Arizona Department of Transportation

ASSET MANAGEMENT, EXTREME WEATHER, AND PROXY INDICATORS PILOT PROJECT

March 2020

Disclaimer

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1. Executive Summary

Transportation infrastructure is a complex system of assets required to deliver multiple services and functions. As fiscal constraints for the development and rehabilitation of roadways remain, and repeated retrofitting to address the impacts of extreme weather and climate risk continue to be cost prohibitive, new and novel approaches to long-term planning, asset management, project development, engineering design, and lifecycle planning are paramount.

The management of the roadway system has now evolved from a decentralized, project-based focus to one that encompasses enterprise-wide endeavors: administration, asset management, technology adoption, planning, design, construction, operations, and maintenance. In addition, the expansion of risk analysis for extreme weather management and climate adaptation has complicated the long-term delivery of these complex transportation systems. ADOT seeks to combine risk, science, technology, and engineering to improve the understanding of natural hazard and weather related risks to its transportation system, in order to accomplish its mission "Connecting Arizona. Everyone. Everywhere. Every Day." and its vision to become the most reliable transportation system in the nation.

One such tool to advance these new realities is Lifecycle Planning (LCP). LCP is a process to estimate cost of managing an asset or asset class, or asset sub-group over its whole life with consideration for minimizing cost while preserving or improving the condition[1]. The purpose of this pilot project is to (1) develop lifecycle planning methods that consider the effects of natural hazard and extreme weather conditions on transportation assets, (2) establish analytical procedures that provide a risk-based approach for identifying assets and locations with a high likelihood of being impacted, (3) develop a flexible, scalable, risk-based geographic information system (GIS) resilience database and real time information dashboard that links transportation asset management, natural hazard and weather, climate impacts, and ADOT infrastructure resilience efforts, and (4) identify actions to improve overall infrastructure resilience linkages, especially for the most vulnerable assets or classes of assets eligible for FHWA Transportation Asset Management Plan (TAMP) reporting.

This project builds on eight years of the Arizona Department of Transportation (ADOT) extreme weather management, climate adaptation, and resilience work. The project follows a risk-based management process to identify the stressors that pose the highest threat to ADOT's transportation system. The pilot project is part of an ongoing work program through which ADOT plans to address the following stressors through the lifecycle planning of roadway assets and asset classes:

- Intense Precipitation
- System Flooding
- Wildfires

[1] 23 CFR 515.5 – Definitions https://www.law.cornell.edu/cfr/text/23/515.5

- Wildfire-Induced Floods
- Drought-Related Dust Storms
- Rockfall Incidents
- Slope Failures
- Increased Surface Temperatures

1.1 Methods/Technical Approach

The pilot approach targeted extreme weather and climate stressors, four prioritized asset classes (bridge, culverts, pavement, roadside vegetation/stabilization) susceptible to those stressors, and the use of GIS as a tool to advance how scientific evidence driven decision making informs transportation systems management and integrates with asset management processes. The pilot integrated extensive internal and external sources of data to identify and synthesize risks and hazards on the ADOT system. Hence, formalizing ADOT's extreme weather and climate adaptation lifecycle planning process for asset management. The intent is to demonstrate through the pilot how lifecycle planning can be a key part of improving resilience to extreme weather and natural hazard events and a contributing baseline approach to incorporate future measurable climate trends; at the same time reducing risk to ADOT's ability to provide safe, reliable, cost-effective roadways. The main steps followed included:

1. Create the GIS Resilience Database to centralize existing locations subject to natural hazard and weather-related risks

2. Advance ADOT's end-to-end engineering process [(Climate Engineering Assessment for Transportation Assets (CEA-TA)] by defining proxy indicator/root cause/probabilistic methods and models by stressor and asset or asset class

3. Link the methods and models to ADOT's asset management program

4. Use the results of the above actions to infrastructure resilience continuous improvement

Exhibit ES-1: ADOT's Pilot Project Approach

Phase 1
- Identify stressors and their associated natural hazard and weather-related risk(s)
    - Identify vulnerable assets
- Identify impact(s) to ADOT's system
- Identify case study area(s) for developing and testing the procedure for evaluating cause of the impacts
- Compile, integrate and analyze data
    - Identify proxy indicators
    - Identify root cause up to and including probabilistic modeling
        - Consider different stages of asset lifecycle (creation, maintenance, preservation, rehabilitation/reconstruction)

Phase 2
- Identify mitigation strategies, including adaptation options and selection criteria

Phase 3
- Incorporate assessment results in decision making

This report describes the work performed under Phase 1 shown in Exhibit ES-1 above. The pilot project is to continue past the reporting period of this document to complete Phases 2 and 3 described above.

1.1.1 What Are Lifecycle Planning Methods and How Will These Be Used?

The lifecycle planning methods are a way to link stressors, their corresponding natural hazard and weather-related risk, and the impacts to the infrastructure. The methods are to serve ADOT in identifying mitigation/adaptation options throughout the different stages of an asset life cycle, including planning, design/engineering, construction, maintenance, and operations. The methods are to integrate information regarding current measures being used within ADOT, as well as identify innovative ideas to mitigate risk through lifecycle planning. Lifecycle planning methods are to be developed to account for the following stressors: intense precipitation, system flooding, wildfire, wildfire-induced floods, drought-related dust storms, rockfall incidents, slope failures and, increased surface temperatures. For this report, the project team predominantly focused on advancing system flooding given the high number of incidents recorded in the GIS Resilience Database.

1.2 Results: Development of a Lifecycle Planning Method for Assets Subject to Weather and Natural Hazard Risk

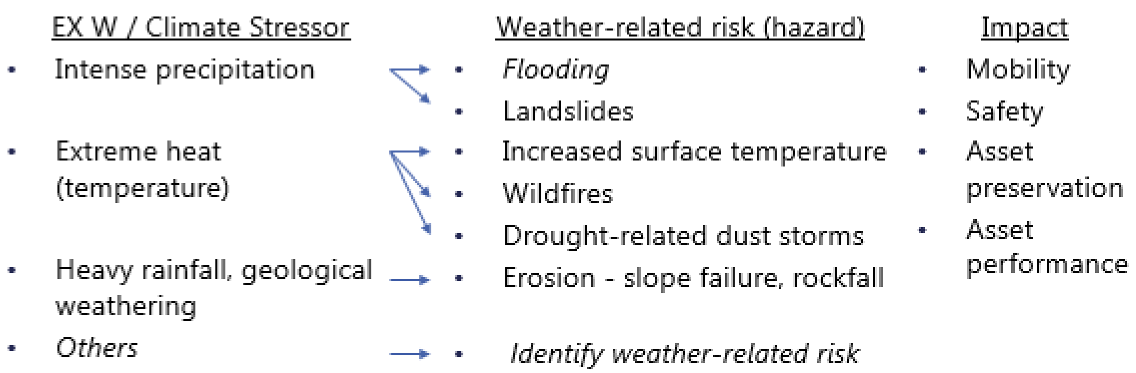
The Resilience GIS Database, the real time information dashboard, the working paper for advancing the CEA-TA probabilistic risk assessment, and documenting life cycle planning and asset management linkages were the main products of this pilot project. This was completed by integrating natural hazard and weather-related incident data, infrastructure information by asset or asset class, live feed from other sources, and connecting these actions to engineering design and asset management. Therefore, allowing for the single collection point and visualization of vulnerable locations; identification of the baseline methods to – establish proxy indicators, conduct root cause analysis that consider different stages of asset lifecycle (creation, maintenance, preservation, rehabilitation/reconstruction), and where needed conduct probabilistic engineering risk assessment. The overall process is based on the following five principles:

- Understanding the relationship between stressors, risk, and impacts to the system
- Availability of historical natural hazard and weather-related incidents
- Asset and resource data (internal and external partners)
- Linking to accepted engineering processes
- Establish life cycle methods – proxy indicators, root cause analysis, probabilistic risk modeling

A statewide outreach to ADOT districts was done as part of this pilot project, requesting data regarding natural hazard and weather related locations of concern to feed the GIS Resilience Database. The team received an overwhelming response from the northeast, northwest, southeast, southwest, central, northcentral, and southcentral districts resulting in the identification of over 500 locations of current areas experiencing natural hazard and weather-related risks, including overtopping at low water crossings, dust storms, flooding, rockfall, wildfire, wildfire-induced flooding, erosion, and slope failures. The most recurring risk mentioned in this dataset was flooding, specifically from the central and northeast districts.

Given the historical focus of the ADOT Resilience Program (Established October 2015) and the recurring flooding problems reported statewide by the different districts, the pilot project team focused on lifecycle planning methods to address flooding. It allows for a crosswalk approach between the stressor, natural hazard and weather-related risk, impact, asset classes, and lifecycle planning strategies/adaptation options. The maps resulting from the GIS Resilience Database allow for the identification of proxy indicators and vulnerable areas. The lifecycle planning methods user(s) are to preliminarily determine agency actions and prioritize low-cost/high-value actions. If no performance improvement is experienced, or if the decision maker decides to do a detailed analysis, the next step is to move toward a root cause engineering analysis up to a probabilistic risk engineering effort, allowing for a deeper, more detailed decision-making process to occur that further incorporates value engineering, risks, cost benefit analysis, and LCP.

Exhibit 1: Example to Link Extreme Weather, Climate Adaptation, Asset Management, and Infrastructure Resilience



1.3 Conclusion and Next Steps

The pilot project presents an assessment of ways to integrate natural hazard and extreme weather, and climate adaptation into asset management by focusing on a lifecycle planning approach that results in cost-effective assessment/mitigation/adaptation strategies by asset or asset class. The proposed risk-based approach is to be further improved along with one of the main pilot project products, the GIS Resilience Database. This tool can enhance scoping efforts by identifying impacts to near-future construction programs and identifying vulnerabilities early in the planning phases. The continued use of the GIS Resilience Database by ADOT practitioners can help improve the preliminarily developed lifecycle planning methods for the stressors and assets addressed in this report. ADOT reported extreme weather and climate aspects in the required 2019 Transportation Asset Management (TAM) Plan. The results from this pilot project will only serve to mature that TAM reporting process and contribute to future system risk management, infrastructure resilience building, and asset management health reporting.

Planned Future Work:

- Continue a Phase 2 of this work, which involves developing lifecycle planning methods for all other stressors identified besides flooding, and incorporating ADOT's field-tested, emerging mitigation practices, and staff recommended practices
- Finalize requirements to comply with 23 CFR Part 667 – Periodic Evaluation of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events
- Standardize a financial decision-making format for extreme weather and climate - RinVEA
- Screen the 2022 Construction Program as resilient
- Introduce resilience to the 2022 Statewide Transportation Improvement Program (STIP)
- Incorporate resilience into Long Range Plan revisions
- Complete development and adoption of probabilistic engineering methodology for asset classes

2. Introduction

In recent years, the United States has experienced an increase in the number of extreme weather events that have damaged transportation infrastructure throughout the country. States recognize natural hazard and extreme weather events have a disruptive impact on operations and pose a safety and economic risk to highway system assets. Transportation agencies across the country are determining how to improve the resilience of their roadway systems to prevent, protect, respond, and recover from impacts.

In 2011, the National Highway Performance Program 23 USC 119 was signed into law, which requires states to begin monitoring their transportation assets. As states continued to evaluate their assets, it has become increasingly important to evaluate how natural hazard, extreme weather events, and measurable future climate trends will impact their transportation network.

In response to these concerns the Federal Highway Administration (FHWA) established a competitively funded pilot program through which State Departments of Transportation (DOTs) can work with the FHWA to monitor and assess these realities within the context of asset management. After these pilots are completed the FHWA will use the reported results to create a guidebook for state DOTs and other roadway agencies on emerging best management practices for addressing extreme weather risks into the lifecycle planning and management of roadway assets.

2.1 Arizona as a Pilot State

ADOT is one of six pilot projects and is evaluating the linkage between asset management, LCP, risk, natural hazard, extreme weather, and measurable climate trends.

Arizona is subject to a variety of events ranging from extreme heat to three types of intense rainfall. These, and other natural hazard and extreme weather events present risks to the availability of the roadway system. For ADOT, it presents significant business risks, such as increasing the lifecycle cost of the assets, and increasing the costs of ensuring operational safety for roadway users.

Extreme weather events have seemingly increased in frequency and severity (Arizona has experienced several 100-1000 year events). Many of Arizona’s transportation assets are negatively affected by natural hazard and weather related risk, and new strategies need to be implemented to lessen their impact. The purpose of this report is to assist ADOT in finalizing the identification of areas where transportation assets are vulnerable. Through this pilot project, ADOT seeks to develop and implement a Lifecycle Planning (LCP) approach, mature ADOT’s CEA-TA end to end engineering process, and develop GIS tools to manage these assets when these types of events occur.

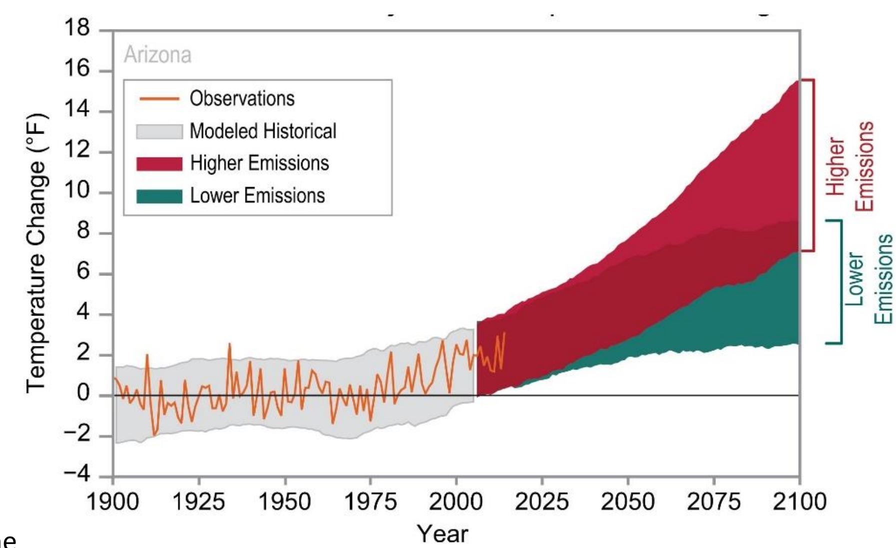
Arizona is one of the largest states in the country with a geographic area covering diverse climates and topography – Seven (7) Vegetation Management Biozones, assets - sea level to 8,000 altitude feet. The southern portion of the State experiences some of the hottest and driest areas in the United States, while the northcentral and northeastern parts of the State experiences cooler temperatures, cold winters, and mild summers.

2.2 Arizona's Temperatures

The average annual temperature in the mountains is approximately 40°F at the highest elevations, while the southern portion of the state often experiences summer temperatures between 105°F and 115°F. Phoenix has the hottest climate of all major U.S. cities. The record high temperature for the state is 128°F recorded at Lake Havasu City on June 29, 1994, while the record low temperature was -40°F at Hawley Lake on January 7, 1971. In 2014, Arizona experienced the hottest year on record, with a statewide average annual temperature of 62.3°F, about 2.3°F above the long-term average of 60.3°F.[2] According to the National Weather Service, the year 2019 broke a five year run (2014 -2018) are all in the top ten for annual average temperature in Phoenix, Arizona since record keeping began in 1896.[3]

Average temperatures in Arizona have risen about 2°F since the beginning of the 20th century. Projections to year 2100 show a continuous rise in temperatures under both lower emissions scenarios and higher emissions scenarios (hottest years being approximately 13°F warmer than the hottest year in the historical record.[4]

Exhibit 2: Arizona's Observed and Projected Temperature Change



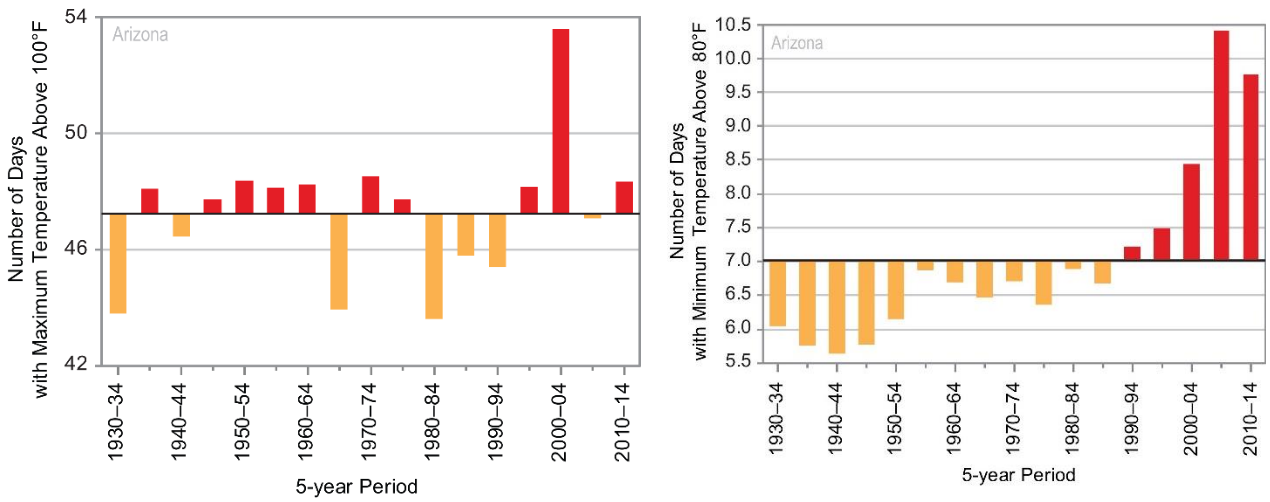
The

Source: North Carolina Institute for Climate Studies (CICS-NC) and NOAA National Centers for Environmental Information (NCEI)

[2] NOAA State Centers for Environmental Information – Arizona State Climate Summary https://statesummaries.ncics.org/az
[3] https://www.weather.gov/psr/Year_in_Review_2019
[4] CICS-NC and NOAA NCEI

Arizona has experienced above average number of extremely warm nights (annual number of days with minimum temperature above 80°F) for the past 25 years. The increase is graphically shown in Exhibit 3 below, along with a graphical representation of the observed number of extremely hot days (maximum temperature above 100°F). Arizona has not experienced a similar trend in the number of extremely hot days, as shown in the exhibit below.

Exhibit 3: Arizona's Observed Number of Extremely Hot Days and Extremely Warm Nights



The number of extremely hot days and the observed number of extremely warm nights (annual number of days with minimum temperature above 80°F) for 1930-2014, averaged over 5-year periods; these values are averages from 27 long-term reporting stations. The dark horizontal line represents the long-term average. Source: North Carolina Institute for Climate Studies (CICS-NC) and NOAA National Centers for Environmental Information (NCEI)

The number of extremely hot days is highly variable in Arizona, with the most recent decade (2005–2014) experiencing a near average number of such days. The state has, however, seen an upward trend in both average daily maximum and minimum summer temperatures, with the highest values for each occurring since the year 2000.

2.3 Arizona's Precipitation

Extreme rainfall events in Arizona pose unique and pertinent threats to ADOT infrastructure. Extreme rainfall can trigger large floods or even debris flows that threaten infrastructure. Well understood flood hydrology in Arizona identifies three unique storm types:

1) In winter, synoptic frontal systems (cold fronts and associated atmospheric rivers) can produce widespread heavy precipitation and large floods in larger catchments (e.g., the large floods of January 1993). The precipitation originating from cold fronts and low-pressure systems that move south from the Pacific Northwest and sweep across Nevada or southern California and into Arizona bring cold air and rain or snow. Snow typically falls on the northern half of the

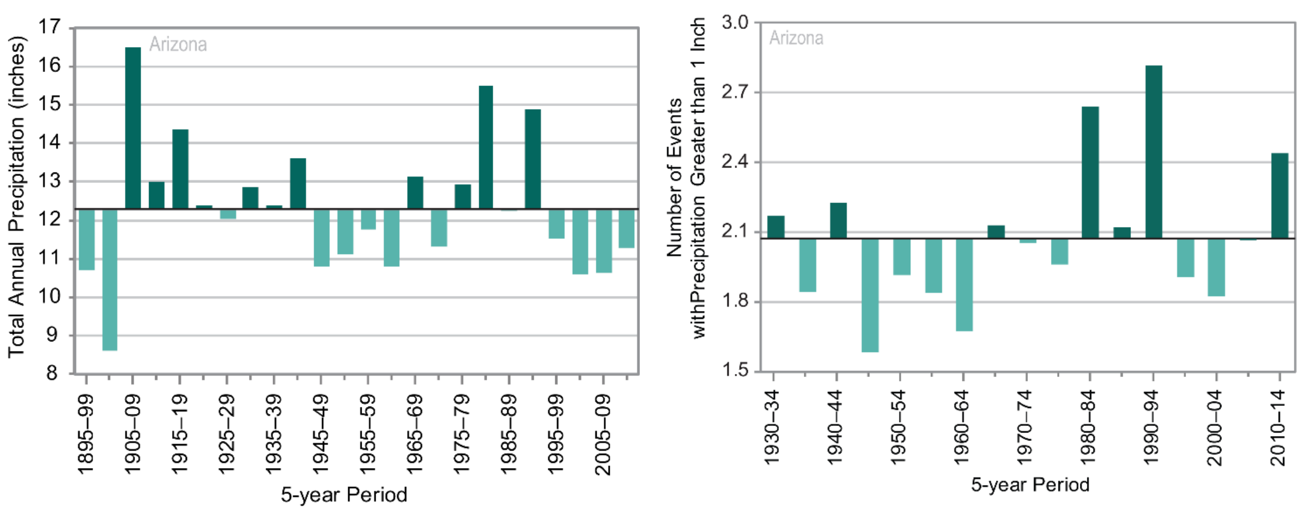
state and the higher elevations, and northern Arizona receives just over half their precipitation in the winter. The winter storms rarely extend into southern Arizona, which results in most of the precipitation occurring during the summer months for southern Arizona.

2) Strong summer thunderstorms associated with the North American Monsoon produce intense, localized rainfall and associate flash floods in smaller catchments (e.g., the Bronco Creek flood of 1971; the July 31, 2006, outbreak of floods and debris flow in southeastern Arizona). Monsoon season in Arizona is the northern extent of the North American Monsoon, which usually begins in early June in central and southern Mexico. During this season, dry westerly winds persist through fall, winter, and spring, shifting to moist southerly winds bringing thunderstorms into Arizona. Approximately half the annual precipitation in central Arizona is due to monsoon activity, and two-thirds to three-quarters of the annual precipitation in southern Arizona. Flash flooding in steep terrain, and urban flooding through low-lying roads can be the result of these intense thunderstorms.[5]

3) Finally, hybrid Arizona flooding events in the autumn combine late monsoon-season tropical moisture with frontal systems that can produce widespread floods (e.g., the October 1983 event associated with tropical storm Octave). Phoenix experienced the largest single storm and second wettest October on record in 2014.

Precipitation has varied widely in Arizona, with annual precipitation being below average amount for the last two decades. However, the number of extreme precipitation events (annual number of days with precipitation greater than 1 inch) has increased in the 2010-2014 year period. Exhibit 4 below shows a graphical representation of these changes.

Exhibit 4: Observed Annual Precipitation (Left) and Observed Number of Extreme Precipitation Events (Right)



[5] Arizona State Climate Office – Weather https://azclimate.asu.edu/monsoon/

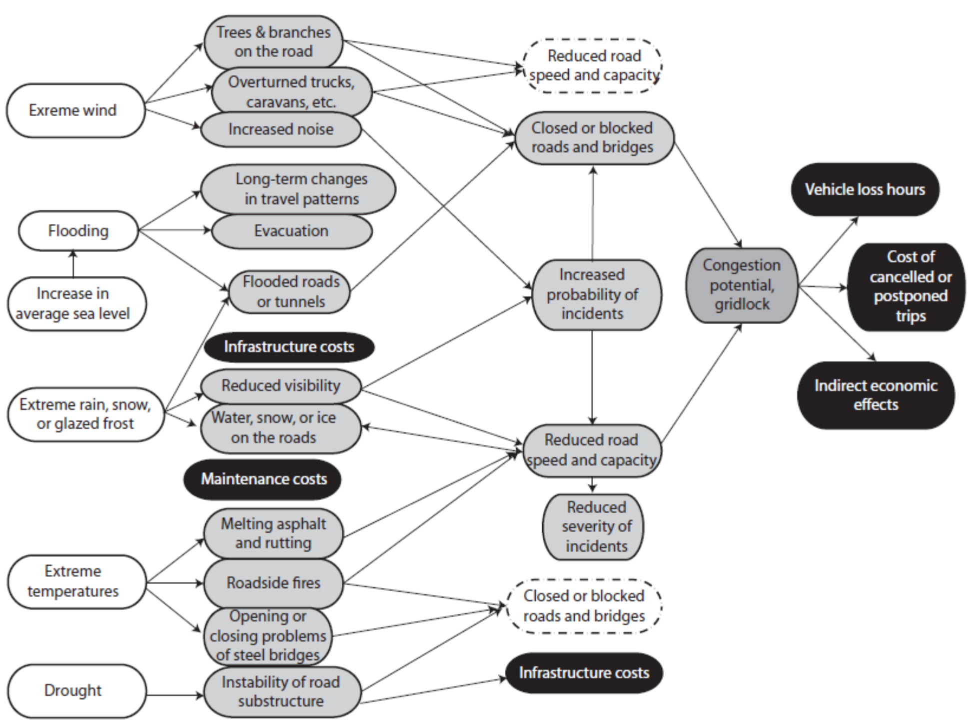
Source: North Carolina Institute for Climate Studies (CICS-NC) and NOAA National Centers for Environmental Information (NCEI)

2.4 Impacts of Extreme Weather and Climate Trends

There is currently a multitude of natural hazard and weather related stressors present in Arizona, but they can largely be separated into two categories: extreme heat and extreme precipitation. The negative impacts of extreme heat could include: pavement deformation, shorter pavement construction windows, heat-related worker safety issues, and public safety issues during lengthy delays. Extreme heat can also lead to an increased amount of dust storms, due to a decrease in vegetation coverage on soil, as well as contributing to an increased number of wildfires. Areas affected by wildfires may see increases of runoff to levels that the current drainage system cannot handle. On the other hand, extreme heat has the benefit of reducing the amount of freeze-thaw impacts to pavements and a reduced amount of snow removal.

Precipitation levels are expected to remain consistent for the near future. However, if precipitation levels rise, the existing drainage and pump stations in the state may become overwhelmed. Another impact of oversaturated soils includes the increased likelihood of rock falls, subsidence, and landslides. Lower number of precipitation events but a higher intensity is a concern. This scenario can heavily impact rural and urban areas alike for safety and economic development.

Exhibit 5: Aggregation of Impacts on Road Infrastructure



Source: Transportation Resilience: Adaptation to Climate Change and Extreme Weather Events, U.S. Department of Transportation, Transportation Research Board[6]

ADOT has been proactively addressing the risks from natural hazard and weather since 2012 and expanded efforts through this pilot and future efforts. The integration of risk, science, technology, and engineering has been the main approach to improve ADOT's understanding of natural hazard and weather risk at the program, project, and asset class level. The combination of these fields allows the identification, prioritization, and development of strategies and actions that ADOT can take across the infrastructure lifecycle to increase resilience.

2.5 Purpose

The purpose of this pilot project is to:

- Develop lifecycle planning methods that consider the effects of extreme weather conditions on transportation assets
- Establish a methodology and analytical procedure that provides a risk-based approach for identifying assets and locations with a high likelihood of being impacted as a results of extreme weather and climate stressors
- Develop flexible, transferable, risk-based tools that link asset management, extreme weather, and climate resilience efforts into the management of different assets
- Identify specific lifecycle planning actions to integrate across the lifecycle of assets to improve resilience

2.6 Goals

The main goals of the pilot project are to:

- Identify, analyze, evaluate, prioritize, and develop plans for addressing the risks associated with extreme weather and climate trends on transportation assets
- Consider entry points into the asset management process to incorporate and monitor these potential risks
- Demonstrate how risk mitigation activities may influence lifecycle planning of assets
- Develop lifecycle plans for assets impacted with the objective of minimizing the whole life cost while preserving or improving the condition of the assets and performance of the system, and
- Document any processes developed to help with transferring lessons learned

[6] Bollinger, L. A., C. W. J. Bogmans, E. J. L. Chappin, G. P. J. Dijkema, J. N. Huibregtse, N. Maas, T. Schenk, M. Snelder, P. van Thienen, S. de Wit, B. Wols, and L. A. Tavasszy. Climate Adaptation of Interconnected Infrastructures: A Framework for Supporting Governance. Regional Environmental Change, Vol. 14, No. 3, 2014

2.7 Scope

This project builds on ongoing ADOT infrastructure resilience work. The project follows a risk-based management process to identify the stressors that pose the highest threat to ADOT's transportation system. The pilot project is part of an ongoing work program through which ADOT plans to establish a process to address the following stressors in the lifecycle planning of roadway assets:

- Intense Precipitation
- System Flooding
- Wildfires
- Wildfire-Induced Floods
- Drought-Related Dust Storms
- Rockfall Incidents
- Slope Failures
- Increased Surface Temperatures

2.8 Document Organization

The project report's organization is based on FHWA's recommended format provided for the Asset Management, Extreme Weather, and Proxy Indicators Pilot studies.

1. Executive Summary
2. Introduction to the Project
3. Context of Pilot
4. Methods/Technical Approach
5. Results and Integration Actions
6. Lessons Learned
7. Conclusions and Next Steps
8. Technical Appendices

2.9 Background and Prior Work

This project applies and/or builds on the following FHWA and ADOT guidance and studies:

- FHWA: Guidance on Incorporating Risk Management into Transportation Asset Management Plans (November 2017)
- FHWA: Guidance on Using a Lifecycle Planning Process to Support Asset Management (November 2017)
- FHWA: Vulnerability Assessment and Adaptation Framework, 3rd Edition (December 2017)
- ADOT: Extreme Weather Vulnerability Assessment (January 2015)
- ADOT: Preliminary Study of Climate Adaptation for the Statewide Transportation System in Arizona (March 2013)

2.10 Integrating Resilience into Asset Management

2.10.1 What has ADOT Done?

During 2013 to 2015, as part of the FHWA Vulnerability to Extreme Weather and Climate Change Pilot program, ADOT assessed the vulnerability of ADOT-managed transportation infrastructure to Arizona-specific extreme weather and measurable climate trends. Long term, Arizona DOT sought 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 and climate risks.

ADOT elected to focus on the Interstate corridor connecting Nogales, Tucson, Phoenix, and Flagstaff (I-19, I-10, and I-17) some 30,000 square miles. 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.

The project team examined climate-related stressors identified by ADOT, selected stakeholders, and the March 2013 *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.

Vulnerability Assessment Methodology (Completed in 2015)

During this assessment, the following three categories of information was gathered: climate data, transportation asset data, and land cover data. Focus Group meetings with internal and external stakeholders early in the study developed 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[7]. 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 using downscaled Coupled Model Intercomparison Project (CMIP) data, 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. 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 ADOT District. Preliminary results were presented in Focus Groups, where ADOT regional staff provided feedback on hypotheses developed through the desktop assessment - Section 5.0 of the *Extreme Weather Vulnerability Assessment* (2015) report.

Climate Data Collection and Processing (Completed in 2015)

Atmosphere-Ocean General Circulation Models (climate models) simulate climate processes at a global scale, ranging in resolution from about 75 to 250 square miles[8]. The process of generating climate data at a more granular scale is called "downscaling." This study used 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 select and apply the most relevant and robust models, emissions scenarios, and downscaling techniques. The parameters used were selected based on conversations with members of Arizona's climate science community.[9]

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 thirteen (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)[10].

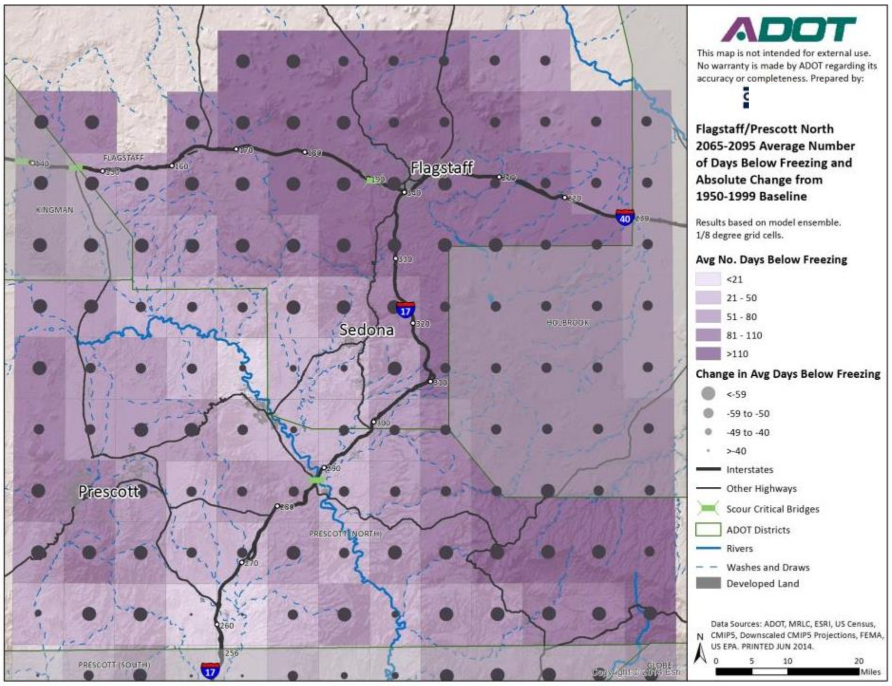
[7] The future analysis periods for extreme precipitation are 2000-2049 and 2050-2099.

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

[9] 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.

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

Exhibit 6: Sample Output - Projected Average Annual Days ≤ 32°F (2065 to 2095), Northern Segment



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. Exhibit 7 shows a projected reduction across all land cover types.

Exhibit 7: Sample Breakdown - Average Annual Days ≤ 32° F, Northern Segment

Average Annual Days ≤ 32° F	% Area	Climate Variables		
		Past*	**2040**	**2080**
		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.

More details about the climate data parameters and climate data fields summary can be found in Appendix A of the full report, which may be accessed at:
https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/index.cfm

2.10.2 Where is ADOT Now?

Transportation infrastructure is a complex system of assets required to deliver multiple services and functions. As fiscal constraints for the development and rehabilitation of roadways remain, and repeated retrofitting to address the impacts of extreme weather and climate risks continues to be cost prohibitive, new and novel approaches to long-term planning, asset management, project development, engineering design, and lifecycle assessment are paramount. ADOT has developed a programmatic approach to addressing all aspects of weather and natural hazards – including extreme weather and future measurable climate trends.

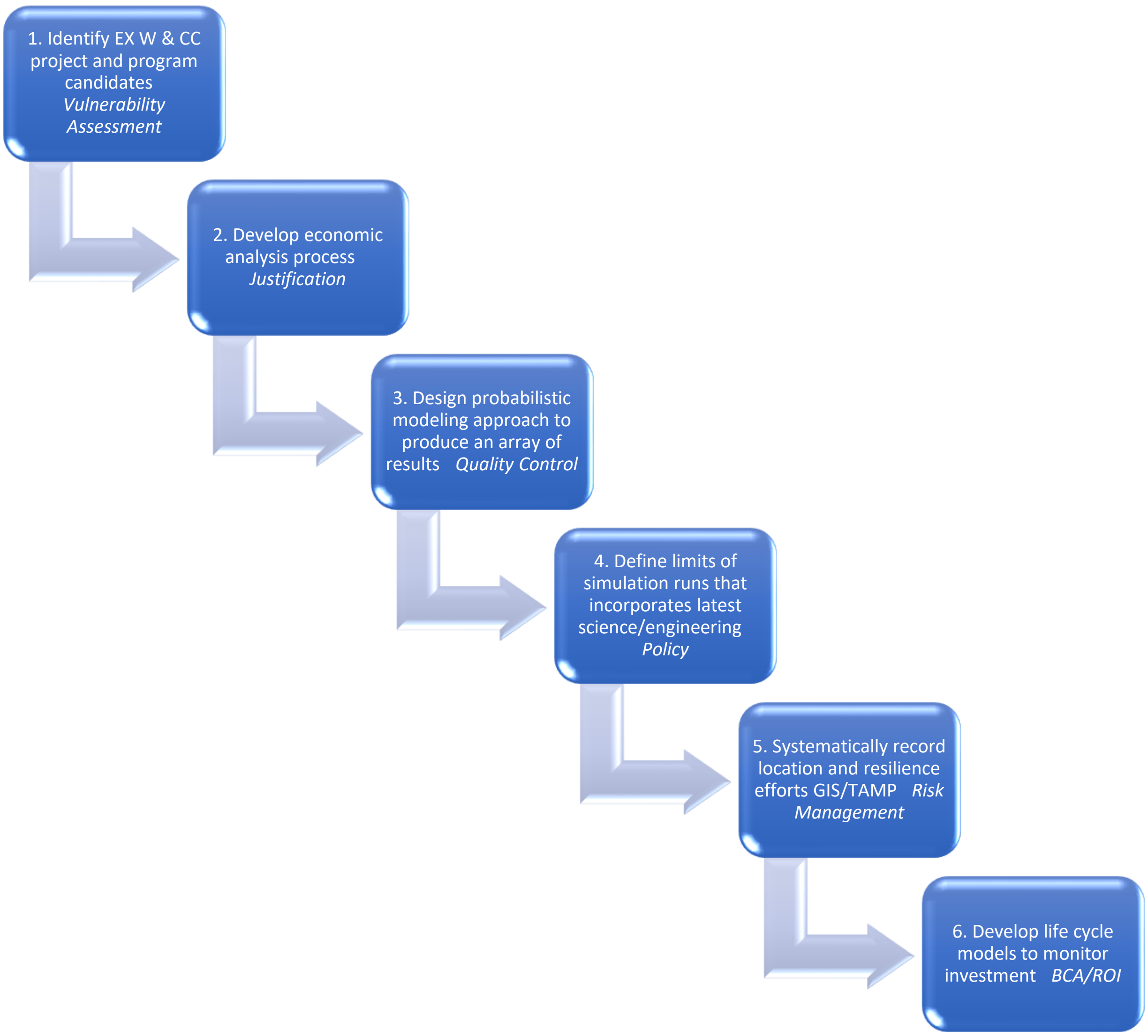
Through a formal Resilience Program and three Transportation Research Board (TRB) papers and presentations; 2015 TRB Annual Meeting, Session 197: *Mainstreaming Climate Change and Extreme Weather Resilience into Transportation*, ADOT introduced the challenge ahead for public entities to coordinate a host of known and unknown extreme weather and climate trends issues. That challenge is:
Continue considering the balance between predictable asset deterioration curves, the sudden and unpredictable nature of extreme weather events and long-term climate trends, new models for risk assessment and lifecycle cost analysis, and appropriate adaptation strategies.

This multiple part challenge requires a new end-to-end engineering approach to incorporate such current and future risks. At the 2016 Annual Meeting ADOT submitted a paper representing the core of that new approach – a Resilience Program and an ADOT/United States Geological Survey Partnership. That paper was graciously recognized as a best paper by the TRB Special Task Force on Climate Change and Energy. Continuing that forward progress – the 2017 TRB paper presented the remaining parts needed to develop a new end-to-end engineering-based asset adaption process – a structured sequence to incorporate extreme weather and climate adaptation into the design engineering process. The paper benefited from preeminent researchers in the two integral, and practice ready, remaining parts – probabilistic modeling for engineering design and infrastructure system design lifecycle outcomes for extreme weather and climate considerations in a transportation engineering setting.

2017 ADOT Climate Engineering Assessment for Transportation Assets (CEA-TA) – A Structured Sequence (*See Exhibit 8 and Appendix A for more details*)

This process was developed during 2017 to 2018; this pilot project is the continuation of this work as activities and projects to implement this sequence progress. The process now in use at ADOT allows engineering/technical capability to manage risk and long term asset management strategies; it also allows for the management of assets (bridges, culverts, pavement, and roadside vegetation/stabilization) in relation to the extreme weather-climate risk of intense precipitation, system flooding, wildfires, wildfire-induced floods, drought-related dust storms, rockfall incidents, slope failures, and measurable climate trends (especially as it relates to precipitation and direct effects of increased surface temperatures) by regions or specific segments emphasized as critical. The structured sequence is best used when proxy indicators and/or root cause analysis[11] are facilitated through Steps 1,2,5,6 have been executed and due to the asset class or single asset priority is in need of deeper engineering informed decision-making effort – therefore rendering a probabilistic modeling exercise (Steps 3 and 4) viable. (See Exhibit 8 below)

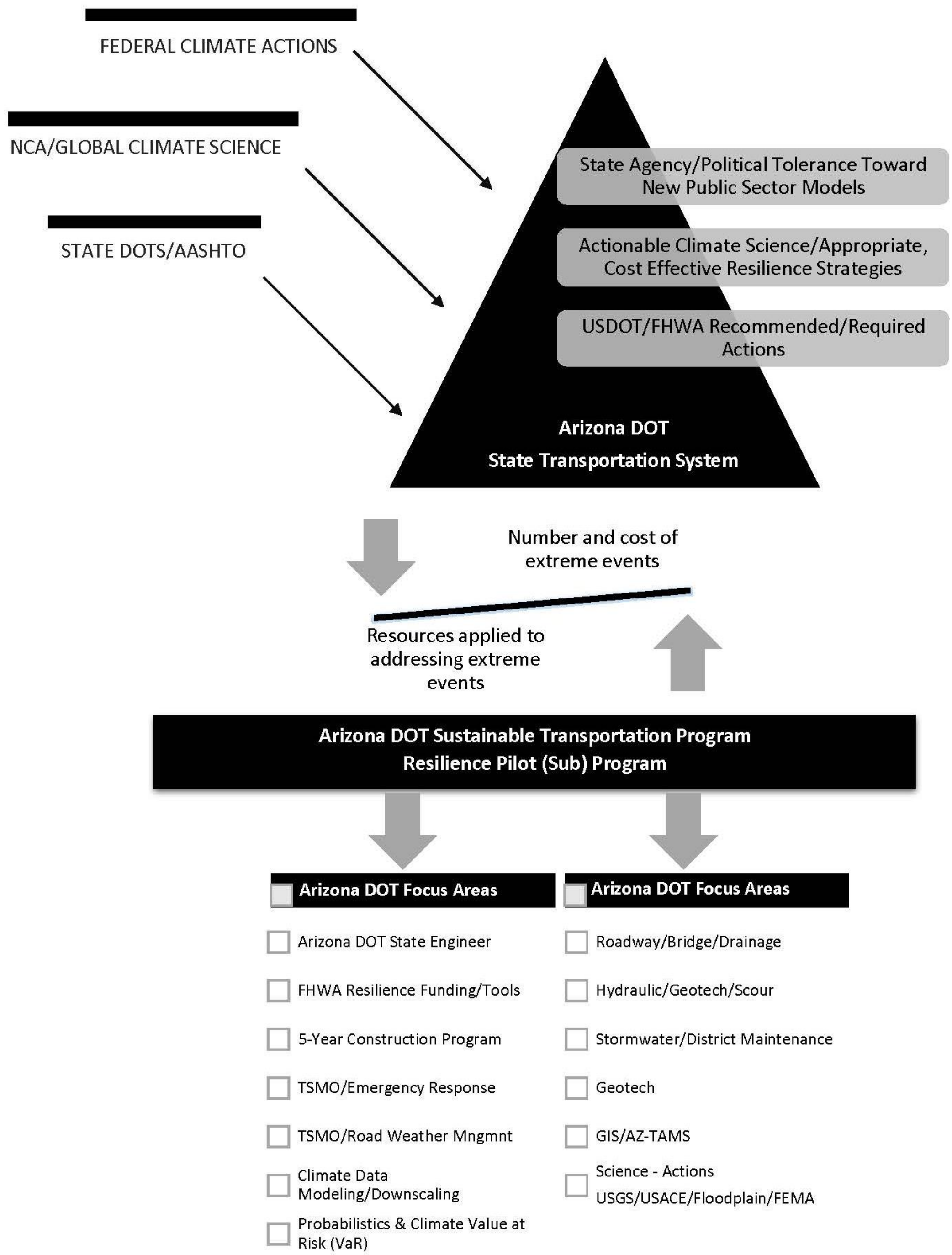
Exhibit 8: ADOT Climate Engineering Assessment for Transportation Assets (CEA-TA) – Incorporating Probabilistic Analysis into Extreme Weather and Climate Change Design Engineering



[11] Root cause analysis refers to the evaluation of a system or asset's lifecycle stages to determine the factors directly contributing to the problem/impact to the roadway. (Examples could include under-capacity drainage systems and/or need for increased maintenance – cleaning of drainage structures to address system flooding)

In addition, ADOT benefited from formalizing the impacts that can influence the Agency and developed a framework to integrate these into different into Agency functional areas. This is shown in Exhibit 9.

Exhibit 9: Surface Transportation System Resilience to Climate & Extreme Weather Events - Arizona DOT Influence Model



ADOT Model - Steven Olmsted solmsted@azdot.gov

2.10.3 Where is ADOT Headed?

Having in place (1) experience working with scientific climate data and downscaling processes, (2) a sequenced asset class-asset management design engineering process, (3) the development of a GIS-based Resilience Database as part of this current FHWA pilot project, and (4) revisiting climate modeling by acquiring data from nineteen (19) models, two time periods for heat. ADOT is ready to downscale the scientific climate data relevant to the remaining 30,000 maintenance lane miles across Arizona's 114,000 acres.

The 2020 effort, already underway and to be completed after the reporting period of this FHWA pilot project, will assess measurable climate trends against the impacts to ADOT's pavement asset class, surface treatments and materials, difficult to manage known freeze-thaw zones, and impacts to roadside vegetation/stabilization (biotic and seeding). All these have been framed to remain in the context of future asset management reporting for infrastructure health opportunities.

Already underway, in partnership with North Carolina State University, the project has run initial Downscaled General Circulation Models through two pathways, two-time periods, and processed all the data directly from the 12 km BCCA downscaled projections (2680 grid elements) using internal MATLAB and LabVIEW script. The project team realizes this was not the easiest way to do it, but it did provide quite a bit of flexibility. A grid layer containing quite a bit of climate information was developed. The variables include:

- Days over 100°F for all 38 models for and the average of RCP8.5 and RCP4.5 sets for 2095-2065 and 2025-2055
- Days over 110°F for all 19 models and the average of RCP8.5 and RCP4.5 sets for 2095 - 2065 and 2025-2055
- Changes in asphalt binder grade which is a bit more reflective of the impacts to pavements than just temperature, etc.), and
- Estimates of miles NHS and SHS routes, and traffic volumes.

For each grid the mileage of roadway by functional classification was extracted (Interstate, US route, and State route). This extraction was coordinated with ADOT's published AADT records. This data was integrated along with other variables to create the GIS Resilience Database built as a result of this pilot project, linking asset management, extreme weather and climate resiliency efforts.

Exhibit 10: Climate Models (19 Models x 2 RCP scenarios)

Modeling Center (or Group)	Institute ID	Model Name
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	ACCESS1.0
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1

Modeling Center (or Group)	Institute ID	Model Name
Canadian Centre for Climate Modeling and Analysis	CCCMA	CanESM2
National Center for Atmospheric Research	NCAR	CCSM4
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1(BGC)
Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancee en Calcul Scientifique	CNRM-CERFACS	CNRM-CMS
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-ESM2G GFDL-ESM2M
Institute for Numerical Mathematics	INM	INM-CM4
Institute Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR IPSL-CM5A-MR
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, and National Institute for Environmental Studies	MIROC	MIROC-ESM MIROC-ESM-CHEM MIROC5
Max Planck Institute for Meteorology	MPI-M	MPI-ESM-LR MPI-ESM-MR
Meteorological Research Institute	MRI	MRI-CGCM3
Norwegian Climate Centre	NCC	NORESM1-ME

2.11 Asset Management Connectivity

By quantifying, scrubbing, and testing the information, while at the same time accepting the infancy of this discipline and data quality, as it pertains to transportation infrastructure, the project team will begin to learn and be educated as to what these data present and how they could be incorporated at the asset class level; in this effort, as it pertains to pavement and heat initially. The effort also includes looking at the recently released FHWA report introducing the user guide portion of the Long-Term Pavement Performance (LTPP) Climate Tool and the LTPP Climate Tool that was developed to provide dissemination of climate data for infrastructure engineering applications.

2.12 Current Activities

Originally brought forward in an ADOT 2013 AASHTO Transportation and Environmental Research Ideas (TERI) database idea (#884) that became NCHRP Report 25-25, Task 94: *Integrating Climate Change and Extreme Weather into Transportation Asset Management Plans* in 2015; ADOT's 2015 Extreme Weather Vulnerability Assessment further recommended integration of extreme weather and climate risk into Transportation Asset Management Plans. ADOT's submitted TAMP included the development of a risk management process, which resulted in a Risk Register as the output; the risk register addresses extreme weather and climate risks. A total of twenty-five (25) risks were identified through this process, with six (6) of them being specific to weather/natural hazard risks. The next step is the implementation of a programmatic framework for integrating these extreme weather and climate risks into engineering design and asset management practices; that effort continues in this pilot project. Two specific asset classes and such risks are discussed below.

1. ADOT is implementing a process of probabilistic engineering with regards to bridges that considers future conditions accounting for natural hazard and weather impacts. Previously, ADOT was using a deterministic approach to measure natural hazard and extreme weather on infrastructure's lifespan. Beginning in 2017, ADOT began to develop a probabilistic model to measure the effects of natural hazard and extreme weather on lifecycle of bridges. The standard, extreme weather and climate loading probabilistic risk modeling pilot project is already underway and full adoption is expected in 2021. Please see further discussion on this in Section 5.1 Bridge Asset Class Probabilistic Methodology Development.

2. ADOT's engineering department has also been monitoring the impact extreme temperatures have had on pavement infrastructure. Not only does extreme heat lessen the lifespan of pavement, but extreme cold does too; as thawing and snow plowing both have negative impacts on the lifecycle of roads. Recent studies have found that heat-resistant pavement mixtures may need to have higher standards, as temperatures that exceed 110°F have become more commonplace. Also, extreme heat poses difficulties in constructing new roads, as construction time is decreased in hot weather for the safety of the workers and the integrity of the paving materials.

The following sub-sections detail ongoing research and development efforts into how best to manage the impacts of extreme weather and climate adaptation on ADOT's assets. These current ADOT practices developed prior to the beginning of this pilot project have been integrated as part of the GIS Resilience Database layers when appropriate, as data to build this tool, and the implementation practices are to be integrated in the further development of the future lifecycle planning standard work.

2.12.1 Statewide Flooding – 5-Year ADOT/USGS Partnership

Infrastructure in or near dryland river channels are susceptible to a variety of geomorphologic and hydrologic hazards caused by floodwaters. Historically, many dryland channels were broad, shallow, and mainly un-vegetated. As a result, floodwaters in the past were conveyed slowly and gently through stream channels and surrounding floodplains at relatively low velocities and shallow flood depth. Today, many dryland channels have changed dramatically and have become largely incised into the floodplain, while the carved banks are being stabilized by vegetation, in many cases by nonnative vegetation. The increase in bank stability may cause channels to incise deeper into floodplains, leading to narrower, less sinuous stream beds that can potentially convey floods at higher velocities. Additionally, channels in this region have the ability to convey and deposit large amounts of sediment, and sediment volumes may become larger as flood velocities increase. Ultimately, larger floods at higher velocities can erode the outside of channel bends where velocities are typically high, and deposit sediment on the inside of bends where velocities are naturally lower. This commonly causes channel migration, meander cutoff, and avulsion. This reality caused the ADOT and the U.S. Geological Survey (USGS) Arizona Water Science Center to develop a partnership to improve water data collection and new technology adoption to help better understand the dynamic hydrologic conditions at bridge sites prior to construction efforts. This partnership is now a national USGS leadership recognized data collection and modeling process that will now be tested and rolled out to all USGS offices across the country over the next five years. This partnership has also started the process of working with the Alaska USGS and State DOT to educate them on this process.

The Laguna Creek Bridge Scour Remediation was a scour remediation project on the existing Laguna Creek bridge located in ADOT's Northeast District. This project served as the first of six pilot efforts to address different types of water exposure on ADOT's highway system. The project tested a suite of USGS next generation technologies as they relate to transportation infrastructure – LiDAR, UAS (drone), Rapid Deployment Streamgage, Non-Contact Velocity Sensors, Video Camera and Particle Tracking Data Collection, 3-D Land Surface Models, Scour Chains, Direct/Indirect Measurement of Discharge, Velocity Vector Analysis, Erosion Change Mapping, Flow Sensors, UAS/UAV Surveying, Terrestrial LiDAR, 2-D/3-D Visualization Tools. The partnership culminated in a December 2019 USGS national best practice publication. ADOT USGS Partnership https://azdot.gov/business/environmental-planning/programs/sustainable-transportation/adotusgs-partnership

Connection to this pilot project: The GIS Resilience Database will serve to aid this partnership, by allowing the integration of data and enhanced data collection efforts to visualize/identify areas at risk, where improved water data collection and new technology is needed to address problems at the planning and design/engineering stages of roadways, drainage, and bridge assets.

2.12.2 Preventing Urban Flooding

As a response to intense precipitation events, ADOT manages storm water pumps to manage the risk of flooding. ADOT operates 72 storm water pump stations on 275 miles of urban freeway in the Phoenix Metropolitan Area. The ability of these facilities to adequately remove storm water from the freeways is critical to prevent flooding. Construction of the pump station system began in 1964 and pump stations have been incrementally added over time. According to a 2016 Phoenix District Pump Station Evaluation, "The incremental construction of the system, over the long-time period, has resulted in a system that lacks uniformity, standardization, and a long-term maintenance and/or replacement plan. This has led to maintenance concerns and issues that have compounded over time and now challenge the System Maintenance Section's maintenance staff resources to adequately maintain and repair the facilities." Furthermore, many of the older pump stations were not designed to handle the additional storm water generated by the widespread freeway expansion that has occurred in the Phoenix area. In 2019, ADOT and Arizona State University began developing a dynamic pump reliability analysis decision-support tool to provide real-time information to operators considering hardware and environmental conditions to prioritize maintenance and rehabilitation. This tool will be positioned to reduce costs associated with maintenance and rehabilitation of pumps while increasing reliability by identifying which hardware should be serviced *ahead* of failure. Since pumping stations are vulnerable to failure under heavy storm events, the tool will evaluate outcomes under different precipitation magnitude scenarios. A predictive model of pumping station failure will first be developed using statistical data analysis (Phase I). The output models relating the factors of failure to the probability of failure will then be coded so that operators and planners can input scenarios of rehabilitation investment decisions for each pumping station regarding manufacturer type, frequency of replacement, and frequency of repair, and scenarios of precipitation magnitudes as input variables (Phase II). See also – Framing the Challenge of Urban Flooding in the United States http://www.trb.org/Main/Blurbs/178978.aspx

Connection to this pilot project: The mapping of these pump stations was incorporated in the GIS Resilience Database as part of this pilot project. As this effort matures, the pump system inventory will be packaged as an asset class and lifecycle planning strategies identified are to be included in future TAMP submittals.

2.12.3 Scour Counter Measures

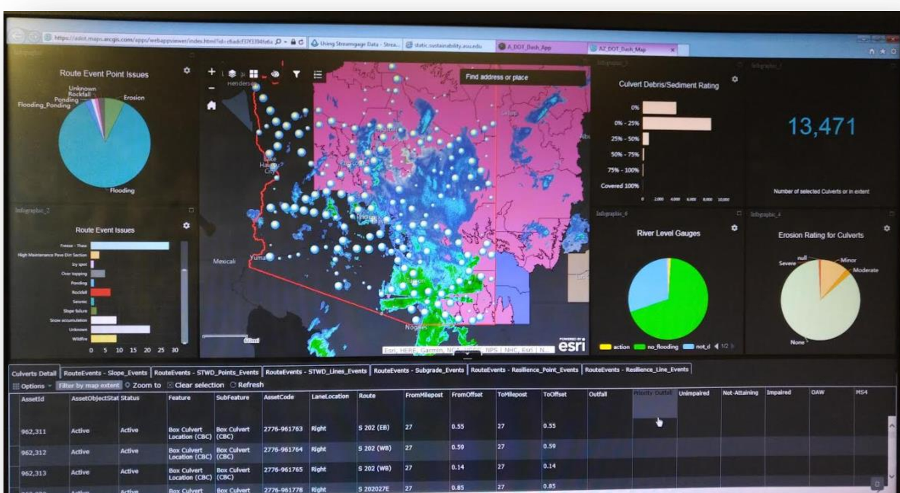
Intense precipitation is one of the main stressors that result in the risk of bridge scour. Scour around bridge piers can lead to bridge failure if not addressed. In 1992, as a result of bridges lost due to scour during the 1970s and 80s, a statewide scour evaluation work plan was developed for all bridges located over water ways. Inspections during the 1990s identified several hundred bridges as being at high risk for scour. Many of these bridges were constructed before 1980 when the adoption of more stringent design criteria improved scour resistance. In the mid-1990s a fund was set up to implement scour counter measures for high risk bridges. Ongoing inspections since then have identified additional bridges at high risk for scour. Currently, there are about 100 bridges that fit in this category. The scour counter measures fund is still in place and new improvement projects are developed yearly.

Connection to this pilot project: This pilot project integrated data regarding scour critical locations as part of the GIS Resilience Database.

2.12.4 Repairing Culverts

Intense precipitation that results in flash floods, and increased temperatures that result in erosion, drought, vegetation loss have risks to the performance of culverts. Culverts are subject to blockage which can lead to flooding of the roadway. Steel pipe culverts can corrode affecting the structural integrity of the pipe. A significant number of culverts in the state are affected by these conditions. The FY 2016 Level of Service evaluation rated drainage structure conditions at a C+[12]. To address this issue the System Management Section of Transportation Systems Management and Operations (TSMO) requested and received $4.3 million in FY 2018 to begin repairing these culverts. The program will begin by repairing the most severely affected culverts starting with 75% blockage and/or 50% rusting. The intention is to continue the program in future years to repair the remaining drainage structures.

Connection to this pilot project: This pilot project integrated data regarding culverts as part of the GIS Resilience Database. In addition, over 14,000 key drainage assets have been mapped into a decision support tool recently completed.



[12] Level of Service – a systematic evaluation process on targeted segments of the highway system that provides an annual condition assessment of various transportation assets.

2.12.5 Geohazard Management Plan (GMP)

After experiencing significant impacts to mobility of the system due to geohazards in the analysis period of 2010 to 2015, ADOT has proactively managed many geohazards through preventative projects thought the Slope Management Subprogram. Geohazards such as landslides, rockfall, debris flow, sink holes, and heaving roadway subgrade have impacts to the maintenance, mobility and risk allocation in an asset management model. Geotechnical assets such as embankments, slopes, walls, foundations, and other earthwork features in the highway have likelihood of failure or can deteriorate over time and cause damage to other transportation assets and corridor performance. The main objective of the GMP is to reduce the risks to ADOT from the various geotechnical features that impact the ability to perform effectively. The methods and process included in ADOT's GMP is also a key component in the development of lifecycle planning mitigation strategies.

Connection to this pilot project: The pilot project team looked to integrate ongoing asset management efforts into the development and enhancement of the strategies currently in place. Historical data regarding geotechnical failures have been integrated into the GIS Resilience Database.

2.12.6 Roadside Vegetation Management Guidelines

ADOT published its Roadside Vegetation Management Guideline in March 2018 to provide an overview of best practices for roadside vegetation management activities for staff in the state. ADOT currently manages vegetation along 1,390 miles of highways across the state. The main goals of roadside vegetation management are maintaining traffic safety, preserving highway infrastructure, and maintaining a resilient native roadside plant community.[13] The Integrated Roadside Vegetation Management (IRVM) provides the necessary soil stabilization and erosion control, which address some of the impacts of extreme weather events. The guidelines also include a section for revegetation. A healthy cover of native vegetation helps to stabilize soil and prevent erosion from wind and water, fills in areas after weed removal or repair of erosion damage, and provides many other benefits stated in the guidelines.

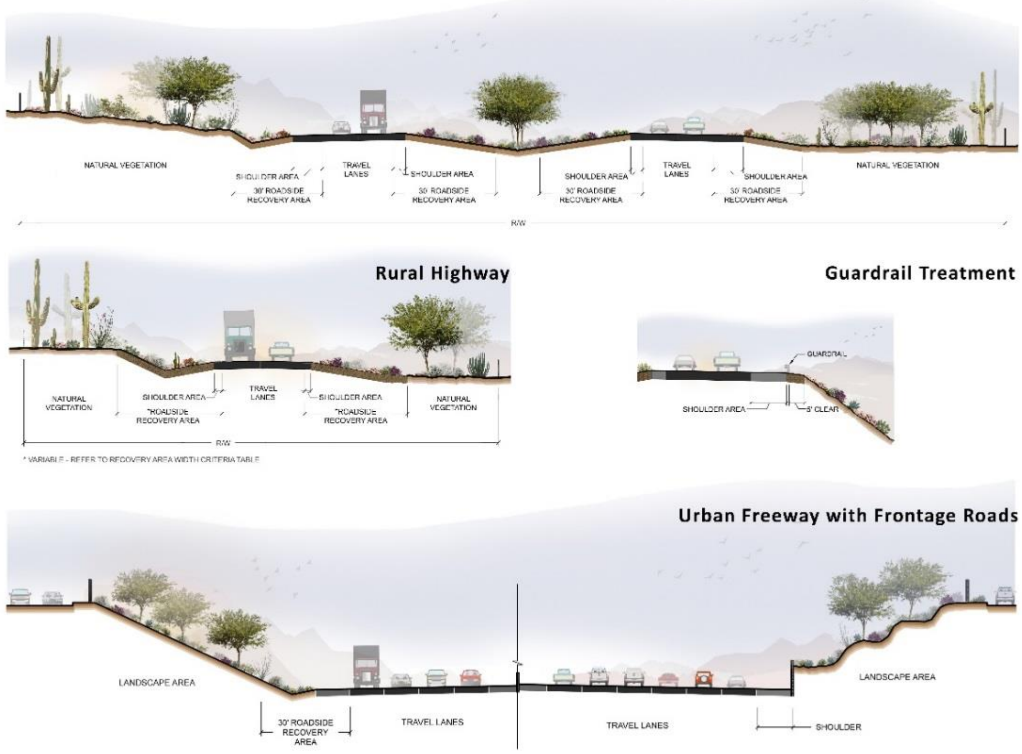
Connection to this pilot project: The ADOT 2015 vulnerability assessment assessed land cover and dominant vegetation type (e.g., Forest, Grassland). These data can significantly influence the impact of weather-related hazards on transportation infrastructure, and therefore land cover is an important for ADOT. The following exhibit provides a graphical representation of the recovery area diagrams and the proposed roadside vegetation management within these.

[13] ADOT Vegetation Management Guidelines https://apps.azdot.gov/files/Sitefinity-Files/Vegetation-Management-Guidelines.pdf

Exhibit 11: ADOT Roadside Vegetation Management – Recovery Area Diagrams

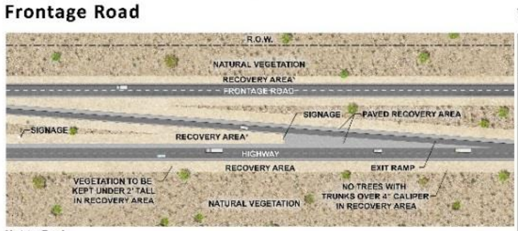
ADOT ROADSIDE VEGETATION MANAGEMENT

Recovery Area Diagrams



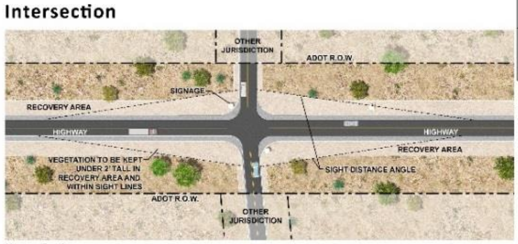
Sight Line Diagrams

Frontage Road



Not to Scale

Intersection



Not to Scale

Recovery Area Information

Width Criteria

DESIGN SPEED	DESIGN ADT*	FILL SLOPES	
		6:1 OR FLATTER	5:1 TO 4:1 INCL
40 MPH OR LESS	Under 750	10	10
	750-1500	12	14
	1500-6000	14	16
	Over 6000	16	18
45-50 MPH	Under 750	12	14
	750-1500	14	20
	1500-6000	18	26
	Over 6000	20	28
55 MPH	Under 750	14	18
	750-1500	18	24
	1500-6000	22	30
	Over 6000	24	30
60 MPH	Under 750	18	24
	750-1500	24	30
	1500-6000	30	30
	Over 6000	30	30
≥65 MPH	Under 750	20	26
	750-1500	28	30
	1500-6000	30	30
	Over 6000	30	30

CUT SLOPES: Where fixed object obstructions are placed on cut backslopes, the recovery area width requirement should meet the recovery area width indicated by the fill slope table shown utilizing the foreslope of the cut as the appropriate fill slope rate.

***ADT:** Average Daily Traffic

NOTE: For additional information see the ADOT Roadway Design Guidelines

Notes

- Maintain Roadside Recovery Area (RRA) using Integrated Vegetation Management (IVM) techniques for errant vehicle recovery and weed control.
- Keep RRA free of all vegetation that will reach a cumulative trunk diameter of 4" before the next scheduled maintenance.
- Prune or remove vegetation as needed to provide visibility of signs and guardrail and maintain ample sight distance on curves and at intersections.
  - Includes brush, tree and tree seedling removal with the potential to impair visibility.
- Vegetation maintenance activities should reinforce the existing/designed topography and should not impact erosion control features.
- Where noxious weeds or oversize vegetation is removed, encourage growth of native or well-adapted perennial grasses, forbs, succulents, cacti and shrubs to promote a healthy ecosystem, suppress unwanted vegetation and provide a fireguard.
- Where mowing is necessary, restrict to one mower-width along shoulders with a minimum mowing height of 4 to 6 inches except as needed to maintain visibility or sight distances.
- Please Refer to ADOT Roadway Design Guidelines figure 306.2 for more information about recovery areas and roadway design.

Recovery Area Diagrams.pdf / June 2017 / Kris Gade

2.12.7 Resilience Investment Economic Analysis (RinVEA) (CEA-TA – Step 2)

During the development of the CEA-TA, a need for a process to assess cost viability and develop a tool to integrate extreme weather and climate justification into asset management and financial decision making was identified. The opportunity presented itself to develop a RinVEA pilot process in connection with the 191 AP 436 H867601C, milepost 436 to Chinle project. This project was a pavement preservation project, with the main purpose to rehabilitate the existing pavement to extend its life and to improve the ride and safety of the roadway. At issue was the presence of 50-year old culverts that had reached end of life. The main objectives of the RinVEA pilot was to conduct basic economic analysis that included the following basic parameters:

- Protect the new $5.2M roadway investment
- Address severe erosional and drainage issues that has led to a 25%-100% degradation at sixty-one (61) of the eighty-six (86) corrugated metal pipe (CMP) drainage structures
- Address drainage excavation, barrow and slope stabilization issues at those structures
- Address severely compromised stormwater management capabilities along this segment of SR 191
- Comply with and proactively address expected regulatory actions on stormwater management, FHWA Order 5520, Presidential Executive Order on Federal Flood Risk Management, and MAP-21 asset preservation performance requirements
- Upgrade ADOT's application of risk-based assessment modeling at the asset class, project development, and localized hydrological event level
- Further ensure use of SR 191 in the remote far northwest of Arizona and a main Apache County connector between SR 264 and US 160 in the advent of an extreme weather event

After ADOT's assessment of the structures, it was determined that extensive stormwater management benefits could be developed to further protect the investment of the project and comply with Environmental Protection Agency and Arizona Department of Environmental Quality stormwater management needs. The subsequent District assessment allowed for an engineering design plan station by station scope of work approach, which was submitted to Statewide Project Management and Roadway for implementation into the project limits plan set. The Environmental Planning area conducted an ADOT Future Inventory System cross check of each of the eighty-six (86) structures to ensure the quality of the asset information and to ascertain the appropriate approach for waters of the U.S. permitting requirements.

This assessment led to additional scope of work, extended the roadway's lifecycle, addressed regulatory requirements, lowered the probability of water getting under the embankment, pipe washout, and overtopping of the road due to buried or lower capacity, end of life drainage structure capabilities.

The following exhibits (12a and 12b) show the pre-and post-construction conditions of this project. This is an example of a $275,000 resilience building outlay that improved asset management, the roadway asset lifecycle, and created a more resilient road segment by measurably improving the ability for the drainage facilities to convey up to the 50-year event. A full discussion of how the RinVEA is now one major component of financial decision making as it relates to asset management – infrastructure resilience can be found in Appendix C.

Exhibit 12a: Images of Chinle Drainage Project Assessment (2015)

Exhibit 12b: Images of Chinle Drainage Project Improvements

2.12.8 Transportation Systems Management and Operations (TSMO) Resilience Program Development – Weather Responsive Management Systems Strategies

Weather-responsive traffic management (WRTM) strategies increase the effectiveness of traffic operations during adverse road weather conditions, and weather-responsive maintenance management (WRMM) strategies help reduce costs associated with winter maintenance. ADOT has decided to adopt weather-responsive traffic and maintenance management strategies, following guidance from FHWA "Guidelines for Deploying Connected Vehicle-Enabled Weather Responsive Traffic Management Strategies". These systems use road weather data from Integrating Mobile Observations (IMO) and connected vehicle technologies, combined with informed decisions stemming from Pathfinder. The adoption of these strategies will enable ADOT and its local partners to be proactive and manage the system before any negative impacts occur, addressing the response and adaptation aspect of resiliency. The results will be having safer roads, informed travelers, and improved environmental sustainability. (FHWA Weather Responsive Strategies). In addition, ADOT was a contributor to the 2015 FHWA TSMO Climate Guidebook. See – https://ops.fhwa.dot.gov/publications/fhwahop15026/fhwahop15026.pdf. These measures are to be integrated in the completion of the lifecycle planning methods and specified as specific adaptation strategies.

2.12.9 Every Day Counts (EDC) Initiatives

ADOT participated in the first institutionalization group to deploy proven innovations and ramped up nine consulting firms to provide 2D hydraulic modeling services. ADOT has institutionalized Collaborative Hydraulics: Advancing to the Next Generation of Engineering (CHANGE) and conducted comparisons of 2D and one-dimensional (1D) modeling tools. Using 2D modeling allowed for more accurate representations of water surface elevations, velocities, and flooding extents; superior visualization of modeling results; better linkage of 2D modeling tools with advanced surveying methods; and is in the Resilience Program toolbox.

WEATHER-RESPONSIVE MANAGEMENT STRATEGIES

Pathfinder is a collaborative strategy for proactive transportation system management ahead of and during adverse weather events. It is part of FHWA's Every Day Counts efforts, and it encourages State DOTs, NWS, and weather service contractors to share and translate weather forecasts and road conditions into clear, consistent, and impact based messages to the public.

Integrating Mobile Observations includes instrumenting transportation agency vehicles with road weather sensors and other automated data collection technologies to acquire location specific data to support decision making.

2.12.10 Addressing Impacts from Freeze-Thaw Cycles: I-40 Project

An I-40 Project has rebuilt five (5) miles of Interstate 40 near Williams and earned a top 10 ranking by *Roads & Bridges*, a construction industry publication for innovation.

The many freeze-thaw cycles seen annually in this area, combined with heavy snow, snowplowing, precipitation, and use by a large number of commercial vehicles, had stressed pavement considerably between Williams and Devil Dog Road. A $34 million project completely removed the existing roadway and replaced the surface with new concrete pavement.

To accelerate improvements, design work was completed in less than three months and construction moved rapidly in part because crews are incorporating Portland Cement Concrete Pavement recycled from this stretch. Using Portland Cement Concrete Pavement as the road surface increases pavement life by up to 60 percent and outlasts asphalt overlays by at least 10 years.[14]

The different efforts mentioned above serve as examples of current practices considered in the development of the GIS Resilience Database and future completion of the lifecycle planning methods, directly linking extreme weather, asset management, and infrastructure resilience.

Exhibit 13: Images of I-40 Project

The $34 million project completely removed the existing roadway and replaced the surface with new concrete pavement. Project won a national *Roads & Bridges* magazine award.

[14] ADOT Project Rebuilding Stretch of I-40 Wins National Award
https://content.govdelivery.com/accounts/AZDOT/bulletins/2139ef5?reqfrom=share

3. Context of Pilot

This section describes:

- The purpose of the pilot and how this work will add value to transportation efforts in reducing asset risk to extreme weather and climate vulnerabilities
- How this work will contribute to managing assets more efficiently over their whole life while minimizing the cost to the extent practical

Lifecycle planning means a process to estimate cost of managing an asset class, or asset sub-group over its whole life with consideration for minimizing cost while preserving or improving the condition.

The Asset Management Rule emphasizes the relevance of lifecycle planning in its definition for asset management, as a "a strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based on quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the lifecycle for the assets at a minimum practical cost" – 23 CFR 515.5."

The effects of extreme weather and natural hazard pose an increasingly apparent risk to the safe, cost-effective operation of a DOT's assets. Such events have become increasingly damaging and problematic to transportation systems in Arizona. These events have and are expected to increasingly impact the operational performance of the transportation network and impact state budgets for repair and lifecycle planning of transportation assets. In short, extreme weather and natural hazard is increasing the cost of providing safe reliable roadway infrastructure. ADOT has long incorporated the management of extreme weather, natural hazard, and climate risks into the lifecycle planning and asset management. This has enabled ADOT to consider the risks to assets, the targeted level of service or performance of these assets, and the costs of managing or reducing the risks to providing these services. Through these efforts ADOT has been able to identify extreme weather, natural hazard, and climate adaptation strategies, and integrate them into agency wide practices.

Taking all this into consideration, the purpose of this project is to further advance a lifecycle planning approach that address the effects of extreme weather, natural hazard, and measurable long term climate conditions on ADOT's transportation assets. The pilot is to advance an approach that builds resilience, reduces risk, across all elements of the asset lifecycle; from advance planning, through design and construction, and into operations and maintenance.

The pilot project was divided into two main efforts:

1. Further explore long established stressors and evaluate their impacts on asset classes. This allows for a clear understanding of the stressor, weather-related risk, and impact to the

roadway through a lifecycle planning approach; to then determine thresholds for proxy indicators, root cause, or probabilistic engineering and cost-benefit analysis is warranted.

2. Develop an integrated GIS database that will enable ADOT to identify location and sections that are at highest risk from the impacts of the stressors described in 1 above.

Further work will address all the stressors and arrive at a risk-based methodology to identify locations at which planning, design, O&M and other activities will be performed as a matter of course to reduce risk.

3.1 Partners and Stakeholders Involved

ADOT benefited from the collaboration and involvement of internal and external stakeholders throughout the project. The main pilot project team consisted of the members shown in Exhibit 14 (See next page).

Exhibit 14: ADOT Project Team – Internal Stakeholders

(See next page)

ADOT Pilot Project Team

Air Quality and Future Greenhouse Gas Emission (GHGe) Risk	Beverly Chenausky, Air Quality Program Manager
TSMO System Risk	Brent Cain, Transportation Systems Management and Operations Division, Director
Geotechnical Design	Brent Connor, Geotechnical Design Section Leader and Planning Engineer
Bridge Asset Class Risk	David Benton, Bridge Group Manager
Traffic Management	Derek Arnson, ADOT Traffic Management Group Manager
Emergency Management	Don Angell, ADOT Emergency Manager
Statewide Operations - District Risk	Jesse Gutierrez, Deputy State Engineer for Statewide Operations
Geotechnical/Geomorphology Risk	J.J. Liu, Geotechnical Group Manager
Materials and Pavement Risk	Kevin Robertson, Surface Treatment Engineer & Pavement Condition & Evaluation Manager
Materials and Pavement Risk	Nye McCarty, Flagstaff Regional Materials Engineer
Roadside Vegetation Risk	Kristin Gade, Roadside Resources Specialist – 2015 EW & Climate Vulnerability Co-Team Lead
Bridge Hydraulics	Nicholas Fiala, Transportation Engineering Specialist
Architecture/Landscaping	LeRoy Brady, Chief Landscape Architect
Materials	Paul Burch, Assistant State Materials Engineer
Construction Program Delivery Risk	Steve Boschen, Infrastructure Delivery and Operations, Director
Environmental Planning	Steve Olmsted, Program Manager
Asset Management	Thor Anderson, Senior Program Manager - TAMP Development
FHWA Division Office	Ed Stillings, FHWA Senior Planner

The consultant team was tasked with the integration of data in GIS and conducting technical analysis. Gannett Fleming Inc. served as ADOT's consultant on the project, with the following members:

- David Rose, Project Director
- Hany Hassaballa, GIS Specialist
- Ister Morales, Project Manager

One of the main external stakeholders that contributed greatly to the development of this pilot project was USGS. The prior established partnership between ADOT and USGS has allowed continuous collaboration between the two agencies. *(See Section 4.2 for more details)*

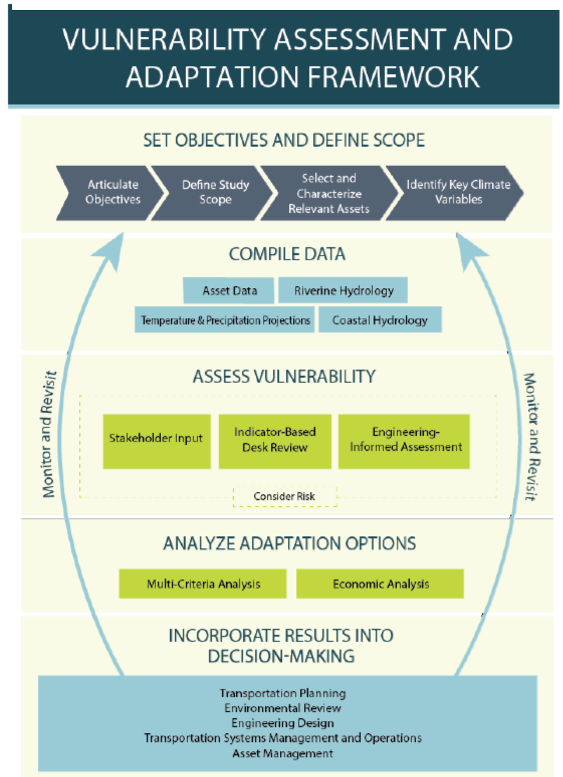
4. Methods/Technical Approach

4.1 Framework

The ADOT pilot approach is based on FHWA's Vulnerability Assessment and Adaptation Framework, 3rd Edition published on December 2017.

One of the key goals to the project is to continue to research and integrate previous and ongoing efforts that show the impacts of extreme weather on ADOT's system. One of the key tasks in understanding the relationship of risks to performance, and the costs of meeting the desired level of performance is analyzing historical data related to weather-hazards, revisiting current practices, and identifying opportunities for enhancements. To address this, the project team examined how stressors are impacting roadway assets and affecting roadway system performance by collecting weather-related incidents from the different districts in Arizona and bringing together previous and ongoing efforts through the Resilience GIS Database and lifecycle planning methods.

Exhibit 15: FHWA's Vulnerability Assessment and Adaptation Framework



The approach is to address how to avoid, reduce, and manage risks by addressing the different lifecycle stages of assets. This allows for specific measures currently being taken, and innovative ideas during the planning, engineering, construction, and maintenance of assets of the transportation system. The project team also recognized that some level of risk has to be accepted and that resilience planning would consider how to minimize the impact of road closures and be ready to reopen as soon as possible.

The project team aimed to examine the different stages of the asset lifecycle and identify strategies to be implemented at each phase to minimize cost while maintaining or improving current conditions.

4.1.1 Stressors Addressed by ADOT

ADOT has made progress towards addressing specific stressors as part of its Resilience Program. The stressors and risks identified in ADOT's Initial TAMP include flooding and flood damage, extreme heat, landslides/slope failures, and rock fall. There were different risk mitigation/treatment strategies for each of these risks identified; these are shown in Exhibit 16 below.

Exhibit 16: Risks and Mitigation Strategies for Stressors Identified (ADOT's Initial TAMP)

Risk Category	Risk Event	Risk Mitigation/Treatment
Agency	Extreme Weather Trends (Environmental Planning, Districts, Transportation System Management & Operations (TSMO), Resilience Program)	Develop an adaptation plan. Build partnerships
Asset	Flood damage including scour (Bridge Group, TSMO, Environmental Planning Group), Resilience Program	Statewide scour evaluation; scour-counter measures program. Pump station improvements. Extreme weather adaptation plan.
Asset	Extreme heat/shortened lifecycle for pavement surface treatments	Improved lifecycle planning / increase surface treatment tool box
Asset	Landslides and/or slope failures (Geotechnical Section)	Identify unstable areas, remediate storm water infiltration, re-contour or stabilize slopes, install monitoring devices.
Asset	Rock Fall (Geotechnical Section, District Maintenance, Resilience Program)	Identify unstable areas, monitoring, rock fall prevention projects. Consider creating a fund for this ongoing challenge. Rockfall change mapping – mobile LiDAR
Asset	Failure of small ($\leq$ 20 feet in length) culverts (TSMO)	Statewide small culvert evaluation, consider culvert upgrades when developing pavement projects.

This project further expands on the identified stressors to develop a lifecycle planning approach for each of the stressors and their respective impacts on transportation assets.

To accomplish this, the project team established through a methodology and analytical procedure that provides a risk-based approach for identifying assets and locations with a high likelihood of being impacted by the results of stressors. The approach was to develop flexible, transferable, and risk-based tools that will provide ADOT with the capacity to link asset management, extreme weather, and climate resilience efforts into the lifecycle planning of different assets. The intent is to be able to apply this risk-based approach to identify specific lifecycle planning actions that ADOT can integrate across the asset lifecycle from the planning, to engineering/construction, through operations and maintenance activities. The bulk of the work extended the ADOT Resilience Program framework developed under the Climate Engineering Assessment for Transportation Assets (CEA-TA).

The pilot approach identified targeted stressors and asset classes. The use of GIS allowed for the integration of multiple sources of data to identify risks and hazards on the ADOT system that are then addressed through lifecycle planning. The intent is to demonstrate through the pilot how the lifecycle planning method can be a key part of improving resilience to extreme weather events and reducing risk to ADOT's ability to provide safe, reliable, cost-effective roadways. These lifecycle planning methods are to be continually improved and enhanced for the efficient management of the assets identified.

4.2 Tasks

The following lists the tasks performed to prepare the pilot project.

The project will continue after the initial submission of this report to complete Task 3 as described below:

Task 1: Developing the Work Plan

The pilot approach was established during this task, to describe the information and work activities that are required to complete the project. The main purpose was to establish and gain consensus from the pilot project team on the execution approach. This consisted of meetings with the project manager to confirm objectives and areas of coordination, collect and review materials from previous and ongoing studies, collect and review data needed in GIS format for subsequent tasks and identify initial project risks.

Task 2: Complete Integration of Extreme Weather, Natural Hazard, and Climate Risks into Asset Management Practices

This task was separated into the three (3) main sub-tasks described below. This task also served as the "compile data" phase in FHWA's Vulnerability Assessment and Adaptation Framework.

Task 2.1: Plan and Conduct Workshop to Refine Methodology and Define the Risks, Proxy Indicator, and Asset Classes and/or Study Areas to be the Focus for the Tool Development

The pilot project team participated in a workshop to determine the risks, climate stressors, asset classes and/or roadways to be the focus for the development of the methodology.

Exhibit 17: ADOT's Pilot Project Approach

- Identify key stressors and their associated weather-related risk(s)
    - Identify vulnerable assets
- Identify impact(s) to ADOT's system
- Identify possible case study area(s) for developing and testing the procedure
- Compile, integrate and analyze data
    - Identify proxy indicators
    - Identify root cause up to and including probabilistic modeling
        - Consider different stages of asset lifecycle (creation, maintenance, preservation, rehabilitation/reconstruction)
- Identify mitigation strategies, including adaptation options and selection criteria
- Incorporate assessment results in decision making

This methodology example included the GIS tasks by using the GIS database as a repository of known natural hazard and weather-related incidents. The root cause(s) were to serve as linkages between the stressor and the impact(s). During the data collection effort, the different districts included preliminary comments regarding proxy indicators and possible root causes of problems, such as:

- For flooding: Possible local low points creating conditions for roadway flooding, low water crossings, other drainage issues
- Temperature changes: more frequent freeze-thaw cycles due to temperature variation resulting in potholes and pavement deterioration

However, for most locations, further studies are needed to determine the appropriate recommended solution.

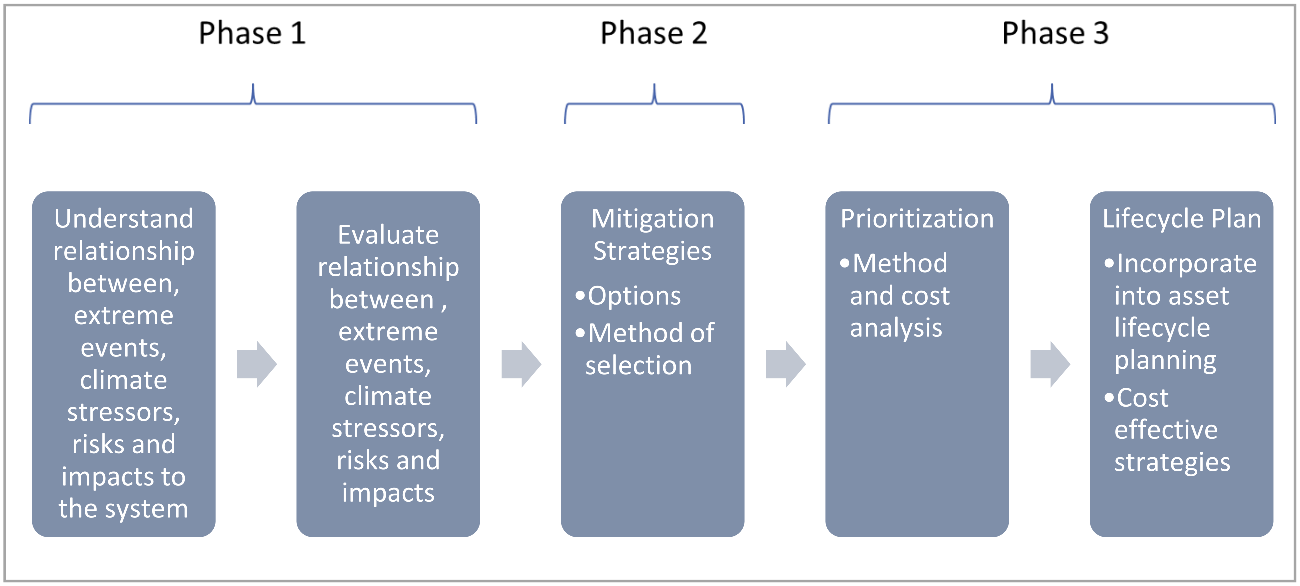
The use of the GIS tool served to identify areas with greater risks of these causes being present and analyze the surrounding area including FEMA's Flood Hazard Zone, USGS soil groups present in that area and any other proxy indicators showing areas at risk. Root causes are to be determined by further research, feedback from ADOT's engineers and maintenance personnel, and ADOT's previous experiences from events and stressors.

This project lifecycle planning method was developed by using the GIS Resilience database, and by identifying possible mitigation strategies for the different stages of the asset lifecycle (planning, engineering/construction, maintenance and operations) for Phases 2 and 3 in Exhibit 18). The templates consist of a listing by stressor, type of impact and corresponding relationships; the mitigation of these is the lifecycle planning approach. The pilot project focused on developing the system flooding template for this report, given the high number of incidents reported by the districts statewide. This lifecycle planning method approach could be extended for other stressors mentioned throughout this document, as well as separating them by asset type or asset classes.

The completion of phases 2 and 3 equate to completing lifecycle planning integration with asset management. The pilot project team plans to tie this methodology to further enhance each step of ADOT's CEA-TEA. This includes the advanced probabilistic engineering analysis option not previously developed. This helps, on ADOT's highest cost – highest priority assets, the option to specify the cost-effective solutions actions in combination with the results of the root cause analysis for a full engineering risk-informed assessment.

The methodology summary is shown in Exhibit 18 (See next page).

Exhibit 18: ADOT Asset Management, Extreme Weather, and Proxy Indicators Pilot Methodology – Extension of CEA-TA (P.12)



Task 2.2: Document Workshop Results and Finalize Methodology

The pilot project team completed this task by developing a document summarizing the approach and agreeing on a sample method for flooding (highlighted) that could be extended for others below:

- Drought-Related Dust Storms
- Increased Surface Temperatures
- Intense Precipitation
- Rockfall incidents
- Slope Failures
- **System Flooding**
- Wildfire
- Wildfire-Induced Floods

Task 2.3: Develop Maps to Support Method

The first step of this sub-task involved the collection of data from different sources for the various stressors. The majority of the data was received in a Geodatabase format, and shape files. This was all initially combined into a single Geodatabase ahead of further organizing and processing.

Project Partners Data Contribution:

Data contributions from different project partners was essential to achieve project objectives. The United States Geological Survey (USGS) has provided guidance on ways to extract historical and current stressors data such as Fire and Fire perimeters. Valuable information on stream flood gauges location and measurement was also provided by USGS, along with historical crop (vegetation) status around the initial areas of interest on I-10 and I-40. The status of the crop varies in between "Active, Fallow, Idle, and Retired".

Several other agencies contributed to the provision of data, specifically live feeds from FEMA, The National Weather Service (NWS – including the National Hurricane Center (NHC) site) the National Oceanic and Atmospheric Administration (NOAA), the Geospatial Multi Agency Coordination site (GeoMAC – from USGS Geosciences and Environmental Change Science Center), and the National Resources Conservation Service (NRCS) under the U.S. Department of Agriculture.

The rest of the project data integrated into the GIS Resilience Database was provided directly by different groups within ADOT. The initial data collection effort consisted of the following example of how relationships are built between stressor, proxy indicator, other data, and asset:

•Historical fire perimeters •*(Stressor)*	•Drought severity •*(Stressor)*	•Soil classification •*(Proxy indicator)*
•Streams, Lakes, Outstanding Arizona waters	•USGS Gages - 25-year flood	•Cities and towns, city boundaries, state boundary, counties boundaries
•Roadway mileposts, right-of-way •*(Asset)*	•Bridges •*(Asset)*	•Box culverts •*(Asset)*

The project pilot team was able to integrate data received into two main groups:

1. Assets & Asset Vulnerability: This includes potential assets that can be affected by the extreme weather occurrence such as culverts, bridges, road pavement, and roadside/vegetation.
2. Risks (Weather, Natural, Climate conditions): This includes extreme weather stressors such as: Intense precipitation (flooding), wildfire, and drought.

The data received and integrated was organized into these two groups to create a Geodatabase shown in the following exhibits.

Exhibit 19a: Geodatabase

Feature class name	Type	No. of Records	Description
Dataset: Assets			
Box_Culvert_Location_CBC	Points	13,336	Location of culverts
Bridges	Points	5,925	Location of bridges
Hydro	Line	6,574	Streams and rivers
ImpairedLakes_2010	Line	40	Impaired Lakes location
ImpairedStreams_2010	Line	104	Impaired streams location
Milepost	Point	6,621	Milepost in major highways
NotAttaining_Lake	Polygon	19	Not Attaining Lake
NotAttaining_Stream	Polygon	857	Not Attaining Stream
OutstandingArizonaWaters_2010	Polygon	35	Outstanding Arizona Waters
RightOfWay	Polygon	98	Right of Way around major highways
State Highway System	Line	120	State Highway System (major Highway names)
Drought (Stressor)			
OrgAssignedPointsFY_All	Points	325	Car crash incident due to dust
Crash_Surface_Drought	Raster	NA	Surface of car crashes
IDW_InjuryType_Drought	Raster	NA	Surface of Incident injury
Flooding_Precipitation (Stressor)			
AZWSC_current_gages	Point	180	USGS Current stream gages location
AZWSC_historic_gages	Point	593	USGS Historic stream gages location
USGS_Gages_25yrFlood	Point	102	USGS stream gages location
Wildfire (Stressor)			
AZ_HIST_FIRE_PERIMTRS_DD83	Polygon	1095	Historic Fire Perimeter
HistoricalFirePerimeter_1970_2017	Polygon	2817	Historic Fire Perimeter
Basemap			
City	Polygon	91	City Boundary

CityTown	Point	91	City Location
County	Polygon	15	County borders
LandOwnership	Polygon	15406	Land ownership type
StateBndry	Polygon	1	State boundary

The rest of the data integrated consisted of live feed data which is updated by others regularly. These are shown in Exhibit 18b.

Exhibit 19b: Geodatabase – Live Feed Data

Live service name	URL	Description	Source
Data Type: Precipitation & Flooding			
Observed River Stages (flooding)	https://idpgis.ncep.noaa.gov/arcgis/rest/services/NWS_Observations/ahps_riv_gauges/MapServer/0	River Gauges status for flood condition (range between: Not flooding to Major Flooding)	National Weather Service (NWS)
FEMA Flood Hazard Zones	https://hazards.fema.gov/gis/nfhl/rest/services/public/NFHL/MapServer/28	Contains information about the flood hazards within the flood risk project area. These zones are used by FEMA to designate the SFHA and for insurance rating purposes.	FEMA
Rain Accumulation by Time	https://livefeeds.arcgis.com/arcgis/rest/services/LiveFeeds/NDFD_Precipitation/MapServer/1	The accumulation of rain since the beginning of the forecast period (last 24 hours)	ESRI Live feed (NOAA, Esri)
Flash Flood Warnings	https://livefeeds.arcgis.com/arcgis/rest/services/LiveFeeds/NOAA_short_term_warnings/MapServer/2	NOAA flash flood warning areas	NOAA, Esri
Data Type: Wildfire			
Active Fire Locations	https://livefeeds.arcgis.com/arcgis/rest/services/LiveFeeds/Wildfire_Activity/MapServer/0	This layer displays point data for large fire incidents	ESRI live feed (USGS, GeoMAC, Esri)
Active Fire Perimeter	https://livefeeds.arcgis.com/arcgis/rest/services/LiveFeeds/Wildfir	This file contains all wildland fire perimeters that were submitted to GeoMAC by the incidents for the	ESRI live feed (USGS, GeoMAC,

	e_Activity/MapServer/2	current year.	Esri)
Smoke Forecast	https://livefeeds.arcgis.com/arcgis/rest/services/LiveFeeds/NDGD_SmokeForecast/MapServer	Smoke forecast for the next 48 hours across the Continental United States	NOAA, Esri
Data Type: Strong Wind & Hurricanes			
Active Hurricane	https://livefeeds.arcgis.com/arcgis/rest/services/LiveFeeds/Hurricane_Active/MapServer	This layer describes the path and forecast path of tropical activity from the National Hurricane Center and Joint Typhoon Warning Center.	ESRI live feed (NHC, Esri)
Wind Forecast	https://livefeeds.arcgis.com/arcgis/rest/services/LiveFeeds/NDFD_WindForecast/MapServer	Wind forecast for the next 72 hours across the Continental United States	NOAA, Esri
Predicted Wind Speed	https://livefeeds.arcgis.com/arcgis/rest/services/LiveFeeds/NDFD_WindSpeed/MapServer	Predicted wind speed for the next 72 hours across the Continental United States	NOAA, Esri
Current Wind speed	https://livefeeds.arcgis.com/arcgis/rest/services/LiveFeeds/NOAA_METAR_current_wind_speed_direction/MapServer	The Current Wind Conditions layer is created from hourly METAR data provided from NOAA	NOAA, Esri
Tornado Warnings	https://livefeeds.arcgis.com/arcgis/rest/services/LiveFeeds/NOAA_short_term_warnings/MapServer/1	NOAA Tornado warnings areas	NOAA, Esri
Data Type: Soil characteristics			
USA Soils Hydrologic Group	https://landscape11.arcgis.com/arcgis/rest/services/USA_Soils_Hydrologic_Group/ImageServer	Physical properties of soil affect the rate that water is absorbed, and the amount of runoff produced by a storm. Hydrologic soil group provides an index of the rate that water infiltrates a soil and is an input to rainfall-runoff models that are used to predict potential stream flow.	Natural Resources Conservation Service (NRCS)

Task 3: Develop a Sample Lifecycle Planning Method (Template) to complement the ADOT CEA-TA process for Assets that are Subject to These Risks

This task was accomplished by using the methodology established through Task 2 to pilot its application to develop a Lifecycle Planning method that took the program level CEA-TA process and developed a project level scoping method. The GIS database was completed integrating data regarding weather-related and natural hazard incidents, infrastructure information, and live feeds from other sources that allow for the visualization of vulnerable locations, possible root case, and indirect indicators. The overall process is based on the following three principles:

- Understanding relationship between stressors, risk, and impacts to the system
- Availability of historical events
- Asset data

This allows for the collection of locations that may be experiencing frequent weather-related natural hazard impacts, synthesized by stressor, and identified by asset or asset class affected.

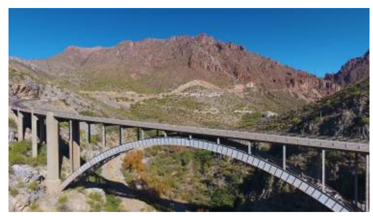
The pilot project team developed a template to use as the preliminary lifecycle planning method. It allows for a crosswalk between the stressor, weather-related natural hazard risk, impact, asset classes, lifecycle planning strategies/adaptation options, and climate attributes layered in to the method. The maps allow for the identification of proxy indicators and vulnerable areas. The asset class, enterprise wide approach allows decision makers to focus on determining an agency action, prioritizing low-cost/high-value actions. If no performance improvement is experienced, or if the decision maker decides to do a detailed analysis, the next step is to move towards a root cause analysis and up to a probabilistic engineering effort, which addresses the root cause approach that provides cost-effective lifecycle planning strategies. The following exhibit explains the process/walk-through the sample template.

Exhibit 20: Lifecycle Planning Process to Link Extreme Weather, Climate Adaptation, Asset Management, and Infrastructure Resilience

#1 Identify **Stressors** (Precipitation, temperature, wind, future climate trends)

#2 Identify **Weather-Related Natural Hazard Risk** (Flooding, slope failure, wildfire, dust storms)

#3 Identify **Impacts** to the roadway (Asset deterioration/failure, mobility, safety)



#5 Identify **Proxy Indicators** (Locations within flood hazard zones, low crossings, previous incidents)

#4 Identify **Asset(s)** at risk (Pavement, bridges, culverts, pumps, others)

RISK Likelihood X Consequence

#6 Agency **Action** (Prevent, protect, respond, recover) **Risk Identification/Resilience Building**

#7 Identify **Lifecycle Planning Strategies** for the planning, design/engineering, maintenance and operations

#8 **Monitoring** (Future incidents, post resilience construction, RROI, process improvement, feedback loop)

Result: Building resilience through a risk-based, cost-effective lifecycle planning mitigation process

The different risks eligible for the lifecycle planning methodology include:

1. Intense Precipitation
2. System Flooding *(addressed in the sample template)*
3. Wildfires
4. Wildfire-Induced Floods
5. Drought-Related Dust Storms
6. Rockfall Incidents
7. Slope Failures
8. Increased Surface Temperatures

The selection of the risks numbered above was done after review of previous pilot projects and discussion with the project team. These have been identified as main risks to ADOT's system based on previous historical data and analysis of changing climate effects on ADOT's assets.

The pilot project team identified three main impacts the stressors/weather-related risks can pose to the transportation system, these include:

1. **Asset Deterioration/Failure**: this includes pavement rutting, cracking, potholes, heaving, washouts, erosion, slope failures, and others.
2. **Mobility**: closures and disruptions to the system, including temporary closures, permanent closures, detours/evacuation routes.
3. **Safety**: low visibility and accidents due to weather conditions.

The asset class depends on the location of the incidents being analyzed. These could be pavements, bridges, culverts, roadside vegetation, geotechnical assets, other structural assets, signs and others.

Proxy indicators were identified by the use of the GIS Resilience database by examining and doing intersection analysis of the roadway system. The example proxy indicators identified include:

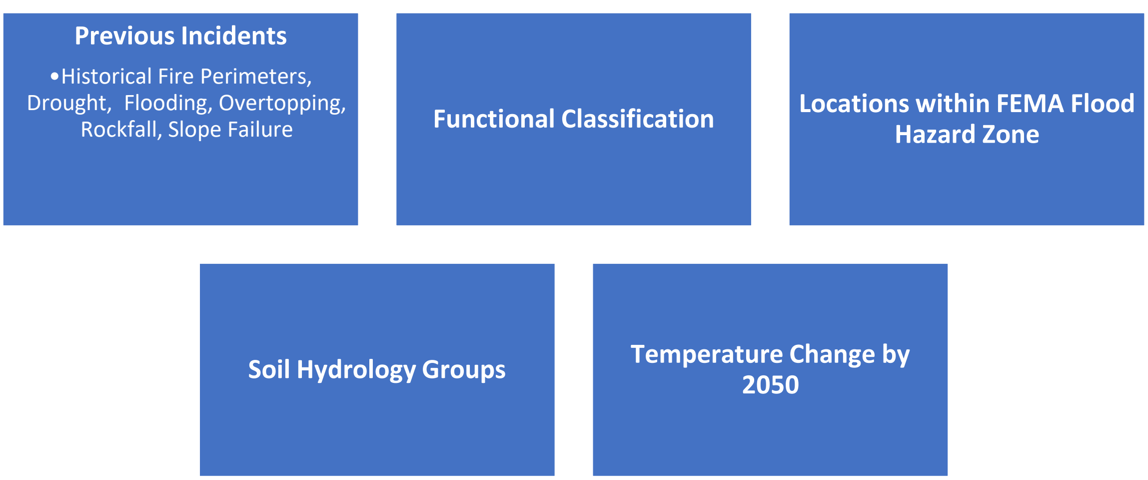


Exhibit 21: Previous Incidents – Extreme Weather Events (Points)

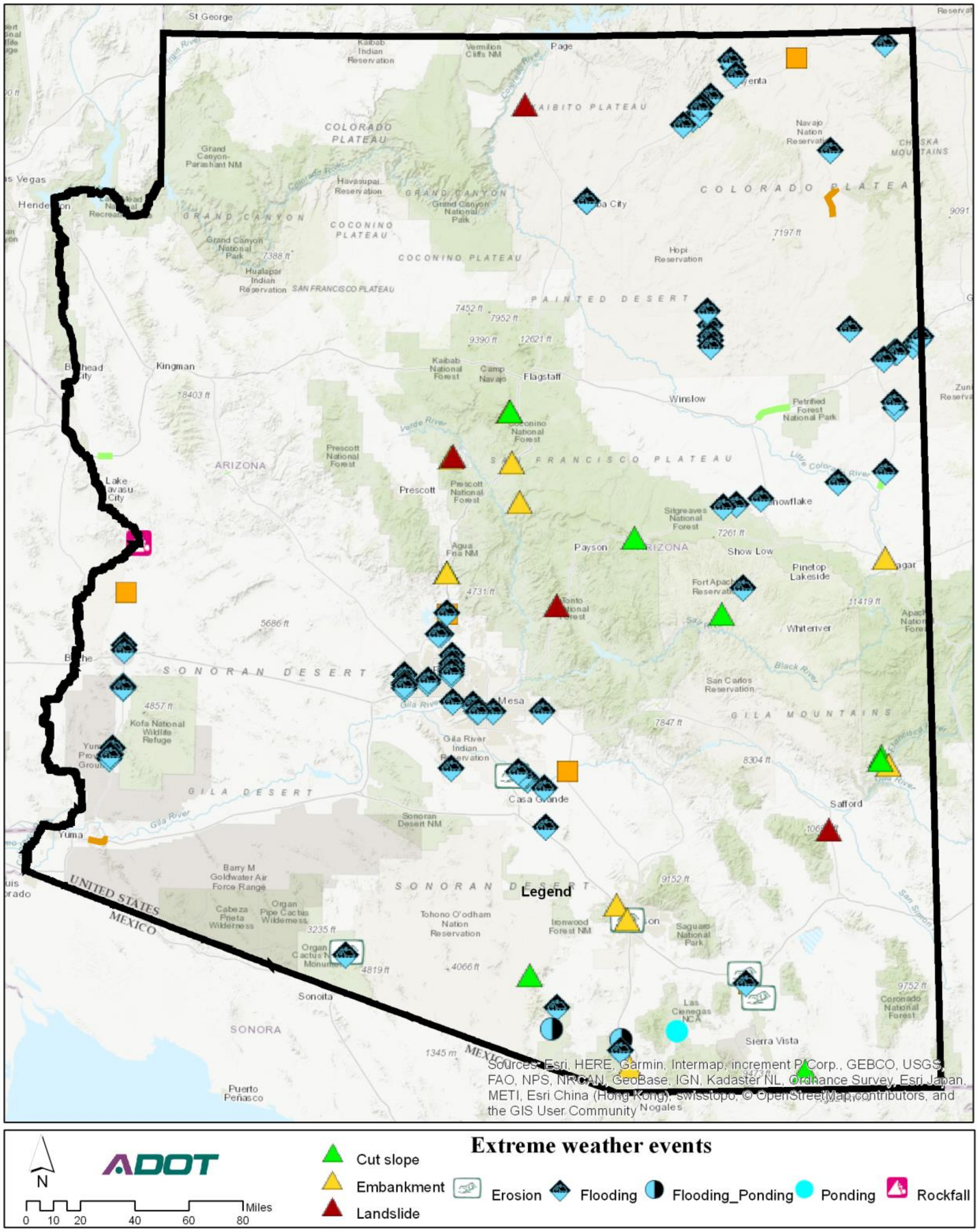


Exhibit 22: Previous Incidents – Extreme Weather Events (Route Lines)

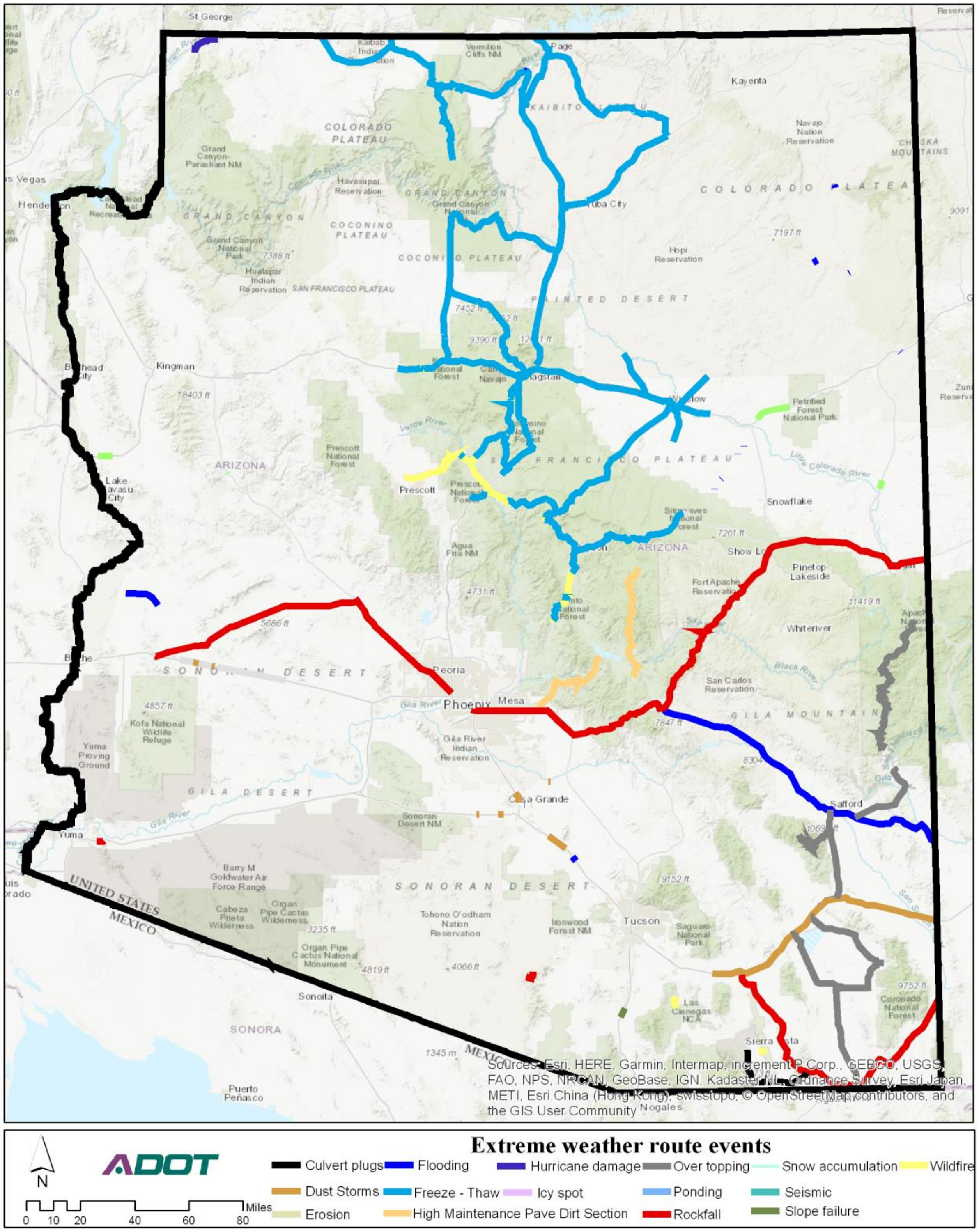


Exhibit 23: Historical Fire Perimeter

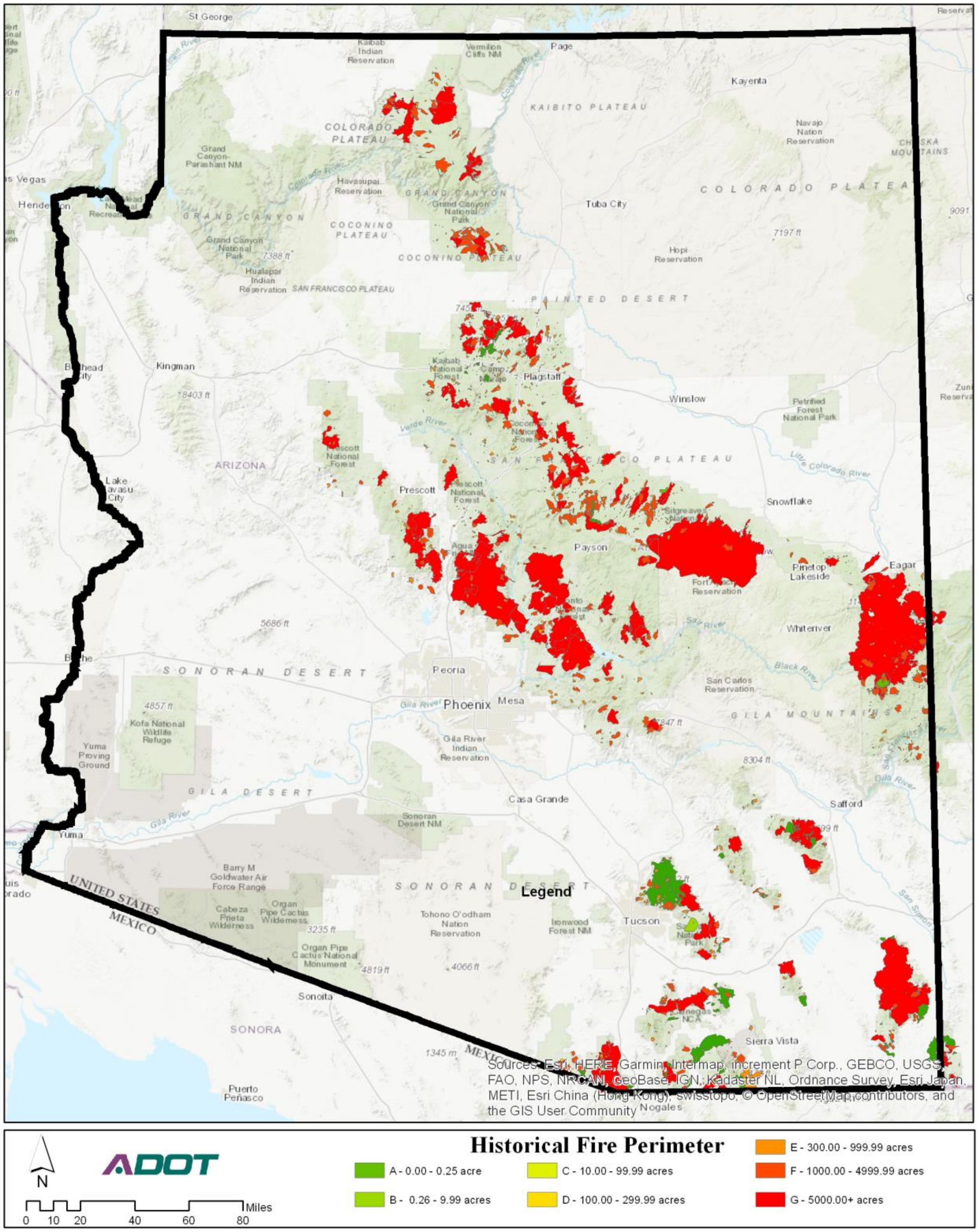
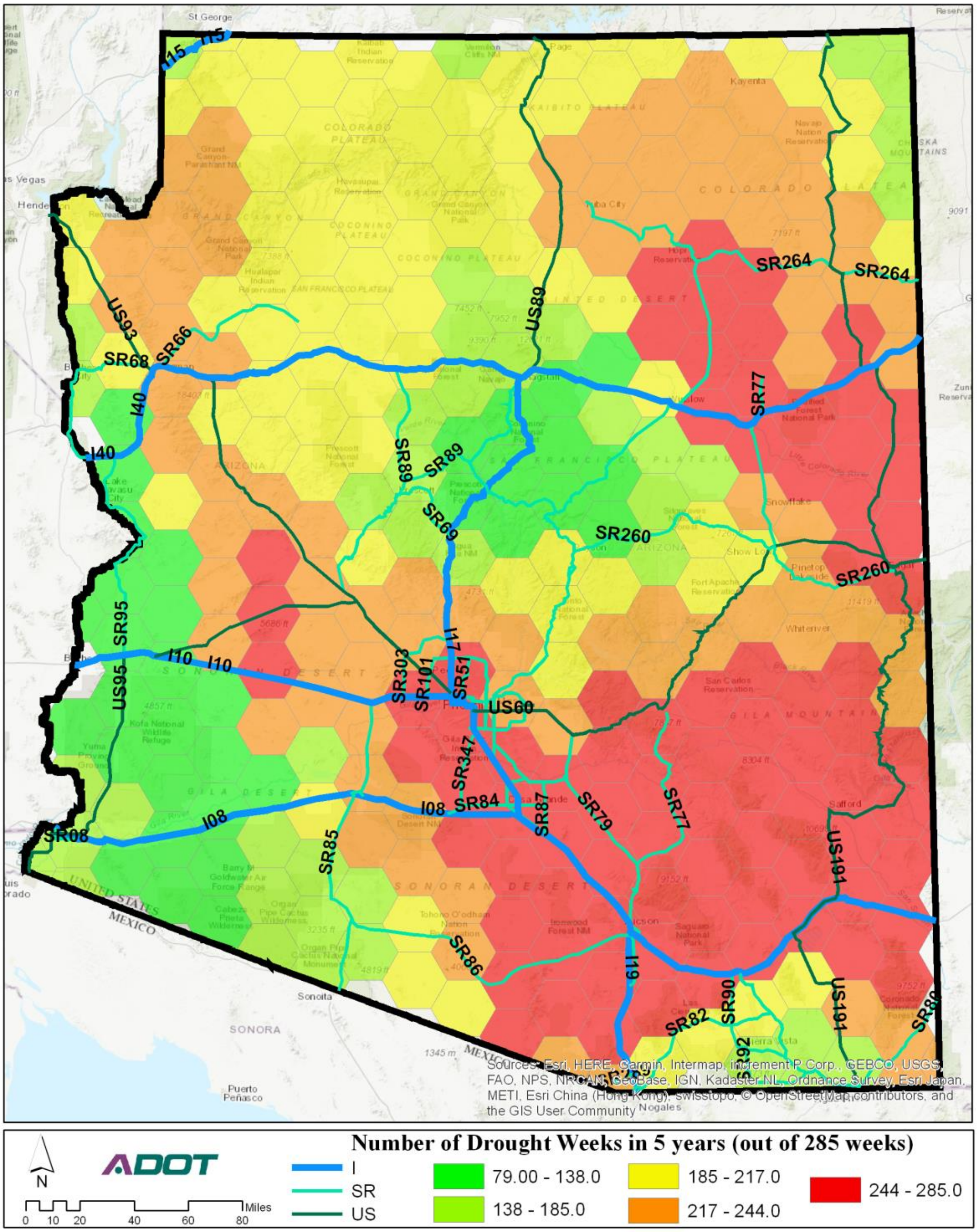


Exhibit 24: Drought Events (Weeks)[15]



15 Five Years of Drought
https://nation.maps.arcgis.com/apps/Cascade/index.html?appid=a9d345446d1a48a2918ff95b51f5841c

Exhibit 25: FEMA – National Flood Hazard Zones

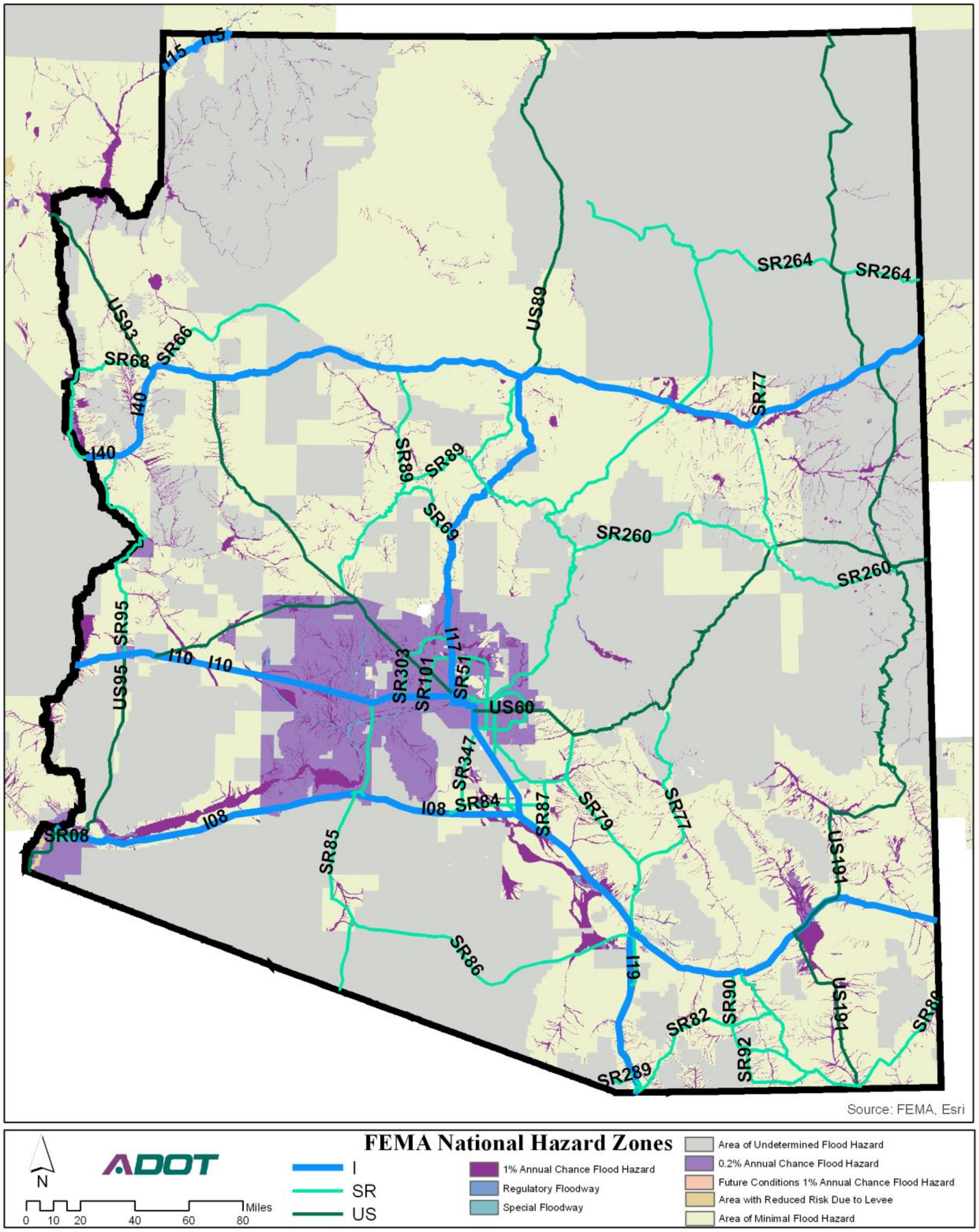


Exhibit 26: USGS Soil Hydrology Groups

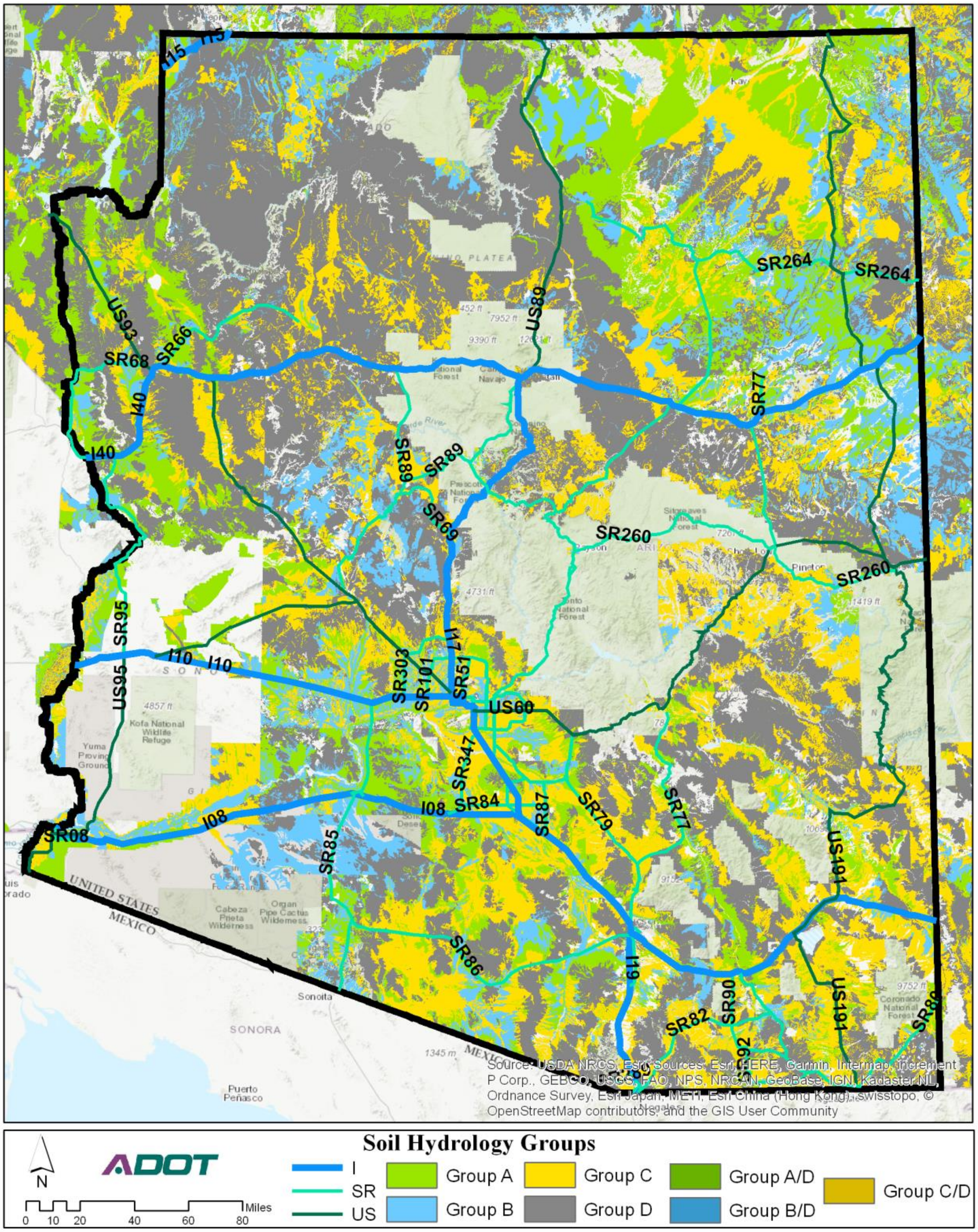
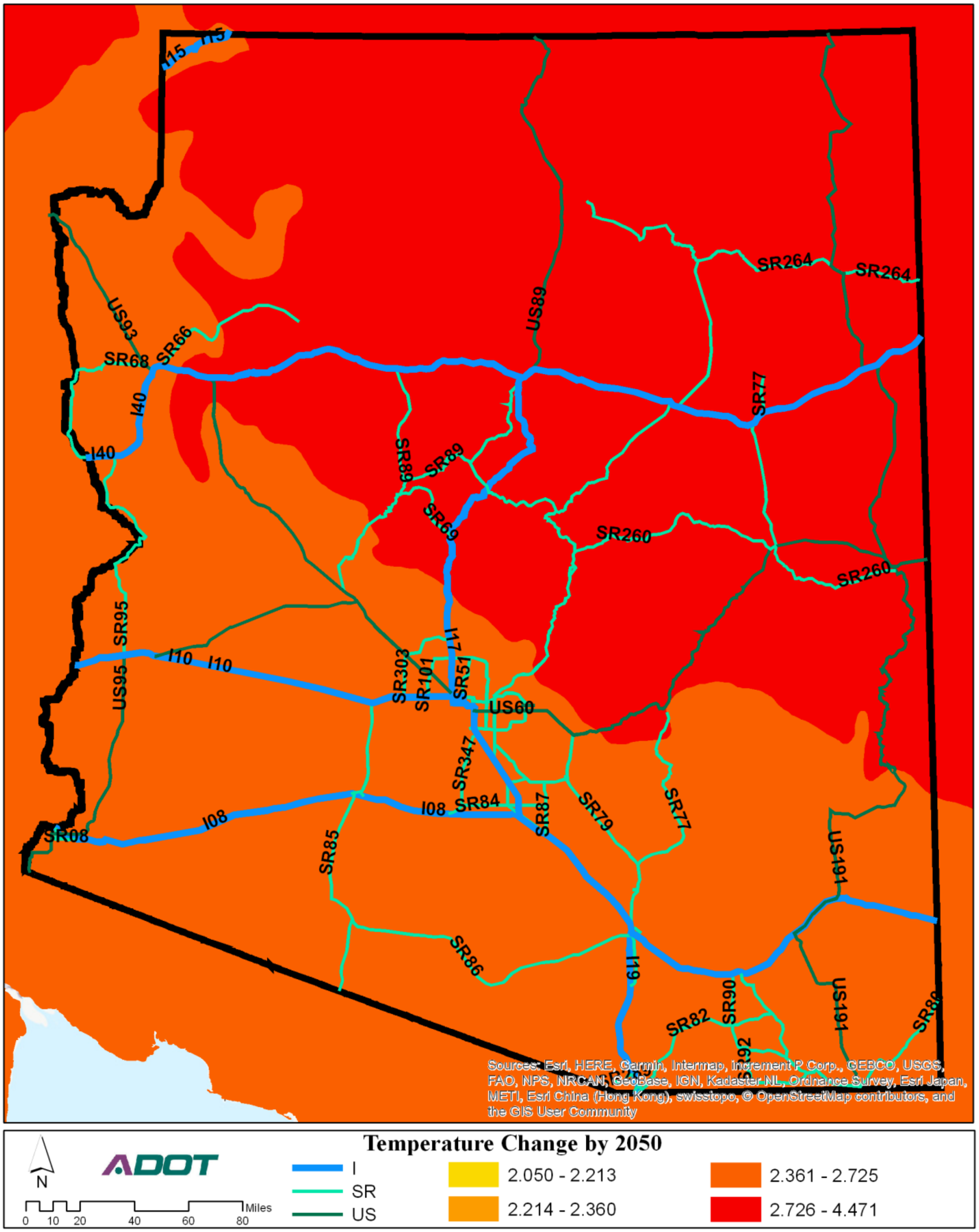


Exhibit 27: Temperature Changes by 2050



After the identification of proxy indicators, the next step is to assess the risk ratings to drive the decision-making process.

The template was developed using a risk-based process and allows for the risk rating to prioritize actions. Risks are ranked by multiplying a likelihood scale by a potential consequences scale to obtain a risk rating. The heat scaled included in ADOT's Initial TAMP is to be used to evaluate the risks and actions. This intuitive tool enables the quick prioritization of risks and guide agency actions.

The lifecycle planning template allows for the assessment and analysis of corridors at specific locations that involve multiple assets, potentially being impacted by numerous stressors. The ratings of likelihood depend on past incidents or future exposure (e.g. pavement rutting, scour critical location, overtopping, etc.) while the consequence rating refers to how critical the impact has been or would be in the future.

Exhibit 28: Risk Rating Scale

		Consequence (C)				
Likelihood(L)		1	2	3	4	5
Level	Descriptor	Negligible	Minor	Major	Critical	Catastrophic
1	Low	1	2	3	4	5
2	Medium Low	2	4	6	8	10
3	Medium	3	6	9	12	15
4	Medium High	4	8	12	16	20
5	High	5	10	15	20	25

Agency sample actions include the following, shown in Exhibit 29 below:

Exhibit 29: Agency Action

Agency Action	Description
Prevention	Vulnerability and risk assessments; Hardening of structures and materials; Detection and monitoring; Asset management techniques; Resiliency Plans
Response	Training; Emergency response guidelines; Practice drills; Alternative service strategies
Recovery	Alternative routing; Fast contracting and project initiation; Staff allocation plans
Investigation (Root-cause)	Engineering studies; Probabilistic analysis; Service planning reviews
Learning	After action reports; Research; Performance assessments

The actions result in various lifecycle planning mitigating strategies, which are grouped following the different lifecycle phases, from planning to design/engineering/construction, maintenance, and operations.

Exhibit 30: Lifecycle Planning Strategies/Adaptation Options

High cost/High value	High cost/High value	Low cost/High value	Low cost/High value
(Planning)	(Design/Engineering/Construction)	(Maintenance Management)	(Operations)

This lifecycle planning approach to addressing extreme weather and climate trends, allows for a prioritization method. The exercise is a cross-walk between the phases shown above in Exhibit 30. It allows for the decision makers to assess when a full root-cause analysis is warranted, or when a probabilistic engineering approach would be most appropriate.

- **Planning**: strategies and policy-based changes, including guidance on addressing extreme weather and changing climate trends adaptation in design guidance, maintenance and operational programs

- **Design/Engineering/Construction**: this refers to built infrastructure measures, such as infrastructure hardening, permanent or temporary infrastructure relocation, use of different materials according to climate zones

- **Maintenance Management**: strategies based on adaptive maintenance, such as tracking hazards, impacts, costs and effectiveness of prior actions taken, post-disaster response, etc. Other regular maintenance strategies, milling, crack sealing, increase sweeping of roads, increase cleaning of culverts and drainage structures prior to rain events, stabilize slopes. Tracking this data of climate and weather-related impacts helps to inform decisions and determine the specific strategies and when these are to be implemented; this information can also inform the determination of further analysis.

- **Operations**: this refers to operational approaches, including the avoidance or reduction of impacts, and timely response to impacts as they occur. Some example strategies include driver notifications of flooded roadway locations and alternative routes, deployment of emergency maintenance patrols after storm events, temporary closures of vulnerable routes, increasing availability of roadway assistance vehicles, lower speed limits during rain events.

The following exhibit shows a template example for Flooding.

Template Organization: The first page focuses on identifying and calculating the risk, while the second page focuses on agency actions based on current practices and/or innovative ideas.

Users of this Tool: The template is to be used by ADOT practitioners who are interested in improving lifecycle planning strategies for assets at risk. The maps previously developed using the GIS Resilience Database allow for the visualization and intersection analysis of natural hazard and weather-related incidents, future risks (climate data) and roadways, highlighting areas in the network that need closer attention.

Template Adaptation Measures: The template is oriented around the effect for multiple assets. Mapping different strategies to the vulnerabilities provides a direct connection from problem to solution. The project team plans to hold a working session (past the reporting period of this report) to further improve this preliminary template in a way to best serve ADOT practitioners. Adaptation strategies can be identified by not only looking at best practices at other states, but current practices being used that may not be known state-wide. Consideration of format changes to focus on specific assets is one of the options at hand, however, the team aims to look at the roadway as a system and identifying the interdependencies of different roadway elements/assets. This will contribute to the collaboration of different work groups within ADOT to develop strategies that improve the resilience of ADOT's system, not just isolating asset classes/work groups within the agency.

Some ADOT example mitigation measures:

- Improvements to wireless communications capabilities and communication redundancies between traffic management centers, resulting in closing the gaps to ensure continuous communication across rural areas in the event of weather-related emergencies

- Installing redundant power supply to cameras to ensure complete coverage to ensure awareness and provision of public safety during severe weather

- Regional coordination for multi-agency communication during weather-related events; redundancy of data servers and networks to ensure information sharing systems are operational during extreme weather events

- Implementing citizen reporting programs allowing travelers to report road conditions, to be able to share real-time information with the public, and deploy workforce vehicles as needed, use this information for road closures, and appropriate treatments. This information could be shared with connected vehicles for in-vehicle alerts in the future

- Partnerships with other agencies, such as the National Guard to ensure there is enough staff to respond to intense and frequent weather events; determining what roles these resources can serve and ways to access them in a timely manner

- Improving cost-tracking for additional resource requirements due to weather-related events, such as increased pavement maintenance costs due to increases in temperature, changes in freeze/thaw cycles resulting in potholes, etc. Establishing funds for unexpected years. The tracking of these costs and inform the budgeting process and protocols to account for these trends. Establish working units with climatologists to account for future events while budgeting and planning

- Increase of inspection frequency identify troubled areas that may require increased rate of inspection to avoid accelerated asset deterioration due to weather-related events; consider downscaled climate models to determine areas that have anticipated greater changes, to dedicate increased inspection resources, determine any needed changes in materials, etc.
- Increase vegetation controls within existing right-of-way, plant more drought tolerant vegetation to avoid fueling wildfires
- Develop plans for debris management, culvert clearing, drainage structure cleaning and other maintenance activities to avoid flooding or other disruptions during weather-related events
- Test asset's performance against future scenarios to understand the range of possible impacts. (Using FHWA's HEC-17 and HEC-25)
- Consider the interdependencies of infrastructure systems, how the transportation system affects the surrounding area, and socioeconomic considerations
- Consider adaptive management approaches to avoid overspending
- Perform root-cause analysis before reaching conclusions to ensure cost-effective mitigation strategies (e.g. "increases in precipitation, even large increases, will not necessarily lead to decreases in slope stability on every slope. Nonetheless, many slopes may be adversely affected. Each slope is unique, and analyses should be performed before conclusions are drawn" – from FHWA's Addressing Resilience in Project Development – Precipitation and Temperature Impacts on Rock and Soil Stability)
- Use of technology and tools to monitor changes and inform whether assets are susceptible to changes in precipitation or other stressors, inform design/engineering parameters, and appropriate maintenance/operations strategies
- Modify current design and procurement criteria to favor durable materials and designs (e.g. pavement materials, drainage features) considering climate trends
- After-action reports with recommendations for improvement following extreme weather events

The above list represents a brief summary of adaptive mitigation strategies from best practices and research. It is important to consider the lifecycle cost of resiliency investments and savings in budgeting and design (*See Exhibit 20 Step #8: Post-Resiliency Building Monitoring*) to improve the decision-making process going forward. The strategy selection process is to be not only through evaluation metric, but by input from practitioners who work on ADOT's programs on a daily basis, understanding the needs for the agency and the community. The following exhibit shows the preliminary development of the lifecycle planning template, offering a cross-walk between impacts, assets, and strategies for all lifecycle phases.

Exhibit 31: Intense Precipitation Lifecycle Planning Template (See Next Two Pages)

Weather-related Risk	Impact	Asset Class	Description	Measure/Threshold	Proxy/Exposure Indicators (GIS Maps/others)	Exposure (Likelihood)	Sensitivity (Consequence)	Risk
Flooding	Asset deterioration/failure	Pavement	Pavement Rutting	24-hour precipitation design threshold	Past Exposure, Proximity to the 100-year floodplain, Locations in estimated higher precipitation changes by 2050			0
			Cracking					0
			Potholes					0
			Heaving					0
			Washout					0
		Bridge	Scour critical	Scour Critical status	Location within flood hazard zone, Low crossings Past exposure/Incidents			0
			Overtopping					0
			Washout					0
		Culvert	Overtopping		Locations within flood hazard zone, Low crossings, Past incidents, Locations in estimated higher precipitation changes by 2050			0
			Blockage					0
			Washout					0
		Embankment	Slope Failure					0
			Rockfall					0
			Erosion					0
	Mobility (Closure/disruptions)	Roadway	Temporary closure		Locations within flood hazard zone, Locations experiencing frequent flooding/standing water, High accident rates			0
			Permanent closure					0
			Detour/evacuation routes					0
	Driver safety/accidents	Roadway	Accidents - wet/icy road condition		Accident crash rates, Historical incidents			0
			Visibility					0

Agency Action	Lifecycle Management Strategies/Adaptation Options Creation (Planning)	(Design/Engineering)	Maintenance (Maintenance Management)	Preservation (Operations)
	- Load restrictions on identified vulnerable roads	- Use materials according to different climate zones (heat tolerant)	- Milling (determine frequency and need by identification of vulnerable locations)	- Increase frequency of inspection and maintenance
		- Use materials according to different climate zones (cold tolerant)	- Crack sealing	- Increase frequency of inspection and maintenance
	- Review/update as necessary the Roadway Design Manual culvert warrants - Statewide culvert management system	- Identify culverts without adequate capacity (due to failures or insufficient Design capacity) for reconstruction - Enhance drainage to minimize disruptions (road closures) and asset deterioration (Pumps)		- Increase frequency of inspections and maintenance
	- Identify culverts and drainage structures at frequently flooded sites to perform low-cost/high-value solutions (cleaning and repairs)		- Increase sweeping of roads at frequently flooded locations - Increase of cleaning of culverts and drainage structures as routine maintenance, and prior to rain events	- Inspection of culverts and drainage structures after rain events
			- Stabilize slopes	- Increase frequency of inspections and maintenance
		- Strengthen ESC protocols		
	- Establish, revisit and update as necessary emergency detours/evacuation routes - Enhance communication channels to inform travelers (ITS options) - Plan for future critical infrastructure outside of flood hazard zone - Avoid future development in zones at risk of flooding through land use policies	- Relocate critical infrastructure currently in severe flooded zones		- Tracking/recording closures as needed - Driver notifications of flooded roadway locations and alternative routes - Deploy emergency maintenance patrols after storm events - Temporarily closure of vulnerable routes (monitor live gauges)
	- Review/improve as necessary systems to monitor and inform travelers			- Increase availability of roadway assistance vehicles
	- Increase traveler awareness of condition (use various methods)	- Reflective striping/markings to increase visibility		- Lower speed limits during rain events

The pilot project team will hold a collaborative session to finalize the lifecycle planning templates for the stressors identified previously and asset classes included in this project.

5. Results and Integration Actions

The pilot project team was successful in identifying an approach that combines risk, science, technology, and engineering to measurably improve ADOT's understanding of weather-related natural hazard impacts to its system, at the program, project and asset class level. This includes work establishing the GIS Resilience Database. The overall approach allows for:

1. The GIS Resilience Database serves as the basis to identify broad locations – corridors/sections/structures at most risk from climate stressors, and those at lower risk
    a. Users can select layers as needed for different analyses, however, the selection of stressors and their corresponding weather-related hazards have been pre-grouped to ease the use of this tool
2. The root cause analysis by stressor allows for the identification of cost-effective lifecycle planning mitigation/adaptation strategies
    a. By working backwards, starting from the impact to the roadway and working back to identify the different roadway elements and any problems within these, the root cause analysis of selected key study areas allows for the identification of specific mitigation strategies to address the problem. Proxy indictors can be used as a starting point; however, the root cause analysis examines assets from the design/engineering phase to the maintenance and operations phases to determine the contributing factors to the problem and highlighting high-value, low cost solutions to be implemented
3. The results of the root cause analysis combined with any probabilistic analysis, result in specific lifecycle planning strategies

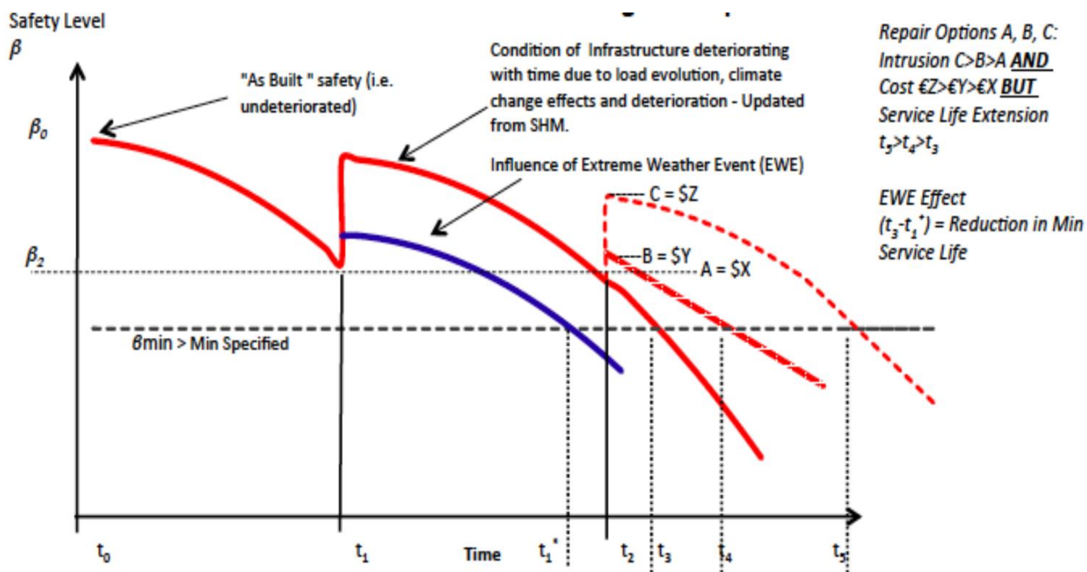
This facilitates ADOT's engineering/technical capabilities to manage risk and develop long-term asset management strategies – the assets (bridges, culverts, pavement, and roadside vegetation/stabilization) in relation to the extreme weather-climate risk of intense precipitation, system flooding, wildfires, wildfire-induced floods, drought-related dust storms, rockfall incidents, slope failures, and measurable climate trends (especially as it relates to precipitation and direct effects of increased surface temperatures) by regions or corridor emphasized as critical.

5.1 Extreme Weather – Natural Hazard - Climate Probabilistic Methodology Development for Bridge Asset Class (ADOT 2019 Pilot Project)

As part of ADOT's extreme weather and climate asset management root cause analysis, the project team set out to customize to ADOT's bridge asset class an additional process of whole lifecycle planning consideration – especially those asset classes being impacted by a myriad of influences and having a 75 – 100-year life span.

The goal is to optimize the operation and maintenance of an increasingly aging stock, which is subjected to evolving loads (e.g. both live loading, extreme event loading, and climate induced loading). "In response to this challenge the past decade has seen increased interest by infrastructure owners and managers in the use of probabilistic methods for the assessment/management of their assets. Employed once a deterministic assessment has rendered a repair/rehabilitate/replace now scenario, the methods have been demonstrated to provide significant cost savings where the required safety of the infrastructure can be demonstrated by probabilistic methods"[16].

Exhibit 32: Infrastructure Whole Life Management Optimization Methodology as The Process



Source: - O'Connor, A. Custom diagram, 2009.

The probability-based classification of the Bergeforsen Railway Bridge in Sweden serves as an example of how probability-based assessment of railway bridges can be applied to reduce maintenance costs through avoidance of unnecessary repair/rehabilitation and/or to optimize those repairs that are shown to be necessary. "The general approach for assessment of existing brides by application of standard general codes is quick and efficient but can be costly in the case of problems with the load-carrying capacity due to expensive strengthening or rehabilitation projects. The individual approach by application of probabilistic-based methods for assessment of existing bridges is based on the concept that a bridge does not necessarily have to fulfil the specific requirements of a general code, as long as the overall level of safety defined by the code is satisfied. The individual approach is able to cut or reduce the strengthening or rehabilitation cost without compromising on the level of safety."[17]

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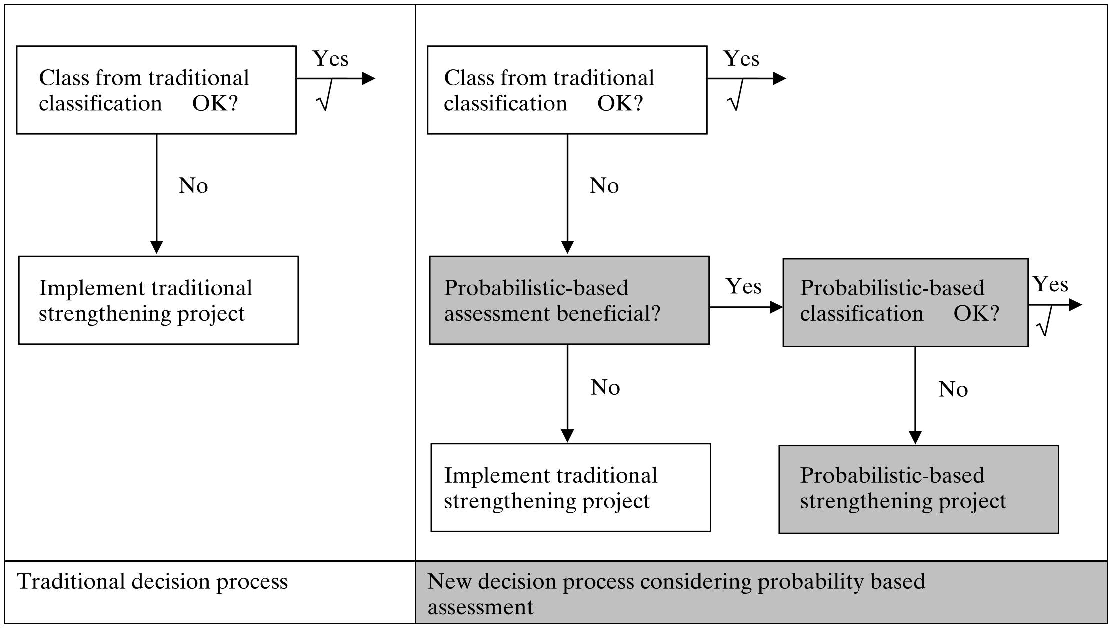
[16] Alan O'Connor (Dr), Claus Pedersen (Dr), Lars Gustavsson & Ib Enevoldsen (Dr) (2009) Probability-Based Assessment and Optimised Maintenance Management of a Large Riveted Truss Railway Bridge, Structural Engineering International, 19:4, 375-382, DOI: 10.2749/101686609789847136

[17] Ibid

Exhibit 33: Deterministic vs Probabilistic Decision Process



Source: - O’Connor, A. Custom diagram, 2009.

The basic principal is to derive a specific code for the considered infrastructure element (e.g. bridge or tunnel) and consequently a specific safety rating. This involves statistical modeling of load and resistance parameters obtained through on-site measurements and from as-built drawings. Updating of these models may be performed where additional information is available (e.g. from Structural Health Monitoring, SHM). The first stage of the process involves deterministic assessment to identify the critical limit state for the structure. This deterministic assessment is performed according to the generalized rules and using generalized partial factors provided by assessment codes. Next a specific probabilistic assessment free from the aforementioned generalizations results in the determination of a formal probability of failure, p_f, or the directly related reliability/safety index, β, applying standard techniques such as First Order Reliability Methods, at the critical limit state. Comparison of the calculated p_f with that specified by legal requirements and demonstration that it exceeds these requirements is deemed sufficient to validate the safety of the infrastructure. In a European context, application of these methods has been demonstrated to provide significant cost savings in both direct and indirect costs associated with optimization of bridge rehabilitation and replacement.[18]

This work is complementary to this pilot project, focuses solely on weather and natural hazard load and resistance parameters, and being funded and underway as a 2020 pilot with ADOT Environmental Planning, ADOT Bridge Group, and two engineering firms. The project team recommends this to be integrated with the final results of this pilot and its subsequent phases for incorporation into ADOT’s asset management plan. For a full working paper on the subject, see Appendix B.

[18] Ibid p. 63

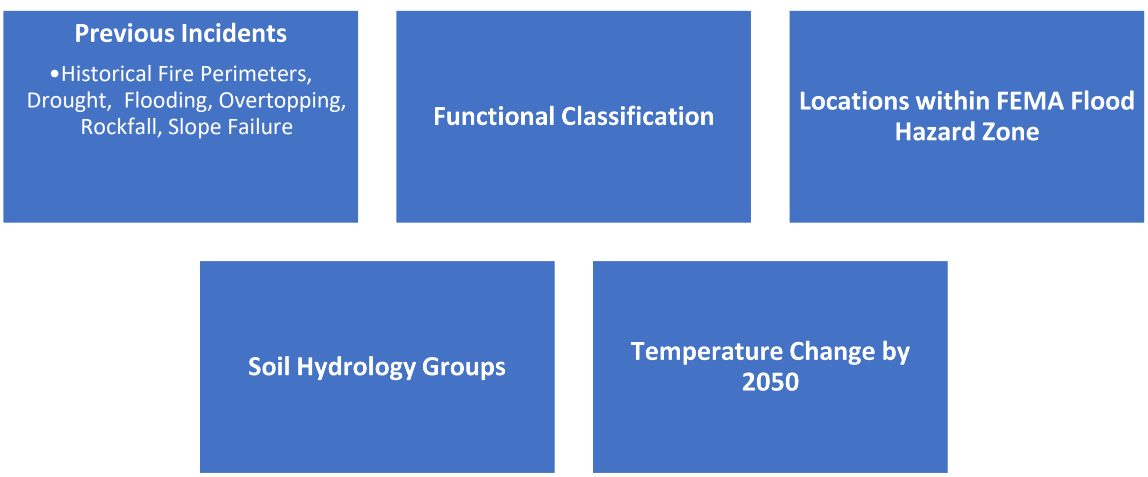
5.2 Other Key Accomplishments

The pilot project allowed for the enhanced delineation of the relationship between stressors, weather-related risks, and impacts to the system by collecting and integrating multiple datasets. The sample lifecycle planning template provided a way to integrate ongoing asset management activities in ADOT into a systematic process that allows for the screening of high-and-low risk locations. The GIS Resilience Database can be used throughout the lifecycle planning process to identify historical events and proxy indicators. This database is to be continually used in the resilience building activities within ADOT and for future screening or projects.

The pilot project benefited from the collaboration and coordination between different departments in ADOT, district offices, and increased interest in the subject of integrating extreme weather, natural hazard, and climate adaptation into asset management processes.

As mentioned starting on page 41, proxy indicators were identified by the use of the GIS Resilience database by examining and doing intersection analysis of the roadway system. The key proxy indicators identified are summarized in Exhibit 34 below.

Exhibit 34: Key Proxy Indicators Identified



6. Lessons Learned

6.1 Challenges Addressed

6.1.1 Integration of Data – Maps for Inclusion in the Template

The pilot project team received a large amount of data to integrate in the GIS Resilience Database, in various forms. The team was tasked with developing maps to be included as part of the lifecycle planning development. Linking the GIS part of the pilot with the asset management tasks was one of the challenges the team encountered. The integration was to be done and combined into a single approach for the pilot project and not separate "sub-projects". The team was able to overcome this challenge by continuous communication with all stakeholders involved. Several brainstorming sessions between the different workgroups were held, to develop a process that seamlessly integrated both parts of the project into a concise approach.

6.1.2 Project Resources

The pilot project includes various stressors, weather-related risks, and impacts to the system, which include impacts to different asset classes. A root cause analysis for each of the conditions is outside of the scope and resources of the project; however, the project team incorporated previously completed pilot project results, such as the Extreme Weather Vulnerability Assessment completed in 2015 to inform the development of this project.

6.1.3 Developing Process to Integrate Extreme-Weather into Asset Management Practices

The integration of extreme-weather and climate adaptation into asset management practices at ADOT continues to be an ongoing activity. ADOT has taken steps to gradually integrate and grow in this field, knowing there continues to be challenges to have a systematic way to build resilience that replaces current "manual" case-by-case activities. Future research could focus on ways to determine system risk prioritization, understanding risks by location, and systematically screening projects for resilience building.

6.2 Recommendations

- While the current approach allows for probabilistic analysis to determined cost savings in lifecycle planning strategies, the pilot project team focused on bridge as the main asset class for this effort given the 2019/2020 risk level pilot project. The team recommends that future enhancements to the lifecycle planning methods include probabilistic processes for other asset classes. Piloting a Computational Modeling for Geotechnical Engineering could serve as a method to accomplish this.[19]
- Involving practitioners within ADOT, especially at the District level for these efforts is key to the development and enhancements to the process. The pilot team received an overwhelming response from the different District offices, offering observations about historical and current conditions that contributed greatly to the project.

[19] TRB Benefits of Computational Modeling for Geotechnical Engineers
http://www.trb.org/main/blurbs/178180.aspx

7. Conclusions and Next Steps

The pilot project presents an assessment of ways to integrate extreme weather and climate adaptation into asset management by focusing on a lifecycle planning approach that results in cost-effective mitigation/adaptation strategies. The proposed risk-based approach is to be further improved along with the GIS Resilience database. This tool can enhance planning efforts by identifying impacts to near-future construction programs, identifying vulnerabilities early in the planning phases, and its continued use by ADOT practitioners can help improve the developed lifecycle planning for the stressors addressed in this report.

7.1 Next Steps: Planned Future Work

ADOT completed initial required assessment **23 CFR Part 667 – Periodic Evaluation of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events.** FHWA Emergency Relief Program (ERP) provides funds for the repair and reconstruction of highways and roads that have sustained serious damage from catastrophic failure or natural disasters, including extreme weather events. Since fiscal year 2012, Congress has appropriated approximately $5.7 billion to the ERP. Draft ADOT 667 process included in Appendix D.

As part of the requirements, State DOTs shall conduct statewide evaluations to determine if there are reasonable alternatives to roads, highways, and bridges that have required repair and reconstruction activities on two or more occasions due to emergency events. ADOT completed this requirement in late 2018. This was included as part of ADOT's 2019 Transportation Asset Management Plan (TAMP).

The first complete **ADOT's TAMP** was submitted by June 30, 2019, to meet all the requirements of 23 U.S.C. 119, together with documentation demonstrating implementation of the asset management plan. The integration of extreme weather, natural hazard, and climate events into asset management business practices was part of the TAMP. The results of this pilot project are to be incorporated into ADOT's future TAMP updates.

In the future, ADOT plans to have comprehensive resilience screening and adaptation as part of:

- TAMP Updates
- 2022 Construction Program
- 2022 Statewide Transportation Improvement Program (STIP)
- ADOT Annual Financial Report (CAFR)
- Long Range Plan revisions
- Lower interest rates on bond pools, and
- Complete development and adoption of probabilistic engineering methodology for asset classes

8. Technical Appendices

8.1 Appendix A: ADOT's Climate Engineering Assessment for Transportation Assets (CEA-TA)

Step 1 – Identify existing weather and climate change project and program candidates (Vulnerability Assessment): 2015 FHWA Pilot Project – 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. To provide a long-term baseline against which to compare the projections, the team also examined temperature and precipitation observations from 1950 through 1999. The report was issues by FHWA in the Spring of 2016.

Step 2 – Develop economic analysis process (Justification): An economic analysis (RinVEA) for the CEA-TA process would consist of using a probabilistic approach to lifecycle cot analysis. The lifecycle cost of an infrastructure asset such as a roadway or bridge, is the total cost to an agency throughout the asset's useful life. This includes the planning, design, construction, maintenance, and decommissioning phases of infrastructure delivery. State DOTs typically approach this process without considering risk and uncertainty that future conditions will be different from the past and assume a uniform distribution of annual maintenance costs and major reinvestment intervals. Long-lived infrastructure must perform under future climate conditions and climate-influenced usage that deviates from the historical data now populating infrastructure economic analysis and asset management models. Changing climate conditions, such as sea-level rise, storm surges, changes in precipitation, hotter temperatures, and others are potential vectors of infrastructure failure and should be taken into consideration in infrastructure economic analysis and asset management models.

Step 3 – Design probabilistic modeling approach to produce an array of results (Quality Control): Optimize operation and maintenance of an increasingly aging stock, which is subjected to evolving loads (e.g. live, extreme weather, and climate induced loading). In response to his challenge the past decade has seen increased interest by infrastructure owners and managers in the use of probabilistic methods for the assessment/management of their assets. Employed once a deterministic assessment has rendered a repair/rehabilitate/replace now scenario.

Step 4 – Define limits of simulation runs that incorporates latest science/engineering (Policy): Climate models can provide insight into future conditions, projecting air temperature, precipitation, evapotranspiration, and other factors of interest to engineers, at various temporal and spatial resolutions. However, there is a considerable disparity in the outputs provided from climate models for impacts analyses and the inputs needed by engineers for planning and design. These discrepancies include mismatches in temporal and spatial scales, complicated data extraction and preparation requirements, sizeable model, data, and scenario uncertainties, and a lack of direction for the rigorous selection of models for use in different engineering applications. Innovative change examples:

- Every Day Counts – 4: Collaborative Hydraulics: Advancing to the Next Generation of Engineering (CHANGE)
- NCHRP 15-61 – Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure
- NCAR – The Future intensification of Hourly Precipitation Extremes – Andreas F. Prein et al. December 2016
- LiDAR, UAS/UAV, 2-D water modeling, 3-D visualization and animation tools
- Translational organizations to provide rigorous standards for interpretation of climate data, development of a single, simplified user interface that accesses all downscaled data sources, and tools that automatically post-process data based on defined standards

Step 5 – Systematically record location and resilience efforts GIS/TAMP (Risk Management): ADOT has been systematically capturing data sets for extreme weather and changes in climate. This pilot project focuses on the creation of an extensive geographic information system (GIS) effort that will subsequently support ADOT's transportation asset management planning (TAMP), the GIS Resilience Database. ADOT's studies showed concerns with the climate and extreme weather vulnerability of bridges, culverts, pavement, and roadside vegetation/stabilization. The integration of data allows for the visualization of weather related stressors and recorded impacts, highlighting areas subject to weather-related risks to which lifecycle planning strategies need to be implemented.

Step 6 – Develop lifecycle models to monitor investment (Benefit Cost Analysis/Return on Investment): Civil infrastructure systems are among the largest local, state and Federal investments, and these infrastructure systems are critical to U.S. economic, environmental and social outcomes. Yet longstanding underinvestment in infrastructure has resulted in the poor condition of much of U.S. infrastructure, with an estimated $3.6 trillion or re-investment needed by 2020. New methods for benefit cost analysis, return on investment studies, and major rehabilitation timeline analyses are needed that incorporate probabilistic approaches, and minimize regret by DOTs under a changing climate. The results of CEA-TA provide that method.

ADOT

A Climate Engineering Assessment for Transportation Assets (CEA-TA)
Incorporating Probabilistic Analysis into Extreme Weather and Climate Change Design Engineering

Steven Olmsted, Arizona Department of Transportation; Alan O'Connor, Trinity College Dublin; Constantine Samaras, Carnegie Mellon University;
Beatriz Martinez-Pastor, Trinity College Dublin; Lauren Cook, Carnegie Mellon University

Abstract

Transportation infrastructure is a complex system of assets required to deliver a myriad of services and functions. As fiscal constraint for the development and rehabilitation of such structures remains; and endless retrofitting continues to be cost prohibitive; new and novel approaches to long term planning and project development, engineering design, and life cycle assessment are paramount. The management of these infrastructure systems has now evolved from a decentralized, project-based focus, to one that now encompasses enterprise wide endeavors – administration, technology adoption, planning, design, construction, operations and maintenance. In addition, the expansion of risk analysis for extreme weather management and climate change adaptation has complicated the long term delivery of these complex transportation systems. At the 2015 Transportation Research Board (TRB) Annual Meeting, Session 197: *Mainstreaming Climate Change and Extreme Weather Resilience into Transportation*, the Arizona Department of Transportation (ADOT) introduced the challenge ahead for public entities to coordinate a host of known and unknown extreme weather and climate change issues. That challenge – Continue considering the balance between predictable asset deterioration curves, the sudden and unpredictable nature of extreme weather events and long term climate trends, new models for risk assessment and life cycle cost analysis, and appropriate adaptation strategies. This multiple part challenge necessitated a new end-to-end engineering approach to incorporate such current and future risks. At the 2016 Annual Meeting ADOT submitted a paper representing the core of that new approach – a Resilience Program and an ADOT/United States Geological Survey Partnership. That paper was graciously recognized as a best paper by the TRB Special Task Force on Climate Change and Energy. In the spirit of continuing that forward progress – this paper presents the remaining parts needed to develop a new end-to-end engineering-based asset adaption process – a structured sequence to incorporate extreme weather and climate change adaptation into the design engineering process. The paper benefits from preeminent researchers in the two integral, and practice ready, remaining parts – probabilistic modeling for engineering design and infrastructure system design life cycle outcomes for extreme weather and climate change in a transportation engineering setting.

Arizona DOT Resilience Program

Transportation infrastructure is a complex system of assets required to deliver a myriad of services and functions. The expansion of risk development for extreme weather management and climate change adaptation has complicated the long term delivery of these complex transportation systems.

In order to develop an innovative approach, the first step was to create a system process that allowed for a shift from a deterministic preset design parameter and/or frequency basis, statistical risk of failure, and historic project and programs budgeting focus – i.e. extreme events not considered – to a probabilistic analysis approach that inputs additional data, vulnerabilities, and considerations not previously considered. In 2015 and 2016 ADOT focused on linking scientific evidence-driven data capture with the design engineering processes through the development of a partnership with the United States Geological Society (USGS). Extensive 2-D/3-D engineered modeling underway.

(CEA-TA) – A Structured Sequence

Identify EX W & CC project and program candidates - *Vulnerability Assessment*

2015 FHWA Pilot Project - 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. To provide a long term baseline against which to compare the projections, the team also examined temperature and precipitation observations from 1950 through 1999. The report was issued by FHWA in the Spring of 2016.

WHY IS MOVING TO A PROBABILISTIC APPROACH EVEN NEEDED?

This question could cover pages and pages. The short answer is easy. In addition to sustainable transportation attributes, there is growing consensus that if transportation systems are going to incorporate extreme weather and climate change, consideration must be developed that account for hydrometeorology/climatology, hydrology, hydraulics, and hydrodynamics. Since all these areas continue to adopt advanced mathematical modeling approaches, it is therefore logical that transportation systems and projects develop also incorporate these progressions.

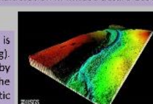
Develop economic analysis process - *Justification*

An economic analysis for the CEA-TA process would consist of using a probabilistic approach to life cycle cost analysis. The life cycle cost of an infrastructure asset such as a roadway or bridge, is the total cost to an agency throughout the asset's useful life. This includes the planning, design, construction, maintenance and decommissioning phases of infrastructure delivery. State DOTs typically initially approach this process without considering risk and uncertainty that future conditions will be different from the past, and assume a uniform distribution of annual maintenance costs and major reinvestment intervals. Long-lived infrastructure must perform under future climate conditions and climate-influenced usage that deviates from the historical data now populating infrastructure economic analysis and asset management models. Climate change impacts, such as sea-level rise, storm surges, changes in precipitation, hotter temperatures, and others are potential vectors of infrastructure failure and should be taken into consideration in infrastructure economic analysis and asset management models.

Resilience Program
Economic Analysis Pilot
US 191 MP 436 to Chinle
PROJECT NO. 191 AP 436 H8676 01 C
FEDERAL AID NO. STP-191-E(214)T
Apache County
Holbrook District

Design probabilistic modeling approach to produce an array of results - *Quality Control*

Optimize operation and maintenance of an increasingly aging stock, which is subjected to evolving loads (e.g. both live loading and climate induced loading). In response to this challenge the past decade has seen increased interest by infrastructure owners and managers in the use of probabilistic methods for the assessment/management of their assets. Employed once a deterministic assessment has rendered a repair/rehabilitate/replace now scenario



Define limits of simulation runs that incorporates latest science/engineering - *Policy*

Climate models can provide insight into future conditions, projecting air temperature, precipitation, evapotranspiration, and other factors of interest to engineers, at various temporal and spatial resolutions. However, there is a considerable disparity in the outputs provided from climate models for impacts analyses and the inputs needed by engineers for planning and design. These discrepancies include mismatches in temporal and spatial scales, complicated data extraction and preparation requirements, sizeable model, data, and scenario uncertainties, and a lack of direction for the rigorous selection of models for use in different engineering applications.

Innovative change examples:

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- LiDAR, UAS/UAV, 2-D water modeling, 3-D visualization and animation tools
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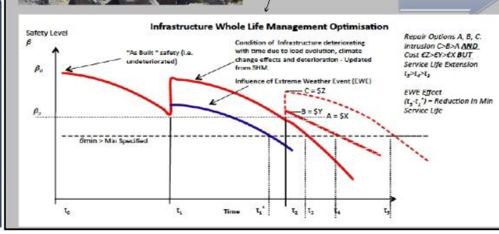


Systematically record location and resilience efforts GIS/TAMP - *Risk Management*

ADOT has been systematically capturing data sets for extreme weather and climate change use through an extensive geographic information system (GIS) effort that will subsequently support ADOT's transportation asset management planning (TAMP). ADOT's studies showed concerns with the climate and extreme weather vulnerability of bridges, culverts, pavement, and roadside vegetation / stabilization. Legislation - Focus in MAP-21 on performance based management and risk-based asset management plans; Inclusion of "resilience" in FAST Act.

Develop life cycle models to monitor investment - *BCA/ROI*

Civil infrastructure systems are among the largest local, state and Federal investments, and these infrastructure systems are critical to U.S. economic, environmental and social outcomes. Yet longstanding underinvestment in infrastructure has resulted in the poor condition of much of U.S. infrastructure, with an estimated $3.6 trillion of re-investment needed by 2020. New methods for benefit cost analysis, return on investment studies, and major rehabilitation timeline analyses are needed that incorporate probabilistic approaches, and minimize regret by DOTs under a changing climate. The results of CEA-TA provides that method.

Acknowledgments

The completion of this project would not have been possible without assistance from many stakeholders both within and outside ADOT that contributed to this effort. Specifically, the International Symposium - *Transportation Resilience: Adaptation to Climate Change and Extreme Weather Events*; June 16-17, 2016 at the European Commission in Brussels, Belgium that was the catalyst for the transatlantic partnering. The ADOT author wishes to acknowledge the efforts and support of ADOT State Engineer's Office and ADOT Environmental Planning.

8.2 Appendix B: A Quantitative Methodology for Probabilistic Consideration of Resilience in Infrastructure Whole Life Management

(O'Connor A., Steven Olmsted, David Leistiko Working Paper)

Available Fall 2020

8.3 Appendix C: Influence of Extreme Weather and Climate in Financial Decision Making

A critical part of ADOT's TAMP financial plan is the agency's investment strategy. A major contributor to that investment strategy is the identification of ways to maintain the asset categories by using risk-based lifecycle planning strategies. One of the fundamental ways in which an Agency can begin to sort and prioritize risk is through the use of the TAMP required risk register. Inherently, there are regulations, constraints, and existing commitments on available funding sources. Once ADOT considers all the asset needs against available resources, making room for extreme weather and measurable long-term climate (EX W & C) trends mitigation strategies is difficult.

Even in light of the above difficulties, ADOT has managed to conduct EX W & C vulnerability assessments, developed a Resilience Program, conducted extreme event modeling and engineering analysis, and resilience building itself.

In concert with using lifecycle planning to support asset management decision making and incorporating risk management into TAM reporting, an Agency needs a formal financial process to consider extreme weather and climate in financial decision making.

The following steps reflect this process at ADOT, which seriously considers these influences in financial decision making and have formed the basis for a comprehensive effort that includes lifecycle planning, risk management, financial decision making, and feedback loops for continuous improvement.

Exhibit C1: Resilience Financial Decision-Making Steps

(See next page)

- Assessment of - Agency/SEO /5-yr Construction Program/Divisions/Districts
- Screen through - Resilience Program
- Looking for - All historical actions and known locations to catalogue (GIS)
- Identified by - Design/Construction/Operations/ Maintenance
- Financially justified with - Resilience Investment Economic Analysis (RinVEA)
- Programmed using - Financial tool box
- Support garnered - Decision maker consensus
- Funding confirmed - Project Resource Board, Project Management, Project Finance
- Resilience Scope of Work developed blending Risk/Science/Technology/Engineering
- Funded projects commence
- System resilience advances
- Lessons learned gained
- Feedback loop to TAM Program Manager and Resilience Program Manager
- Feedback loop to methodology - Risk/Science/Technology/Engineering

ADOT Resilience Program building efforts have been underway and are continuing. Exhibit D2 below shows a summary of resilience building projects.

Exhibit C2: ADOT Resilience Building Projects

(See next page)

Project Number	Rt.	System Location	Resilience Work Completed	Project Cost	Resilience & Financial Decision-Making Outcome
Resilience Building Project #1	SR 191	Chinle, AZ	31 Drainage Structures Rehab	$6m	Roadway and embankment now protected to the 50-year storm event
Resilience Building Project #2	SR 160	Laguna Creek Bridge	Gabion basket bank protection	$1m	Bridge now protected to the 500-yr storm event - Tribal Partner - key corridor
Resilience Building Project #3	SR 95	Fortuna Wash Bridge	Bridge replace	$9.3m	Bridge now protected against Fortuna Wash floodwaters flowing over the road, secured the $500m in area economic impact, reduced/eliminated considerable detour
Resilience Building Project #4	I-8	Foothills Blvd to Dome Valley	Roadway deterioration and clogged and corroded drainage structures due to storm events and aging repaired	$14m	Vulnerable NHS asset improved - Access for City of Yuma, Yuma Port of Entry, State of California, Yuma International Airport, USMC Air Station Yuma, Barry M. Goldwater Air Force Base, Port of San Luis SR 95, MP .01 Mexico Border
Resilience Building Project #5	I-17	New River Bridges Structures - N and S	Concrete floor approximately 3 feet below the channel bed underneath the bridges. Cutoff walls at both upstream (approximately 4 feet deep) and downstream (approximately 6 feet deep)	$2m	Vulnerable NHS asset improved Maricopa County and its 4.2m residents
Resilience Building Project #6,7,8 underway					
Resilience #9,10 identified entering design					
Resilience Operating Project #1 (TSMO)	Phx		Pump Station Optimization Tool for operators and capital investment	$200K	Developing predictive model of probability of pumping station failure. Variable examples: season, condition, manufacturing date, date of last repair, size, sufficiency of capacity, precipitation magnitude, and manufacturer type.

8.4 Appendix D: ADOT Part 667 Draft

Infrastructure Delivery and Operations

An Arizona Management System Agency

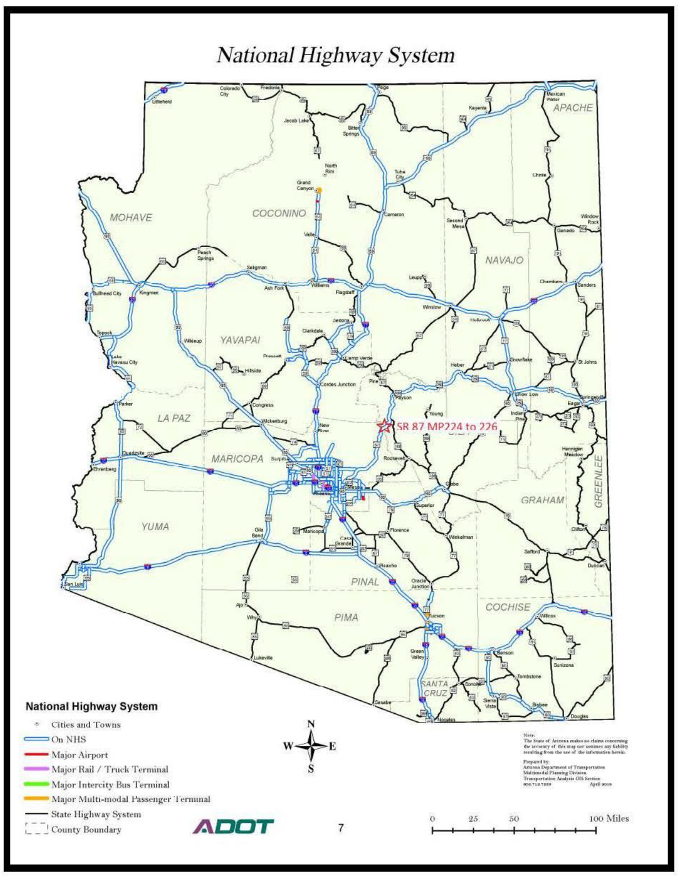
Douglas A. Ducey, Governor
John S. Halikowski, Director
Dallas Hammit, State Engineer
Steve Boschen, Division Director

November 26, 2018

Subject: Recurring NHS Emergency Projects with Geotechnical Origins

A comprehensive review was conducted of ADOT's historical projects, from January 1, 1997 to Current, on the National Highway System (NHS) that have been designated as Emergency Repair (ER). The results of the review indicate a total of one location on the NHS has produced multiple ER projects since January 1, 1997.

PROJECT LOCATION



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End of Report