Quality (ADEQ) is studying water quality impacts.

2. Stakeholders discussed key issues to consider for this study:
    a. Dust storms. ADEQ has some data, but National Weather Service (NWS) says there are not enough sensors to show statewide effects.
    b. Extreme Event Data/Projections. Some data available from ADHS (extreme heat) and the Southwest Regional Climate Assessment.
    c. Transportation impacts on adjacent ecosystems are also a topic of interest for future investigation (but not covered by the current project).

Appendix D. Scientific Stakeholder Meeting Notes

1. Project Overview, Objectives, and Approach

Thor Anderson (ADOT) provided an overview of the study objectives and approach:

a. Assess vulnerability of critical transportation infrastructure between Nogales and Flagstaff (I-19, I-10, and I-17); and

b. Integrate infrastructure data, climate data, landscape/ecological data and stakeholder input.

c. Develop predictions for climate stressors (precipitation and temperature), focusing on the extremes relative to infrastructure thresholds;

d. Evaluate secondary impacts from these stressors, such as wildfires, dust storms, stormwater runoff (post-storm and fire), and heat sensitivity of infrastructure (pavement, etc.);

e. Identify unique transportation vulnerabilities associated with the biomes in the study area; and

f. Coordinate with ADOT’s Transportation Asset Management Plan to identify the assets most vulnerable to extreme weather.

2. Climate Scenario Assumptions

a. The group discussed parameters for several regional climate scenario studies, including Assessment of Climate Change in the Southwest (statistically downscaled and dynamically downscaled models), and Seasonal Hydroclimatic Impacts of Sun Corridor Expansion (Georgescu).

b. The U.S. Department of Transportation’s Coupled Model Intercomparison Project (CMIP) Processing Tool was suggested for ADOT’s Assessment. Participants were asked to provide input regarding the key variables, assumptions, thresholds and supplementary data that should be used to provide the most accurate climate scenarios possible for this assessment.

c. The project team suggested that climate projections should reflect sensitivity thresholds tied to ADOT’s facility design and maintenance guidelines and specifications.

d. There needs to be a balance between infrastructure hardening, aesthetics, and funding. These decisions will be made at a policy level. This Vulnerability Assessment can inform policy development and provide adaptation strategies that can be incorporated into existing planning and decision-making processes and tools.

e. A participant suggested selecting one emissions scenario; it is resource intensive to downscale multiple scenarios.

    i. SRES (AR4). Participants suggested that B1 is unrealistic and suggested the A2 emissions scenario. This is the preferred scenario for dynamic downscaling and was used in each of the recent climate studies.

    ii. Representative Concentration Pathways (RCP): As ADOT is concerned primarily with extremes, +8.5 was the suggested RCP scenario.

f. Models. Participants said there are few models that have a good representation of natural climate variability in Arizona, such as the El Nino cycles. A ranking of the various models exists. UA's Department of Atmospheric Sciences can send information on the model rankings. ADOT could determine the model metrics most important to the Vulnerability Assessment and select a model(s) that is strong on those metrics. One participant suggested the following metrics:

    i. Climatology,

    ii. Atmospheric variability,

    iii. Surface temperatures, and

    iv. Precipitation.

g. CMIP application. CMIP5 data is preferred for downscaling. It was suggested there is too much focus on CMIP backcasting, when there is a wealth of detailed historical atmospheric data available from the past 50 to 60 years that can be analyzed based on past events to make future assumptions.

h. There are additional studies currently underway that will provide data. Those studies may not coincide with this Vulnerability Assessment timeframe, but could be referenced as a future data source.

i. Climatology and atmospheric variability. Seasonality is not factored into any of the precipitation models. Participants noted that winter precipitation is much more predictable than in the summer, and thus there is more confidence in the winter precipitation modeling outputs. It was suggested that ADOT use historical observed data and atmospheric circulation patterns to validate model assumptions, focusing on daily or monthly precipitation data during certain seasonal cycles.

j. Spatial Resolution. 12.5 km is the standard already for CMIP5 data. 50 km is the standard for dynamically downscaled models. Participants were not concerned about precision or uncertainty issues pertaining to 1/8 degree downscaling.

k. Surface temperatures. The models are better at predicting temperatures than precipitation. There is confidence in the BCSD temperature projections. The CMIP tool would work well.

l. Precipitation. There is less confidence in the validity of precipitation projections than in temperature projections, due to the inconsistent and seasonal nature of rainfall in Arizona. Most of the yearly rainfall is concentrated in a few annual events.

    i. It is important to consider additional factors that contribute to runoff and flooding, such as erosion and man-made structures, rather than just a 24-hour maximum precipitation event. It is also difficult to account for changes in topography in the projections. ADWR recently completed a study of probable maximum precipitation (PMP) and has developed a PMP modeling tool, which may be useful for this study or future work.

    ii. Since so much of the threat to transportation infrastructure is from extreme precipitation and flow events, rather than averages, the extreme events are what ADOT needs to plan for. For example, ADOT needs guidelines that can be built into construction contracts and corresponding responsibility for erosion control. ADOT would like to identify the pinchpoints along the corridors identified in the study where the drainage structures are at higher risk of being compromised.

    iii. USGS staff said they will have two new tools available soon on the web site: a GIS-based tool to show the 500-year maximum flows at any given point on a map, and a debris flow model which can be used to identify potential areas where flows may be a problem following a wildfire.

m. Directionality/Output Ranges. Specific suggestions were not provided for the output ranges. Participants noted that ADOT should focus on the range of extremes that would trigger infrastructure damage or secondary stressors.

n. Temporal resolution. ADOT’s preferred analysis years don’t correspond cleanly with recent climate studies in the southwest (e.g., 2100).

3. Ecology

a. The EPA has four levels of eco regions. Level III (the second finest resolution level, which is typically used for models) and Level IV (the smallest scale, which is comparable to a vegetative community scale) are levels that could be used for this assessment.

    i. The Bureau of Land Management (BLM) has an ongoing Rapid Ecoregional Assessment (REA) project. They are assessing some Level III Ecoregions across the U.S. REAs assess changes across several phenomena (e.g., climate change, vegetative communities, land use, etc.). Two REA regions are located in Arizona: the Sonoran Desert Ecoregion (assessment complete) and the Madrean Archipelago Ecoregion (assessment in progress).

    ii. Biotic Communities are another scale to assess biomes (vegetation types) at a landscape level. They are based on Brown (1994). ADOT seed mixes are based on the biotic communities.

    iii. Due to data availability and scale, EPA Level III Ecoregions and Biotic Communities are the proposed levels for this assessment.

b. There are three EPA Level III Ecoregions in the study area (Sonoran Desert, Madrean Archipelago, and Arizona/New Mexico Mountains).

c. There are eight biotic communities in the study area, five of which intersect the Vulnerability Assessment corridor.

d. The Nature Conservancy completed a study three to four years ago using the Fourth Assessment Report models (CMIP3) and BCSD models. They used a different landscape scale, however. The findings are:

    i. 50 to 100 years out, not much difference was observed with average temperature change;

    ii. Precipitation projections are associated with less confidence; and

    iii. The study analyzed averages, not extremes – this differs from the proposed Vulnerability Assessment approach, where extremes are the most relevant to assessing transportation infrastructure vulnerability.

e. Participants agreed that EPA Level III Ecoregions and Biotic Communities are good starting points for this project.

f. The Nature Conservancy indicated its 50- to 100-year projections did not reveal much difference between current and future ecoregions. It was noted the Bureau of Land Management REA studies did find some changes in ecoregions over time.

4. Watersheds

a. There are 10 watersheds overlapping the Vulnerability Assessment corridor. These are 8-digit HUC watersheds. These areas shape the landscape and provide important information relating to extreme weather impacts.

b. USGS representatives had two suggestions:

    i. Extend the data to 6-digit HUC watersheds to capture major flooding on the Gila, Verde and Salt Rivers; and

    ii. Alternatively, extend the corridor buffer to include 8-digit HUC watersheds upstream of the project corridor related to major rivers in the project area (e.g., Gila, Verde, Salt Rivers).

c. Wildfires. Can cause changes in vegetation. ADOT wants to determine how projected changes in ecoregions may make an area more vulnerable to wildfire and identify those areas along highway corridors. One approach suggested could be to look at the proportion of forest to other vegetation types.

d. Invasive species. There are several invasive species (e.g., Buffel grass and chick grass) that have taken over along sections of ADOT highway corridors. Invasive species cause broader changes in vegetation, which can result in the movement of wildlife, which may increase highway corridor wildlife crossings. Invasive species are generally more susceptible to fire. Wildfires can in turn have an impact on hydrological flows.

e. Dust storms. If vegetation is lost in the Sonoran Desert ecoregion, there will be increased dust storm occurrences. UA is conducting dust storm studies. UA participants indicated it is difficult to determine the origin of the dust source from large-scale monsoons because there are currently no dust sources included in models. It is complicated to model dust storms because of step changes in land use and minimal information on dust intensity.

    iii. USGS has staff working on dust storm issues and will provide information to the study team.

5. Hydrology

a. Probable Maximum Precipitation (PMP) Model. As noted previously, the Arizona Department of Water Resources recently completed a PMP study, and has developed a geographic information system (GIS)-based modeling tool to determine maximum precipitation levels at any location, which may be useful for ADOT's assessment.

b. Groundwater recharge. According to USGS representatives, the effects of extreme events on groundwater recharge are still largely unknown.

c. Scale. The recommended scale for rainfall is watershed. For runoff, the appropriate scale is much smaller.

d. Hydrology, ecology and climatology are interrelated. The study team should attempt to use a holistic approach when modeling scenarios. One participant noted the modeling efforts should start with man-made changes and their effects (e.g., heat islands affect monsoons). There are several sources for urbanization models, including U.S.

Environmental Protection Agency (EPA) and the metropolitan planning organizations (MPO).

e. It was suggested the study team dynamically model wildfires, and then tie that into the ecology and hydrology models. NAU has wildfire models, as do some Nature Conservancy chapters in California.

f. Riparian corridor changes are an important data consideration. AZGFD has relevant data.