Arizona Department of Transportation

ASSET MANAGEMENT, EXTREME WEATHER, AND PROXY INDICATORS PILOT PROJECT

February 2019

Contents

1. Executive Summary ES-1
1.1 Methods/Technical Approach ES-2
1.1.1 What Are Lifecycle Planning Templates and How Will These Be Used? ES-3
1.2 Results: Development of a Lifecycle Planning Template for Assets Subject to Weather-Related Risks ES-3
1.3 Conclusion and Next Steps ES-4
2. Introduction 1
2.1 Arizona as a Pilot State 1
2.2 Arizona's Temperatures 2
2.3 Arizona's Precipitation 3
2.4 Impacts of Extreme Weather and Climate Trends 5
2.5 Purpose 6
2.6 Goals 6
2.7 Scope 7
2.8 Document Organization 7
2.9 Background and Prior Work 7
2.10 Integrating Climate Adaptation into Asset Management 8
2.10.1 What has ADOT Done? 8
2.10.2 Where is ADOT Now? 11
2.10.3 Where is ADOT headed? 14
2.11 Asset Management Connectivity 15
2.12 Current Activities: Existing Extreme Weather Management and Mitigation Practices and Research and Development Activities 16
2.12.1 Statewide Flooding – 5-Year ADOT/USGS Partnership 17
2.12.2 Preventing Urban Flooding 18
2.12.3 Scour Counter Measures 18
2.12.4 Repairing Culverts 19
2.12.5 Geohazard Management Plan (GMP) 19
2.12.6 Roadside Vegetation Management Guidelines 20
2.12.7 Resilience Investment Economic Analysis (RinVEA) (CEA-TA – Step 2) 22
2.12.8 Transportation Systems Management and Operations (TSMO) Resilience Program Development – Weather Responsive Management Systems Strategies 24

2.12.9 Every Day Counts (EDC) Initiatives 24
2.12.10 Addressing Impacts from Freeze-Thaw Cycles: I-40 Project 25
3. Context of Pilot 26
4. 4. Methods/Technical Approach 30
4.1 Framework 30
4.1.1 Stressors Addressed by ADOT 30
4.2 Tasks 32
Task 1: Developing the Work Plan 32
Task 2: Complete Integration of Extreme Weather and Climate Risks into Asset Management Practices 32
Task 3: Develop a Lifecycle Planning Template for Assets that are Subject to These Risks 39
5. Results and Integration Actions 55
5.1 Bridge Asset Class Probabilistic Methodology Development (ADOT 2019 Pilot Project) 55
5.2 Other Key Accomplishments 58
6. Lessons Learned 59
6.1 Challenges Addressed 59
6.1.1 Integration of Data – Maps for Inclusion in the Template 59
6.1.2 Project Resources 59
6.1.3 Developing Process to Integrate Extreme-Weather into Asset Management Practices 59
6.2 Recommendations 59
7. Conclusions and Next Steps 61
7.1 Next Steps: Planned Future Work 61
8. Technical Appendices 62
8.1 Appendix A: ADOT's Climate Engineering Assessment for Transportation Assets (CEA-TA) 62
8.2 Appendix B: A Quantitative Methodology for Probabilistic Consideration of Resilience in Infrastructure Whole Life Management 65
8.3 Appendix C: Influence of Extreme Weather and Climate in Financial Decision Making 91
8.4 Appendix D: ADOT Part 667 Draft 94
8.5 Appendix E: ADOT Emergency Relief Environmental Process 103

List of Exhibits

Exhibit ES-1: ADOT's Pilot Project Approach 2
Exhibit 1: Example to Link Extreme Weather, Climate Adaptation, Asset Management and Infrastructure Resilience 4
Exhibit 2: Arizona's Observed and Projected Temperature Change 2
Exhibit 3: Arizona's Observed Number of Extremely Hot Days and Extremely Warm Nights 3
Exhibit 4: Observed Annual Precipitation (Left) and Observed Number of Extreme Precipitation Events (Right) 4
Exhibit 5: Aggregation of Impacts on Road Infrastructure 5
Exhibit 6: Sample Output - Projected Average Annual Days ≤ 32°F (2065 to 2095), Northern Segment 10
Exhibit 7: Sample Breakdown - Average Annual Days ≤ 32° F, Northern Segment 10
Exhibit 8: ADOT Climate Engineering Assessment for Transportation Assets (CEA-TA) – Incorporating Probabilistic Analysis into Extreme Weather and Climate Change Design Engineering 12
Exhibit 9: Surface Transportation System Resilience to Climate & Extreme Weather Events - Arizona DOT Influence Model 13
Exhibit 10: Climate Models (19 Models x 2 RCP scenarios) 14
Exhibit 11: ADOT Roadside Vegetation Management – Recovery Area Diagrams 21
Exhibit 12a: Images of Chinle Drainage Project Assessment (2015) 23
Exhibit 12b: Images of Chinle Drainage Project Improvements 23
Exhibit 13: Images of I-40 Project 25
Exhibit 14: ADOT Project Team – Internal Stakeholders 27
Exhibit 15: FHWA's Vulnerability Assessment and Adaptation Framework 30
Exhibit 16: Risks and Mitigation Strategies for Stressors Identified (ADOT's Initial TAMP) 31
Exhibit 17: ADOT's Pilot Project Approach 32
Exhibit 18: ADOT Asset Management, Extreme Weather, and Proxy Indicators Pilot Methodology 34
Exhibit 19a: Geodatabase 36
Exhibit 19b: Geodatabase – Live Feed Data 37
Exhibit 20: Lifecycle Planning Template Process to Link Extreme Weather, Climate Adaptation, Asset Management and Infrastructure Resilience 40
Exhibit 21: Previous Incidents – Extreme Weather Events (Points) 42
Exhibit 22: Previous Incidents – Extreme Weather Events (Route Lines) 43
Exhibit 23: Historical Fire Perimeter 44
Exhibit 24: Drought Events (Weeks) 45
Exhibit 25: FEMA – National Flood Hazard Zones 46
Exhibit 26: USGS Soil Hydrology Groups 47
Exhibit 27: Temperature Changes by 2050 48
Exhibit 28: Risk Rating Scale 49
Exhibit 29: Agency Action 49
Exhibit 30: Lifecycle Planning Strategies/Adaptation Options 50
Exhibit 31: Intense Precipitation Lifecycle Planning Template (See Next Two Pages) 52
Exhibit 32: Infrastructure Whole Life Management Optimization Methodology as The Process 56
Exhibit 33: Deterministic vs Probabilistic Decision Process 57
Exhibit 34: Key Proxy Indicators Identified 58

Exhibit C1: Resilience Financial Decision-Making Steps 91
Exhibit C2: ADOT Resilience Building Projects 92

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 risks continues 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 weather-related risks to its transportation system, in order to accomplish its mission "Connecting Arizona. Everyone. Every Day. Everywhere" 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 and 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 a lifecycle planning template that considers the effects of extreme weather conditions on transportation assets, (2) 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 climate stressors, (3) develop a flexible, transferable, risk-based tool that links asset management, extreme weather, and climate resiliency efforts into the management of different assets, and (4) identify specific lifecycle planning actions to integrate across the lifecycle of assets to improve resiliency, especially for asset classes most vulnerable or for asset classes required for the 2019 FHWA TAMP reporting.

This project builds on eight years of the Arizona Department of Transportation (ADOT) extreme weather management, climate adaptation, and resiliency 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
- Wildfire-Induced Floods
- Drought-Related Dust Storms
- Rockfall Incidents
- Slope Failures

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

- Increased Surface Temperatures

1.1 Methods/Technical Approach

The pilot approach identified targeted climate stressors, four prioritized asset classes susceptible to those stressors, and uses GIS as a tool to integrate extreme weather, climate resiliency and asset management. 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 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. These preliminary developed lifecycle planning templates are to be continually improved and enhanced for the efficient management of the assets identified. The main steps followed included:

1. Create the GIS Resilience Database to identify locations subject to weather-related risks
2. Develop proxy indicator/root cause/probabilistic analysis or models by stressor to understand the impacts to the roadway
3. Prepare asset class specific lifecycle planning templates
4. Use the results of the asset class analysis to specify lifecycle planning actions

Exhibit ES-1: ADOT's Pilot Project Approach

Phase 1	• Identify key stressors and their associated 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 Templates and How Will These Be Used?

The lifecycle planning templates are a way to link stressors, their corresponding weather-related risk, and impacts to the infrastructure. The templates are to serve ADOT in identifying mitigation/adaptation options throughout the different stages of an asset life cycle, including planning, design/engineering, maintenance, and operations. The templates 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 Templates are to be developed to account for the following stressors: drought-related dust storms, increased surface temperatures, intense precipitation, rockfall incidents, slope failures, system flooding, wildfire, and wildfire-induced floods. For this report, the project team completed a preliminary template for system flooding given the high number of incidents recorded in the GIS Resilience Database. Phase 2 of the project will involve the completion of the rest of the lifecycle planning templates through a desktop exercise with the project team.

1.2 Results: Development of a Lifecycle Planning Template for Assets Subject to Weather-Related Risks

The Resilience GIS Database was one of the main products of this pilot project. This was completed by integrating weather-related incident data, infrastructure information, and live feeds from other sources, that allow for the visualization of vulnerable locations and identification of proxy indicators. The overall process is based on the following three principles:

- Understanding the relationship between stressors, risk, and impacts to the system
- Availability of historical weather-related incidents
- Asset and resource data (internal and external partners)

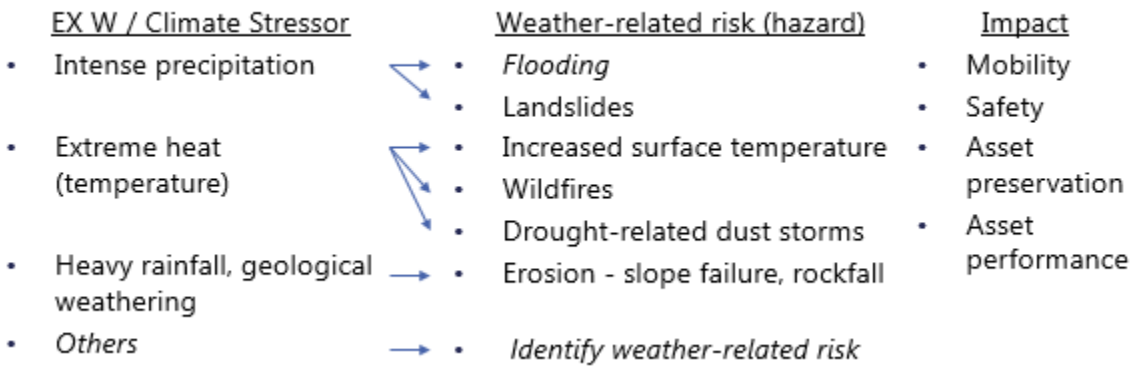
This allowed for the collection of locations that have experienced frequent weather-related impacts, synthesizing them by stressors, and identifying the asset classes affected.

A statewide outreach to ADOT districts was done as part of this pilot project, requesting data regarding natural disaster locations 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 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 recurring flooding problems reported statewide by the different districts, the pilot project team developed a preliminary lifecycle planning template to address flooding. It allows for a crosswalk between the stressor, 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 template users(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 incorporates risk 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 extreme weather and climate adaptation design into asset management by focusing on a lifecycle planning approach that results in cost-effective 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 templates for the stressors and assets addressed in this report. ADOT plans to report 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 and contribute to future system risk management, infrastructure resilience building, and asset management health reporting.

Planned Future Work:

- Complete Phase 2 of this work, which involves developing lifecycle planning templates 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
- Complete ADOT's 2019 TAMP
- Screen the 2020 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 these 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 resiliency of their roadway systems to prevent, protect, respond, and recover from the impacts of extreme weather events.

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 future extreme weather events 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 extreme weather events and their impact on 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, extreme weather and measurable climate trends.

Arizona is subject to a variety of extreme weather events ranging from extreme heat to intense rainfall in what is often referred to as the “monsoon season”. These 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.

These extreme weather events have increased in frequency and severity as climate trends continue to change and affect the United States. Many of Arizona’s transportation assets are negatively affected by weather and natural hazard 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 our transportation assets are vulnerable to extreme weather events and measurable climate trends. Through this pilot project, ADOT seeks to develop and implement a Lifecycle Planning (LCP) approach 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

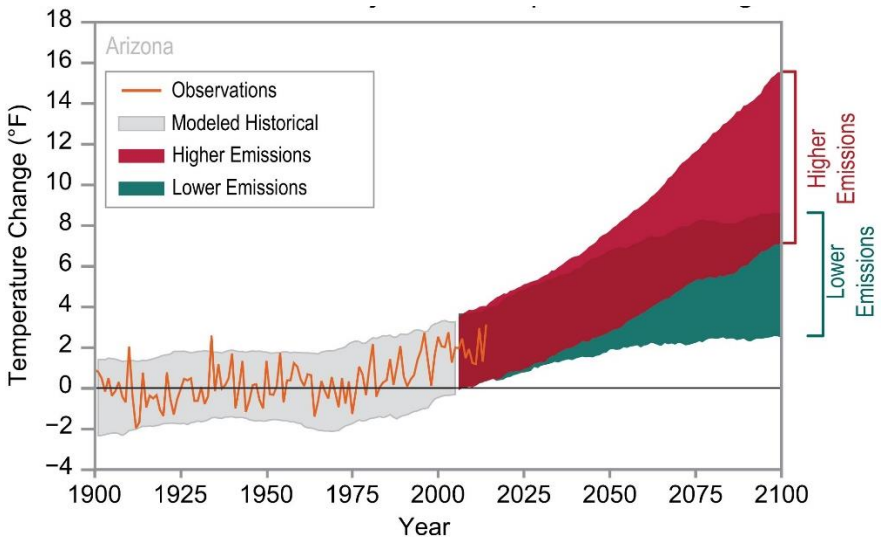
the northcentral and northeastern parts of the State experiences cooler temperatures, cold winters, and mild summers.

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, the state 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]

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.[3]

Exhibit 2: Arizona's Observed and Projected Temperature Change



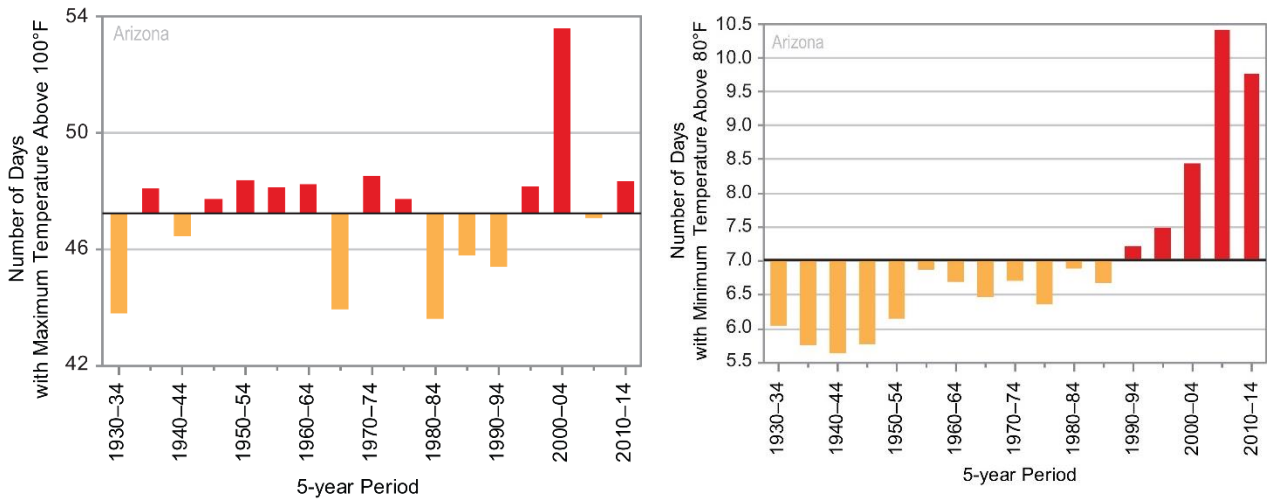
Source: North Carolina Institute for Climate Studies (CICS-NC) and NOAA National Centers for Environmental Information (NCEI)

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

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

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. For the past 25 years, Arizona has experienced an above average number of extremely warm nights.

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:

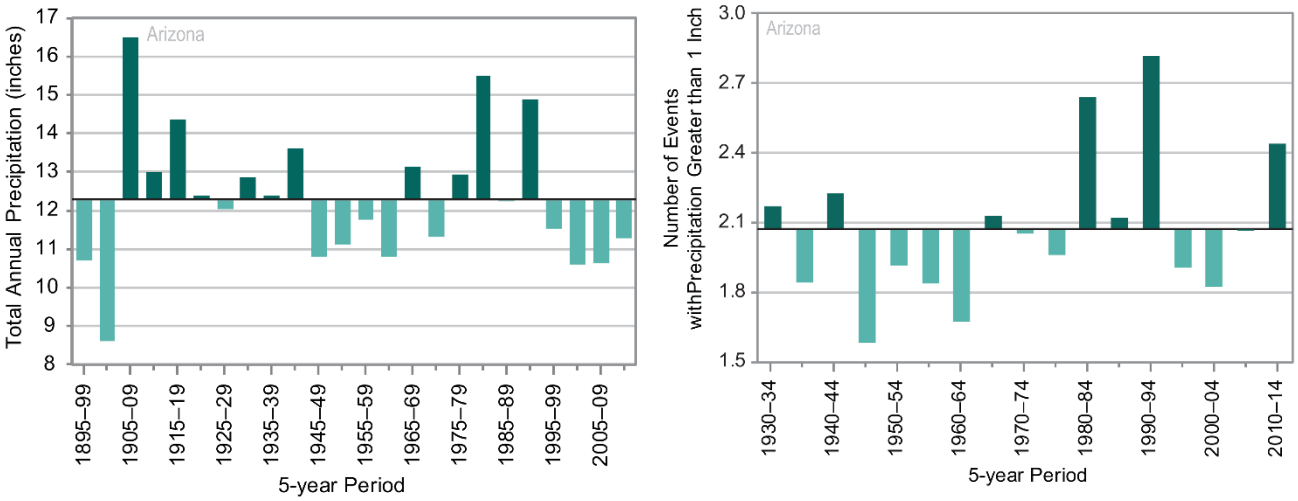
1) In winter, synoptic frontal systems (cold fronts and associated atmospheric rivers) can produce widespread heavy precipitation and large floods in larger catchments (e.g., the large floods of January 1993). The precipitation originating from cold fronts and low-pressure systems that move south from 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.[4]

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).

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) have 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)



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

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

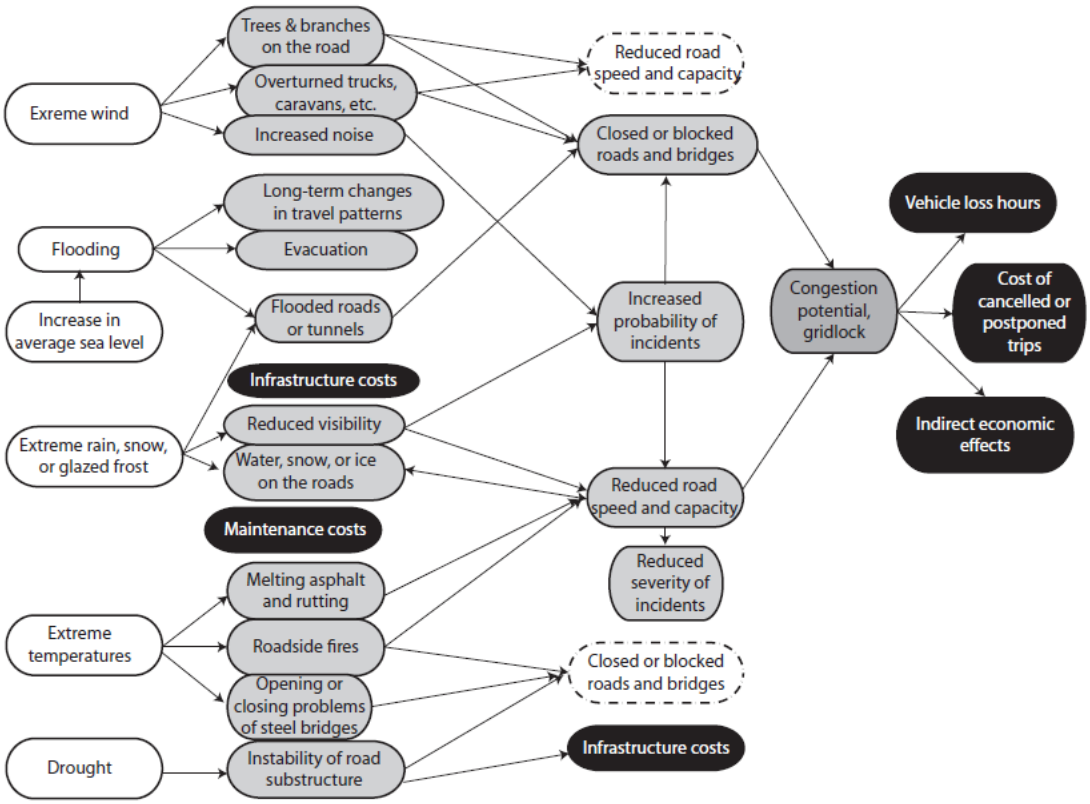
2.4 Impacts of Extreme Weather and Climate Trends

Given the trends in rising temperatures and lower annual precipitation, Arizona faces the potential of serious impacts from more frequent and extreme droughts in its environmental, agricultural, and transportation systems. Wildfires are projected to increase in frequency and severity.

There are currently a multitude of weather stressors present in Arizona, but they can largely be separated into two categories: extreme heat and extreme precipitation. Currently it is projected that the number of days that are hotter than 100°F are expected to double in low desert areas by 2080. 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.

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[5]

ADOT has been proactively addressing the risks from extreme weather and looks to expand this analysis 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 weather hazards 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 a lifecycle planning template that considers 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 climate stressors
- Develop a flexible, transferable, risk-based tool that links asset management, extreme weather, and climate resiliency efforts into the management of different assets, and
- identify specific lifecycle planning actions to integrate across the lifecycle of assets to improve resiliency

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

[5] 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 resiliency and climate adaptation 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 *(addressed in this report)*
- 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 Climate Adaptation 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[6]. 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 to weather-related hazards. The assessment qualitatively addresses the complex, often uncertain interactions between climate and extreme weather, land cover types, and transportation facilities—with an ultimate focus on potential risks to infrastructure by ADOT District. Preliminary results were presented in Focus Groups, where ADOT regional staff provided feedback on hypotheses developed through the desktop assessment. The results of the assessment are presented in *Section 5.0 of the Extreme Weather Vulnerability Assessment (2015)* report, organized first by District, then by stressor type (e.g., Extreme Precipitation). Stressor projections are further delineated by land cover types (e.g., Desert), which are considered qualitatively as potential risk "modifiers"—factors that could either alleviate or aggravate the impacts of extreme weather phenomena.

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[7]. 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.[8]

To retrieve downscaled climate data, the team leveraged the U.S. DOT *CMIP Climate Data Processing Tool* (2014). In order to automate the downscaling process—a necessity given the approximately 450 CMIP grid cells covering the study area (multiplied by as many as seven climate models, three-time periods, and 13 climate variables)—the team enhanced the Tool to facilitate batch processing and to derive a wider range of variables (such as the projected 100-year 24-hour rainfall magnitude)[9].

---

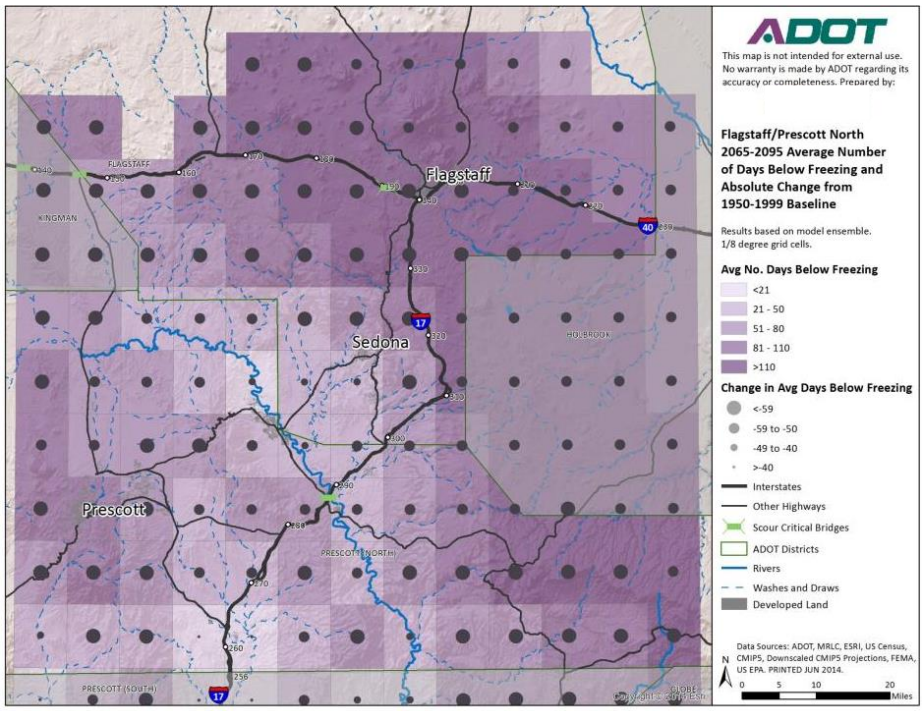
[6] The future analysis periods for extreme precipitation are 2000-2049 and 2050-2099.

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

[8] 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.

[9] 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.

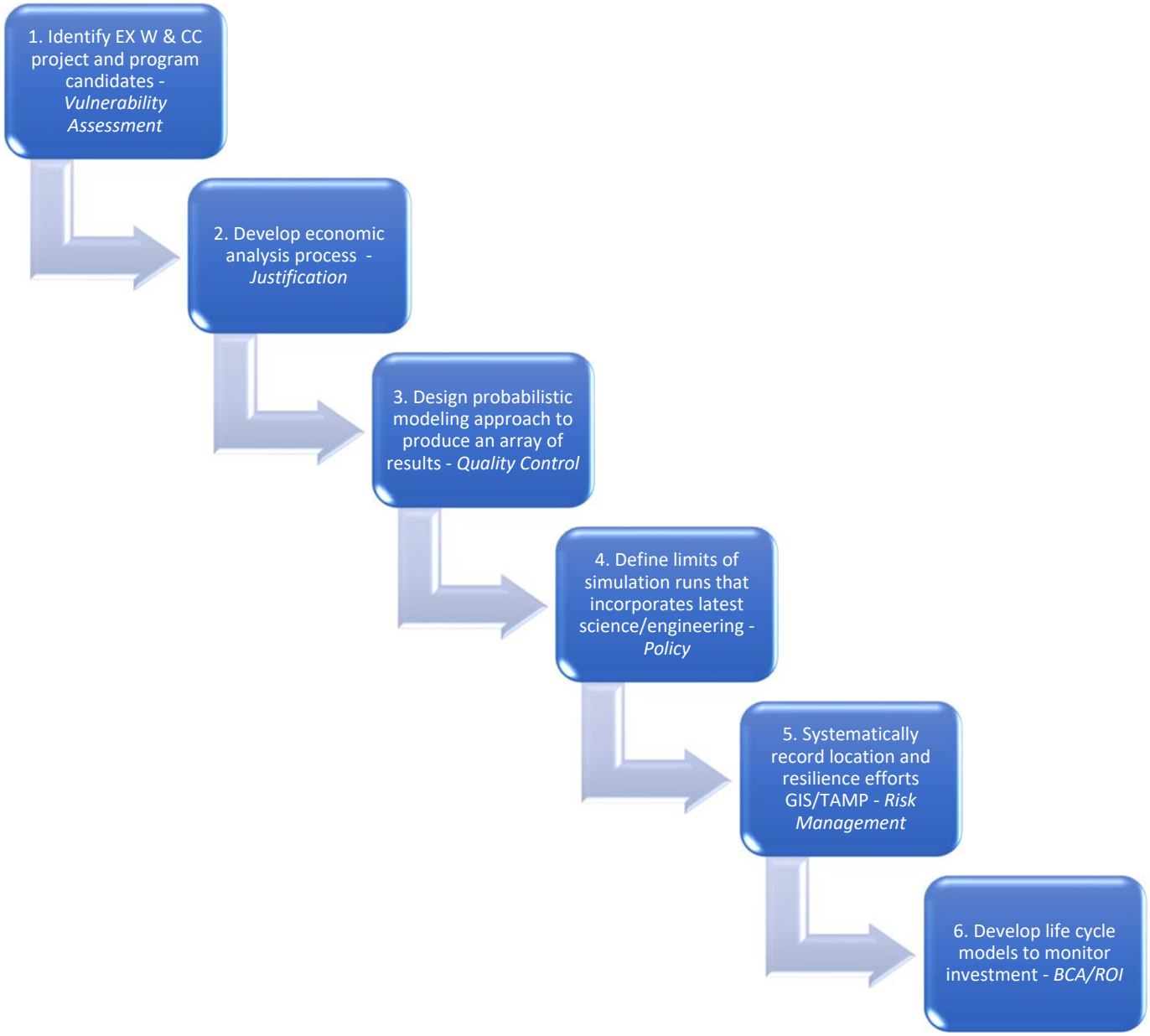
Continuing that forward progress – the 2017 TRB paper presented the remaining parts needed to develop a new end-to-end engineering-based asset adaption process – a structured sequence to incorporate extreme weather and climate adaptation into the design engineering process. The paper benefited from preeminent 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[10] 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)

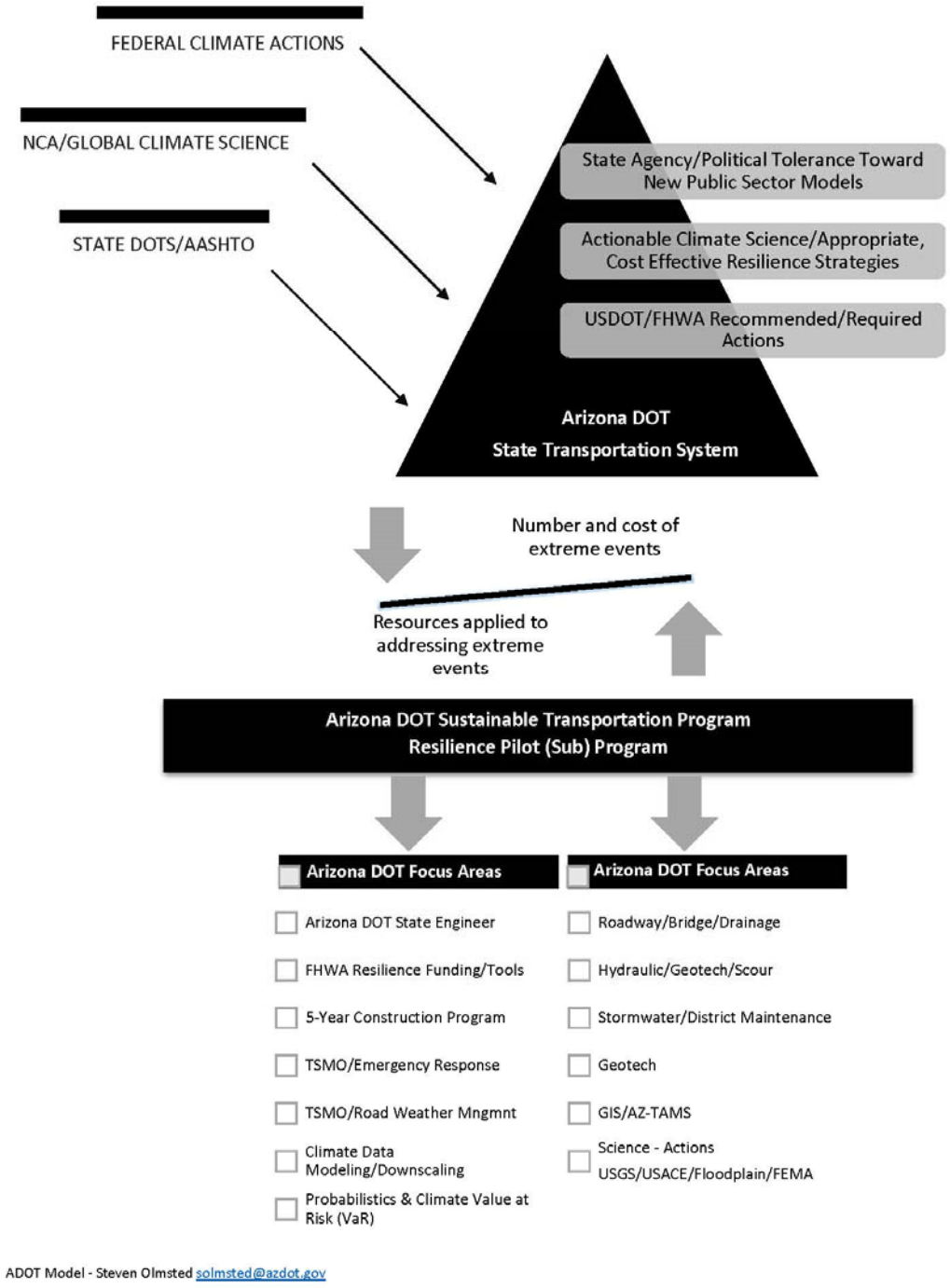
Exhibit 8: ADOT Climate Engineering Assessment for Transportation Assets (CEA-TA) – Incorporating Probabilistic Analysis into Extreme Weather and Climate Change Design Engineering



[10] 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 developing 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, and (3) the development of a GIS-based Resilience Database as part of this current FHWA pilot project, 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 2019 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
Canadian Centre for Climate Modeling and Analysis	CCCMA	CanESM2
National Center for Atmospheric Research	NCAR	CCSM4

Modeling Center (or Group)	Institute ID	Model Name
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: Existing Extreme Weather Management and Mitigation Practices and Research and Development Activities

Based on the ADOT's 2015 Extreme Weather Vulnerability Assessment, ADOT recommended to integrate extreme weather risks into the Transportation Asset Management Plan and to utilize cost-effective strategies to deal with these concerns. Arizona's Initial TAMP included the development of a risk management process, which resulted in a Risk Register as the output; the risk register addresses extreme weather risks. A total of 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; this pilot project attempts to accomplish this through the development of lifecycle planning templates for stressors and assets subjects to these risks.

1. ADOT is implementing a process of probabilistic engineering with regards to bridges that considers future conditions accounting for some of the impacts of climate stressors. Previously, ADOT was using a deterministic approach to measure an infrastructure's lifespan. The difference is that the old methods are based on historical experience whereas the probabilistic approaches recognize that this does not reflect the future impacts of climate stressors. Beginning in 2015, ADOT began to develop a probabilistic model to measure the lifecycle of bridges, which include factors like extreme weather events and asset vulnerability. The standard, extreme weather and climate loading probabilistic risk modeling pilot project is already underway and full adoption is expected in 2019. This pilot project seeks to integrate this work as part of the course of action within the lifecycle planning templates. The decision to perform a root cause analysis/probabilistic engineering for bridge design engineering will still remain ad hoc until case studies are developed. Please see further discussion on this in Section 5.1 Bridge Asset Class Probabilistic Methodology Development and a full working paper in Appendix B.

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 lifecycle planning templates as part of Phase 2 of this project after the reporting period of this report.

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.

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 bridge assets. Current measures to adopt this technology is also a contributing factor considered in the preliminary lifecycle planning templates. Especially as it relates to the first LCP methodology spreadsheet for system flooding.

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 a major university will develop a dynamic pump reliability analysis decision-support tool using Excel 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 into Excel 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).

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, lifecycle planning strategies identified are to be included in the development of lifecycle planning templates.

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 of 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. Current scour counter measures and innovative solutions are to be integrated in the development of lifecycle planning templates, during Phase II of this pilot project (not covered in this report).

2.12.4 Repairing Culverts

Intense precipitation that results in flashfloods, 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+[11]. 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. Current methods to repair culverts to avoid blockage that leads to flooding on the roadway are to be captures during the final development of lifecycle planning templates, under the maintenance and operations phases.

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. Current mitigation

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

strategies and innovative solutions are to be included in the final development of the lifecycle planning templates, past the reporting period of this document.

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.[12] The Integrated Roadside Vegetation Management (IRVM) provides the necessary soil stabilization and erosion control, which address some of the impacts of extreme weather events. Erosion and other damage resulting in the need for soil stabilization can be caused by storms, concentrated water flow, and other causes. 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 pilot project team was interested in addressing erosion and soil stabilization, which can be incorporated into the lifecycle planning template as part of the maintenance adaptation options. The following exhibit provides a graphical representation of the recovery area diagrams and the proposed roadside vegetation management within these.

See Exhibit 11 on the next page for Roadside Vegetation Management – Recovery Area Diagrams.

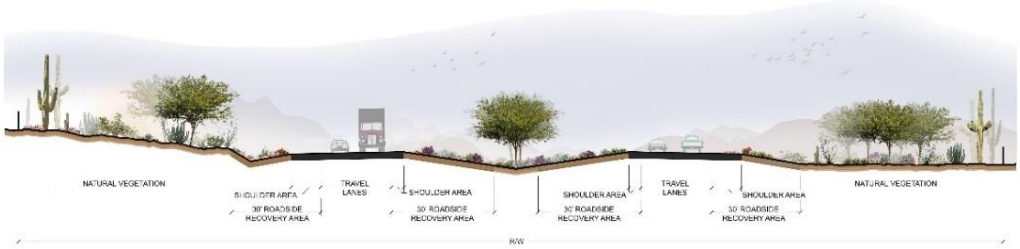
[12] ADOT Vegetation Management Guidelines https://apps.azdot.gov/files/Sitefinity-Files/Vegetation-Management-Guidelines.pdf

Exhibit 11: ADOT Roadside Vegetation Management – Recovery Area Diagrams

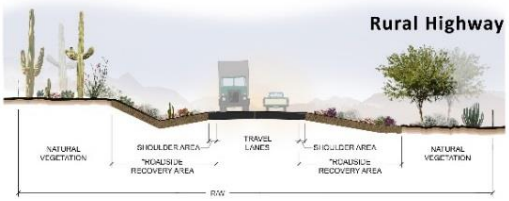
ADOT ROADSIDE VEGETATION MANAGEMENT

Recovery Area Diagrams

Rural Interstate



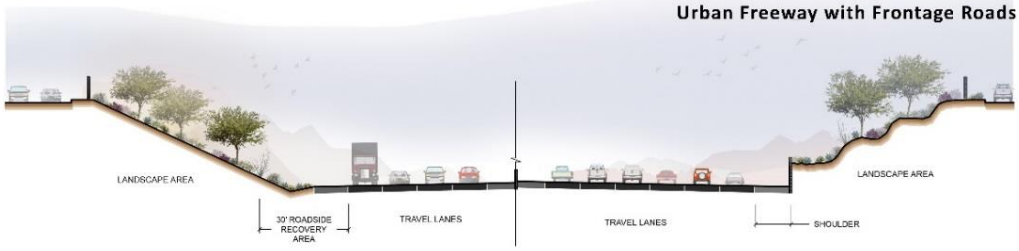
Rural Highway



* VARIABLE - REFER TO RECOVERY AREA WIDTH CRITERIA TABLE

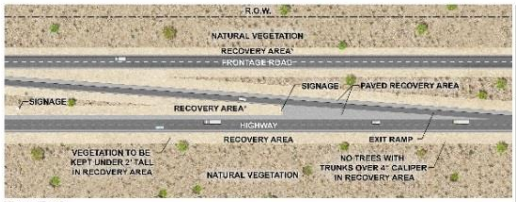
Guardrail Treatment

Urban Freeway with Frontage Roads



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 design engineering and asset management into 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 ADOT Stormwater Environmental Protection Agency and Arizona Department of Environmental Quality 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 Group 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 an expanded 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 TSMO Climate Guidebook. These measures are to be integrated in the completion of the lifecycle planning template 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; and better linkage of 2D modeling tools with advanced surveying methods.

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 is rebuilding five (5) miles of Interstate 40 near Williams; this has been ranked in the nation's top 10 by Roads & Bridges, a construction industry publication.

The many freeze-thaw cycles seen annually in this area, combined with heavy snow, snowplowing and use by a large number of commercial vehicles, had stressed pavement considerably between Williams and Devil Dog Road, creating large maintenance costs for ADOT after every winter storm. A $34 million project completely removed the existing eastbound roadway and replaced the surface with new concrete pavement, and crews are nearly done with work overlaying the westbound roadway with new concrete pavement.

To accelerate improvements, design work was completed in less than three months and construction has 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.[13]

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 templates, directly linking extreme weather, asset management and climate resiliency efforts.

Exhibit 13: Images of I-40 Project

The many freeze-thaw cycles seen annually in this area, combined with heavy snow, snowplowing and use by a large number of commercial vehicles, had stressed pavement considerably. A $34 million project completely removed the existing eastbound roadway and replaced the surface with new concrete pavement, and crews are nearly done with work overlaying the westbound roadway with new concrete pavement. Project won a national Roads & Bridges magazine award.

[13] 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 and 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 pose an increasingly apparent risk to the safe, cost-effective operation of a DOT's assets. Extreme weather 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 is increasing the cost of providing safe reliable roadway infrastructure. For ADOT the challenge is to incorporate the management of extreme weather and climate risks into a lifecycle planning or asset management approach. This will enable 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 climate risks to providing these services. Through these analyses ADOT can identify extreme weather and climate adaptation strategies that are integrated into its asset management practices.

Taking all this into consideration, the purpose of this project is to advance a lifecycle planning approach that address the effects of extreme weather conditions on ADOT's transportation assets. The pilot is to advance an approach that builds resiliency, 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. Select climate 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 in the lifecycle

planning templates to then determine when a root cause, probabilistic engineering, 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, developing the technical approach for the project 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

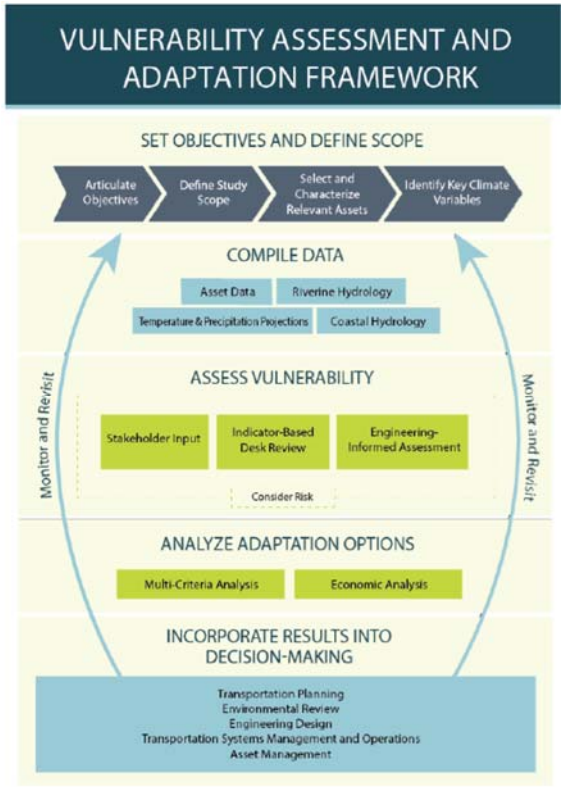
One of the main external stakeholders that contributed greatly to the development of this pilot project was USGS. The prior established partnership between ADOT and USGS has allowed continuous collaboration between the two agencies. *(See Section 4.2 for more details)*

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.

Exhibit 15: FHWA's Vulnerability Assessment and Adaptation Framework



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 climate 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 climate 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 templates.

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 resiliency 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 (≤ 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 pilot project team established through a pilot 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 climate stressors. The approach is to develop a flexible, transferable, and risk-based tool 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 pilot approach identified targeted climate 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 preliminary developed lifecycle planning templates are to be continually improved and enhanced for the efficient management of the assets identified.

4.2 Tasks

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 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 Extreme Weather 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

Phase 1
- 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)

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

Phase 3
- Incorporate assessment results in decision making

This methodology included the GIS tasks by using the GIS database as a repository of known weather-related and natural hazard incidents. The root cause(s) were to serve as linkages between the climate

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.

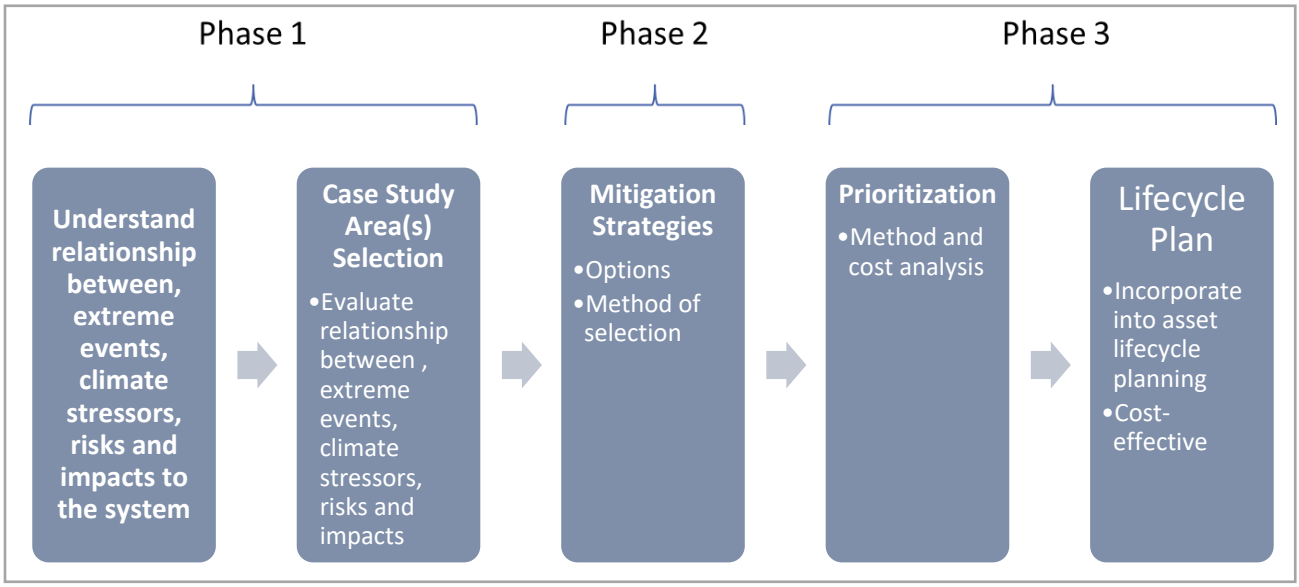
The use of the GIS tool served to identify areas with greater risks of these causes being present and analyze the surrounding area including FEMA's Flood Hazard Zone, USGS soil groups present in that area and any other proxy indicators showing areas at risk. Root causes are to be determined by further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

The lifecycle planning template 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. The project is to continue past the reporting period of this document to finalize the lifecycle planning templates for the other stressors mentioned, as well as separating these by 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 ADOT's CEA-TEA by conducting a climate engineering assessment and/or probabilistic modeling effort on an asset. The probabilistic analysis helps 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



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 the different templates to be developed for:

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

Task 2.3: Develop Maps for Inclusion in the Templates

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:

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 (Climate condition): 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/Wildfire_Activity/MapServer/2	This file contains all wildland fire perimeters that were submitted to GeoMAC by the incidents for the current year.	ESRI live feed (USGS, GeoMAC, 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 Lifecycle Planning Template for Assets that are Subject to These Risks

This task was accomplished by using the methodology established through Task 2.2 to pilot its application to develop a Lifecycle Planning Template. The GIS database was completed integrating data regarding weather-related incidents, infrastructure information, live feeds from other sources that allow for the visualization of vulnerable locations, possible root case(s) 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 template. It allows for a crosswalk between the stressor, weather-related risk, impact, asset classes, and lifecycle planning strategies/adaptation options. 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 template.

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

#1 Identify **Stressors** (Precipitation, temperature, wind)

#2 Identify **Weather-Related 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, others)

RISK = Likelihood X Consequence

#6 Agency **Action** (Prevent, protect, respond, recover)

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

#8 **Post-Resilience Building Monitoring** (Future incidents, ROI)

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

The different risks ADOT identified to address in the lifecycle planning templates include:

1. Intense Precipitation *(To be completed after this report)*
2. System Flooding *(Addressed in this report)*
3. Wildfires *(To be completed after this report)*
4. Wildfire-Induced Floods *(To be completed after this report)*
5. Drought-Related Dust Storms *(To be completed after this report)*
6. Rockfall Incidents *(To be completed after this report)*
7. Slope Failures *(To be completed after this report)*
8. Increased Surface Temperatures *(To be completed after this report)*

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 key proxy indicators identified include:

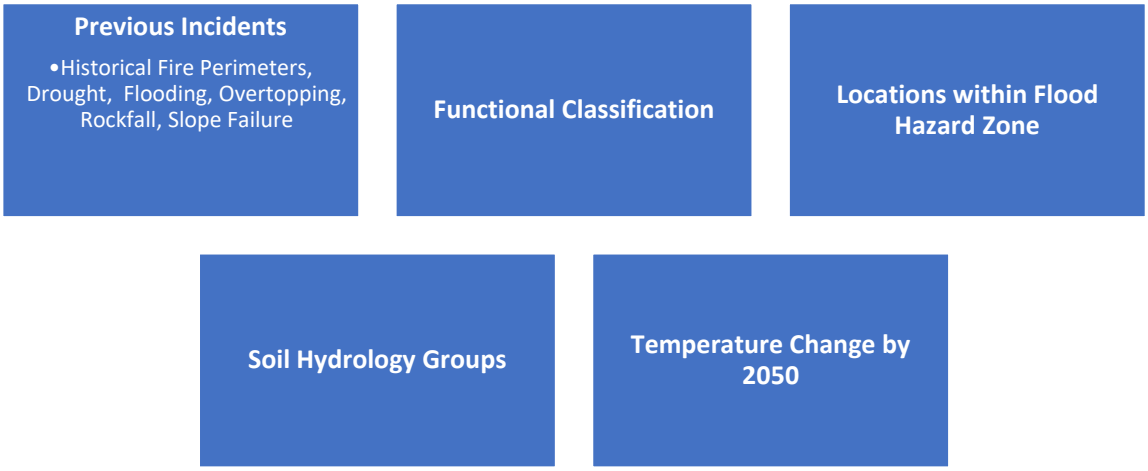


Exhibit 21: Previous Incidents – Extreme Weather Events (Points)

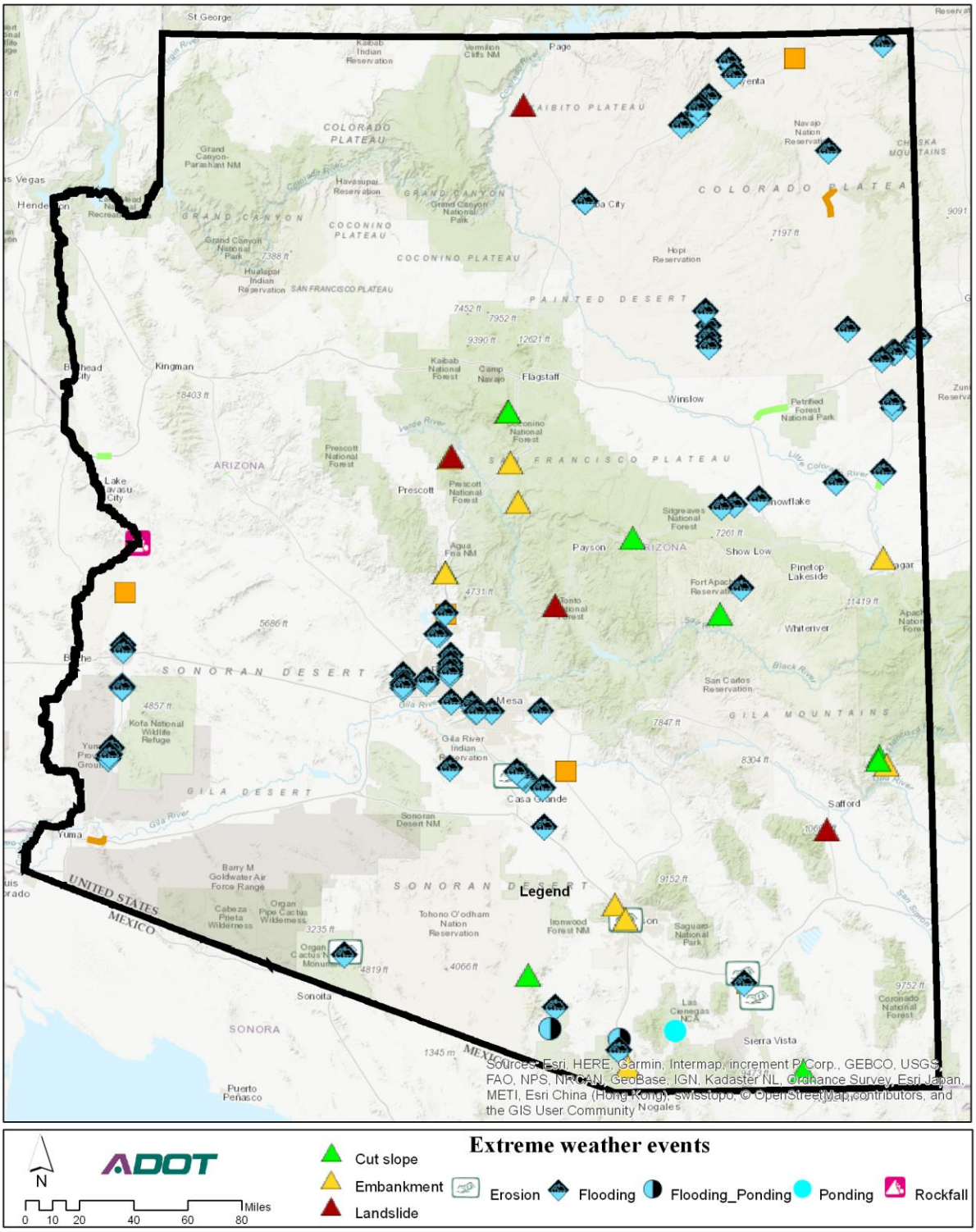


Exhibit 22: Previous Incidents – Extreme Weather Events (Route Lines)

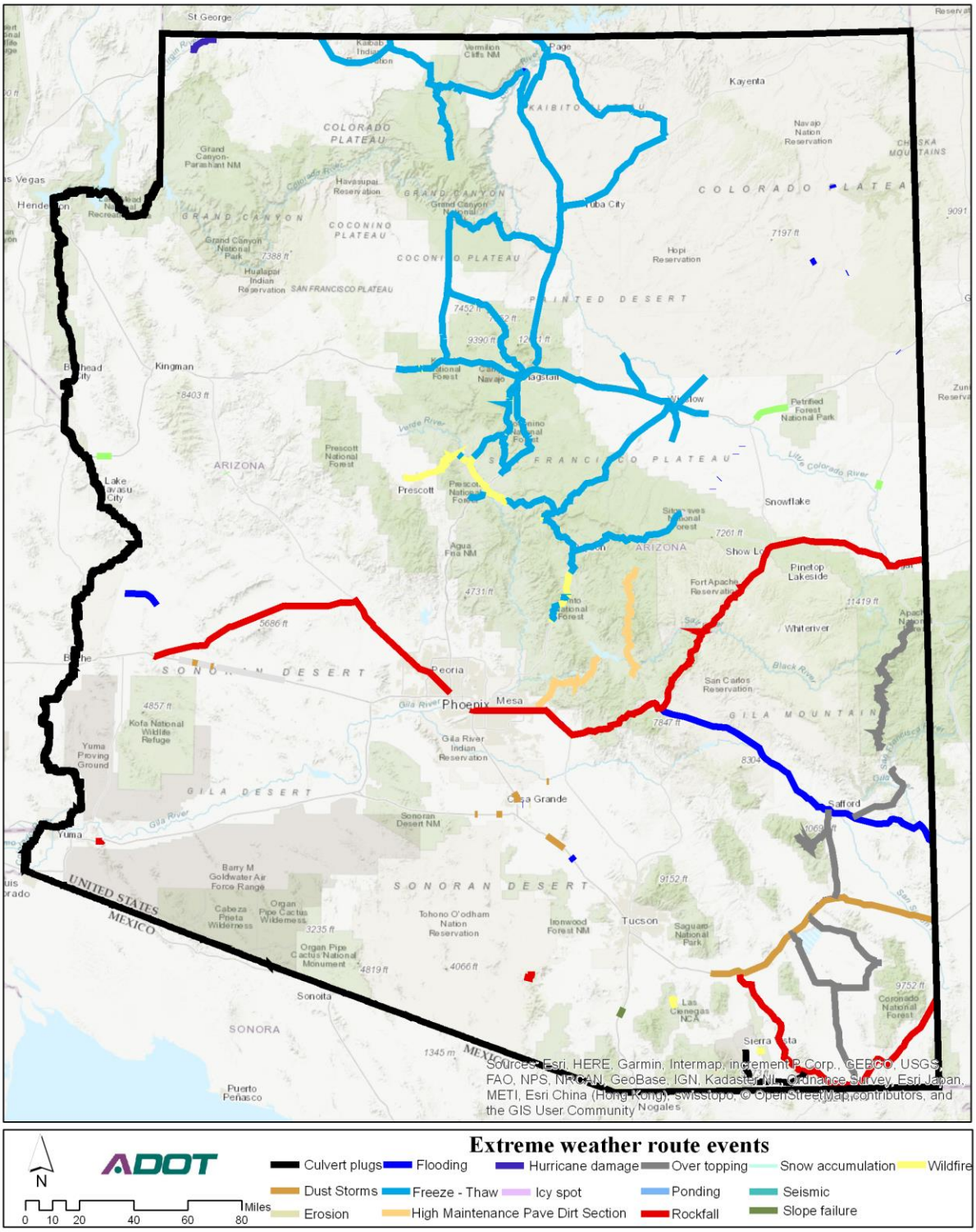


Exhibit 23: Historical Fire Perimeter

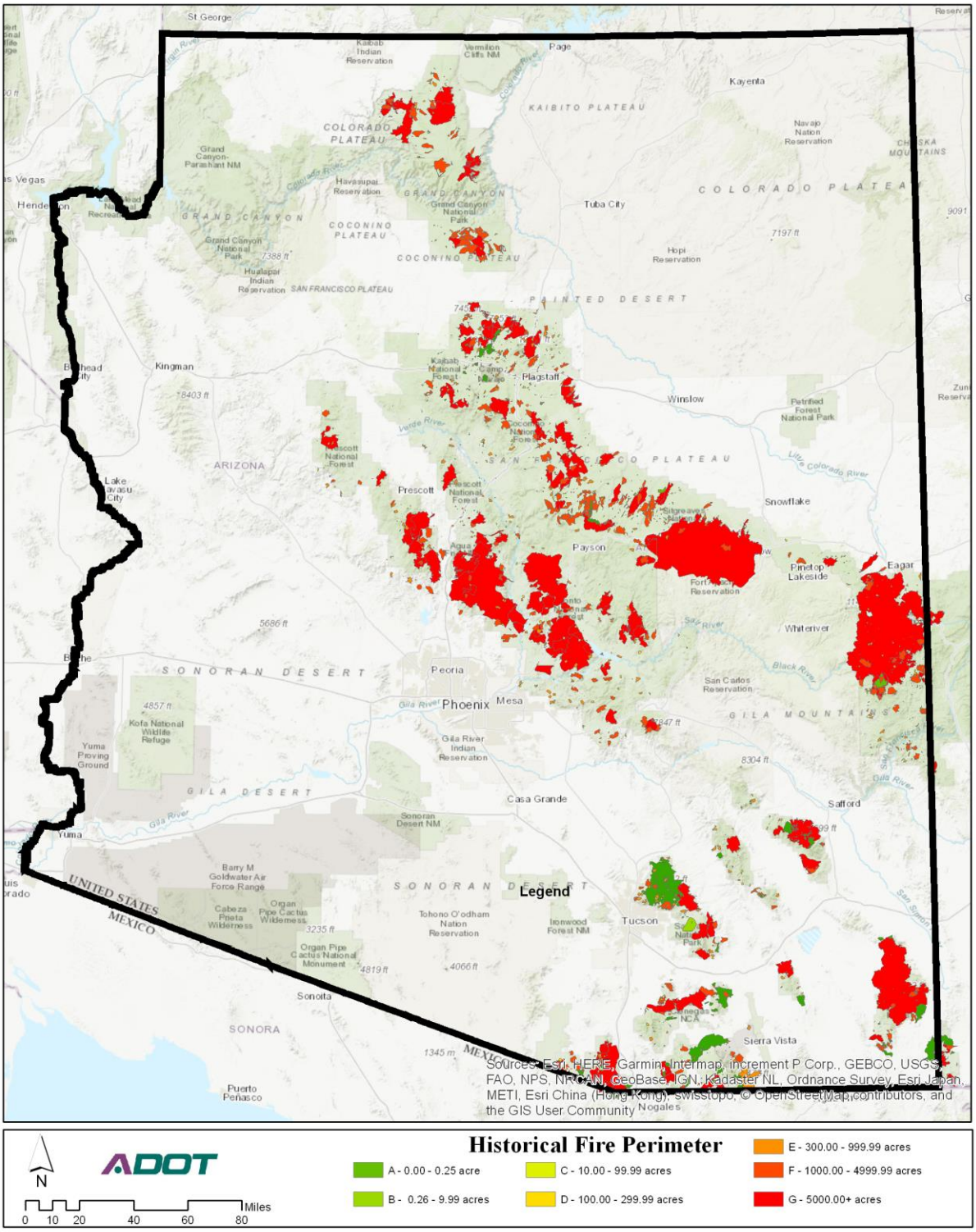
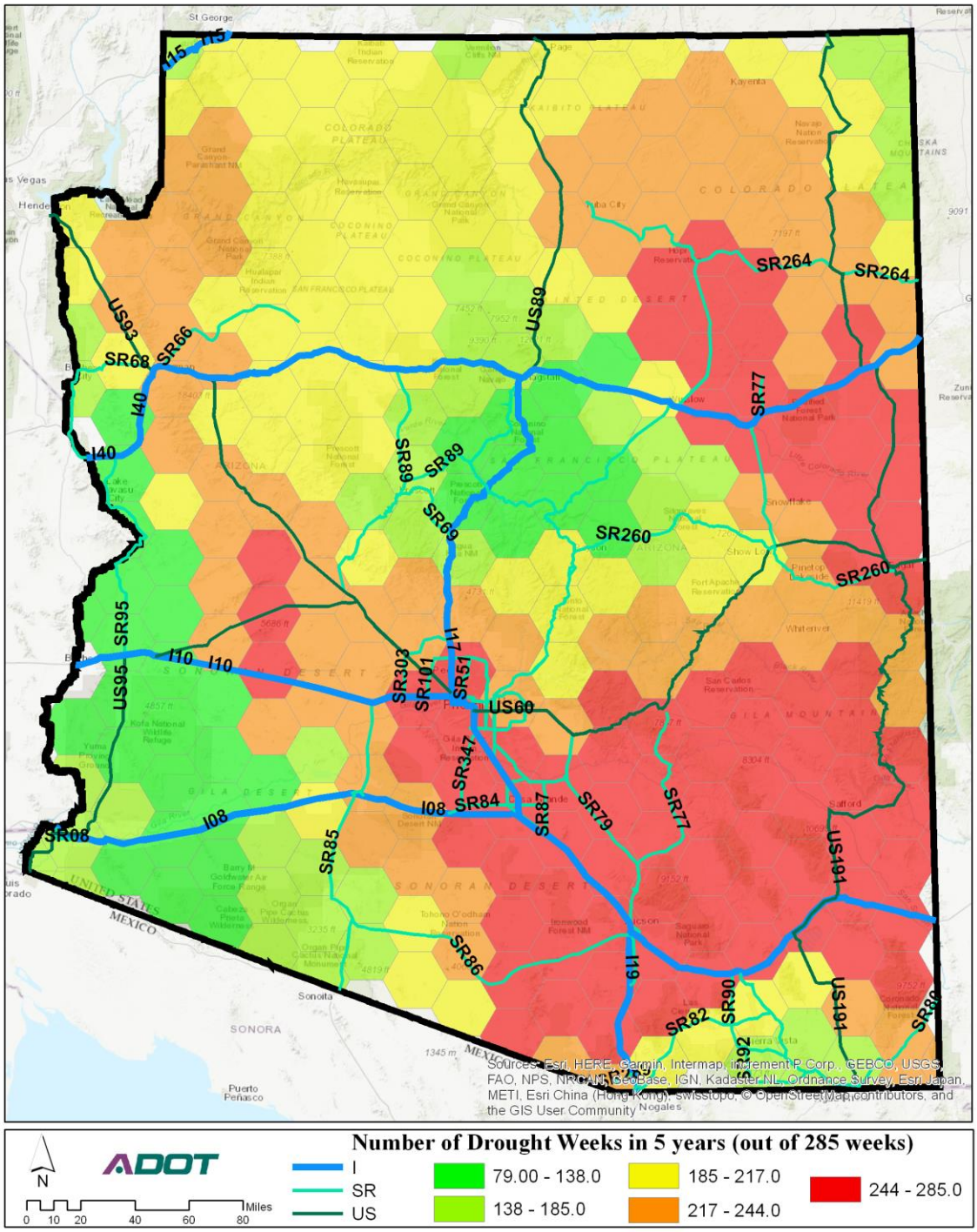


Exhibit 24: Drought Events (Weeks)[14]



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

Exhibit 25: FEMA – National Flood Hazard Zones

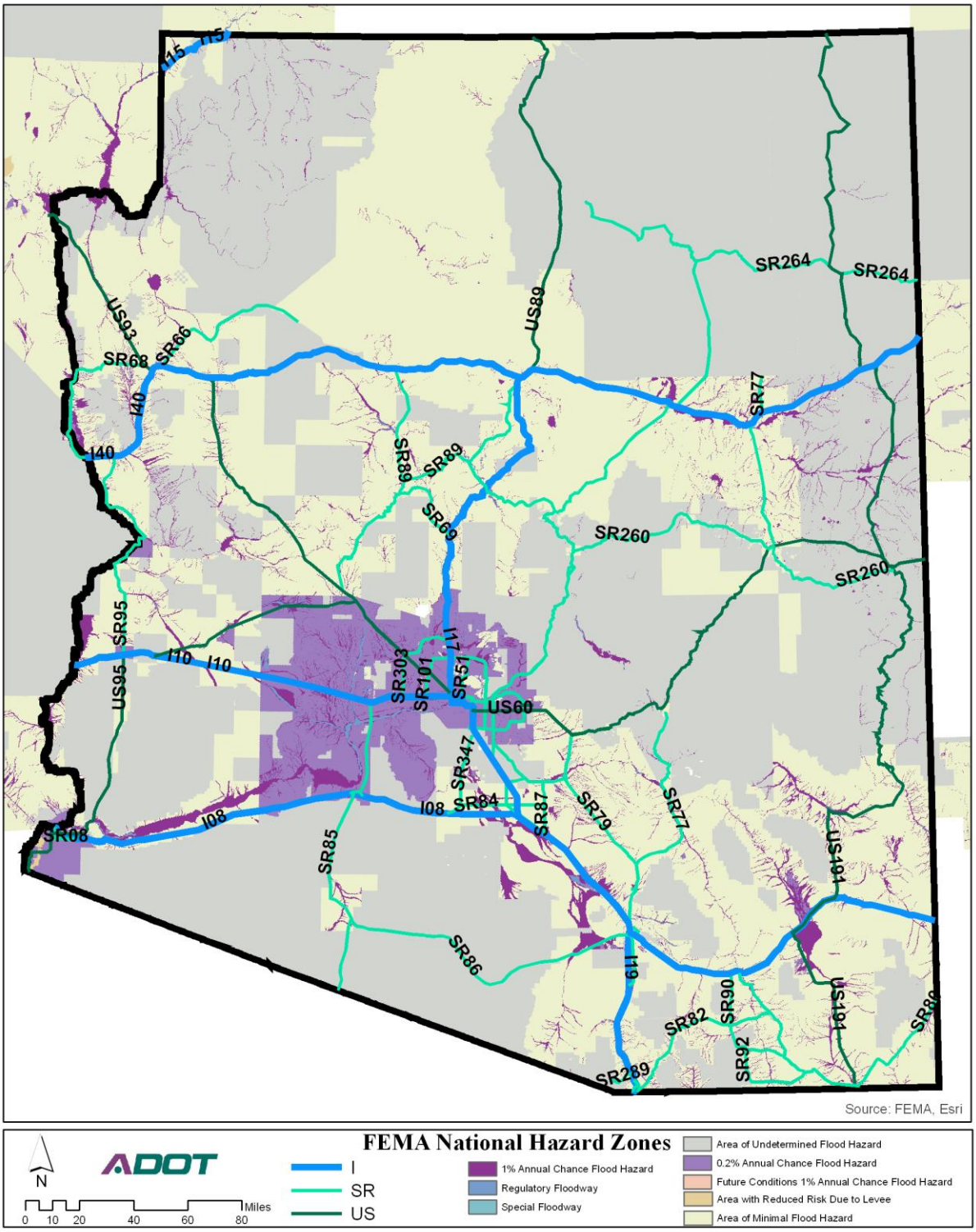


Exhibit 26: USGS Soil Hydrology Groups

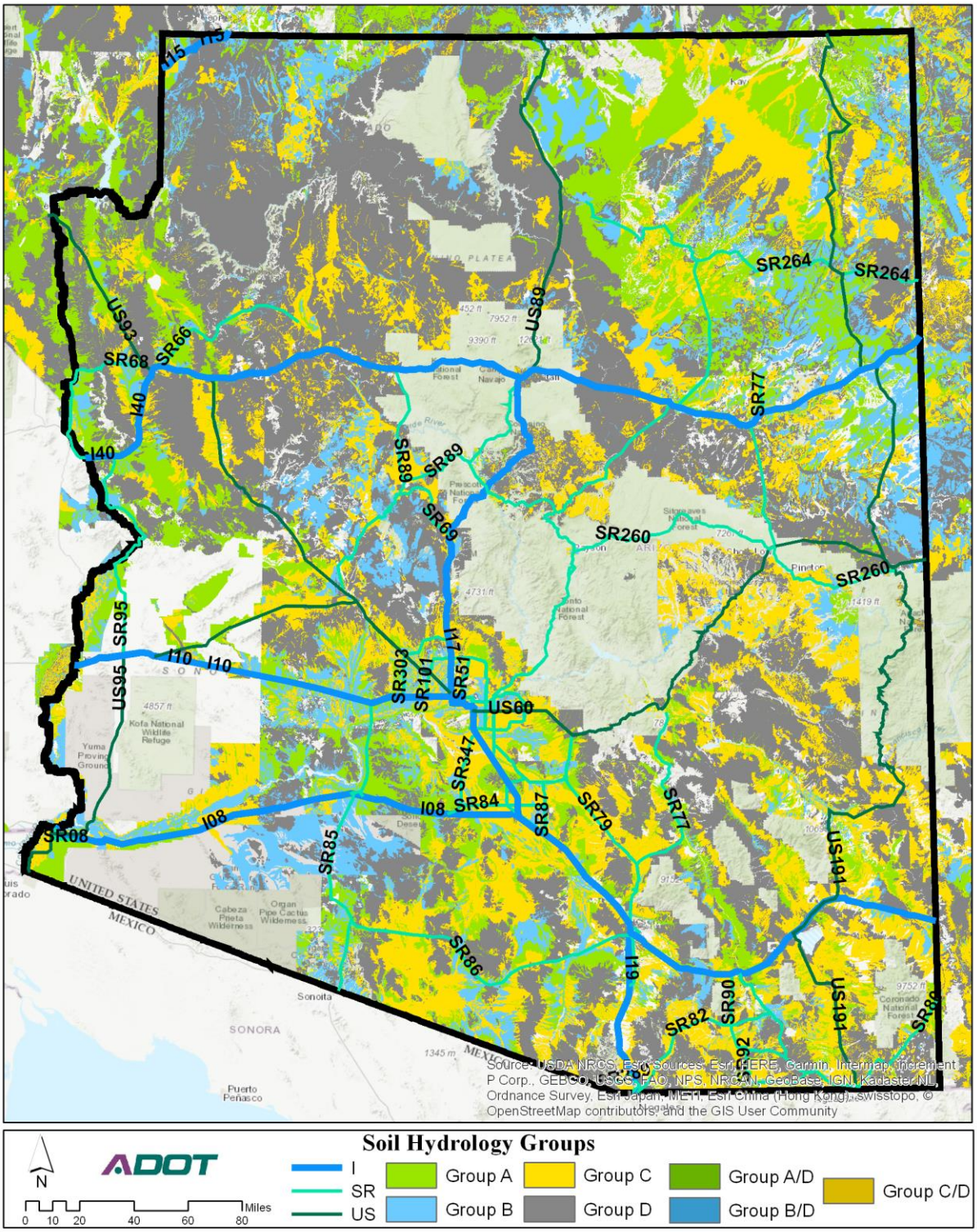
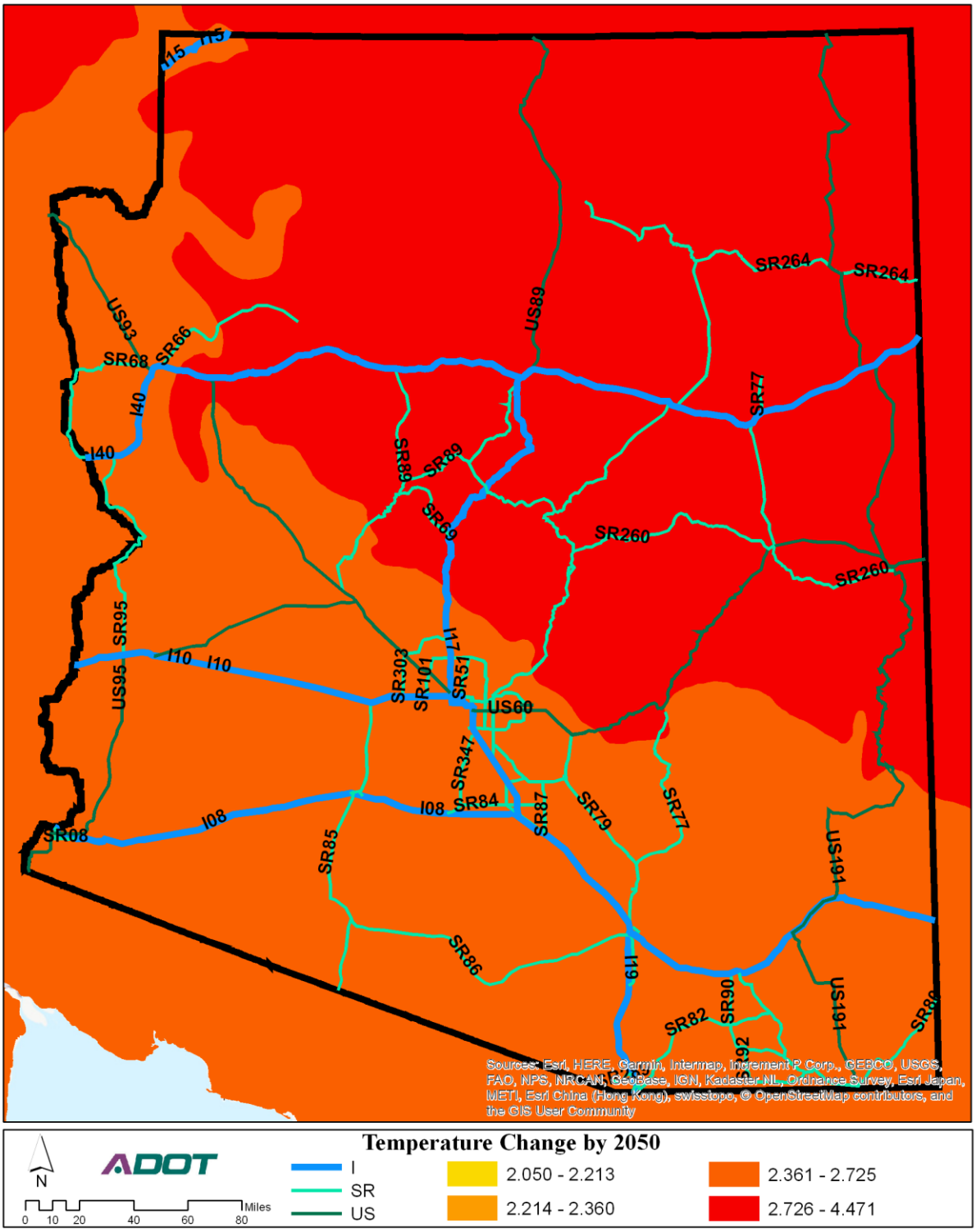


Exhibit 27: Temperature Changes by 2050



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 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, 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)	(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**: 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 Intense Precipitation.

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 templates are 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 historical weather-related incidents, future risks (climate data) and roadways, highlighting areas in the network that need closer attention.

Template Adaptation Measures: The templates are 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 resiliency of ADOT's system, not just isolating asset classes/work groups within the agency.

Some of the measures taken by other states include:

- 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 (See Appendix B for more details)

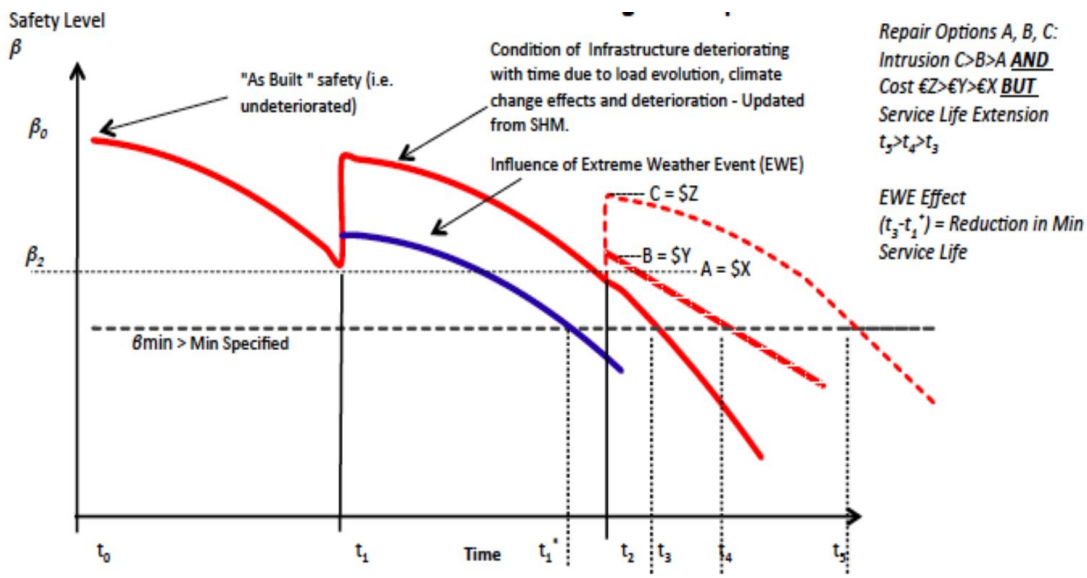
This facilitates ADOT's engineering/technical capabilities to manage risk and develop long-term asset management strategies – the assets (bridges, culverts, pavement, and roadside vegetation/stabilization) in relation to the extreme weather-climate risk of intense precipitation, system flooding, wildfires, 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 Bridge Asset Class Probabilistic Methodology Development (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"[15].

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

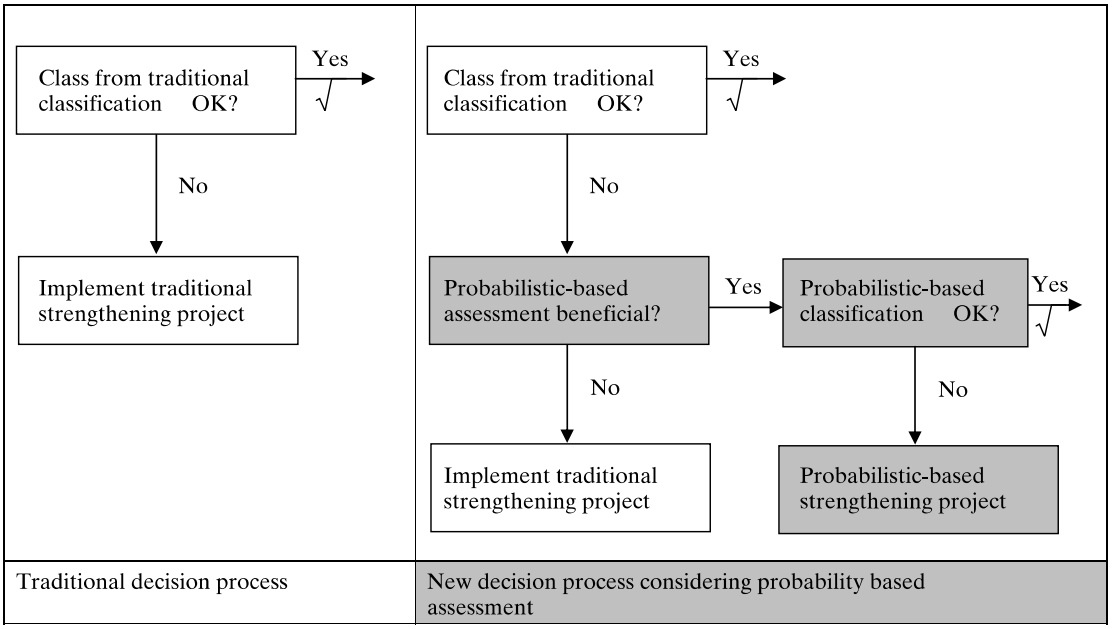


Source: - O'Connor, A. Custom diagram, 2009.

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."[16]

[15] 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
[16] 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 modelling 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.[17]

This work is complementary to this pilot project and being funded and underway as a 2019 pilot. 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.

[17] Ibid p. 63

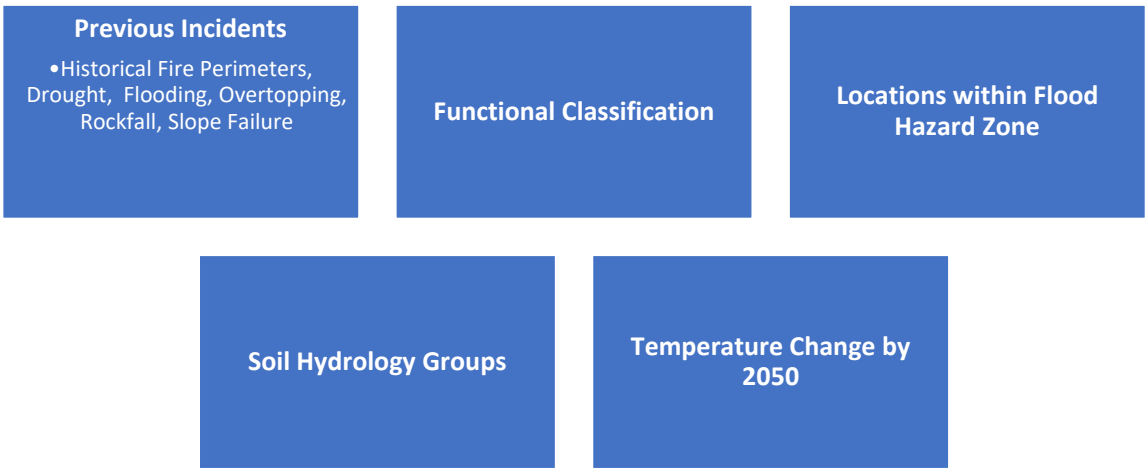
5.2 Other Key Accomplishments

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 preliminary lifecycle planning template developed provides 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 and climate adaptation into asset management processes.

As mentioned on page 48, 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



The pilot project team plans to continue a second phase of this project, which will consist of completing the lifecycle planning templates by incorporating ADOT's field tested, emerging mitigation practices, and staff recommended practices. This is to be achieved through a collaborative project team work session to finalize the lifecycle planning templates and to define a proof of concept, implementation approach and plan to be integrated in ADOT's asset management business practices.

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 template 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, as mentioned on page 62 of this report, the pilot project team focused on bridge as the main asset class for this effort given the 2019 risk level pilot project. The team recommends that future enhancements to the lifecycle planning templates include probabilistic

processes for other asset classes. Piloting a Computational Modeling for Geotechnical Engineering could serve as a method to accomplish this.[18]

- 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.

[18] 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 templates 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 is in the process to complete this requirement by November 23, 2018. This is to be included as part of ADOT's 2019 Transportation Asset Management Plan (TAMP).

The first complete **ADOT's TAMP** is currently ongoing and will be 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 events into asset management business practices will be part of this TAMP. The results of this pilot project are to be incorporated into ADOT's Final TAMP.

In the future, ADOT plans to have comprehensive resilience screening and adaptation, through the completion of:

- 2019 TAMP
- 2020 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 FHWAA 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 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. 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. both live loading 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.

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*

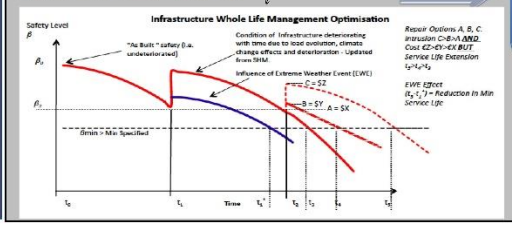
Optimize operation and maintenance of an increasingly aging stock, which is subjected to evolving loads (e.g. both live loading and climate induced loading). In response to this challenge the past decade has seen increased interest by infrastructure owners and managers in the use of probabilistic methods 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:

- 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



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 15-17, 2016 at the European Commission in Brussels, Belgium that was the catalyst for the transitional planning. 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. Working Paper)

DRAFT

A Quantitative Methodology for Probabilistic Consideration of Resilience in Infrastructure Whole Life Management

List of Figures

Figure 1 Recovery functions for (a) average prepared community, (b) not well prepared community, (c) well prepared community (Cimellaro, Reinhorn and Bruneau, 2010) 11
Figure 2 Effects of an event with intensity I_1 on the fragility curve: (a) functionality, (b) fragility curves (Solomos and Caverzan, 2014) 12
Figure 3 Effects of resourcefulness and recovery phase on the fragility curve; (a) functionality, (b) fragility curves (Solomos and Caverzan, 2014) 12
Figure 4 Effects of structural performance enhancement after recovery phase on the fragility curve; a) functionality, (b) fragility curves (Solomos and Caverzan, 2014) 13
Figure 5 Effects of retrofitting on the fragility curve and structural functionality; a) functionality, (b) fragility curves 13
Figure 6 Schematic of Time Dependent Fragility Framework (Ní Choine, 2013) 16
Figure 7 (a) Example Fragility Function, and (b) Evaluating Individual Damage-State Probabilities (Porter, Hamburger and Kennedy, 2007) 17
Figure 8 Quantitative Resilience Assessment Framework 20

DRAFT

Glossary

Acronyms

Acronym	Definition
CDF	Cumulative Distribution Function
CI	Critical Infrastructure
FORM	First Order Reliability Method
PDF	Probability Distribution Function
SORM	Second Order Reliability Method
US DHS	United States Department of Homeland Security

DRAFT

Definitions

Critical Infrastructure Systems and assets, whether physical or virtual, providing essential functions and services to Member States, whose incapacitation or destruction would have a debilitating impact on security, national economic security, national public health or safety, or any combination of these (RESILENS consortium, 2016)

Fragility In the context of this report, fragility refers to the probability of limit state exceedance of a structure for a given hazard intensity measure.

Robustness Strength, or the ability of elements, systems and other units of analysis, to withstand a given level of stress or demand without suffering degradation or loss of function (Bruneau *et al.*, 2003)

Redundancy The extent to which elements, systems, or other infrastructure units exist that are substitutable, i.e. capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality (Bruneau *et al.*, 2003).

Resourcefulness The capacity to identify problems, establish priorities, and mobilise resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis; resourcefulness can be further conceptualised as consisting of the ability to apply material (i.e., monetary, physical, technological, and informational) and human resources to meet established priorities and achieve goals (Bruneau *et al.*, 2003).

Rapidity the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption (Bruneau *et al.*, 2003).

Safe-to-fail The extent to which innovative design approaches are developed, allowing (where relevant) controlled, planned failure during unpredicted conditions, recognising that the possibility of failure can never be eliminated. This may involve new approaches to design, to complement traditional, incremental risk-based design (Park *et al.*, 2013).

Infrastructure Hierarchy Beginning with the smallest part of a system, a **component** refers to a sub-part of a structure, e.g. a beam or column. An **element** is a structure composed of a number of components, e.g. a bridge, tunnel or building. A **network** is composed of a number of elements, e.g. rail or road network. A **multi-modal network** may be composed of several networks, e.g. multiple transport networks road, rail etc.

Vulnerability Vulnerability refers to the propensity of elements and assets to suffer adverse effects when impacted by hazard events (Hughes and Healy, 2014).

DRAFT

Table of Contents

List of Figures i
Glossary ii
Executive Summary 5
1 Introduction to Infrastructure Resilience 6
1.1 What is Resilience? 6
1.2 Infrastructure Resilience 7
1.3 Why is Resilience important? 7
2 Measuring Resilience - Review of Developed Tools 9
2.1 Qualitative Tools 9
2.2 Quantitative Tools 9
3 Proposed Framework for Resilience Assessment 14
3.1 Quantitative Resilience Assessment Framework 14
4 Recommendations / Conclusions 20
References 21

DRAFT

Executive Summary

Resilience is quickly becoming a widespread method of assessing how a system, community or society responds to and recovers from a hazard. Hazards considered in this document include extreme weather and climate hazards such as extreme rainfall, flooding etc. Once 'rare' extreme weather events are now becoming increasingly frequent due to climate change, bringing with them the potential to cause significant disruption to infrastructure networks.

There are a number of qualitative and quantitative resilience ranking or measurement methods available in the literature. This report makes recommendations on the use of quantitative tools, in order to determine a system's resilience to a given event. Qualitative tools are effective indicators of a system or network's overall performance and can incorporate detail on a system's organisational structure and preparedness, as well as structural/technical capacities. However, typically, they do not provide detailed information on how an individual element or component may respond to a hazardous event. A quantitative method may thus be more suited to accurately determining a component's resilience based on its structural capacity. Quantitative analysis incorporating probabilistic fragility curves may be used to assess potentially vulnerable locations or hot spots. The resultant fragility curves can then be combined to determine resilience of an entire network or system. The capacity of the system to cope with any hazard may then be fully understood allowing recommendations to be made from both a global system perspective as well as at a local element level.

Keywords: Resilience, fragility curves, quantitative assessment.

DRAFT

1 Introduction to Infrastructure Resilience

This section gives a definition of resilience and describes the importance of infrastructure resilience.

1.1 What is Resilience?

Resilience is defined as the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of function and structure. This could be in response to a climate hazard (e.g. flooding, hurricane), natural hazard (e.g. earthquake), or a man-made hazard such as a cyber-attack or terrorism. Once 'rare' extreme weather events are now becoming increasingly frequent due to climate change, bringing with them potential to cause significant disruption to infrastructure networks. Note that the focus of this study is the resilience of infrastructure objects to climate change and extreme weather events hazards.

Multiple definitions for resilience exist in published literature, however, the description typically centres on the ability of a system to recover and return to normal function following a hazard within a reasonable time. The concept of resilience originated in the fields of psychology and psychiatry in the 1940's (Waller, 2001; Johnson and Wiechelt, 2004), and has been used widely in the areas of environmental research, physics and sociology (Holling, 1973; van der Leeuw and Aschan-Leygonie, 2000). Resilience is frequently used to describe the ability of a community to respond and adapt following a hazard. It is only recently that this term has been applied to infrastructure and more specifically, transport infrastructure. The following is a selection of definitions of resilience:

- Holling, 1973, working in the field of ecology describes resilience as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables"
- Wildavsky, 1988, refers to resilience as "the capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back"
- In a study on community resilience to seismic events, Bruneau *et al.*, 2003 defined resilience as "the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes."
- In relation to disaster response workers, the following definition is given for resilience: "Resilience describes an active process of self-righting, learned resourcefulness and growth - the ability to function psychologically at a level far greater than expected given the individual's capabilities and previous experiences." (Paton, Smith and Violanti, 2000)
- In relation to transport infrastructure, Croope and McNeil, 2011, introduced the concept of resilience as "the ability of a system to withstand or respond to changes". System resilience is also described as "the system's ability to provide and maintain an acceptable level of service when normal operations are challenged".
- With respect to infrastructure: "given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to efficiently

DRAFT

reduce both the magnitude and duration of the deviation from targeted system performance levels", (Vugrin *et al.*, 2010).

1.2 Infrastructure Resilience

Multiple definitions for resilience, and particularly infrastructure resilience are presented in the H2020 project RESILENS (RESILENS consortium, 2016). The principal definition used in the RESILENS study is taken from the US Department of Homeland Security (DHS) 'National Infrastructure Protection Plan (NIPP)', 2013 and is stated as follows: "The ability of a system or systems to survive and thrive in the face of a complex, uncertain and ever-changing future. It is a way of thinking about both short-term cycles and long-term trends: minimizing disruptions in the face of shocks and stresses, recovering rapidly when they do occur, and adapting steadily to become better able to thrive as conditions continue to change. Within the context of critical infrastructure (CI), the resilience process offers a cyclical, proactive and holistic extension of risk management practices."

A number of definitions for resilience consider the resilience life cycle; that is before, during and after a hazard. Bruneau *et al.*, 2003 describes resilience as the "ability of the system to reduce the chances of a shock, to absorb a shock if it occurs (abrupt reduction of performance) and to recover quickly after a shock (re-establish normal performance)".

Note that two approaches to resilience measurement are presented in the literature. The first is a qualitative approach which can be used to determine overall network or system resilience based on technical, organisational, social and economic aspects. Within this approach, aspects such as robustness, resourcefulness, redundancy and responsiveness are considered. The second is a quantitative method adopting fragility curves which is to be used to determine resilience of individual structural components. Note that this method focuses on the structural integrity and robustness aspects of resilience and does not consider consequences. The basis of the quantative methodology is presented in this report. Consequences and other aspects of resilience may be considered in further studies.

1.3 Why is Resilience important?

Climate studies have demonstrated that once 'rare' events are now becoming more and more frequent due to climate change effects, resulting in a need for our infrastructure to become more resilient (Hughes and Healy, 2014, Carey *et al.*, 2017). That is, a requirement for physical structures to withstand higher loading more frequently, for our emergency response organisations to react quickly, and for systems to resume normal operations quickly following a hazard/extreme event.

Godschalk, 2003, focusing on cities, describes the importance of resilience as twofold:

1. Firstly, because the vulnerability of technological and social systems cannot be predicted completely, resilience - the ability to accommodate change gracefully and without catastrophic failure - is critical in times of disaster. If we knew exactly when, where, and how disasters would occur in the future, we could engineer our systems to resist them. Since

DRAFT

hazard planners must cope with uncertainty, it is necessary to design cities that can cope effectively with contingencies.

2. Secondly, people and property should fare better in resilient cities struck by disasters than in less flexible and adaptive places faced with uncommon stress. In resilient cities, fewer buildings should collapse, fewer power outages should occur, fewer households and businesses should be put at risk, fewer deaths and injuries should occur and fewer communications and coordination breakdowns should take place.

It is therefore important that we can quantify infrastructure resilience so we can better predict how infrastructure will respond to a hazardous event and we can better prepare for these events.

DRAFT

2 Measuring Resilience - Review of Developed Tools

2.1 Qualitative Tools

A number of qualitative tools have already been developed and presented in the literature. These typically rank infrastructure according to their resilience based on a number of categories that are difficult to quantify, such as culture, leadership or adaptive capacity. Qualitative methods are typically more suited to assessment of a network or system as a whole rather than assessment of individual elements (Hughes and Healy, 2014). Qualitative methods are not intended as the focus of this report.

2.2 Quantitative Tools

2.2.1 Introduction

Quantitative tools for resilience measurement can be beneficial as they provide an objective measure for resilience so that infrastructure components or networks may be compared to one another. However, they typically focus on structural capacity of a system, element or component neglecting global structures such as organisational or economic capacity (Hughes and Healy, 2014).

2.2.2 Resilience Measurement Including Functionality and Fragility

A concept introduced by Bruneau *et al.*, 2003, is the idea of resilience as a quality measurement (*Q(t)*) varying with time. This was also used and referred to as resilience index by Nogal *et al.*, 2017. More specifically, system performance can range from 0% for no service to 100% at full service. For example, a system may be operating at 100% at time t_0, however, post-hazard at time t_1, this may be reduced to 50%. Over time, full service may be restored and if the system is completely repaired, 100% may again be achieved. Loss of resilience, *R*, or expected degradation in quality, is defined according to Equation 1 (Bruneau *et al.*, 2003; Bruneau and Reinhorn, 2007):

$$\boldsymbol{R = \int_{t_0}^{t_1} [100 - Q(t)]\, dt} \qquad \textbf{Eq. 1}$$

The quality measurement, *Q(t)* represents capacity or functionality of a system and may be expressed as follows (Bruneau and Reinhorn, 2007):

$$\boldsymbol{Q(t) = 100 - [L \cdot F \cdot \alpha_R]} \qquad \textbf{Eq. 2}$$

$$\boldsymbol{Q(t) = 1 - [L(t_{0E}) \cdot f_{rec}(t, t_{0E}, T_{RE}) \cdot \alpha_R]} \qquad \textbf{Eq. 3}$$

Where $L=L(t_{0E})$ is the magnitude of loss function defined below, $F = f_{rec}(t,t_{0E},T_{RE})$ represents the recovery function after the time of event occurrence t_{0E}, where T_{RE} is the recovery period, α_R is the functionality recovery factor (α_R = 1 for full capacity replacement, α_R > 1 if increased capacity is

required or α_R <1 if less than full capacity replacement is required). All of the above variables in Eq. 2 vary between zero and one except where specified for α_R.

The Loss Function $L(t_{0E})$

The loss function $L(t_{0E})$ is measured as the ratio of the actual loss (monetary, physical, technological and informational) at an expected performance limit state (LS) with respect to the cost of maintaining the full performance measure (FP) expressed in the same units as the loss, expressed as:

$$L(t_{0E}) = [L_{LS}(t_{0E})/FP] \cdot P_{LS}(R_{res} \geq LS) \qquad \textbf{Eq. 4}$$

Where $P_{LS}(R_{res} \geq LS)$ is the probability that the system response R_{res} will exceed the performance limit state, *LS*. This probability function is also known as the fragility function.

As described by Solomos and Caverzan, 2014, losses may be subdivided into direct (L_D) and indirect losses (L_I). Direct losses are those that occur instantaneously during the event, whilst indirect ones also have a temporal dependence. These losses may be further subdivided into economic losses (L_{DE}, L_{IE}) and casualties (L_{CE}, L_{CE}). Further detail on how to define and describe these losses is discussed in Cimellaro, Reinhorn and Bruneau, 2010 and Solomos and Caverzan, 2014.

The Recovery Function

The recovery *F* may also be described by a function f_{rec} which is dependent on recovery time T_{RE}. There are a number of options for the recovery function which can be chosen dependent on the system and society preparedness response (Solomos and Caverzan, 2014). These are linear, exponential and trigonometric as shown in Figure 1 and defined as follows:

Linear: $$f_{rec}(t) = a\left(\frac{t-t_{0E}}{T_{RE}}\right) + b$$

Exponential: $$f_{rec}(t) = ae^{\left[\frac{-b(t-t_{0E})}{T_{RE}}\right]}$$

Trigonometric: $$f_{rec}(t) = \frac{a}{2}\{1 + \cos[\pi b(t - t_{0E})/T_{RE}]\} \qquad \textbf{Eq. 5}$$

Where *a* and *b* are constant values that are calculated using curve fitting to available data sources and t_{0E} and T_{RE} are the time of event occurrence and recovery time respectively as described earlier.

DRAFT

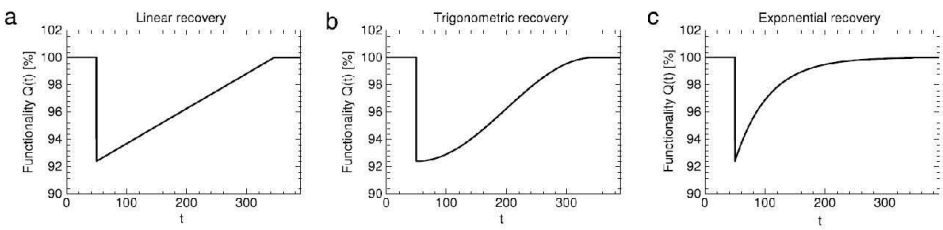


Figure 1 Recovery functions for (a) average prepared community, (b) not well prepared community, (c) well prepared community (Cimellaro, Reinhorn and Bruneau, 2010)

The type of function to be used is dependent on the information available about the system. If there is no information available regarding the preparedness, resources available and societal response, then the linear recovery function may be used (Figure 1(a)). The trigonometric function may be used when there are limited resources or there is a lack of organisational preparedness (Figure 1(b)). The exponential recovery function can be used when the societal response is driven by an initial flow of resources but then the rapidity of recovery decreases as the process nears its end (Figure 1(c)) (Cimellaro, Reinhorn and Bruneau, 2010; Solomos and Caverzan, 2014).

We have thus now established relationships between resilience and functionality, functionality and loss and also between loss and fragility, allowing component or system resilience to be calculated through the use of fragility functions and curves.

2.2.3 Functionality and Fragility Curves

Probabilistic assessment may be introduced to resilience measurement through fragility curves which have been used in a number of studies in order to determine the probability of damage following an event of specific intensity (Bruneau and Reinhorn, 2007; D'Ayala *et al.*, 2014; Solomos and Caverzan, 2014; Barberis *et al.*, 2015; Ní Choine, O'Connor and Padgett, 2015; Guidotti *et al.*, 2016, Nogal *et al.*, 2017). Fragility curves are essentially cumulative distribution functions indicating probability of limit state exceedance of a structure for a given hazard intensity measure (Guidotti *et al.*, 2016), and usually "take the form of lognormal cumulative distribution functions, having a median value ϑ and logarithmic standard deviation, β" (Porter, Hamburger and Kennedy, 2007).

The European Commission's "Review on resilience in literature and standards for critical built-infrastructure" (Solomos and Caverzan, 2014) builds on fragility curves first presented in Bruneau and Reinhorn, 2007 in relation to earthquake resilience, and develops them further. Fragility curves may be defined as follows (Barron-Corvera, 2000; Reinhorn, Barron-Corvera and Ayala, 2001, Bruneau and Reinhorn, 2007):

$$\boldsymbol{Fragility} = \boldsymbol{F_Y} = \boldsymbol{P_{LS}\{R_{res} \geq LS|I\}} \qquad \textbf{Eq. 6}$$

where R_{res} is the response parameter (damage, deformation, displacement, force, velocity, acceleration etc.), LS is the limit state response parameter linked to the damage, and I is the intensity of the event.

Following on from this, fragility curves for the system may be constructed and system functionality over time may be assessed (Solomos and Caverzan, 2014). Functionality curves describe system performance or quality, *Q(t)*, before, during and after a hazardous event. They can also demonstrate the influence of retrofitting and resourcefulness as shown in the following figures taken from Solomos and Caverzan, 2014. In Figure 2(a), the functionality over time is presented. The structure remains undamaged up to time t_0 when an event of intensity I_1 occurs. Until that time, the fragility of the structure is represented by the blue curve in Figure 2(b). Due to the event, the system's fragility is increased, and is now represented by the red line in Figure 2(b). Therefore, if another event of intensity I_1 occurs, the fragility, or probability of damage to the structure is higher than for the undamaged structure.

Figure 3 illustrates how repairs progressively shift the fragility curve back to the original condition that existed before the instant t_0 and finally attained at t_1. This requires financial investment (resourcefulness). If additional investment is available, it is possible to increase the functionality to above the pre-event condition with a reduced fragility, thus reducing the likelihood of damage from a similar hazard of such intensity as in Figure 4.

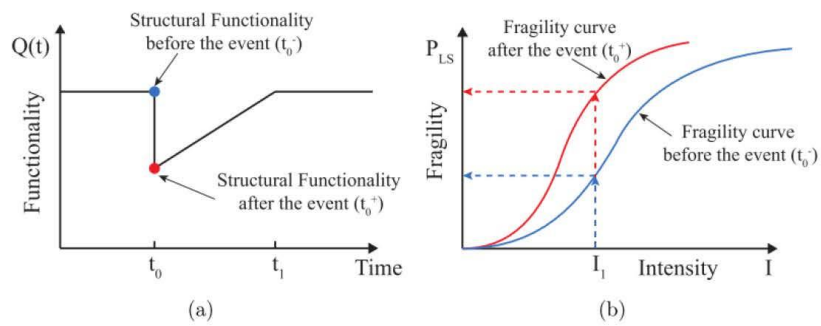


Figure 2 Effects of an event with intensity I_1 on the fragility curve: (a) functionality, (b) fragility curves (Solomos and Caverzan, 2014)

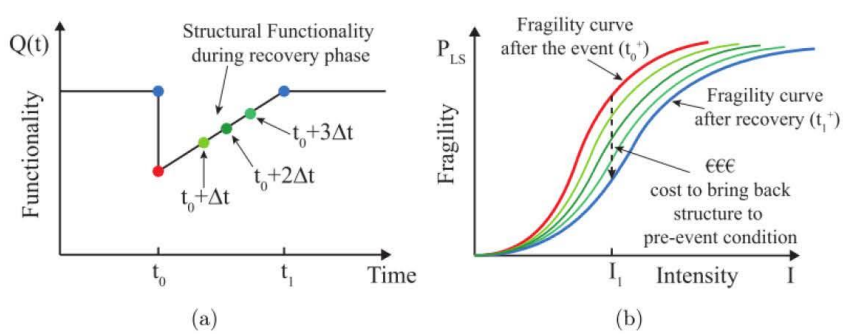


Figure 3 Effects of resourcefulness and recovery phase on the fragility curve; (a) functionality, (b) fragility curves (Solomos and Caverzan, 2014)

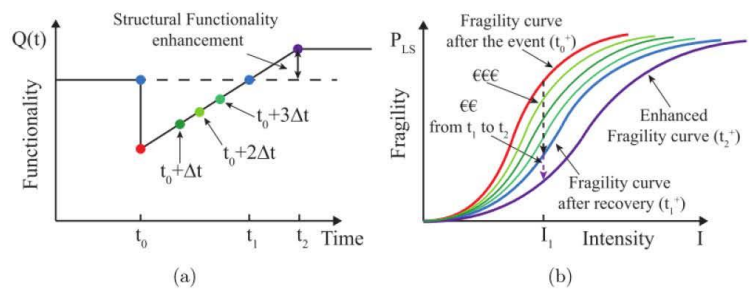


Figure 4 Effects of structural performance enhancement after recovery phase on the fragility curve; a) functionality, (b) fragility curves (Solomos and Caverzan, 2014)

The benefit of retrofitting can be seen in Figure 5 where the functionality has been increased prior to the event occurring at time t_0. If an event of intensity I_1 was to occur, the damage occurring should now be reduced when compared to the structure prior to retrofit.

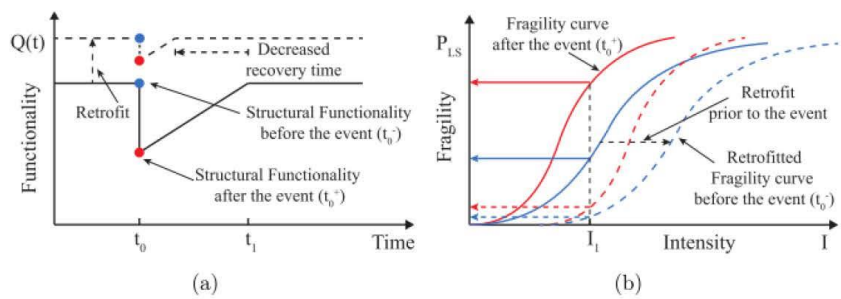


Figure 5 Effects of retrofitting on the fragility curve and structural functionality; a) functionality, (b) fragility curves

3 Proposed Framework for Resilience Assessment

3.1 Quantitative Resilience Assessment Framework

Network components or elements of interest may be assessed using quantitative methods adopting fragility curves and functionality curves. Fragility curves incorporate probabilistic assessment of individual elements as they represent the probability that the response of a structure exceeds a given threshold (of damage) for an event of specific intensity. The general expression for fragility is as follows:

$$P_{failure} = P((Demand > Capacity)|IM) \qquad \textbf{Eq. 7}$$

where *IM* is the hazard intensity measure.

This can also be extended to a network or system resilience assessment by combining fragility curves. Following the theory and methodology presented in Section 2.2.2, the following section demonstrates how to construct fragility curves which contribute to the resilience calculations.

3.1.1 Probabilistic Modelling Using Fragility Curves

Fragility curves for an infrastructure asset can be derived from a number of methods including field data, analytical methods or expert opinion. Ideally, field data on the component or element of interest at varying levels of demand would be available (Porter, Hamburger and Kennedy, 2007). However, field data can be expensive and difficult to obtain and so it will often be unavailable. In this case, fragility curves may be developed from alternative sources such as using expert opinion or numerical analysis (Porter, Hamburger and Kennedy, 2007; Jaiswal, Wald and D'Ayala, 2011).

For this study, it is proposed that fragility curves will be developed initially using numerical analysis using the following methodology as described in detail in (Ní Choine, 2013 and D'Ayala *et al.*, 2015) and summarised here as per Figure 6:

1. Selection of hazard or loading type
2. Development of a group of stochastic models representing the response at various points along the service life of the infrastructure element
3. Generation of (ideally stochastic) capacity models at various points along the service life of the infrastructure element
4. Generation of probabilistic demand model
5. Formulation of time dependent fragility curves

The first step is to establish the type of hazard or loading to be assessed, and generate a number of loading values within an expected range at the location of interest. A series of finite element models of the infrastructure element can then be developed, pairing the loading models randomly to each structural model. The maximum responses of the components thought to contribute to the vulnerability of the infrastructure are recorded. The pristine response models are then modified to

DRAFT

account for deterioration and the process is repeated at various points along the service life of the structure.

Probabilistic loading demand models are established for the component at each of the discrete points in time considered in the analysis. This provides a probabilistic model for each of the component demands for a given loading quantity. Probabilistic capacity models are also developed for each of the component limit states based on experimental results or expert opinion based on observed damage during past hazards. Similar to the demand models, the capacity models are developed at each service life point considered in the analysis. The lognormal distribution is typically used here to model demand and capacity as it fits a variety of component failure data well. It is a non-negative distribution which can also fit normally distributed data if required (Porter, Hamburger and Kennedy, 2007). If the demand and capacity are assumed to be lognormally distributed at each point in time along the infrastructure's service life (Cornell *et al.*, 2002; Ghosh and Padgett, 2010, 2012), the time dependent component fragility can be expressed as (Melchers, 1999):

$$P\left(\frac{Demand(t)}{Capacity(t)} > 1.0|IM\right) = \Phi\left(\frac{\ln\left(\frac{S_D(t)}{S_C(t)}\right)}{\sqrt{\beta_{D|IM}^2(t)+\beta_c^2(t)}}\right) \qquad \textbf{Eq. 8}$$

Where $S_D(t)$ and $\beta_{D|IM}(t)$ are the time dependent median and dispersion of the fragility function, $S_c(t)$ and $\beta_c(t)$ are the time dependent median and dispersion of the lognormally distributed component capacity and Φ is the standard normal cumulative distribution function.

For cases where the loading and capacity variables cannot be appropriately modelled by lognormal distributions, alternative reliability analysis protocols should be followed. A simulation procedure should be followed whereby the intensity measure (or hazard model) is varied over time, and the associated fragility (or failure probability) is calculated, e.g. using FORM, SORM or simulation (Connolly and O'Connor, 2017).

DRAFT

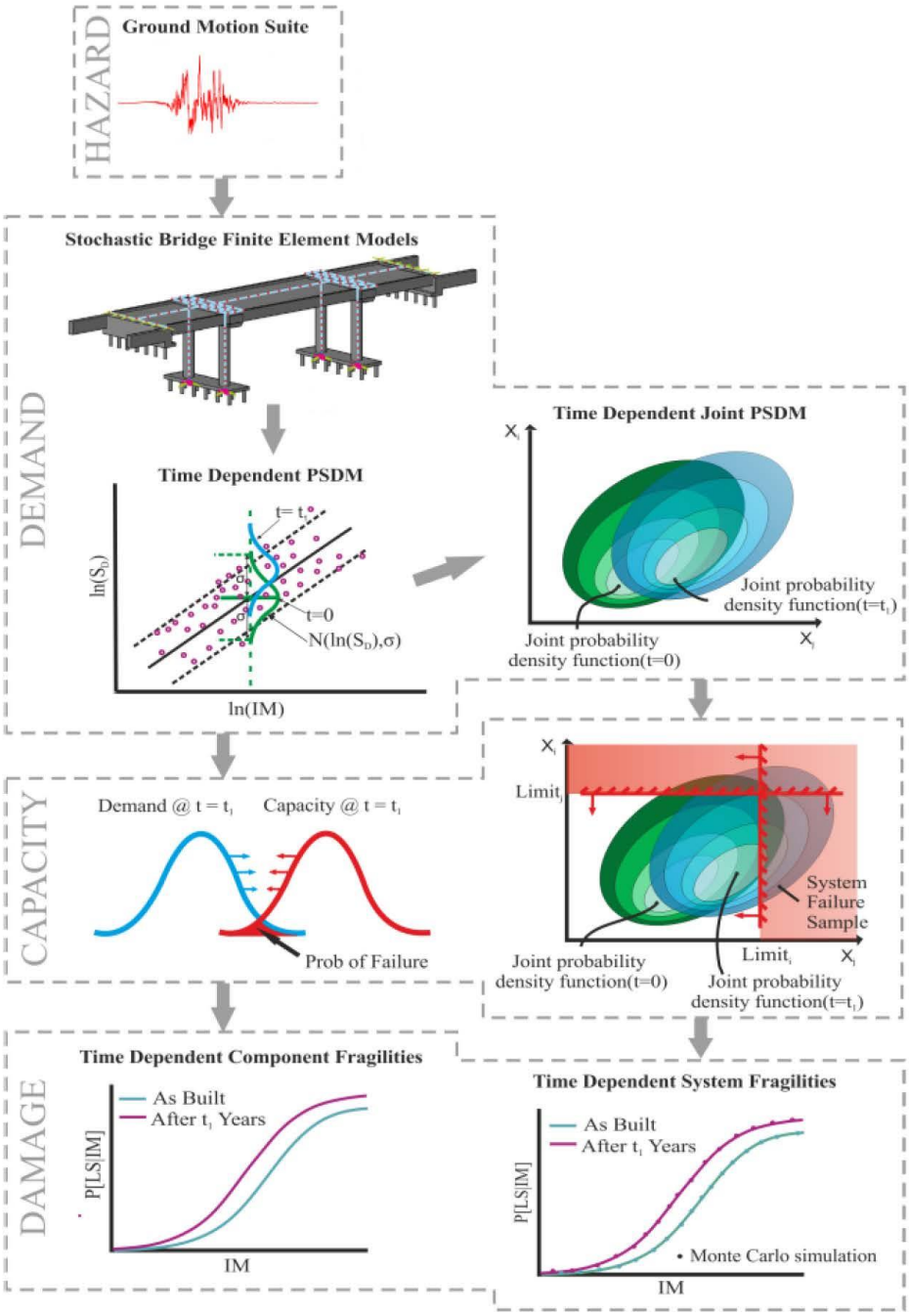


Figure 6 Schematic of Time Dependent Fragility Framework (Ní Choine, 2013)

3.1.1.1 Selection of Loading Type

It is important to establish the type of loading to be applied to the model. This will vary depending on the type of hazard assessed. For example, for an earthquake, this may be a set of ground motions. In the case of traffic network modelling, it may be additional traffic on the network due to failure of a component or closure of a route. It is important that the loading modelled covers the range of intensity levels expected at the location of interest.

3.1.1.2 Generation of Stochastic Models

The next step is to generate a number of statistically significant yet nominally identical stochastic models of the component of interest, at each point in time along the service life of the structure. This is done by sampling on the probability distributions of uncertain structural parameters such as concrete strength, steel strength, foundation stiffness etc. Some parameters are assumed to deteriorate with time whilst others are assumed constant over the service life of the infrastructure. Each of the loading files is applied to each of the finite element models in order to obtain a probabilistic distribution of the structural response over the service life of the component (Shinozuka *et al.*, 2003; Ní Choine, 2013).

3.1.1.3 Component Limit States

Once the loading has been determined and the simulations have been performed, the next step is to determine how to quantify the damage caused by the hazard/loading. Damage states can be subjective and vary in the literature. For example, three damage states were used in Barberis *et al.*, 2015; no damage; moderate damage; and complete damage. Four damage states (slight, moderate, extensive and complete damage) as described in FEMA, 2005 were used in Ní Choine, O'Connor and Padgett, 2015. In this way, an entire system may be categorised based on how damage to a specific component contributes to damage of the overall system. An example cumulative distribution fragility function for a particular damage state is shown in Figure 7(a) and the calculation of the probability that a component will be in damage state "*i*" at a particular level of demand, d is shown in Figure 7(b).

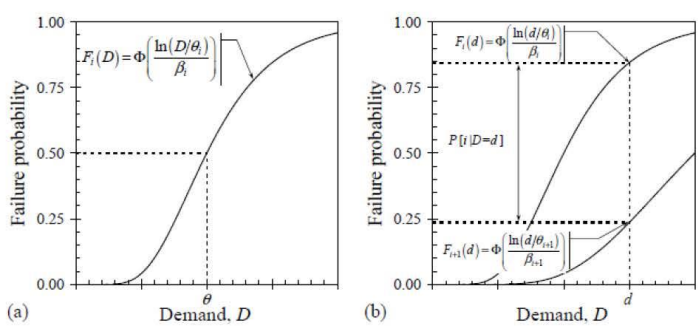


Figure 7 (a) Example Fragility Function, and (b) Evaluating Individual Damage-State Probabilities (Porter, Hamburger and Kennedy, 2007)

The component fragility functions may be combined to determine an overall level of system damage. However, it may be difficult to compare the consequences of damage of one component to another. Components may be categorised according to their contribution to the overall system damage which can inform repair and maintenance work as described in Ramanathan and Narayan, 2012. In this work which focuses on bridge assessment, primary components may be categorised as those that affect the vertical stability and load carrying capacity of the bridge, whilst secondary components may be defined as those that do not affect the vertical stability of the structure.

3.1.1.4 Determining Resilience from Fragility Curves

In order to determine system or network resilience, functionality curves may be generated from the fragility curves, and resilience may be quantified from this. As demonstrated in Figure 2, functionality curves may be used to describe system or network functionality or capacity before, during and after a hazardous event. If fragility is already determined, functionality may then be calculated incorporating losses using Eq. 2. Loss of resilience, *R*, and thus resilience can subsequently be calculated using Eq. 1.

3.1.1.5 Overall System response to component failure

Failure of a component may have varying impact on the system as whole. As stated earlier, infrastructure components may be classified as primary or secondary depending on the impact of their failure on the overall damage to the system. If extensive or complete damage to a component would affect the stability of the infrastructural element, then it is considered a primary component. If damage to a component would not affect stability of the infrastructure, then it may be categorised as a secondary component. In this manner, the effect of failure of a component on the overall system may be determined similarly.

3.1.1.6 Generate System/Network fragility curves

Component fragility curves may be combined to generate fragility curves at a network level by summing the failure probabilities for each component in the network, provided component failures are independent mutually exclusive events. That is, the system analysis involves a logical consideration of the relevant potential failure events at a given limit state.

So, the probability of the limit state being exceeded for the network is dependent on the sum of the probabilities of the limit states being exceeded for all mutually exclusive *k* components in a series network.

$$\underbrace{P_{LS}}_{\text{Network}} = \sum_k \underbrace{P_{LS}}_{\text{Component}} \qquad \textbf{Eq. 9}$$

Note that the system probability value determined from Eq. 9 could theoretically be greater than 1.0, therefore, care should be taken in the logical consideration of the relevant components.

Once the network fragility curves are developed, network losses, functionality and resilience may then be calculated using Equations 1, 2 and 3. This calculation may also be extended to determine system functionality and resilience.

DRAFT

4 Recommendations / Conclusions

This report presents a quantitative methodology for resilience assessment. The methodology employs detailed structural data on system components, to perform the quantitative assessment employing fragility curves. This methodology may also be extended to system or network level, combining component fragilities to determine overall network resilience.

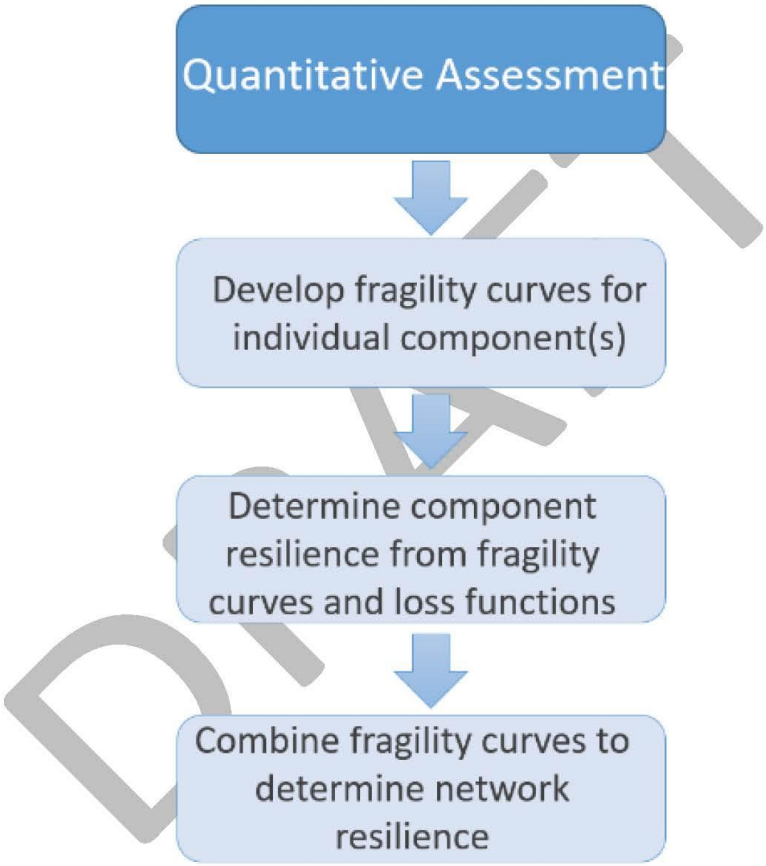


Figure 8 Quantitative Resilience Assessment Framework

References

Alshehri, S. A., Rezgui, Y. and Li, H. (2014) 'Delphi-based consensus study into a framework of community resilience to disaster', *Natural Hazards*, 75(3), pp. 2221–2245. doi: 10.1007/s11069-014-1423-x.

Barberis, F. *et al.* (2015) 'Fragility Curves of Restoration Processes for Resilience Analysis', in *12th International Conference on Applications of Statistics and Probability in Civil Engineering*. Vancouver, Canada, pp. 1–8. doi: 10.14288/1.0076254.

Barron-Corvera, R. (2000) *Spectral evaluation of seismic fragility of structures*. State University of New York at Buffalo.

Bruneau, M. *et al.* (2003) 'A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities', *Earthquake Spectra*, 19(4), pp. 733–752. doi: 10.1193/1.1623497.

Bruneau, M. and Reinhorn, A. (2007) 'Exploring the concept of seismic resilience for acute care facilities', *Earthquake Spectra*, 23(1), pp. 41–62. doi: 10.1193/1.2431396.

'BS (British Standard) 65000 - Guidance for Organisational Resilience' (2014).

Carey, C. *et al.* (2017) *Deliverable 6.3 - Report on benefits of critical infrastructure protection*. Available at: http://rain-project.eu/wp-content/uploads/2017/08/6.3_-FInal.pdf.

Chang, S. E. and Shinozuka, M. (2004) 'Measuring improvements in the disaster resilience of communities', *Earthquake Spectra*, 20(3), pp. 739–755. doi: 10.1193/1.1775796.

Cimellaro, G. P., Reinhorn, A. M. and Bruneau, M. (2010) 'Framework for analytical quantification of disaster resilience', *Engineering Structures*. Elsevier Ltd, 32(11), pp. 3639–3649. doi: 10.1016/j.engstruct.2010.08.008.

Connolly, L. and O'Connor, A. (2017) *Deliverable 2.1 Guideline for Probability Based Multi Criteria Performance Optimisation of Railway Infrastructure*. Dublin.

Cornell, C. A. *et al.* (2002) 'Probabilistic Basis for 2000 SAC Federal Emergency Management Agency Steel Moment Frame Guidelines', *Journal of Structural Engineering*, 128(4), pp. 526–533. doi: 10.1061/(ASCE)0733-9445(2002)128:4(526).

Croope, S. and McNeil, S. (2011) 'Improving Resilience of Critical Infrastructure Systems Postdisaster', *Transportation Research Record: Journal of the Transportation Research Board*, 2234, pp. 3–13. doi: 10.3141/2234-01.

D'Ayala, D. *et al.* (2014) 'Guidelines for Analytical Vulnerability Assessment of Low / Mid-Rise Buildings', (FEBRUARY).

D'Ayala, D. *et al.* (2015) 'INFRARISK: Novel Indicators for identifying critical Infrastructure at Risk from Natural Hazards - Deliverable D3.2 - Fragility Functions Matrix', (603960), p. 166. Available at: http://www.infrarisk-fp7.eu/sites/default/files/docs/INFRARISK_Del.3.2–Fragility_Functions_Matrix_final.pdf.

Ettouney, M. *et al.* (2011) *Integrated Rapid Visual Screening of Buildings*.

FEMA (2005) 'HAZUS-MH Software'. Washington D.C.

DRAFT

Ghosh, J. and Padgett, J. E. (2010) 'Aging Considerations in the Development of Time-Dependent Seismic Fragility Curves', *Journal of Structural Engineering*, 136(12), pp. 1497–1511. doi: 10.1061/(ASCE)ST.1943-541X.0000260.

Ghosh, J. and Padgett, J. E. (2012) 'Impact of multiple component deterioration and exposure conditions on seismic vulnerability of concrete bridges', *Earthquakes and Structures*, 3(5), pp. 649–673. doi: 10.12989/eas.2012.3.5.649.

Godschalk, D. R. (2003) 'Urban Hazard Mitigation: Creating Resilient Cities', *Natural Hazards Review*, 4(3), pp. 136–143. doi: 10.1061/(ASCE)1527-6988(2003)4:3(136).

Guidotti, R. *et al.* (2016) 'Modeling the resilience of critical infrastructure: the role of network dependencies', *Sustainable and Resilient Infrastructure*. Taylor & Francis, 1(3–4), pp. 153–168. doi: 10.1080/23789689.2016.1254999.

Holling, C. S. (1973) 'Resilience and Stability of Ecological Systems', *Annu.Rev.Ecol.Syst.*, 4, pp. 1–23. doi: 10.1146/annurev.es.04.110173.000245.

Hughes, J. F. and Healy, K. (2014) *Measuring the resilience of transport infrastructure*. Available at: http://www.nzta.govt.nz/assets/resources/research/reports/546/docs/546.pdf.

Jaiswal, K., Wald, D. and D'Ayala, D. (2011) 'Developing empirical collapse fragility functions for global building types', *Earthquake Spectra*, 27(3), pp. 775–795. doi: 10.1193/1.3606398.

Johnson, J. L. and Wiechelt, S. a (2004) 'Introduction to the special issue on resilience.', *Substance use & misuse*, 39(5), pp. 657–670. doi: 10.1081/JA-120034010.

Jonkeren, O. and Giannopoulos, G. (2014) 'Analysing Critical Infrastructure Failure with a Resilience Inoperability Input–Output Model', *Economic Systems Research*, 26(1), pp. 39–59. doi: 10.1080/09535314.2013.872604.

van der Leeuw, S. E. and Aschan-Leygonie, C. (2000) 'A long-term perspective on resilience in socio-natural systems', *Workshop on system shocks - system resilience*, World Scie, pp. 1–32. doi: 10.1142/9789812701404_0013.

Lian, C. and Haimes, Y. Y. (2006) 'Managing the risk of terrorism to interdependent infrastructure systems through the dynamic inoperability input–output model', *Systems Engineering*, 9(3), pp. 241–258. doi: 10.1002/sys.20051.

Melchers, R. E. (1999) *Structural Reliability Analysis and Prediction*. 2nd edn. Edited by Wiley. Wiley.

'National Infrastructure Protection Plan (NIPP)' (2013) *Department of Homeland Security*, pp. 1–57.

Ní Choine, M. (2013) *Seismic Reliability Assessment of Aging Integral Bridges*. Trinity College Dublin.

Ní Choine, M., O'Connor, A. J. and Padgett, J. E. (2015) 'Comparison between the Seismic Performance of Integral and Jointed Concrete Bridges', *Journal of Earthquake Engineering*, 19(1), pp. 172–191. doi: 10.1080/13632469.2014.946163.

Nogal, M. *et al.* (2017) 'Novel Probabilistic Resilience Assessment Framework of Transportation Networks against Extreme Weather Events', *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, 3(3), p. 4017004. doi: 10.1061/AJRUA6.0000908.

Nogal, M., Napoles, O. M. and O'Connor, A. (2016) 'Understanding the Vulnerability of Traffic Networks by Means of Structured Expert Judgment Elicitation', in *Proceedings of the Irish Research*

DRAFT

Transport Network. Dublin.

Okoli, C. and Pawlowski, S. D. (2004) 'The Delphi method as a research tool: an example, design considerations and applications', *Information & Management*, 42(1), pp. 15–29. doi: 10.1016/j.im.2003.11.002.

Park, J. *et al.* (2013) 'Integrating risk and resilience approaches to catastrophe management in engineering systems', *Risk Analysis*, 33(3), pp. 356–367. doi: 10.1111/j.1539-6924.2012.01885.x.

Paton, D., Smith, L. and Violanti, J. (2000) 'Disaster response: risk, vulnerability and resilience.', *Disaster Prevention and Management: An International Journal*, 9(3), pp. 173–179. doi: 10.1108/09653560010335068.

Porter, K., Hamburger, R. and Kennedy, R. (2007) 'Practical Development and Application of Fragility Functions', *Structural Engineering Research Frontiers*, pp. 1–16. doi: 10.1061/40944(249)23.

Ramanathan, K. and Narayan (2012) *Next Generation Seismic Fragility Curves for California Bridges Incorporating the Evolution in Seismic Design Philosophy*. Georgia Institute of Technology. Available at: https://smartech.gatech.edu/bitstream/handle/1853/44883/ramanathan_karthik_n_201208_r.pdf.

Reinhorn, A., Barron-Corvera, R. and Ayala, A. (2001) 'Spectral Evaluation of Seismis Fragility of Structures', in *ICOSSAR*.

RESILENS consortium (2016) 'Methods for Resilience Assessment', p. 138. Available at: resilens.eu/wp-content/uploads/2016/06/D2.2-Methods-for-Resilience-Assessment-Final.pdf.

Rinaldi, S. M., Peerenboom, J. P. and Kelly, T. K. (2001) 'Identifying, understanding, and analyzing critical infrastructure interdependencies', *IEEE Control Systems Magazine*, 21(6), pp. 11–25. doi: 10.1109/37.969131.

Sempier, T. T. *et al.* (2010) 'Coastal Community Resilience Index: A Community Self-Assessment', (November), p. 19.

Setola, R., De Porcellinis, S. and Sforna, M. (2009) 'Critical infrastructure dependency assessment using the input-output inoperability model', *International Journal of Critical Infrastructure Protection*. Elsevier B.V., 2(4), pp. 170–178. doi: 10.1016/j.ijcip.2009.09.002.

Sharifi, A. (2016) 'A critical review of selected tools for assessing community resilience', *Ecological Indicators*. Elsevier Ltd, 69, pp. 629–647. doi: 10.1016/j.ecolind.2016.05.023.

Shinozuka, M. *et al.* (2003) 'Resilience of Integrated Power and Water Systems', *Seismic Evaluation and Retrofit of Lifeline Systems*, pp. 65–86. Available at: https://www.researchgate.net/profile/G_Cimellaro/publication/268203195_Multi-Dimensional_Fragility_of_Structures_Formulation_and_Evaluation/links/5527ace20cf2e486ae412302/Multi-Dimensional-Fragility-of-Structures-Formulation-and-Evaluation.pdf?origin=publ.

Solomos, G. and Caverzan, A. (2014) *Review on resilience in literature and standards for critical built-infrastructure*. doi: 10.2788/872668.

Verhagen, A. P. *et al.* (1998) 'The Delphi list: A criteria list for quality assessment of randomized clinical trials for conducting systematic reviews developed by Delphi consensus', *Journal of Clinical Epidemiology*, 51(12), pp. 1235–1241. doi: 10.1016/S0895-4356(98)00131-0.

DRAFT

de Villiers, M. R., de Villiers, P. J. T. and Kent, A. P. (2005) 'The Delphi technique in health sciences education research', *Medical Teacher*, 27(7), pp. 639–643. doi: 10.1080/13611260500069947.

Vugrin, E. D. *et al*. (2010) 'A Framework for Assessing the Resilience of Infrastructure and Economic Systems', in *Sustainable and resilient critical infrastructure systems*. Berlin: Springer-Verlag, pp. 77–116. doi: 10.1007/978-3-642-11405-2_3.

Waller, M. a (2001) 'Resilience in ecosystemic context: evolution of the concept', *The American Journal of Orthopsychiatry*, 71(3), pp. 290–297. doi: 10.1037/0002-9432.71.3.290.

Wildavsky, A. (1988) *Searching for Safety*. New Brunswixk, NJ: Transaction Publishers.

Zobel, C. W. (2011) 'Representing perceived tradeoffs in defining disaster resilience', *Decision Support Systems*. Elsevier B.V., 50(2), pp. 394–403. doi: 10.1016/j.dss.2010.10.001.

DRAFT

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 commences
- System resileince 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

(See pages 95 – 102)

ADOT

An Arizona Management System Agency

Infrastructure Delivery and Operations

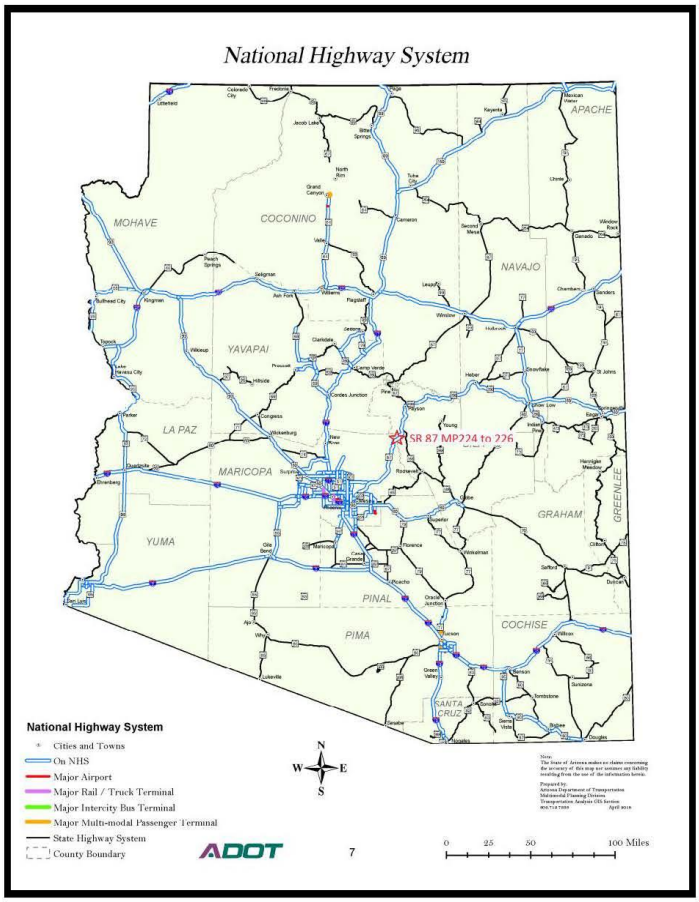
Douglas A. Ducey, Governor
John S. Halikowski, Director
Dallas Hammit, State Engineer
Steve Boschen, Division Director

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



OVERVIEW

TABLE 1 – Summary of ER projects on SR 87 MP 224 to 226

Project No.	TRACS	Begin MP	End MP	Year	Construction Scope
ER-087-224	H6745 01C	224	226	2005	SLOPE STABILIZATION
ER-087-B-NFA	H7035 01C	224.02	224.92	2008	EMBANKMENT AND SLOPE REPAIR
ER-087-B(201)A	H7700 01C	223.92	224.96	2009	SLOPE STABILIZATION
ER-087-B(208)A	H8175 01C	224.21	224.42	2010	SLOPE UNLOADING
ER-087-B(207)A	H8072 01C	224	225	2011	SLOPE STABILIZATION

Heavy rains in 2004 and 2005 caused the cut slopes and soil nail walls between MP 224 and MP 226 began to experience localized failures. Project ER-087-224, TRACS No. H6745 01C ($2.4M) removed several of the failed soil nail walls and regraded the cut slopes to reduce the steepness of the slope grades. The excavated material was utilized to buttress an existing 100+ ft embankment with 1.5:1 (H:V) slope rate. This embankment was exhibiting signs of failure with tension cracking affecting the pavement.

Project ER-087-B-NFA, TRACS No. H7035 01C ($5.1M) began construction in March, 2008. The project removed additional soil nail walls that had failed, flattened the existing cut slopes, and continued the embankment buttress stabilization. During the early portion of the project, and after a period of heavy precipitation events, a landslide at MP 224.3 closed the highway for approximately 1 week. Additional excavation, soil-nail wall removal, and embankment construction was added to the project. A total of 89 soldier piles (30" diameter x 43' deep) and 9 drilled shafts (48" diameter x 65' deep) were also added to the project. A total of approximately 186,300 cubic yards (CY) of material was excavated, and utilized to improve stability of the 100+ ft embankment.

Project ER-087-B(201)A, TRACS No. H7700 01C ($1.8M), was constructed in 2009 as a result of the geotechnical investigation and monitoring. The drilled shafts and soldier piles previously installed in 2008 as emergency mitigation measures were being displaced and bent by a continued slow slide movement. A total of 26 drilled shaft shear piles (66" diameter x 73' deep) were installed in the landslide, and approximately 75,000 CY of material was excavated and used to construct additional NB embankment buttress near MP 226 in anticipation of a possible alignment shift. A rock buttress was placed behind the SB barrier between MP 224.3 (STA 2816+00) and MP 224.4 (STA 2824+00) to aid in stabilizing the local slide at that location. A separate rock buttress was placed behind the SB barrier from MP 224.0 (STA 2803+00) to MP 224.1 (STA 2805+00) to stabilize a partially failed soil nail wall. The 12-foot diameter multiplate pipe in Slate Creek (MP 226) was extended.

Heavy rains in January 2010 resulted in a change in the slide conditions and the slide began to show an increase in the rate of movement due to increased pore water pressure heads in the perched groundwater trapped in the landslide near STA. 2820. To save the shear piles, Project ER-087-B(208)A,

TRACS No. 8175 01C, excavated approximately 62,000 CY above the shear piles, and installed a series of horizontal slope drains to reduce the groundwater in the slopes adjacent to the roadway..

Project ER-087-B(207)A, TRACS No. H8072 01C ($1.5M) was constructed in February of 2012. This project removed the Northbound (NB) upper tiered wall and a portion of the damaged NB lower wall near MP 224.2. An estimated 124,000 CY of material were excavated and used to construct additional NB embankment buttress near MP 226.

Figure 2 – Southbound Slope Failure

Figure 3 – Northbound Slope Failure

ROOT CAUSE ANALYSIS

Stability failure of the slopes is attributed to global stability failure due to low shear strength soil and periods of high rainfall. Saturation of the low plasticity silt and clay deposits behind and under the earth retaining structures creates lateral forces and weakens the shear strength of the soils. Saturation of the site soils is increased due to the fractured, inconsistent depositional history of the site soils due to historic landslides. Fissures and soil physical property changes within the soil mass creates zones of water infiltration and retention. Retention of water within the soil mass creates excessive lateral forces which have caused catastrophic failure of the slopes during and after periods of heavy precipitation.

Heavy rainfall and catastrophic failure of the slopes have shown a strong cause and effect relationship. Piezometer instrumentation has documented significant increases in groundwater elevation following periods of heavy rainfall. Loss of shear strength of the saturated soil combined with lateral forces due to saturation is the root cause of the slope failures.

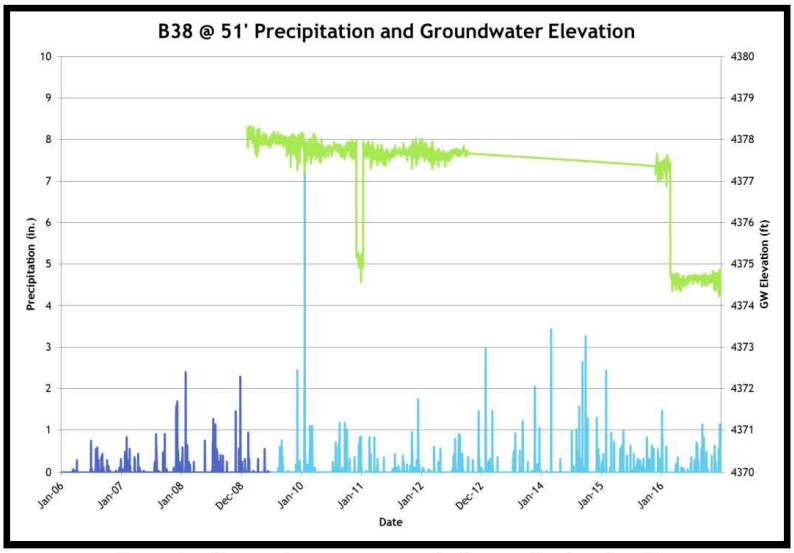


Figure 4 – Piezometer measurement of groundwater elevation

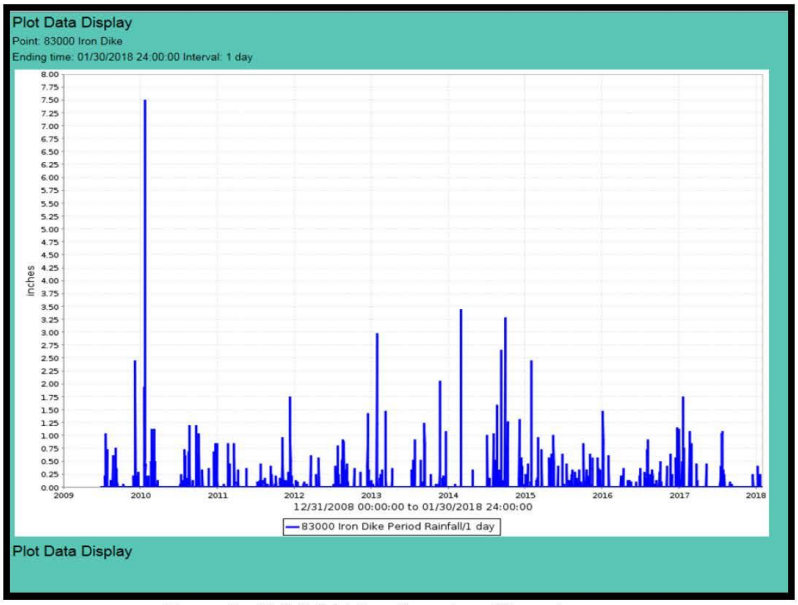


Figure 5 – Rainfall history from Iron Dike rain gauge

RISK ASSESSMENT

The fractured, inconsistent deposition of site soils during historic landslide events combined with low plasticity silts and clays physical properties of site soils creates high risk for future slope instability. The low plasticity silts and clays readily absorb water and exhibit low to no shear strength when saturated. The landslide depositional history has created fissures and high permeability zones which allow a high rate of permeability. Saturation of site soils must be mitigated to limit risk of future slope stability failures.

Mobility impacts to SR 87 are probable if slope stability failures occur. SR 87 is a major commerce corridor between Phoenix and Payson. In March of 2008, slope failure closed SR 87 for approximately 1 week resulting in loss of commerce and monetary impacts to the travelling public.

Continued monitoring is recommended to identify slope movement and other indications of instability. Increased frequency of monitoring is recommended following periods of rainfall.

ALTERNATIVE SOLUTIONS

Mitigation measures to date have included slope flattening, shear piles, lateral drains, rock buttresses, and drainage channeling. Installation of shear piles has proven ineffective due to inability to control large lateral forces due to saturated soils. Control and removal of the subsurface water with lateral drains has been an effective mitigation strategy. Slope flattening has also proven to be an effective mitigation strategy. Rock buttressing has also proven to be an effective strategy.

Table 2 – Mitigation Strategy Alternative Evaluation

MITIGATION STRATEGY	COST	EFFECTIVENESS
Slope Flattening	HIgh	High
Shear Piles	HIgh	Low
Lateral Drains	Low	High
Rock Buttressing	Medium	High
Surface Drainage Control	Low	Medium

PREFERRED ALTERNATIVES

Control of the subsurface water content through lateral drains is the most cost effective mitigation strategy. Additional strategies to stabilize the near surface with native plant vegetation should be investigated. Initial layback of slopes where wall failures have occurred are necessary to provide a slope angle that is suitable for vegetation establishment and erosion control. Slope flattening should be minimized to limit impacts to right of way.

Rock buttressing provides stability and a highly permeable pathway to remove water from the toe of slope. Importation of angular rock and disposal of displaced soil is expensive. Surface drainage control provides low cost and benefits the management of slope erosion. Control of surface water also reduces the volume of water that may infiltrate the site soils. Lining of drainage channels with an impermeable barrier may be an effective strategy.

NEXT STEPS

Continued monitoring of the area is recommended. Installed instrumentation and lateral drainage systems should be maintained. The following two slopes have been identified for immediate mitigation:

Northbound slope from station 2804+00 to station 2810+00 has developed surficial indications of a slope failure following heavy rains from the remnants of hurricane Rosa. The fissure is located approximately 70 feet in elevation above SR 87 and extends laterally for 200+ feet. Depth of the fissure is approximately 12 feet deep. Width is approximately 12 inches. Continued rainfall will produce additional movement toward SR 87. A mitigation project should be immediately planned.

Figure 6 – North Bound Slope Failure at Station 2807+00

The South Bound slope from station 2801+00 to 2806+00 upper tier was removed in a previous project. Since the upper tier removal, the lower tier has begun failing. Heavy erosion is also occurring above the lower tier. The slope is in excess of 100 feet tall and will continue to erode and additional sections of the lower wall tier will continue to fail.

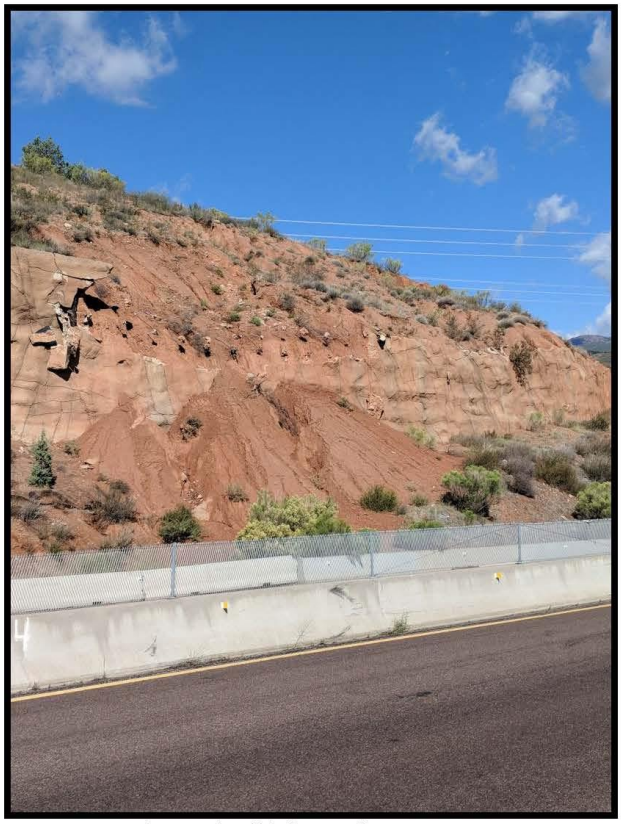


Figure 7 – South Bound wall failure and erosion at station 2803+00

8.5 Appendix E: ADOT Emergency Relief Environmental Process

(See pages 104 – 112)

Emergency Project (ER) Procedures

FHWA Emergency Relief Program

Congress authorized in Title 23, United States Code, Section 125, a special program from the Highway Trust Fund for the repair or reconstruction of Federal-aid highways and roads on Federal lands which have suffered serious damage as a result of (1) natural disasters or (2) catastrophic failures from an external cause. This program is commonly referred to as the emergency relief or ER program. Applicability of ER to a catastrophic failure due to an external cause is based on the criteria that the failure was not the result of an inherent flaw in the facility but was sudden, caused a disastrous impact on transportation services, and resulted in unusually high expenses to the highway agency.

Emergency repairs to restore essential travel, minimize the extent of damage, or protect remaining facilities are normally classified as categorical exclusions under 23 CFR 771.117(c)(9) for repairs that occur within the existing right of-way and in a manner that substantially conforms to the preexisting design, function, and location as the original and commence within a 2-year period beginning on the date of the declaration. If impacts to protected or otherwise sensitive or high-value resources are possible, advance coordination with the appropriate local, State, and Federal resource agencies should be closely considered to avoid or minimize project delays or shutdowns.

The FHWA Emergency Relief Manual defines two categories of emergency relief: 1) emergency repairs and 2) permanent repairs. Emergency repairs are repairs undertaken during or immediately after a disaster to restore essential traffic, to minimize the extent of damage, or to protect the remaining facilities. State and local transportation agencies may start emergency repairs without prior FHWA authorization. Permanent repairs are those repairs undertaken after the occurrence of a disaster to restore the highway to its pre-disaster condition.

General ER Procedures

Week One - Five (5) Business Days

1. ADOT identifies an emergency situation
2. Governor's Office declares an emergency
3. ADOT receives declaration from FHWA
4. Environmental Planning (EP) is informed by the SEO or District Engineer of the declaration
5. ADOT EP attends the ER Kick-off (KO) meeting
6. ADOT EP establishes at the KO meeting who the land owner and coordinating agency will be
7. ADOT EP visits location (optional)
8. ADOT EP notifies FHWA Division Office the intent to use a CE (c)(9) Emergency repairs under 23 U.S.C. 125.
9. ADOT discusses with FHWA Area Engineer any considerations relevant to the undertaking
10. ADOT EP Planner develops a scope of work (SOW) with the District Resident Engineer (RE) or other assigned to the project
11. ADOT EP issues new project email to technical teams include the project, the CE type, the scope of work, and explain the parameters in which this CE type allows for clearance

to be issued with the tech teams initial reviews. The understanding is emphasized that each discipline will give their cursory review, technical approach that will be undertaken, and any long term repair agency scoping needs identified

Week Two – Five (5) Business Days

1. ADOT EP technical submits their initial review based on the SOW provided in week one
2. ADOT EP Planner confirms with the District RE and project team any changes to the SOW
3. ADOT Technical Teams conclude and request relevant environmental commitments to include;
   - i Hazardous Materials develops a roadway excel spreadsheet of other dataset that defines their structures of concern and initially agrees to any NESHAP or pavement striping obliteration
   - ii Biology coordinates with relevant parties and issues an in-house biology document
   - iii Water Quality reviews for relevant work
   - iv Cultural concludes informational consultation with relevant parties
4. ADOT EP Planner reconfirms SOW with District RE
5. ADOT EP Planner drafts CE and Environmental Commitments
6. ADOT EP Planner forwards CE (c)(9) RE email requesting tech review
7. Initial Environmental Clearance issued
8. ADOT EP Planner follows up with technical disciplines to establish any long term needs

Week Two Concludes

Emergency Relief (ER) Reimbursement Process in Arizona

Purpose

The Federal Highway Administration (FHWA) Emergency Relief (ER) program provides funds for the repair or reconstruction of Federal-aid highways and roads that suffered serious damage from natural disasters (e.g. flood, landslides, fire) or catastrophic failures from external causes (e.g. barge collides with a bridge pier).

The FHWA has published a comprehensive ER Manual which provides detailed information on the ER Program including eligibility of Damage Repair work, the ER application process, the Disaster Assessment and Damage Survey Summary Report, and Project Procedures and Requirements. We encourage you to become familiar with this Manual and to contact ADOT Systems Management or the Federal Highway Division Office for more information and technical guidance. The ER Manual can be found at the following link: (http://www.fhwa.dot.gov/reports/erm/er.pdf).

This process document is created as a supplement to the FHWA ER Manual to provide state-specific instructions on the ER process in Arizona. The affected agencies need to follow certain guidelines for processing the request for ER funds and reimbursement by FHWA . Systems Management of the Arizona Department of Transportation (ADOT) will serve as the main point of contact for ER fund requests. This document summarizes the basics of the ER Program, outlines the information we need from affected agencies, and narrates the ER reimbursement process.

ER Basics

The ER Program provides funds for the repair of federal-aid roads and bridges following the event of an eligible disaster as determined by the FHWA.

For a Disaster Event to be eligible for ER funding:

1) The disaster event must have caused a total of $700,000 in eligible damage to Federal-Aid Roadways. (Can be the combination from several agencies that are affected by a particular event)
2) The President and/or Governor must issue an official declaration of emergency

Generally, all elements within the cross section of a highway that are damaged as a direct result of a disaster are eligible for repair under the ER program. Typically, the ER program will only reimburse the costs to restore the roadways to their pre-disaster conditions. Improvements beyond replacement in-kind will not be reimbursed unless prior approval is provided by FHWA.

Only Federal-aid roads and streets functionally classified as Rural Major Collectors and above are eligible for ER funding. Roads functionally classified as Local Roads and Streets, and Rural Minor Collectors are not eligible for ER Funding. ADOT Systems Management can assist you in determining

the functional classification of the road. You can also check the road classification by visiting https://www.azdot.gov/maps/functional-classification-maps.

There are two categories of emergency relief: 1) Emergency Repairs and 2) Permanent Restoration.

Emergency Repairs are repairs undertaken during or immediately after a disaster to restore essential traffic, to minimize the extent of damage, or to protect the remaining facilities. Emergency repairs do not require prior authorization from FHWA. The owner should immediately proceed with emergency repairs and carefully document the extent of the damage and all repair costs. Photographs before and after repairs are especially helpful in documenting the extent of the damage and the repair measures taken if repairs were to be performed immediately. ER Funds will reimburse 100% of the cost of Emergency Repairs incurred in the first 180 calendar days following the onset of the emergency conditions. Wherever possible, the federal-aid provisions should be followed (e.g. Davis-Bacon wages, Buy America Act, NEPA Clearance, etc).

Permanent Restoration refers to those repairs undertaken to restore the highway to its pre-disaster condition and generally not with the primary purpose to restore essential traffic, minimize the extent of damage, or protect the remaining facilities. Permanent Restoration Repairs accomplished during and after 180 days following the onset of the emergency conditions will be reimbursed at the normal pro-rata share for Federal-aid projects in Arizona –94.34% on the interstate and 94.30% on all other roads. Costs incurred prior to the onset of the emergency condition are not eligible for ER funds. Prior authorization from FHWA for Permanent Restoration repairs is required and all federal-aid provisions and regulations must be followed. Improvements beyond replacement in-kind will not be reimbursed unless prior approval is provided by FHWA.

Please report all damage sites or potential damage sites to ADOT Systems Management as soon as possible. All sites must be reported within two years of the disaster event, although sites should be reported immediately to ensure their inclusion in the ER Program. In addition, all ER-funded projects are expected to proceed to the construction phase by the end of the second federal fiscal year following the end of the fiscal year in which the disaster event occurred.

ER Reimbursement Process Guidance (Flow chart attached)

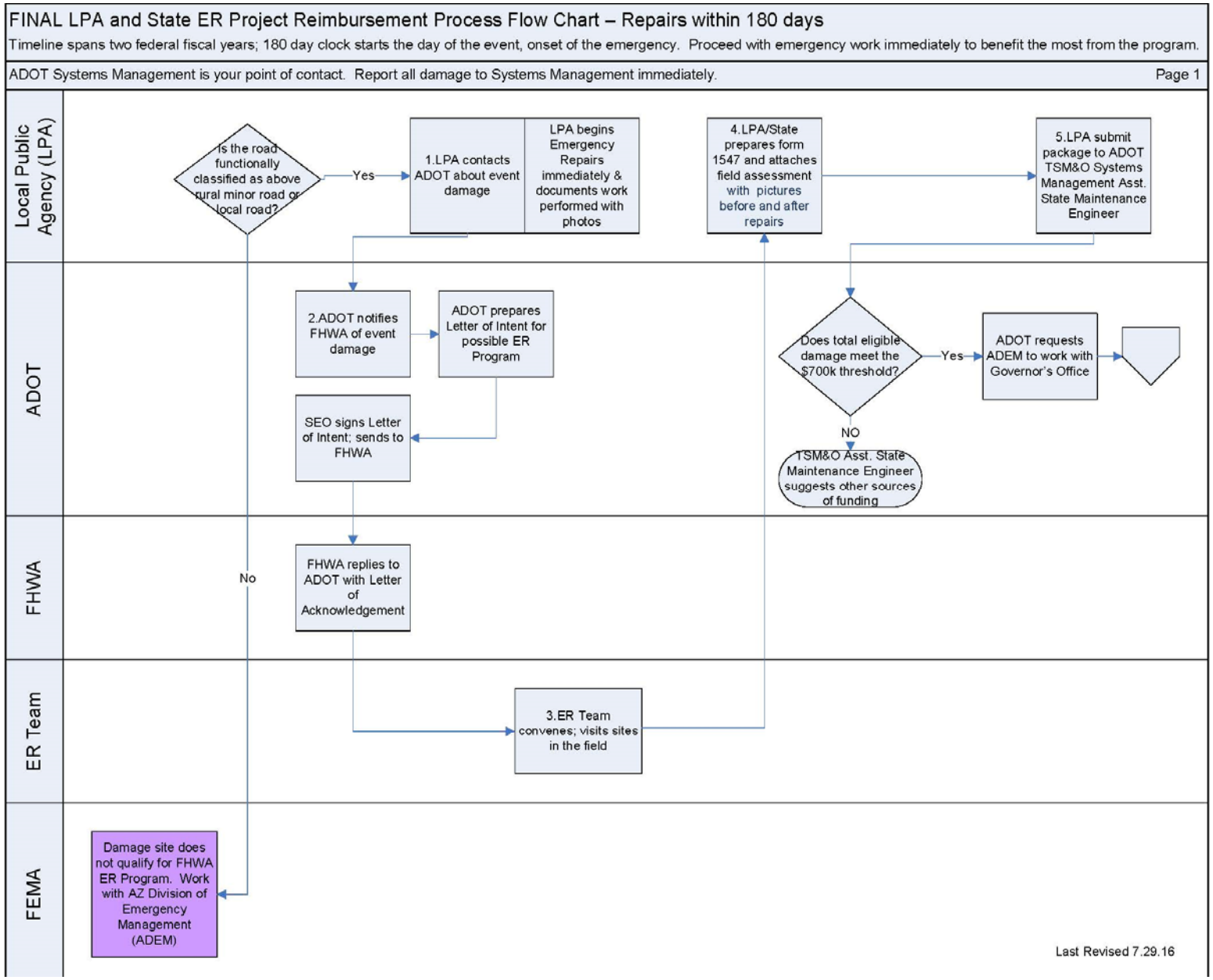
1. Local Public Agency (LPA) contacts Arizona Department of Emergency Management (ADEM) and ADOT TSM&O Systems Management (Marwan Aouad, Asst. State Maintenance Engineer)
    a. Decision is made (either ADEM or FHWA) and work starts (in-kind only)
    b. Documentation required: **name of the highway or local roadway, location (milepost for state projects), date of event, date of inspection and a preliminary cost estimate**
2. ADOT contacts FHWA (Ammon Heier) for funding availability per the event (funding for ER projects is requested twice a year)
    a. ADOT Letter of Intent needed for state or LPA request
    b. State Engineer's Office (SEO)signs Letter of Intent; sends to FHWA
    c. FHWA replies to ADOT with Letter of Acknowledgement
3. Joint ADOT/FHWA/LPA Response Team assembled and field sites visited
4. LPA/State prepares the Detailed Damage Inspection Report form (FHWA-1547) http://www.fhwa.dot.gov/reports/erm/fhwa1547.pdf
    a. Must identify when repairs will be done
    b. Provide accurate but conservative estimates

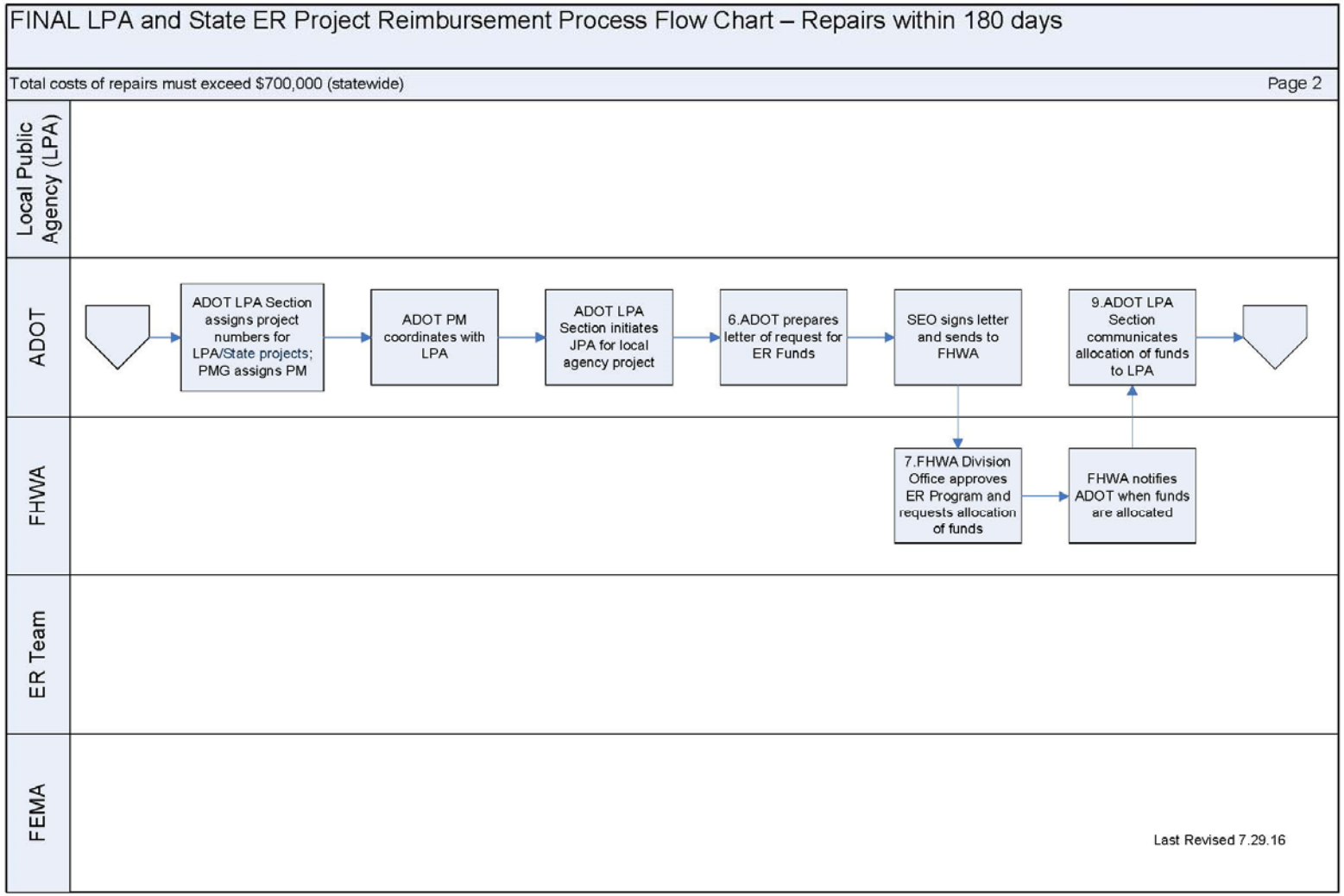
    *Include design, post-design services, and ADOT review fees, where applicable. As you proceed with your repairs, make sure that you keep track of your expenditures to justify the estimated costs in Form FHWA-1547. **All ADOT emergency repair costs by maintenance forces must be reported in PeCoS using either the Project number as identified earlier or the Tracs Number if it has already been established.**

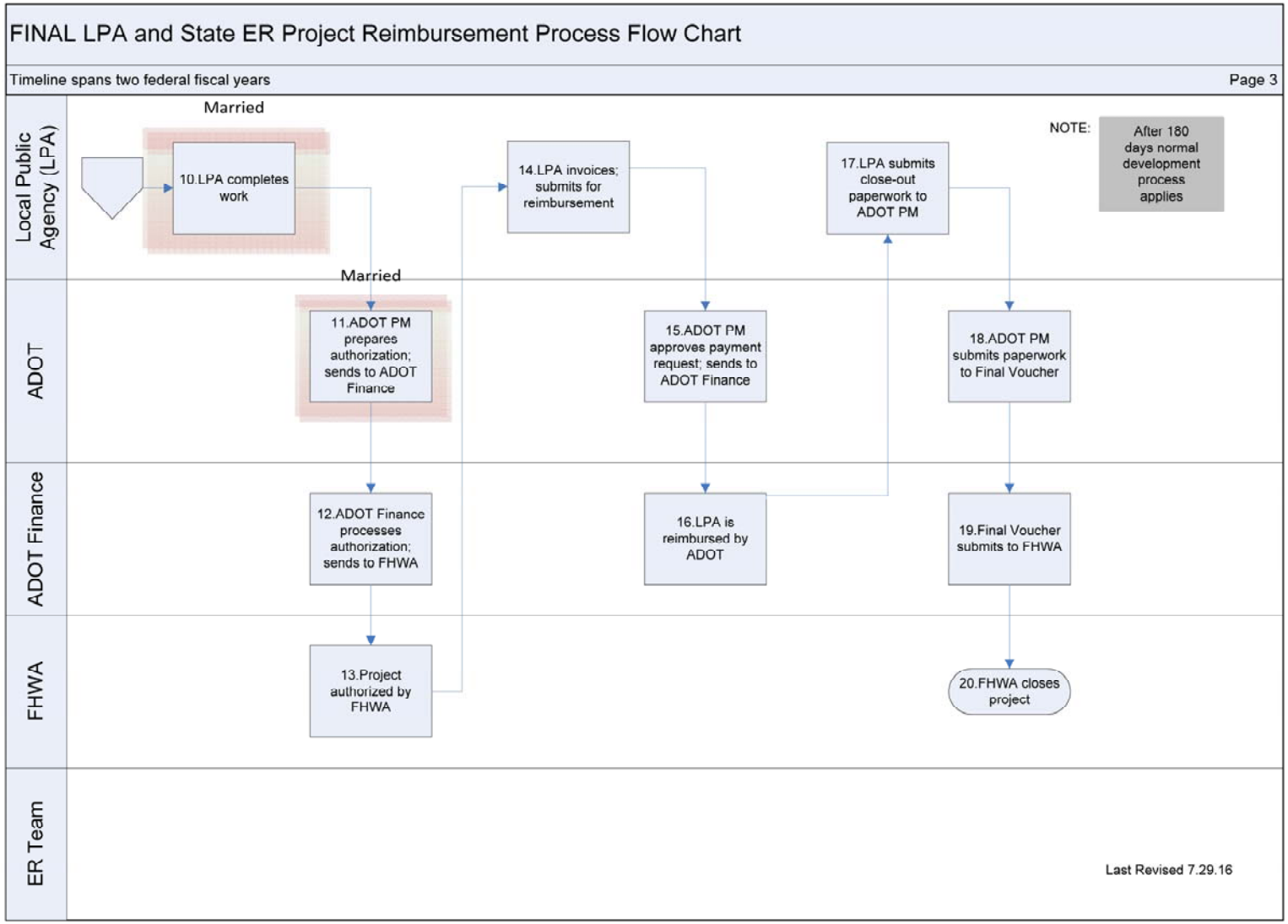
5. LPA/State submits form and any questions to TSM&O Systems Management, Asst. State Maintenance Engineer (Marwan Aouad at maouad@azdot.gov or 602/712-7949).
    a. ADOT assembles all projects for evaluation to ensure the $700k threshold is met
    b. ADOT request ADEM to work with Governor's Office to issue Declaration of Emergency
    c. ADOT LPA Section initiates Intergovernmental Agreement (IGA) beginning this process
    d. ADOT LPA Section assigns project numbers and federal aid numbers for LPA/State ER projects
    ~~e.~~ ADOT Project Management Group (PMG) assigns PM ~~along with State project numbers and federal aid numbers~~
    f. ADOT PM coordinates with LPA
6. ADOT prepares Letter of Request; SEO signs letter and sends to FHWA with Governor's Declaration of Emergency; copy LPA and PM
7. FHWA Division Office approves Emergency Program and requests allocation of emergency funding from FHWA Headquarters in Washington.

    *An appropriation code for the allocation will be provided to ADOT TSM&O Systems Management and Program Finance Sections
8. FHWA notifies ADOT of allocation (This could be an extended period of time to receive reimbursement.)
9. ADOT LPA Section prepares and distributes establishment letter to LPA (State N/A)

10. LPA completes work
11. ADOT PM prepares authorization; sends to ADOT Finance
12. ADOT Finance processes authorization; sends to FHWA
13. Project authorized by FHWA
14. LPA invoices ADOT for reimbursement
15. ADOT PM approves payment request; sends to ADOT Finance
16. LPA is reimbursed by ADOT
17. LPA submits close-out paperwork to ADOT PM
18. ADOT PM submits paperwork to Final Voucher
19. Final Voucher submits to FHWA
20. FHWA closes project


FINAL LPA and State ER Project Reimbursement Process Flow Chart – Repairs within 180 days
Timeline spans two federal fiscal years; 180 day clock starts the day of the event, onset of the emergency. Proceed with emergency work immediately to benefit the most from the program.
ADOT Systems Management is your point of contact. Report all damage to Systems Management immediately.
Page 1
Local Public Agency (LPA)
ADOT
FHWA
ER Team
FEMA
Is the road functionally classified as above rural minor road or local road?
Yes
No
1.LPA contacts ADOT about event damage
LPA begins Emergency Repairs immediately & documents work performed with photos
4.LPA/State prepares form 1547 and attaches field assessment with pictures before and after repairs
5.LPA submit package to ADOT TSM&O Systems Management Asst. State Maintenance Engineer
2.ADOT notifies FHWA of event damage
ADOT prepares Letter of Intent for possible ER Program
SEO signs Letter of Intent; sends to FHWA
Does total eligible damage meet the $700k threshold?
Yes
NO
ADOT requests ADEM to work with Governor's Office
TSM&O Asst. State Maintenance Engineer suggests other sources of funding
FHWA replies to ADOT with Letter of Acknowledgement
3.ER Team convenes; visits sites in the field
Damage site does not qualify for FHWA ER Program. Work with AZ Division of Emergency Management (ADEM)
Last Revised 7.29.16


FINAL LPA and State ER Project Reimbursement Process Flow Chart – Repairs within 180 days
Total costs of repairs must exceed $700,000 (statewide)
Page 2
Local Public Agency (LPA)
ADOT
FHWA
ER Team
FEMA
ADOT LPA Section assigns project numbers for LPA/State projects; PMG assigns PM
ADOT PM coordinates with LPA
ADOT LPA Section initiates JPA for local agency project
6.ADOT prepares letter of request for ER Funds
SEO signs letter and sends to FHWA
9.ADOT LPA Section communicates allocation of funds to LPA
7.FHWA Division Office approves ER Program and requests allocation of funds
FHWA notifies ADOT when funds are allocated
Last Revised 7.29.16


FINAL LPA and State ER Project Reimbursement Process Flow Chart
Timeline spans two federal fiscal years
Page 3
Local Public Agency (LPA)
ADOT
ADOT Finance
FHWA
ER Team
Married
10.LPA completes work
14.LPA invoices; submits for reimbursement
17.LPA submits close-out paperwork to ADOT PM
NOTE:
After 180 days normal development process applies
Married
11.ADOT PM prepares authorization; sends to ADOT Finance
15.ADOT PM approves payment request; sends to ADOT Finance
18.ADOT PM submits paperwork to Final Voucher
12.ADOT Finance processes authorization; sends to FHWA
16.LPA is reimbursed by ADOT
19.Final Voucher submits to FHWA
13.Project authorized by FHWA
20.FHWA closes project
Last Revised 7.29.16