



Safe-to-Fail Adaptation Strategies for Phoenix-area Roadways Under Increasing Precipitation

A Collaborative Research Project between Arizona State University's Urban Infrastructure Anatomy & Sustainable Development and Construction Materials & Methods Classes

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1. PROJECT OVERVIEW

In Spring 2016 Arizona State University's Urban Infrastructure and Sustainable Development (UIA) class in collaboration with an undergraduate Construction, Material and Equipment (CON 252) class conducted a research study to assess and improve Maricopa County's (whose seat is Phoenix, Arizona) roadway infrastructure resilience to flooding. This research project was split into five main tasks. First, the report discusses historical extreme events. Next flooding is forecasted in Maricopa County through a hydrological model. Third, the vulnerability of the infrastructure is studied and a vulnerability index is proposed. Fourth, a multi-criteria decision analysis framework is developed to compare different infrastructure adaptation strategies. Fifth, barriers for overcoming institutional barriers are identified..

2. INTRODUCTION

Climate change is expected to cause more flooding in the US Southwest, thereby threatening infrastructure. Researchers have predicted that extreme weather events are increasing. Several past high-intensity precipitation events have led to significant flooding that has damaged infrastructure.

In 2014, Phoenix was exposed to a major precipitation event that resulted in flooding of Interstate 10. During the October 2014 floods about 10,000 people lost power in the state [1], 200 homes were impacted, and dozens of water rescues occurred. It was also the cause of several deaths. The Arizona flood resulted in estimated damage of approximately \$17 million. Although climate models predict a decrease in overall precipitation in the Phoenix metropolitan area, the intensity of precipitation events is expected to increase.

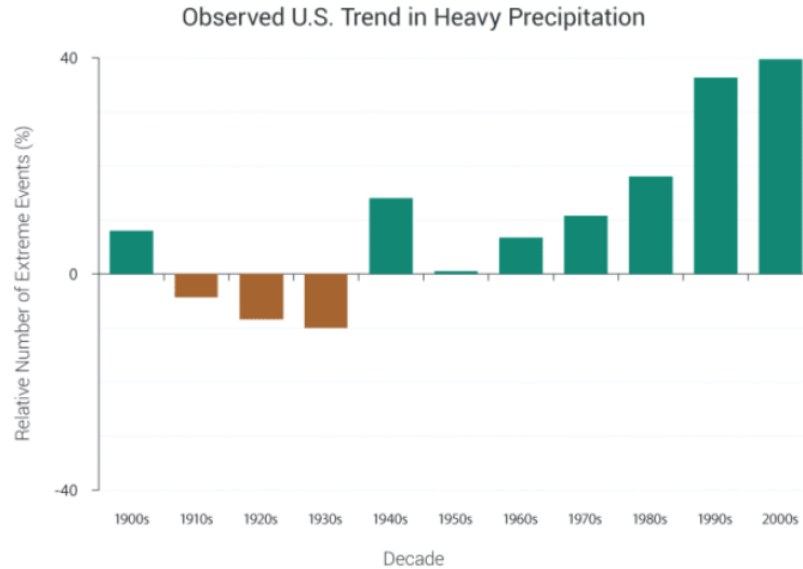


Figure 1: Predicting an increase in the extreme weather events (Flooding) in the U.S [2]

With the proposition of increasing intensities of precipitation events new insights are needed for not only protecting roadways and the services they provide from climate change, but doing so in a more robust approach.

2.1. Project Organization Structure:

The research embraces a vertically integrated problem-based learning framework that has been developed and implemented at Arizona State University between a lower-division construction management course, Construction Materials, Methods and Equipment (CON 252) and the graduate Urban Infrastructure Anatomy and Sustainable Development course.

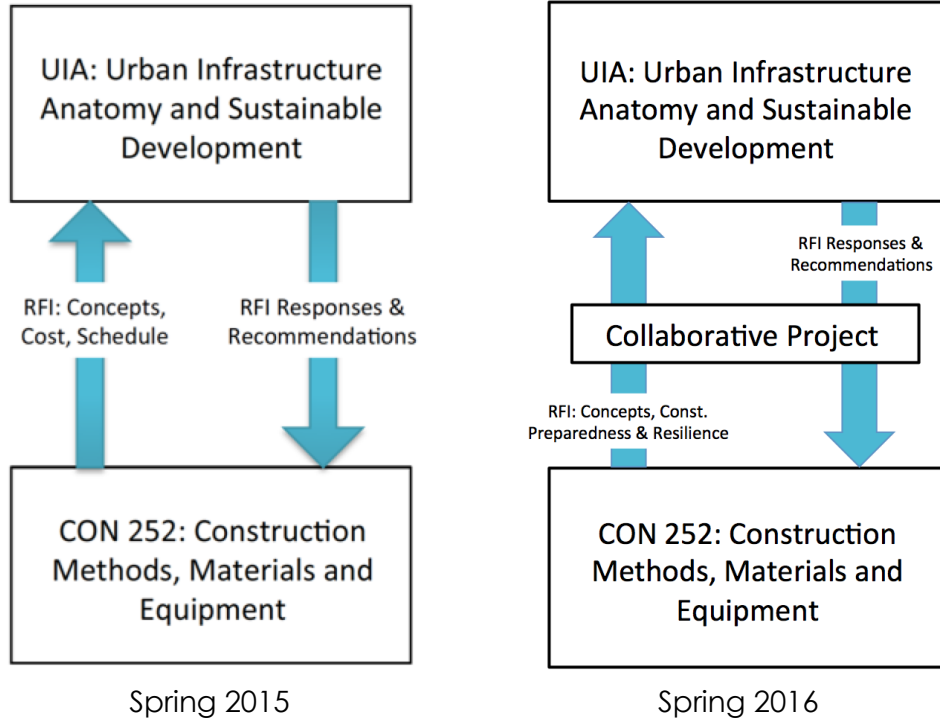


Figure 2: Embracing a vertical integration pedagogy between a grad and an undergraduate class

3. HISTORY OF EXTREME EVENTS:

The section provides a strategic analysis pertaining to the history and complex evolution of Phoenix's road infrastructure to answer the question of: How has metropolitan Phoenix's road infrastructure changed over time as a result of flooding?

The adopted methodology was to collect information from journal sources, local government documents, print and non-print media, government agencies, historical newspapers, and historical books (i.e. Suburban Nation). Sources were selected based on their credibility, peer-reviewed status, and relevancy. Additionally, the convenience and snowball sampling approach was applied to conduct interviews with four professionals who work on transportation and water systems in the Phoenix metropolitan area.

Firstly the documentation of floods spanning the last 160 years, which had 'significant impacts' on the transportation infrastructure, was identified. Subsequently, the economic and social systems within the Phoenix metropolitan area depend on this infrastructure. 'Significant impact' was defined based on the following criteria: 1) structural damages to the transportation infrastructure include the washing away or crumbling of pavement, dam failure, and deterioration of bridges, 2) financial loss includes the cost of repairing damages and modifications to the physical infrastructure as well as the economic impact to local businesses, and 3) social impact which is not easily quantified was considered when determining significant of flooding events.

Major flood events were identified based on the United States Geological Society (USGS) National Water Summary dating back 160 years [4]. The USGS is a credible source for geographic data and measuring economic loss due to flooding events.

Additionally, the study considered urban processes and decisions prior to flood events that may have increased damage, such as the development of urban sprawl. In order to better understand the historical dimensions of this complex problem, academic journals such as The Journal of Arizona History and books including Desert Visions and the Making of Phoenix, 1860-2009 were reviewed. These sources explain how urban design interacts with stormwater management, how road networks evolved due to extreme flooding, and why different types of infrastructure continued with uninterrupted service while others failed during extreme flooding events.

Furthermore, the research considered changes to local and state design codes, emergency management plans, and federal policy impacted flooding in the Phoenix area. Specifically, investigating migration and development patterns that were influenced by flooding along with the policies that were implemented as a reaction to flood events. The analysis included the evolution of transportation infrastructure due to complex decision drivers and the repercussions of those decisions on future flooding and transportation design. Historical economic, social, and political changes pertaining to transportation infrastructure and water management shape the current state of these systems and will impact future flood events. The following historical narrative informs the subsequent chapters of vulnerability and adaptation.

3.1. Early History Of Growth And Flooding In Phoenix:

Jack Swilling set up mining camps across Arizona during the 19th century and hired miners to recreate the Hohokam canals [5]. Shortly after, settlers began to establish a grid-based town near the center of the Valley [6]. These settlers named the town Phoenix, depicting a people rising from the ashes in honor of the Hohokam Tribe.

In the years that followed, the expansion of the canal system created opportunities for new agricultural communities across the region, including Mesa and Tempe. Mormon immigrants created Mesa's first canal during the late 19th century. The Arizona Canal built from 1883 to 1885, spans nearly 50 miles and connects the cities of Scottsdale, Phoenix, Glendale and Peoria. The canal was constructed by the Arizona Improvement Company, a group that sold water and land along the canal [6].

Early settlers discovered that the land bordering canals were fertile and thus planted trees including cottonwood, ash, poplar, and willow [6]. Over time, more predictable irrigation systems combined with almost constant sunshine enabled the production of agricultural products. These goods were transported by rail to other Arizona towns after the national railroad expanded into Phoenix in 1887 [6]. The connection to the national railroad was particularly valuable for Tempe and Phoenix as it presented huge opportunities for shipping agricultural goods and new construction materials besides adobe (i.e. wood). Furthermore, this transportation innovation opened a pathway for migration and tourism [7]. Agricultural production, population, development, and land prices increased as a result of the railroad connection [6]. While exciting and lucrative, this growth was not exempt to crises.

In 1891 Phoenix experience its first major flood. Many irrigation systems and adobe buildings in the Phoenix area were washed away [6]. Damage included the destruction of the first few miles of the Tempe Canal, three miles of the Mesa Canal washed away, and the Highland Canal overflowed [8]. The flood damaged irrigation canals, flooded fields, and washed away diversion dams that disrupted businesses, daily life, and resulted in massive economic losses. A railroad bridge and telegraph service also failed, but were rapidly repaired [6].

As a result of this major flood in 1891, the first sewer system in Phoenix was created to help manage water during floods [8]. This extreme event also caused \$1 million damage and was the highest rate of flow of the Salt River recorded to date, moving at 300,000 cubic feet per second. In spite of the flood's impact, flooding became a low priority because this event was followed by a period of water scarcity [8]. Drought shifted priorities toward water storage and inspired a Congressional committee to investigate the feasibility of a storage dam and identified possible locations on the Salt River. Congress agreed and the construction of the Granite Reef Diversion Dam was finished in 1908, and the Roosevelt Dam was completed in 1911 [8].

By the turn of the century, perceived water security fueled Phoenix's population growth. The local government then increased services including power, further water management, and a streetcar [6]. Phoenix began to resemble the modern day auto-centric city observed today as transportation improved, airports were established, and the popularity of cars increased in the 1920's [6]. In fact, streetcar ridership was split in half from 1920 to 1924, mostly due to the rise of the automobile [6]. Streets began to break away from the grid pattern, and instead formed cul-de-sacs and curved roads without sidewalks. The New Deal enabled more road development and decreased barriers to homeownership, further boosting Phoenix's suburban development and facilitating regional sprawl [6]. The New Deal also led to the development of the Civilian Conservation Corps, which improved the canal system to increase water security and decrease flooding [9].

Post-WWII decision-makers transitioned their vision for the local economy away from agriculture to manufacturing and tourism, which required improvements in road infrastructure and connectivity. The Arizona Highway Department (AHD) was established in 1927 to help manage the

area's growing road infrastructure [PC. 1]. AHD later became the Arizona Department of Transportation (ADOT), and still manages the state's highway infrastructure.

Phoenix's economic growth and increased connectivity lead to greater social vulnerability to flooding. Water management systems established in the early 20th century provided a sense of safety and the illusion of predictability for flooding [6]. A major flood hit Queen Creek in 1954 that resulted in federal disaster relief loans [10]. This funding was enabled by the 1950 Federal Disaster Relief Act, which allowed the President to declare major disasters and provide federal assistance when prompted by a state governor [11].

A report from the Flood Protection Improvement Committee in 1958 articulated the urgent need to establish a Flood Control District in Phoenix; one of the Committee's objectives was to 'establish an organization capable of financing and administering operations' [12]. The Army Corp of Engineers created flood control plans for the Phoenix Metro over 30 years earlier, but was unable to move forward until there was an organization willing and able to maintain it. Fear of an anticipated flood combined with the Flood Improvement Committee's request for a flood control district led to the creation of the Maricopa Flood Control District (MFCD) in 1959 by Governor Fanin [13,14]. MFCD implemented fail-safe flood control projects throughout the region and enabled the Army Corp's long awaited project to move forward [13]. Extreme flooding events continued despite the new institutions focused on decreasing vulnerability to flooding.

3.2. Technological Innovation:

The floods of 1965 and 1966 destroyed utility towers, damaged airport runways, and caused over \$6 million in damage [15]. The flood washed out over 15 river crossings because bridge footings along the Salt River were commonly set into alluvial fill since bedrock is too deep to reach [15]. A design decision practiced for centuries, building dips into roads to channel water, proved effective [PC. 1]. However, low dikes were built across dips on the approach of bridges that rerouted two floods in 1978, scouring a large hole within a foot of the pier footings [15].

Phoenix's growing population increased traffic congestion and state-level regulations led city engineers to design bridges to withstand more extreme flooding events [15]. Additionally, stormwater retention via basins has been the accepted way to reduce 100-year runoff releases since the 1970s [16]. These extreme-flooding events shifted thinking away from designing small bridges and river crossings, which was the status quo from 1945 to 1980 [15].

Unfortunately, these preventative measures failed to protect the city from flooding events affecting Phoenix from 1978 to 1980. Due to these extreme events, Phoenix received Federal Flood Disaster Assistance funds three times within 24 months, where by 1979 these floods caused over \$230 million in damage [17]. Also, in February 1980 flooding closed all but two road crossings in the metropolitan Phoenix. The Arizona Department of Transportation responded by creating the Transportation Contingency Plan for Salt River Flooding in the Phoenix Metropolitan Area [18].

This plan states, 'The approach of this planning effort has been to identify, stimulate, and incorporate the plans and thinking of various valley agencies into one document' [18]. The primary goal of the plan was to reduce future road issues during flooding events through 'traffic control, ridesharing, bus service, and rain service' [18]. Strategically allowing some

roads to flood would allow staff to focus on providing other means of transportation. Other proposed actions included making Mill Avenue a two-way street, designating HOV lanes, creating an emergency helicopter service, establishing park and ride areas to encourage bus use, and establishing a way to disseminate public information about flooding emergencies [18]. The focus on public transportation was fueled by the belief that roads would be safer if fewer cars were on them during a flood. Outcomes of these decisions to build public transportation are apparent in the urban landscape today. At the time of this report there were 20 road crossings over the Salt River in metropolitan Phoenix and thirteen of were closed during small flooding events [18].

Flooding events from 1978 to 1980 resulted in major design changes at the County level pertaining to bridge design [PC. 2]. New bridge structures included 1) a design that prevents scouring at piers and serves as a grade control structure, and 2) an experimental method that uses flexible spurs with permeable panels of synthetic nets (Association of State Floodplain Managers, 1996). Specifically, ADOT began replacing flood-prone bridges with designs built to withstand 210,000 cubic feet per second with drilled shaft supports [19]. ADOT installed drilled concrete shafts with a diameter of 6 to 10 ft. for lateral stability and decreasing scouring. Approaches were protected by placing roller-compacted soil cement on riverbanks, or by using rock-filled wire-basket gabions that only fail locally [19]. Upgraded bridge foundations and bank stabilization helped strengthen bridges in Maricopa County to withstand 100-year flows. The reduced flow velocity helped move water towards the center of the channel instead of enhancing erosion and sedimentation [20].

In 1983, the Environmental Protection Agency revealed a study that showed how stormwater retention could control the flood peak flow rates, but manmade drainage systems increased surface erosion and

transported shock loads of chemicals and pollutants into natural streams in urbanized areas [16]. In response to the needs of water quality control, the design of detention basins in the 1980s evolved to include a permanent pool that could handle frequent runoff events. Stormwater infiltration and filtering devices were added to the detention basin system to remove solids through the sedimentation process [16].

3.3. Built & Natural Environment Challenges:

Since the 1950s decision makers advocated for increased green infrastructure, although it wasn't called green infrastructure at the time. For example, Phoenix Mayor Jack William said in 1956, 'It is becoming more and more obvious that the City must pass some ordinance relating to shrubs and trees and plantings in front of buildings, on parking lots...' [6]. William went on to suggest requiring business districts to landscape with water retaining vegetation to prevent the region from transforming into '...a vast wasteland of dust, gravel, bricks, concrete, and black-topped parking lots...' [6]. His call to action occurred after the Salt River Project worked with the Federal Rehabilitation and Betterment Program in 1950 to line canals with concrete requiring the removal of tens of thousands of trees [6]. In the decades of development to follow, the ubiquity of air conditioners provided little incentive for builders to replant trees and other vegetation.

The fertile farmland surrounding Phoenix was quickly transformed into subdivisions. Air quality concerns continued to rise during this time, and harmed the region's marketing efforts as 'a place for healthy living'. Urban sprawl in metropolitan Phoenix was unintentional; however, the local government was uninterested in stopping it until the late 1980's [21]. The absence of an urban growth boundary or strict land use regulations helped developers leapfrog parcels of land in metropolitan Phoenix,

greatly expanding the development footprint. Low-density, auto-dependent growth in Phoenix is still practiced by developers going farther away from development to get lower land prices and attract residents who are looking for a non-urban lifestyle [21].

The City of Phoenix today is 517 square miles and connected by an extensive network of streets [22]. During the end of the 20th century, major roadways were built to connect suburbs including State Loop 101 (built in 1998), State Route 51 (1987), I-10 (1990), State Route 143 (1991), State Loop 202 (1990), and State Loop 303 (1991) [23]. It's important to note, all of the aforementioned highways will require substantial maintenance in 30-40 years due to the lifecycle of this type of infrastructure; since the 1960s, many highways in metropolitan Phoenix were intentionally built in depressions for noise abatement. As a result, highways designed in this way require pumping stations to remove standing water during rain events. Currently, six ADOT employees maintain all 73 pumping stations in Phoenix [PC. 3].

The addition of traditional asphalt roadways and sprawling development increased the amount of impermeable surfaces across the city. Extreme flooding disrupts the economy and puts lives at risk since so many residents are dependent on vehicles for transportation to any services [24]. This reality became expensively evident approximately two years ago.

A record breaking 2.9 inches fell on September 8, 2014- flooding 200 homes closing 30 roads, and requiring dozens of people to be rescued [25]. Retention basins and canals overflowed onto streets and into communities. Mayor Stanton stated, 'Last night the city of Phoenix and our entire region saw levels of rainfall we haven't seen in nearly a century...Thank God there have been no fatalities as a result of this historic rainfall and flooding' [25]. Interestingly, cars on I-10 at E. 43rd Avenue

were submerged in water because one of the pumping stations experienced a technical failure. However, this section of the highway was drained in less than 30 minutes once the pumping station was repaired. [PC.3]. This example speaks to the fail-safe nature of highway infrastructure in Phoenix due to historical decisions around road placement.



Figure 3: Flooding implications in Phoenix, 2014

3.4. Recent Design Changes:

According to Leigh Padgitt, a Municipal Stormwater Program Coordinator for ADOT, stormwater treatment means going beyond stabilization requirements to actively treat and remove pollutants from discharge [PC. 4]. Most manual adjustments are fueled by federal regulation every five years and changes are not very reactive to flooding events. Green infrastructure and low impact development concepts have been required by federal regulation since 2002, and were fully implemented in 2008. However, rain gardens and green infrastructure ideas are difficult to implement on certain roads including highway systems. The design cannot withstand water building up under the roadbed or it undermines the pavement profile and the road may fail. Thus, green infrastructure ideas must be balanced with the infrastructure's stability requirements [PC. 4].

Although technology hasn't evolved enough to fully embrace green infrastructure benefits, other innovations helped reduce flooding issues and hastened repair in the 21st century. For example, when bridges fail due to flood damage, a replacement bridge can be designed off site and rolled into place- thus decreasing the repair time and returning it to function. Additionally, eroded metal lining in pipe culverts can be repaired without removing the pipe. These operational changes were enabled by technological advancements that save money and time. As discussed previously, organizational improvements and preventative measures have been made in response to flooding, but typical manual adjustments are due to regulation- not flooding events [PC. 4].

The Central Arizona Project (CAP), Arizona's largest water provider uses multiple water infrastructure networks has started to reevaluate how their design decisions impact flooding. Recently, CAP changed pipelines crossing riverbeds to ensure more adaptability to extreme dry and wet seasons [26]. Specifically, CAP replaced worn casted concrete inverted siphons at major river crossings with steel pipes and cast-in-place concrete pipes [26]. This change decreases the likelihood of a bridge failure during heavy rain events.

Phoenix is currently the 6th most populous city in the United States, with nearly 4.3 million people living in the auto-centric metropolitan area [27]. Periods of flooding and drought in Phoenix have been a problem since settlers first arrived- making water management a top priority for the region throughout time. Since the majority of residents and tourists depend on cars to navigate the region, road infrastructure vulnerability to flooding is a serious economic, social, and technical concern. Past decisions around road design, flooding response, and water systems shaped current concerns and opportunities for increased resilience. Understanding the past helps provide perspective for decision-makers,

academics, and residents to better interpret the present and co-create a desired future. Further, an in-depth analysis of possible future flooding frequency and severity will be explored in the following chapter. With insight into the past and potential futures pertaining to flooding, solution recommendations become more grounded and robust.

4. FORECASTING FLOODING, HYDROLOGICAL MODEL:

Precipitation intensities in the arid regions of the Southwest are increasing in the upcoming decades. If local drainage conditions are inadequate to accommodate rainfall through a combination of evaporation, infiltration into the ground, and surface runoff, accumulation of water in certain areas may cause localized flooding problems [29]. This study is a modeling effort aimed at determining which neighborhoods in the City of Phoenix area are susceptible to flooding in the upcoming decades (2020 - 2070). The long-term functionality of EPA's Stormwater Management Tool (SWMM) was used to model the nodal flooding regimes that lead to flooding given time-series precipitation inputs from historical precipitation data with climate change prediction adjustments from the Climate Change Adjustment (CAT) tool. The flood forecasting results shows that among 325 modeled storm drain points, which are potential urban flooding locations, 55 locations were identified as being at the risk of more than six inches of flooding depth from the historical maximum data. Compared to the historical data, in the near future, there will be 3.6 % increase of locations that are flooded above 6 inches, and in the far future, there will be 25.5 % increase, which is 14 more location points than the historical data. There will also be a 400 % increase in the number of locations that exceed two feet flooding depth both in the near and far future, even in the scenario of Median change. We found that the nodes that flooded the most are the ones that have very high imperviousness

rate coupled with high precipitation values compared to the other nodes. Urban floods have multiple hydrologic and hydraulic causes that make the modeling and prediction of floods a significant task. According to FEMA, there are at least two major types of floods that occur in inland urban areas: 1) floods from riverine stream overflows and 2) floods caused by improper urban drainage unrelated to stream overflow (FEMA). FEMA reports, "around 20-25 percent of all economic losses resulting from flooding occur in areas not designated as being in a 'floodplain,' but as a consequence of urban drainage" (FEMA). The focus of this study is to model urban flooding from storm water runoff through urban drainage systems at the city scale. The Environmental Protection Agency's Storm Water Management Tool (SWMM) is used to model the increased precipitation and flooding in the City of Phoenix in the future scenarios of 2020-2045 and 2049-2070.

4.1. Identifying The Geographical Boundary:

The analysis was conducted on the City of Phoenix because there is great potential for disastrous flooding to occur because there have been large roadway flooding incidents in the past because it is the most populous city in the region. Figure 7 shows the City of Phoenix boundary overlaid with the watershed sub-basins within the city boundary.

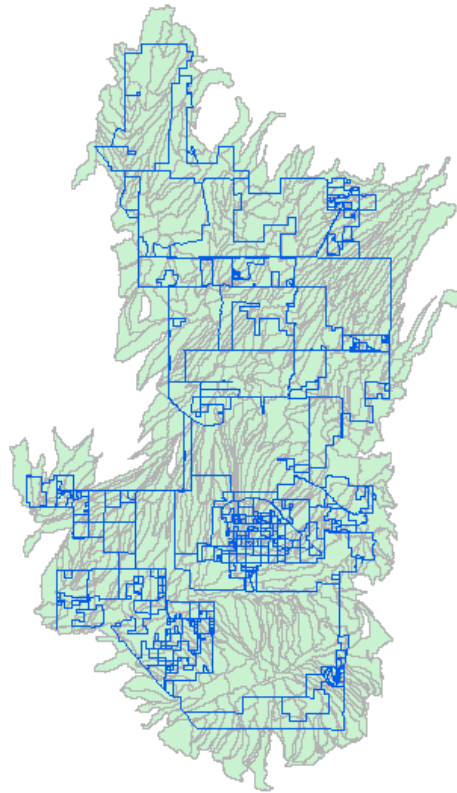


Figure 4: Subcatchments and City of Phoenix boundaries (blue line).

4.2. Software Overview:

The most commonly used software program to model urban drainage networks is the United States Environmental Protection Agency's Storm Water Management Model (SWMM). SWMM is a dynamic hydrology-hydraulic model used for planning, analysis and design related to stormwater runoff, combined, and sanitary sewer and other drainage systems in urban and non-urban areas [30]. It is used for single event or long-term simulation of runoff of quality and quantity of stormwater. The model is conceptually divided into four sections of water cycle. The water in terms of precipitation is generated in the atmosphere which is received by land surface and either infiltrate to the groundwater or runs through surface routing system via pipes, channels and other conveyance elements.

SWMM is conceptually made with a set of connected objects that performs individual function within the model. Rainfall by any rain event can be represented by rain gauges and it is described by rainfall hyetograph in model. Sub-catchments receive the rainfall, are described by area, land characteristic such as imperviousness, depression storage, width, slope and soil properties. After the rainfall event and water received by sub-catchment, infiltration can be described by the Horton, Green-Ampt model. If water is not infiltrated, it becomes surface runoff and is transported through a series of conduits to a final outfall. Routing in the SWMM model is described by steady flow, kinematic wave routing or a dynamic wave routing [30].

SWMM provides integrated environment by running hydraulic and water quality simulations and it gives results in variety of formats, it includes:

- Colored coded drainage area and conveyance system maps.
- Time series graphs and maps.
- Profile plots.
- Statistical frequency analysis.

The SWMM-CAT (Climate Adjustment Tool) is also available for use as an add-on to the SWMM program. The add-on adjusts precipitation and evaporation input data for any specific location (latitude, longitude) or zip code to reflect the changes to the values caused by climate change in the future (2020 - 2070 data available); moreover, climate change projection data 30 miles by 30 miles gridded CMIP3 data [31].

4.3. Methodology:

The long-term (continuous) functionality of SWMM was used to model the nodal overflow regime that leads to flooding given hourly time-series precipitation inputs from historical precipitation data with future prediction adjustments from the SWMM-CAT add-on. In order to simulate

the characteristics of surface water runoff and subsurface flow in a defined basin or sub catchment, the following data were required as inputs to the SWMM model: Precipitation data for each rain gauge, the slope and width of all sub-basins, the percent imperviousness of land cover, and conduit diameter, length, and roughness [30,31]. With this data, the drainage network and sub-basins were created, characterized and simulated, using outputs from the ArcGIS, and SWMM-CAT software tools [32].

4.3.1. NETWORK AND SUB-BASIN CREATION

The network of the physical components: sub-basins, sewer conduits, and conduit junctions, were drawn in the SWMM graphical user interface using outputs from ArcGIS. To delineate sub-basins in ArcGIS, a digital elevation map of broader Phoenix area was obtained for geomorphological analysis from USGS with a 1/3 arc second resolution of each pixel. DEM manipulation was first processed to fill existing sinks (no data pixels) in the map to reduce errors for flow direction analysis. Flow direction analysis was followed based on elevation (Figure 8). After flow directions were calculated, streams were defined and segmented on the map. These processes were performed to provide information needed for catchment grid delineation (Figure 9). Then, subcatchments were divided and drawn into polygons which has approximately 1-mile width based on stream flow direction (Figure 10). At each subcatchment, drainage lines were calculated to find the drainage outlet point of each subcatchment (Figure 11). Up to this hydrological modeling, all data processes were done in larger area beyond urban Phoenix, because of uncertainty of geomorphology of target area. In ArcGIS, after all hydrologic preprocessing were done, data layers (i.e. DEM, flow direction, subcatchment polygons, drainage lines, drainage points) were cut based on the city boundary map to find out subcatchments that are associated

with the city region (Figure 13). The DEM data source was retrieved from the U.S. Geological Survey, The National Elevation Dataset (NED), 1/3 arc second (approx. 10m):

1. City boundary data source: ASU GIS repository, Annexation City of Phoenix
2. Impervious rate data source: U.S. Geological Survey, The National Land Cover Database (NLCD), 2011 Edition, amended 2014

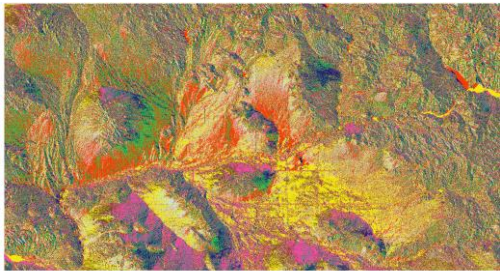


Figure 5: Calculated flow direction based on elevations

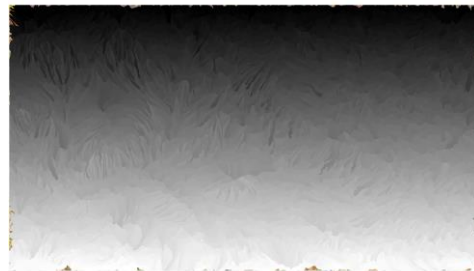


Figure 6: Stream and catchment grid delineation.

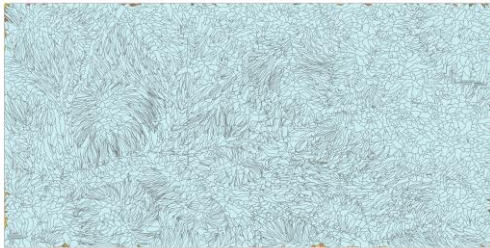


Figure 7: Sub-catchment polygons.

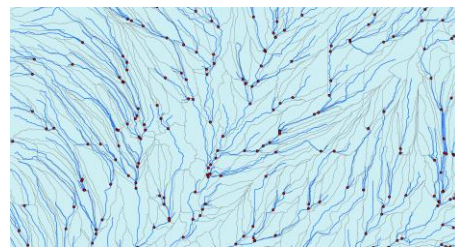


Figure 8: Zoomed in drainage lines (blue line) and points (red dot) at each sub-catchment.

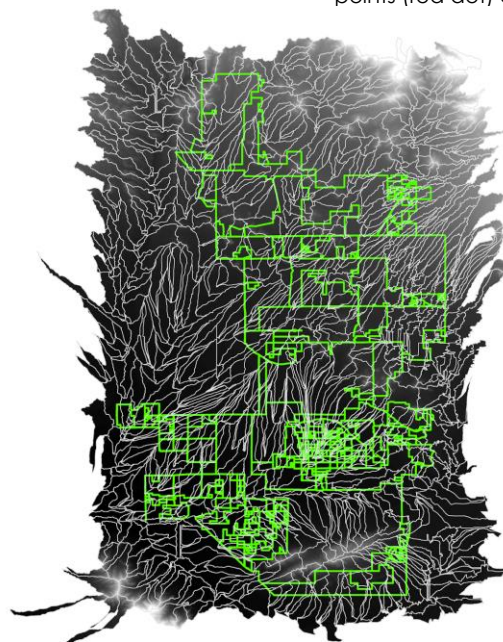


Figure 9: TRIMMED DATA LAYERS

Since there is a limitation of getting exact locations of drainage outlet points of the city, we assumed that drainage outlets are located intersections of roads based on an exemplary quarter section map that City of Phoenix provided along with drainage points that were calculated by hydrological analysis. As a result of discussion, the Authors decided to locate outlets by 0.5~1 mile distance interval to complement the limitation and facilitate manual pinpointing process in SWMM modeling [33] (Figure 13 and 14).

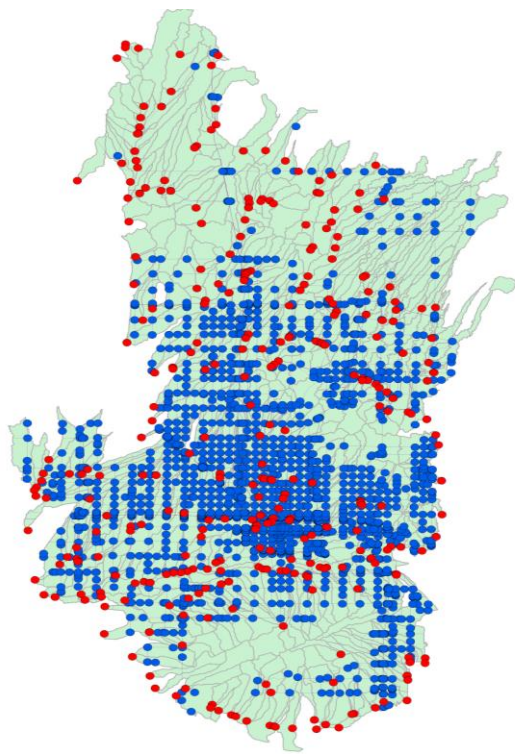


Figure 10: Outlet locations (Red: Drainage point, Blue: Road intersection).

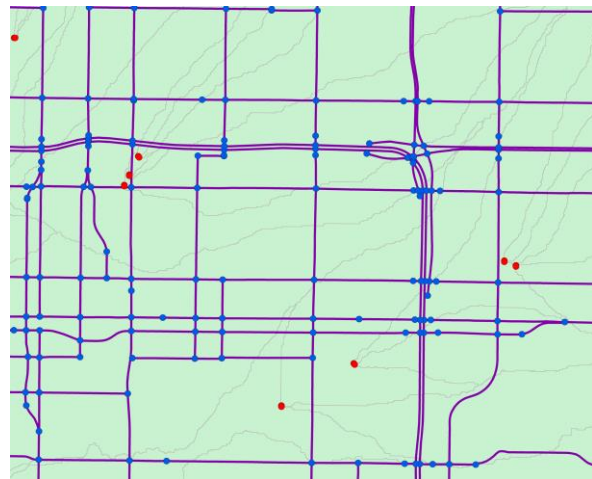


Figure 11: Zoomed in outlet locations near I-10 and I-17 intersection (Red: Drainage point, Blue: Road intersection, Purple line: AZ major roads)

4.3.2. NETWORK AND SUB-BASIN PROPERTIES IDENTIFICATION

ArcGIS was used to obtain the area, slope, and percent impervious land cover inputs. City documents were used to obtain conduit length, conduit geometry, and conduit roughness inputs. Figure 6 shows the impervious data that was generated from ArcGIS to create the area (km² and

acres), mean slope (degree and %), and mean impervious rate (%) for each subcatchment.

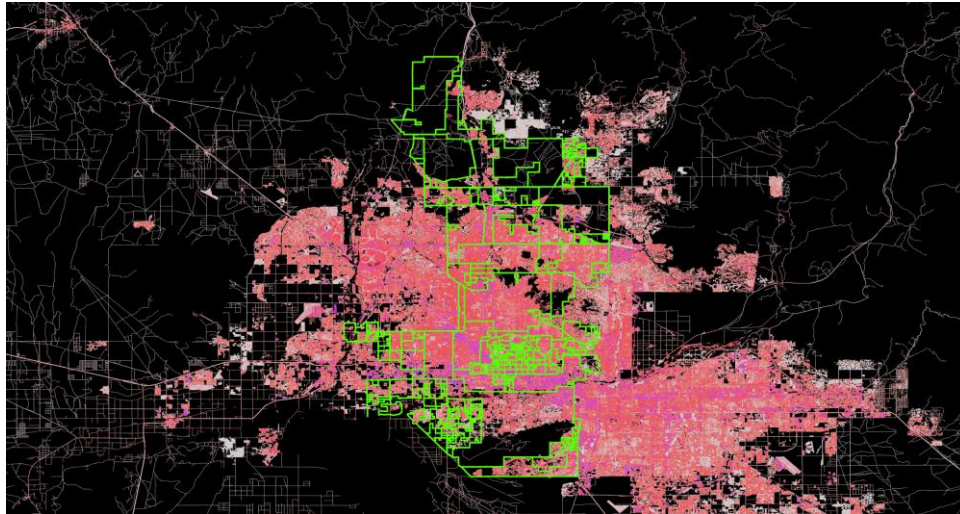


Figure 12: Impervious rate (%) in broader Phoenix area. Redder means higher impervious rate.

The distinction between impervious and pervious surfaces is defined by the infiltration capacity. For instance, infiltration is assumed to be zero in impervious areas. The only precipitation losses in impervious areas are a result of evaporation and depression storage [34]. Land use data was from the planning and development department in Maricopa County. Land cover data came from the southwest regional gap analysis project [35].

From a review of seven of the City of Phoenix's drainage quarter section maps [36] the conduit data in terms of location of pipe, type of pipe and size of pipe were retrieved. From these maps, it was abstracted that conduits segments were generally 1-mile long due to the gridded roadway system, conduits running under major highways would have diameters of 21 ft., and conduits running under arterials and collectors would have diameters of 3 ft. and 1.5 ft. respectively. From the types of pipe, RCP (Reinforced concrete pipe), RGRCP (Rubber Gasket Reinforced Concrete Pipe), CP (Concrete Pipe), the main type of pipe is RCP (Reinforced Concrete Pipe) with a roughness coefficient of 0.012 in mm.

4.3.3. FUTURE PRECIPITATION MODELING

Hourly precipitation values for the maximum 100-year frequency 24-hour storm event were input into the SWMM model at each rain gauge to model the baseline precipitation scenario. The historical rainfall data was collected from the Maricopa County Flood Control District [37]. These precipitation values were then adjusted to reflect changes in hourly precipitation intensities for 2020-2045 and 2049-2070 future scenarios, using the SWMM Climate Change Adjustment tool (CAT). To make the adjustments, a zip code in the Phoenix area was input into the SWMM-CAT graphical user interface along with the choice of scenario of Hot and Dry, Medium Change, or Warm and Wet climate scenarios based off of 9 representative global climate models. The climate change projection data in SWMM-CAT has been taken from another tool created by the EPA called CREAT (Climate Resilience Evaluation and Awareness Tool) which uses statistically downscaled General Circulation Model (GCM) projections from the World Climate Research Programme (WCRP) Coupled Model Inter-comparison Project Phase 3 (CMIP3) archive as the source of its climate change data. SWMM-CAT limited its use of CMIP3 results to the nine GCMs that were most representative of US climate conditions and used the IPCC's "middle of the road" projection. This projection is characterized by (1) rapid economic growth, (2) peak global population in mid-century, (3) the quick spread of new and efficient technologies, (4) the global convergence of income and ways of life, and (5) a balance of both fossil fuel and non-fossil energy sources. The SWMM-CAT graphical user interface is shown in Figure 16.

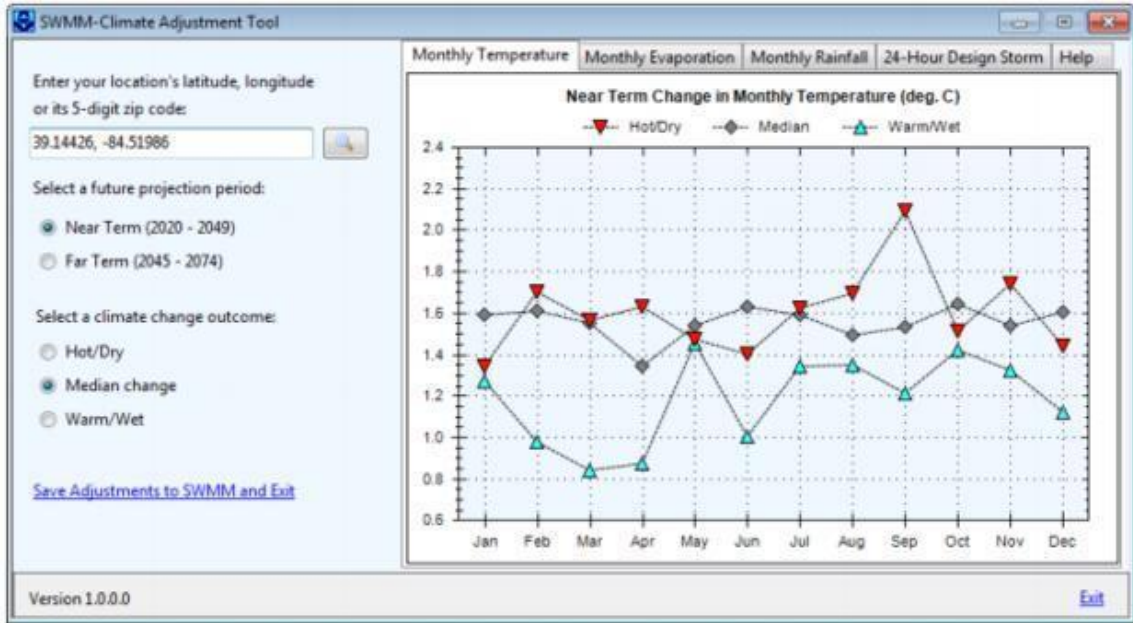


Figure 13: SWMM-CAT graphical user interface

4.3.4. SWMM SIMULATIONS AND FLOODED NODES IDENTIFICATION

Rainfall/Runoff simulations were then run for the duration of the 24-hr storm events to see the amount of flooded conduit junctions above the flooding thresholds. Flooding thresholds were defined according to FEMA who says that flooding depths above 6 inches can make drivers lose control of cars, depths above 1 foot can cause vehicles to float, and depths above 2 feet can cause vehicles to float away [38] After running a 24-hr SWMM model simulation for each historical and future scenario, the number of nodes that flooded above these thresholds were identified and compared. Figure 11 shows an example of a SWMM model simulation where nodal flooding volumes are color-coded.

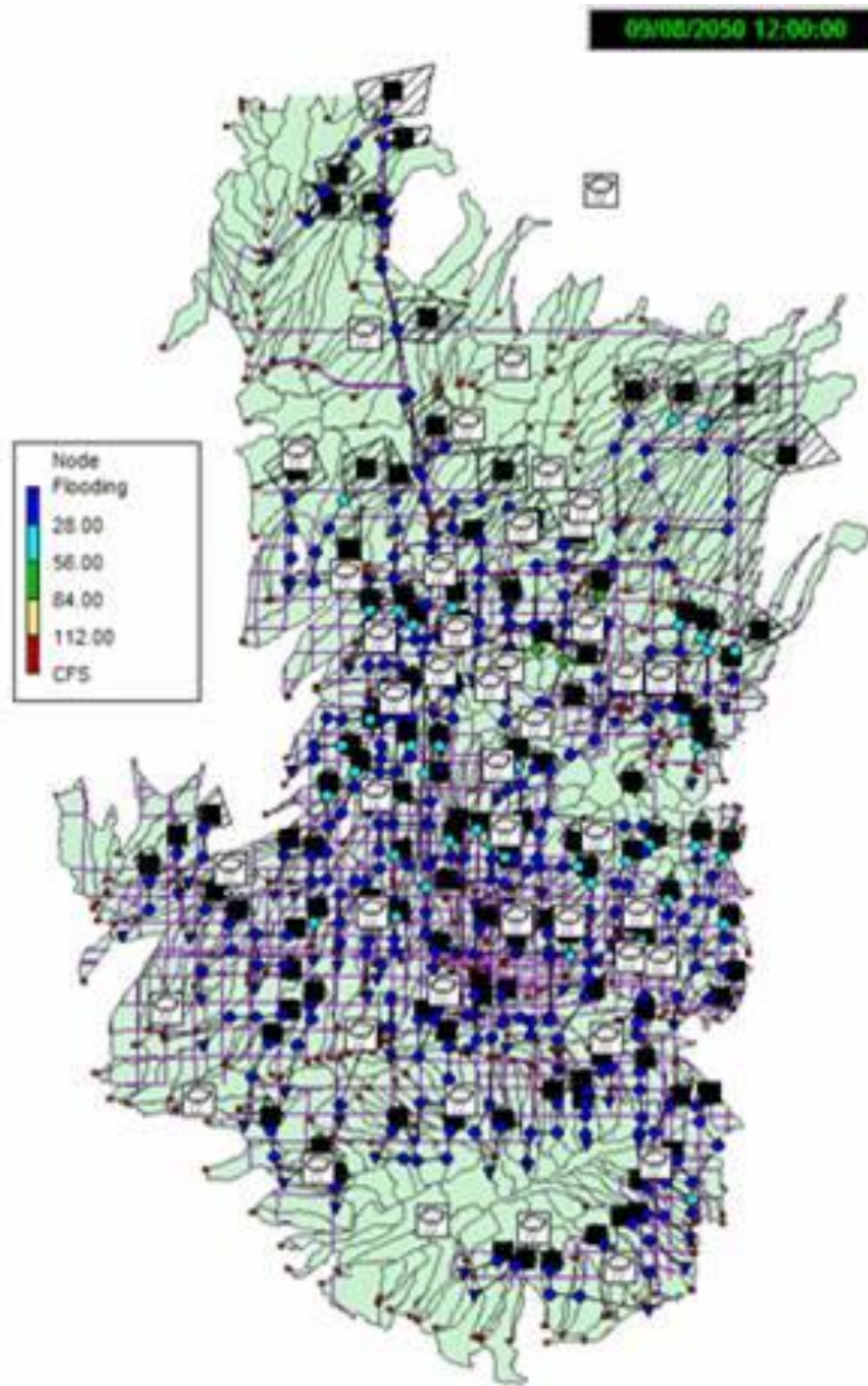


Figure 14: EPA SWMM model of City of Phoenix storm water sewer network. Nodes are color coded to aid in viewing flooding results.

4.4. Outcomes

4.4.1. CLIMATE CHANGE EFFECTS ON PRECIPITATION

The intensity of 24-hr storm events and the resulting urban flooding will increase in the future and especially in the time period of 2045-2070. As can be seen in Figure.18, the hourly precipitation values during the storm in the future scenario are increased by up to 0.05 inches from the historical case.

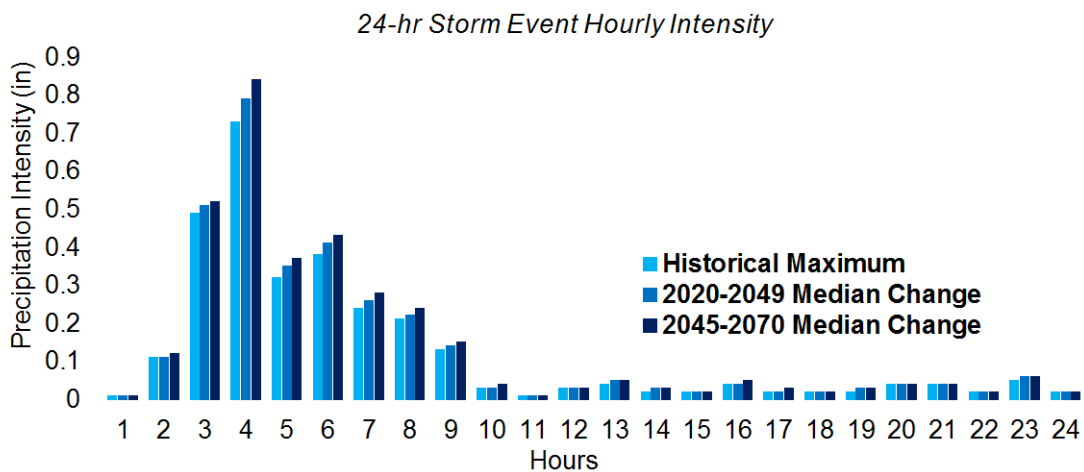


Figure 15: Historical and Future Precipitation Intensities for 24-hr 100-yr storms in Phoenix. The precipitation intensity increases into the near-term and far-term future scenarios.

4.4.2. FLOODED NODES PREDICTION

When overflow at drain points are not contained within the drainage network and leaves the system, it often results in flooding on impervious roadway surfaces in urban area. Six inches of water reach the bottom of most passenger cars and cause loss of control. One foot of water will float many vehicles, and two feet of moving water will carry away most vehicles, including SUVs and pickup trucks [38]. Thus, we estimated potential flooding locations in the city of Phoenix that will have more than six inches, one foot and two feet of flooding depth respectively by modeling stormwater drainage networks in the city. The drain points in the

city that are vulnerable to flooding were identified through 24-hr flooding volume simulations.

The flood forecasting results show that among 325 modeled storm drain points, which are potential urban flooding locations, 55 locations were identified as being at the risk of more than six inches of flooding depth from the historical maximum data. Compared to the historical data, in the near future, there will be 3.6 % increase of locations that are flooded above 6 inches, and in the far future, there will be 25.5 % increase, which is 14 more location points than the historical data (Figure 19).

We further assess the flooding intensity to the one-foot and two feet at each location for three different climate projections. The results show that there will be 400 % increase in the number of locations that exceed two feet flooding depth both in the near and far future, even in the scenario of Median change (Figure 20). We found that the nodes that flooded the most are the ones that have very high imperviousness rate coupled with high precipitation values compared to the other nodes. The subcatchment slope and the pipe diameter did affect much on increase in flooding intensities.

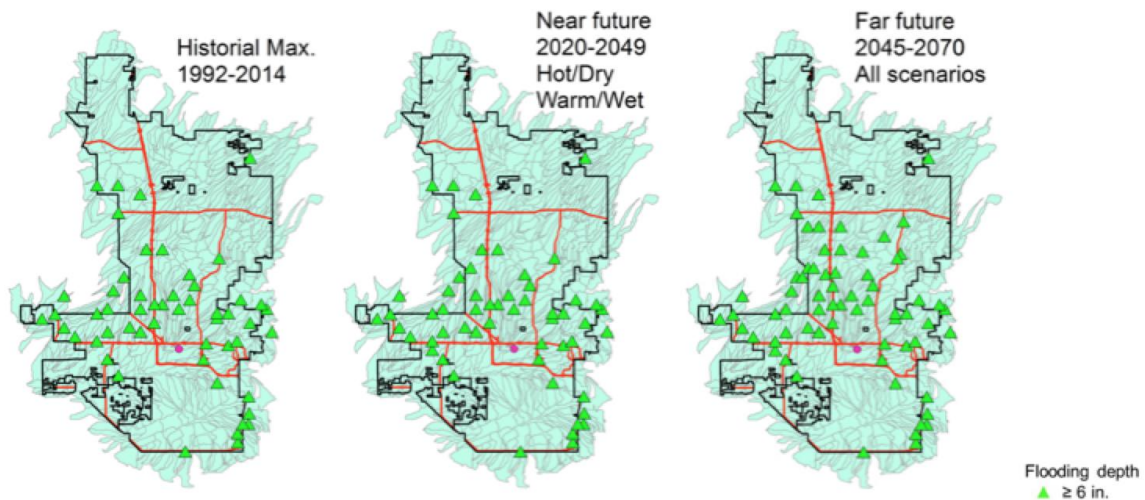


Figure 16: Locations of flooding above six inches for all scenarios

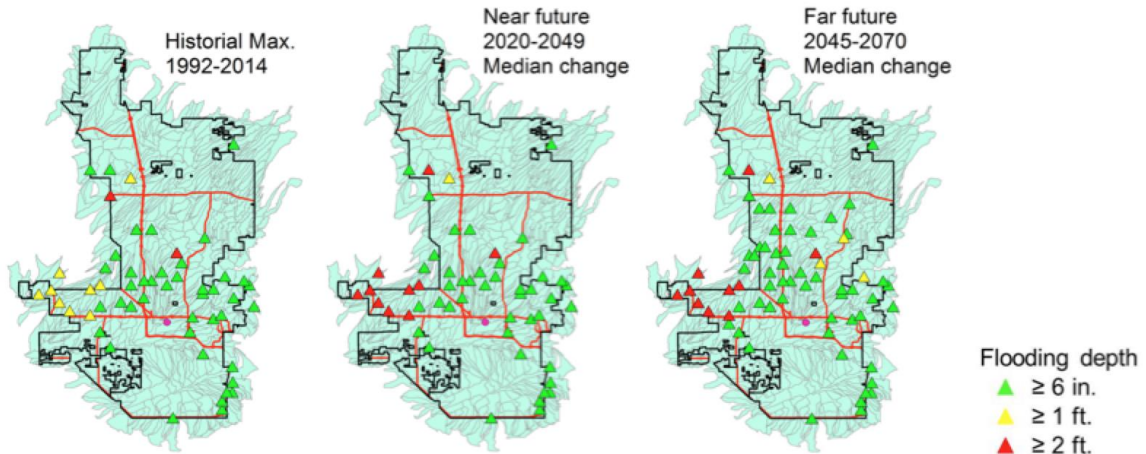


Figure 17: Locations of all levels of flooding in the median change scenario.

Table 1: Number flooded nodes under historical and future precipitation scenarios in the City of Phoenix

Flooding Depth	Historical	2020-2049			2045-2070		
		Median Change	Hot/Dry	Wet/Warm	Median Change	Hot/Dry	Wet/Warm
6 in - 1 ft	55	55	57	57	69	69	69
1ft - 2 ft	11	11	11	11	14	14	14
2 ft +	2	10	10	10	10	10	10

Table 2: Percent Increase in flooded nodes above 6 inches from historical conditions

Climate Scenarios	Near future (2020-2049)	Far future (2045-2070)
Median Change	0%	25.5%
Hot/Dry	3.6%	25.5%
Warm/Wet	3.6%	25.5%

Table 3: Percent Increase in drastically flooded nodes from historical conditions

Flooding Intensity (Median change)	Near future (2020-2049)	Far future (2045-2070)
▲ ≥ 6 in.	3.6%	25.5%
▲ ≥ 1 ft.	0%	27.3%
▲ ≥ 2 ft.	400%	400%

4.4.3. DISCUSSIONS AND IMPROVEMENTS

The flood forecasting results show that there could be a significant increase in roadway flooding in Phoenix in the upcoming decades. In the near future, there could be a 3.6 % increase in the number of locations that are flooded above 6 inches, and in the far future, there could be 25.5 % increase. There could also be a 400 % increase in the number of locations that exceed two feet flooding depth both in the near and far future, even in the scenario of Median change. In all scenarios, the nodes with the most amount of flooding have very high imperviousness rate coupled with high precipitation values compared to the other nodes.

If we consider regional stream river flooding potentials added to the urban flooding at drain points, the impact on roadways by flooding calculated in this study can be rather conservative, while the consequences of flooding can actually be worse. For example, one potential extreme flooding node is located at the intersection of 91st and Glendale Avenue in Phoenix. Here, stormwater is collected at the drain and flows to the Agua Fria-New River, which is an outlet point of drainage pipelines. In this subcatchment area, highway 101 is located less than one mile from the drain point and the river stream. This implies that the road can be affected both urban and stream flooding at the same rainfall event and may cause a major road system failure. Therefore, it suggests a need for future research on improved urban flood forecasting models coupled with regional flooding models, especially for the drainage networks located in stream floodplain areas. Increases in peak river discharge flow will lead to a reduced capacity for drainage outflow to the stream, which may hold ponded stormwater longer in the flooded area. The flood forecast results emphasize the importance of the "Safe-to-Fail" approach departing from the traditional approach of "Fail-Safe" to design resilient infrastructures. As future precipitation projection shows

drastic increase of extreme flooding locations, infrastructures need to be improved and designed in a way that their systems are capable of adapting to uncertainties of extreme weather and unpredictable consequences of infrastructure failure to climate change.

5. VULNERABILITY TO FLOODS:

As global climate change increases the impacts of extreme flooding in urban areas increases as well; it is important to consider the impacts that flooding imposes on vulnerable populations due to the reliance of services and accessibility of roadways. In Maricopa County, flooding is a significant natural disaster that threatens the region especially since it's a populated region that is subject to sudden flash flooding with little to no predictability. With expected denser populations, the impacts of an impaired service or roadway from flooding can have varying degrees of damages that can accumulate significantly in highly concentrated vulnerable areas.

The term vulnerability has many diverse applications and definitions. In the context of extreme flooding events and climate change, vulnerability is broadly defined as one's ability to anticipate, cope, and recover from the damaging hazards of flooding. It is also interrelated to the susceptibility of risk a person or system to a hazard, and is often associated with the resiliency of a system or person from the output of an extreme event. In other words, being vulnerable is having the inability to mitigate or prevent the damaging impacts of an extreme event, possessing limited accessibility of resources or minimal capacity to recover, and the susceptibility or exposure to risk.

Although the impacts of flooding can proliferate itself into many affected dimensions, for the purpose of this research the scope of analysis has been narrowed into two categories, 1) social and 2) infrastructure vulnerability. By utilizing the data from GIS, in conjunction with the outputs of the forecasting studies, were developed to identify the geographic distribution of roads and the vulnerable population districts in the Maricopa County.

5.1. Social Vulnerability:

As the frequency of natural disasters increase with recent climatic trends, the populations affected face similar increases and can be left most vulnerable [39]. Social vulnerability is a product of inequality [40] and is most apparent after a disaster has occurred, when different patterns of recovery are observed among certain population groups [41]. In comparison to physical and economic vulnerability, social vulnerability requires more time, resources and political will to redress [42]. This is so because people that are more socially vulnerable generally live in the highest risk locations with substandard housing; additionally they have little to no knowledge or political connections that allow them to take advantage of recovery resources available [43]. Populations that are socially vulnerable in pre-flood conditions may face similar if not worse conditions from the occurrence of a flood. In the advent of climate change and increase in extreme weather conditions, social vulnerability is a big threat to public health

Scholars have defined social vulnerability in numerous ways, each with the consensus that natural hazards affect people and societies differently [41; 44; 45; 46]. These differences are caused by the unequal exposure to risk by making some people more prone to disaster (inequality) [45; 41; 43], and can be related to how a society defines the attribute of persons [46]. Social vulnerability is defined as the socioeconomic, demographic and housing characteristics that influence a person's ability to cope with, respond to, and recover from a natural hazard [47]. Cutter and Emrich define social vulnerability as the susceptibility of social groups to the impacts of hazards, as well as their resiliency or ability to adequately recover from them [48]. Similarly, it entails potential losses due to hazardous events, and society's resistance and resilience to that hazard

[49]. From all the definitions it is noted that the common key component of focus is on human resilience to hazards.

Scholars in different fields seem to agree that vulnerability is not just a result of natural occurrences but is also affected by the social standing of an individual in a society. Social vulnerability is always a product of inequality [43]. Thomas et al., recognizes that social structure and roles produce extensive human suffering and differential impacts. Social systems generate unequal exposure to risk, affect the highly exposed population's sensitivity to this exposure, and influence their capacity to respond and adapt, hence making them more vulnerable to natural disasters than others [44; 45]. Gilbert Fowler White once said that "Floods are acts of God but flood losses are largely acts of man" [50.], implying that the effects of natural disasters depend on how socially vulnerable a person is as opposed to the magnitude of the very disaster. The socio-cultural condition and political and economic practices that occur prior to the natural hazard occurrence turn it into a human catastrophe [45], and the natural disasters only serve to reveal the human vulnerability arising from inequalities [46]. There are social, economic, demographic and housing characteristics [47] that either amplify or diminish the vulnerability of an individual to natural hazards.

5.1.1. INDICATORS OF SOCIAL VULNERABILITY

Different scholars and agencies have identified different indicators of social vulnerability, tailored for the specific area, hazard, or time. Among these the most common ones include: age, income, education, gender, ethnicity/race, immigrant communities, people with disability and transient people including homeless and those in shelters [41; 45; 43]. This study measures six indicators of social vulnerability, adopted from the Social Vulnerability to Environmental Hazards report by Cutter [41]: Age,

gender, education, race/ethnicity, income, and other populations in regards to as transients.

To determine the correct weights to use for the methodology, a thorough literature review was done on different social vulnerability analyses. Susan Cutter's paper, Social Vulnerability to Environmental Hazards, created a social vulnerability index and weights for each variable, much like other literature of analysis that were conducted. Much of current research looks at social vulnerability pertaining to extreme heat. Although many of these studies on extreme heat have been helpful to guide the research, the indices provided by those studies were too specific for measuring social vulnerability for flooding. Cutter's looked at the social vulnerability analysis to all natural hazards across the entire country, however for this study the scope was narrowed to the indicators below.

5.1.1.1. Age

“ Nearly half of all deaths in hurricane Katrina were people over 75 years...because many nursing homes had inadequate plans for evacuation” [45] and over 70% of fatalities were people above the age of sixty five [50].

The age of a person affects their physical abilities, such as their mobility to move out of harm's way [47], as well as their mental ability to understand, communicate, and respond to warnings that can place impact the vulnerability of their position. When a road is impaired by flooding, children and elderly are considered increasingly vulnerable--especially in circumstances where they are isolated, as they may have higher reliance to access basic amenities. Driving mobility is either impaired or illegal for these age groups, and can be a potential barrier in suburban areas that are auto-oriented, lack safe or accessible transit alternatives, or are food and resource deserts. These populations also face greater biological risks

and increased susceptibility to disease, with higher risks of safety and emergency response needed. In addition, they are more sensitive to the effects of stresses on the food and water supply, as they have higher reliance on these systems and reduced ability to mobilize quickly [51].

5.1.1.2. Gender

Human Vulnerability Research Institute identified women as a group that experiences challenges in recovering from hazards compared to men due to the predominance of sector-specific employment, lower wages, and family care responsibility. Women generally tend to be poorer relative to men, and may not have the necessary resources to respond to and recover from disasters, especially if they are single mothers, in addition to barriers shaped by traditional gender roles [50]. For example, if a roadway were to be impeded by flooding blockages, the lost productivity in the occurrence of several hours to days may not affect a male counterpart that has a minor financial advantage of expendable income or savings; a woman in this scenario may face added responsibilities that they are expected to manage, and may not be compensated nor have the added security of a flexible occupation role if the delay is prolonged for several weeks.

5.1.1.3. Education

Educational attainment has a high correlation to income status, in that, limited education constrains the ability to secure a high paying job, and also the ability to understand warning information and access to recovery information [47]. Directly, formal education is considered as a primary way individuals acquire knowledge, skills, and competencies that can influence their adaptive capacity, and indirectly through improved socio-

economic status, which is associated with, diversified communication linkages and wider social networks [52].

5.1.1.4. **Race/ethnicity**

“Disasters are income neutral and color-blind” [42]

Race and ethnicity impose language and cultural barriers, and affect access to post-disaster funding. Race and ethnicity are inferential proxies for the process of inequality, which creates marginalized groups in society, often neglected within disaster management plans [41]. Race and ethnicity play a crucial role in vulnerability as it has high correlation at determining the vulnerability that overlaps in the other indices. Minorities, especially in Phoenix, have a historical complexity that puts certain races and ethnicities at a significant higher disparity to fall into several vulnerable indices over others. They also deal with complex issues such as more barriers of financial stratification, social barriers such as racism that can isolate and exclude whole ethnic communities from gaining financial investment with resources to recover, as well as less buffers in place to mitigate damage due to low socioeconomic status, health, gender norms in some ethnic groups, and generally different demographic populations.

5.1.1.5. **Income/ Socio-economic Status**

“The poor were left to ride out the storm in their homes or move to the shelters of last resort” [41]

Poverty is viewed as an indicator of lack of or limited access to resources and income opportunities [53]. Socioeconomic status affects the ability of a community to absorb losses and be resilient to hazard impacts [47]. Additionally, those of low socioeconomic status are more willing to take risks, particularly living in floodplains for example that face higher

insurance rates, but may be the only affordable options for those with limited income. These populations may not possess enough disposable income to invest in preventable measures with upfront costs, and are the ones who may face the most damage as a result; combined with the other factors, those of low socioeconomic status also may have smaller capacity to recoup and access resources for recovery.

5.1.1.6. *Transient Populations*

Other populations that are also considered as vulnerable include those who are homeless, commute long distances, or have special needs that require additional resources. The data and literature for these populations are difficult to consistently assess, however the lack of resources such as shelter and high risk and dependency to the physical environments are well known amongst policy groups. These populations are often mobile, or rely on public areas to recuperate from the external elements with long exposures. Even commuters who travel long are either confined to travel for long hours, which can lead up to several hours if a major road is blocked, otherwise rely on public transit that may take equally as long and exposed. Populations with special needs may also be considered vulnerable because depending on their condition may be inhibited from making decisions, physically accessing sidewalks and other barriers by themselves.

5.1.2. *SOCIAL VULNERABILITY ANALYSIS:*

Measuring social vulnerability takes into consideration many different factors, such as demographic and socio-economic indicators. These different indicators contribute to making an individual more vulnerable to extreme flood events. Identifying these communities and the location in

relation to flood plains will help determine who is most vulnerable and why. In most cases individuals that are of a certain age, income and race are unable to cope or recover from extreme flooding events; whether that is mobility to evacuate an area, having knowledge if their home is within a floodplain, or having the capability to pay damages to their personal property after a flood event. The original analysis looked at a countywide social vulnerability analysis and then narrowed down the research to cover only city of Phoenix. This section will discuss the methodology that was used to define and analyze the social vulnerability. To identify who is most vulnerable, a social vulnerability index was created to recognize certain variables that would make an individual most vulnerable. Six indicators were originally chosen to analyze including; race, age, income, education, gender and transient populations. Afterwards, the Authors determined weights for each indicator to convey the importance of each indicator. As previously indicated, Cutter's work was used to decide the weights, and thus calculate the social vulnerability for each of the aforementioned pillars. The broad perspective, although might not be as accurate, provided enough information to do social vulnerability analysis that looked at most of the vulnerability indicators.

The three indicators that were chosen for this analysis are: age, income and race. Each indicator was given detailed specifications to determine which cohorts of the population would be most vulnerable to flooding. For age, it was determined that anyone who is under the age of 18, and over the age of 65, whom were considered most vulnerable. For income, any household that was considered low income or below were considered vulnerable. Lastly, picking the minority populations whom include: African American, Hispanic, Asian, and Native American people. American Community Survey (ACS) data was collected through Social Explorer and

three data sources from the ACS 2014 5-year Estimate were used: (1) Average Household Income, (2) Age, and (3) Race. The data were examined at a census tracts level to be more accurate on where these individuals are located. To calculate for vulnerability each census tract was given a 0-1 score then each weight was multiplied by 0 or 1. 0 being that an area does not have a particular demographic or socio-economic variable and 1 being that it does. Once all vulnerability weights were calculated for each indicator a total vulnerability analysis was prepared by calculating all weights through census tracts.

Table 4: Social Vulnerability Measures based on Cutter's Weightings

Social Vulnerability Measure	Weight
Income	12.4
Age (Below the age of 18 and above the age of 65)	11.9
Ethnicity: African American	6.9
Ethnicity: Hispanic	4.2
Ethnicity: Native American	4.1
Ethnicity: Asian	3.9

To display the location of vulnerable populations Geographic Information System (GIS) was used to create thematic maps of the city of Phoenix. A variety of tools were used to clip and spatially join data to represent total social vulnerability. Symbology within ArcGIS was used to represent the different categories. Six ranges were chosen to present the data from least vulnerable to critically vulnerable. Gradient maps of age, income, and race were also generated to look at the total number of people within each census tract. The maps generated from this analysis not only indicated how vulnerable the city of Phoenix is but also identifies the exact vulnerable population's location.

5.1.3. SOCIAL VULNERABILITY OUTCOMES

The results from the social vulnerability analysis identify where individuals are located and to what degree the city of Phoenix is vulnerable. Through the data analysis process mentioned in the methodology, three maps were created to represent the vulnerability analysis (Figure 21, 22 & 23). Each vulnerability indicator was mapped individually, with the exception of race, which mapped all minority populations, and then was calculated to create a total vulnerability map. A second set of maps was created (Figure 23) to present the total number of individuals for each indicator to give a more holistic representation of these populations.

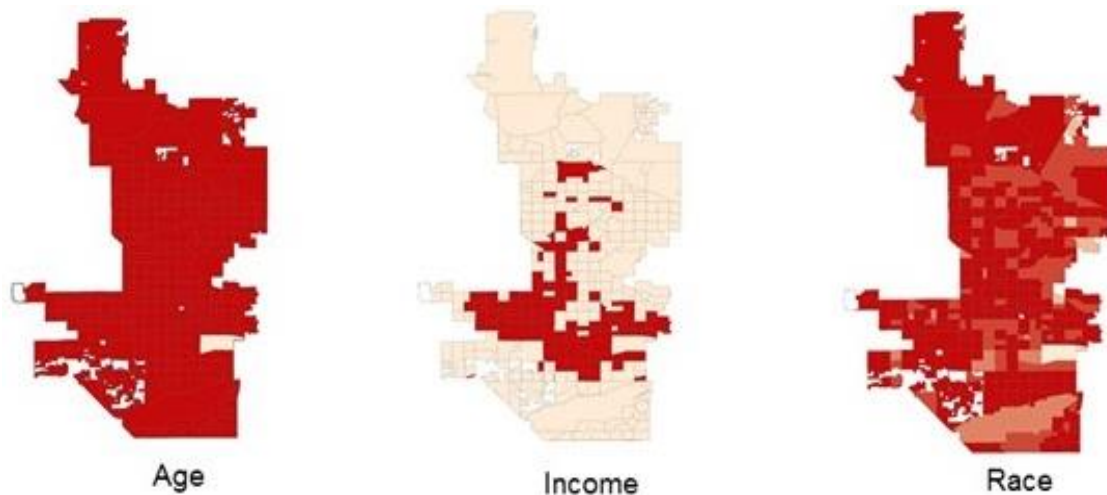


Figure 18: Vulnerability Analysis per Census Tract – Age, Income and Race

The vulnerability analysis illustrates that most census tracts contain individuals that were considered most vulnerable. Age and Race were predominantly exhibited that almost all the census located in city of Phoenix had individuals that were considered vulnerable. Though income well represented individuals that were considered low-income or below that most of the data had huge limitations. To expand upon the current analysis gradient map were produced to demonstrate the total number of people. The gradient maps produced were more representative of the location of vulnerable populations.

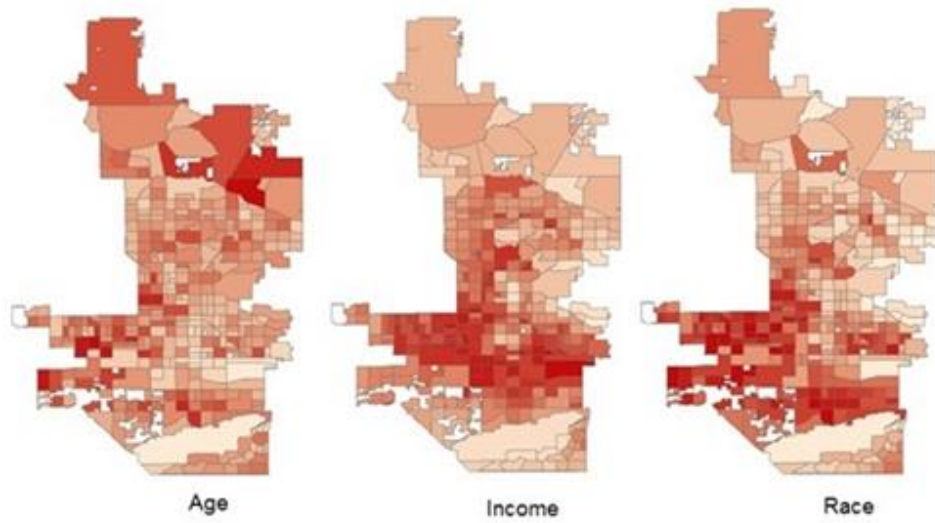


Figure 19: Total Number of Individuals per Census Tract – Age, Income and Race

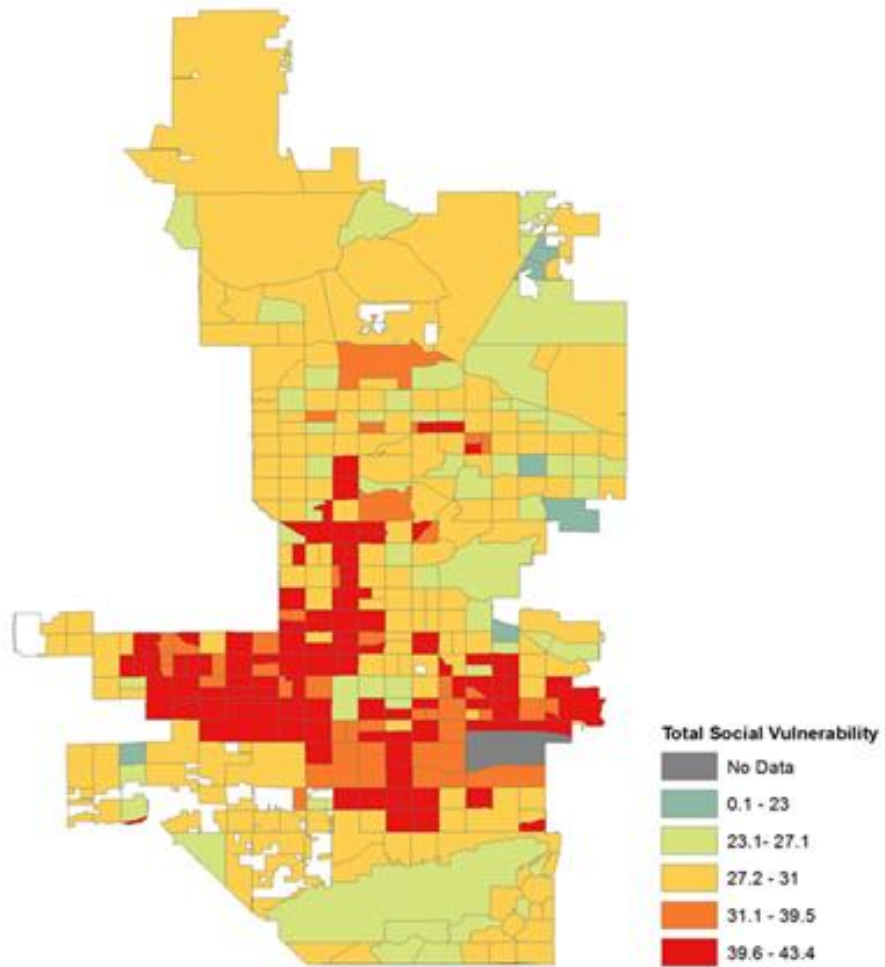


Figure 20: Total Vulnerability Analysis

From the above analysis (figure 23) the graph clearly identifies the social vulnerability analysis, which signifies the most vulnerable populations of individuals are located within West Phoenix and close to the downtown area of Phoenix. Should flooding occur, vulnerable populations in red indicate that there is a high concentration of kids/elderly, low socioeconomic status, and neighborhoods with high minority populations would be most impacted, and should be considered for prevention strategies and political support for disaster strategies. This data provides focus areas of where to implement solutions for these populations to cope with and recover from extreme flood events. Although social vulnerability indicates where most vulnerable populations are located, infrastructure vulnerability identifies the exact roads that are most vulnerable to flooding.

5.2. Infrastructure Vulnerability:

Infrastructure vulnerability can be defined as inability of infrastructure to withstand the effects of the climate change or to a given element at risk resulting from a given hazard at a given severity level. Damage to infrastructure can severely impede economic activity. Measuring the comparative vulnerability of infrastructure can help in building more sustainable infrastructure in the future and strengthening of the existing conditions of road for climate change.

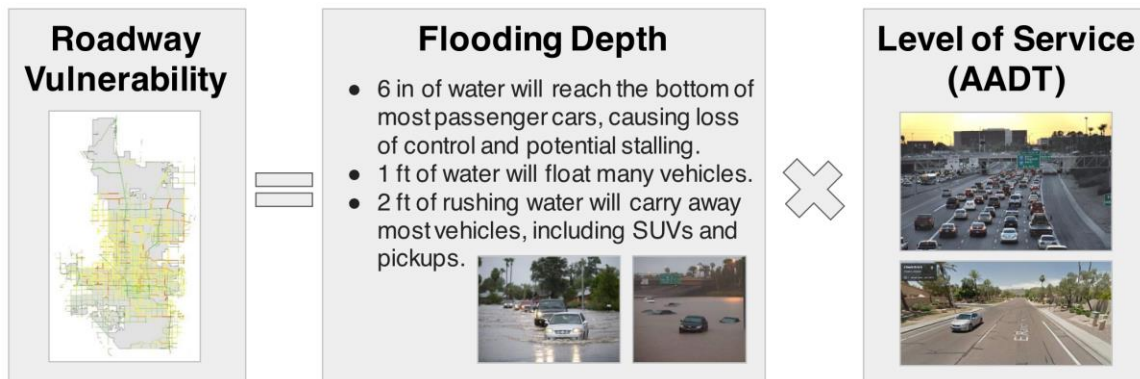


Figure 21: The utilized equation to measure the roadway vulnerability

5.2.1. INFRASTRUCTURE VULNERABILITY METHODOLOGY AND ANALYSIS:

Current roads within the southwest are highly susceptible to damage from flooding. It is clear as climate change becomes an increasing issue within the southwest region, including the greater Phoenix area, as it is forecasted to experience more frequent and extreme flood events. In 2014 an extreme flood event hit the Phoenix area where a total only 3.29 inches fell within a matter of hours [54]. While such a small number seems insignificant to cause any major damage this flood event created a severe amount of damage to homes, roads and local businesses. This incident damaged and completely flooded a large section of Highway 10 [54]. With this said identifying which roads are most vulnerable to flooding is a growing concern for the Phoenix area. Consequently, this analysis identifies which roads are most vulnerable to flood events.

To create a road vulnerability analysis, similar to the social vulnerability, an index of factors that would make a road most vulnerable was created. Although many variables contribute to roads vulnerability, five indicators were identified including: 1) Road type, 2) Level of Service (AADT), 3) Water capacity, 4) Age of the road, and 5) Most recent renovation.

The first step in this analysis was detecting which road types would be most vulnerable. Major/minor arterials and local highways/interstates were recognized to be the most vulnerable to flooding due to their level of service and density of built environment. Smaller local roads, private roads and rural roads were left out of this analysis since the focus of this project was on dense urban areas. To gain a better understanding of road vulnerability a number of sources were used such as Arizona Department of Transportation and Valley Metro. Data was collected regarding road types, traffic flow and capacity annually, as well as material. The main source of data, was Arizona Department of Transportation in addition to other provided within the forecasting chapter. Originally roads were going

to be ranked on a scale of 1 to 6, 1 being the best and six being the worst condition of the weight or most vulnerable to flood. The idea was that the higher a score the more likely that road would suffer from severe damage due to flooding. However, after reviewing the data that was collected and the relevance which some of the weights lacked, the indicators were eventually changed in accordance with the data provided by in the previous chapter, forecasting the flooding region. The data provided within the forecasting chapter included data sets in excel files provided by the National Oceanic and Atmospheric Administration (NOAA). Along with their dataset in excel GIS was also provided that rendered maps of the Phoenix area showing major drainage points. With this data they were able to identify which drainage nodes were going to flood and at what depth. The GIS provided also showed major/minor roads, and precipitation/runoff data. . Using the definition provided by ADOT and NOAA, a flood event occurs on a roadway when the vehicle is rendered immobile. In this case that would be 6 inches of water in Arizona.

After identifying the definition of a flood, data was collected on future flood event as explained within the forecasting chapter. The research deployed the prediction on precipitation events forecasted precipitation/flooding depth from 2020-2045 and 2045-2070. The forecasting data highlighted the levels at which the water would rise in the city. Moreover, drainage points were identified based on the correlation between the forecasting the anticipated vulnerability. Based upon the forecasting it was manageable to provide information to predict the depths at which each drain would flood during each given precipitation event for the given years. After Identifying, which nodes would flood, the Authors decided that the depths of 6 inches, 1ft, and 2ft, was going to be the designated flooding definition. With the precipitation

event data already incorporated with major roadway data and drainage node data.

A geographic information systems (GIS) analysis was then conducted to give a visual that identifies the road within the city of Phoenix. Flooding node data provided by the forecasting chapter, which displayed nodes of future flooding. Each node displayed a different depth of flooding: 6 in, 1ft and 2ft. The flooding node data was then spatially joined with the major roads file for the city of Phoenix. To calculate the vulnerability, the depth of flooding to multiplied by the level of service of each road. For any road that did not intersect with a flooding node they were calculated by 3 in to give a better representation of flooding intensity. Once the data has been fully processed in GIS the data was symbolically categorized to display the total road vulnerability.

5.2.2. INFRASTRUCTURE VULNERABILITY OUTCOMES:

The road vulnerability analysis provides information to which roads are most vulnerable and where those roads are located within the city of Phoenix. Before completing the vulnerability analysis major roads within Phoenix, other maps were created to represent these roads and flooding nodes used to identify the flooding depths within Phoenix (Figure 25). The city of Phoenix has an extensive network of major/minor arterials as well as a series of local highways/interstates that have been considered when applying the flooding nodes.

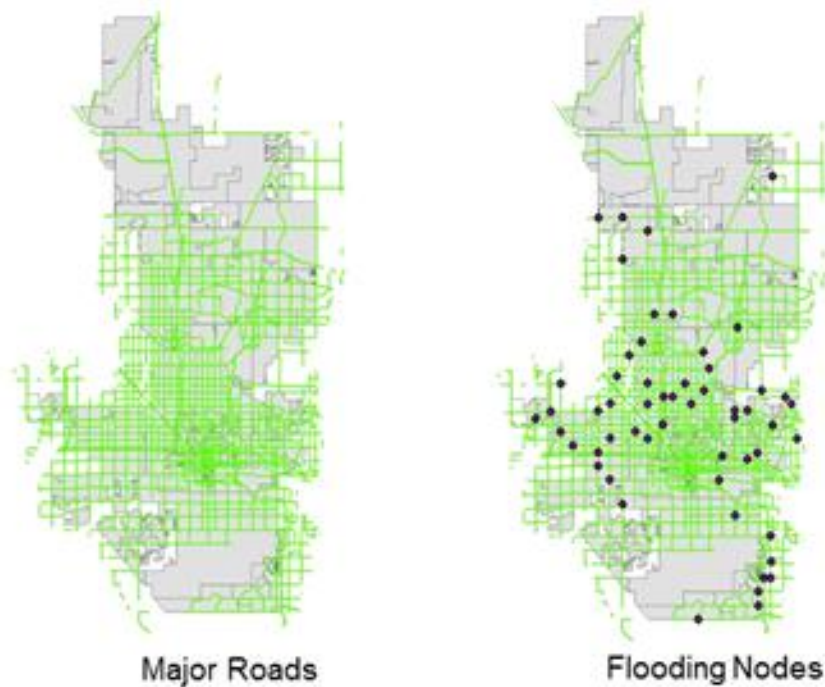


Figure 22: Major Roads and Flooding Nodes Map

Although few roads were categorized as critically vulnerable (figure 26), the outcome of this analysis is that there is that most of the road network within the city of Phoenix is substantially vulnerable to flooding events with various degrees of criticality. Moreover, the most vulnerable roads within Phoenix are minor/major arterial roads. Some of the least vulnerable roads within the dataset are major highways or interstates, which seemed

startling due to the fact that in 2014 the major damaged road from flooding was Highway 10. Further analysis should be considered to the flooding vulnerability for each of the road types to maintain a more holistic vision of road's vulnerability.

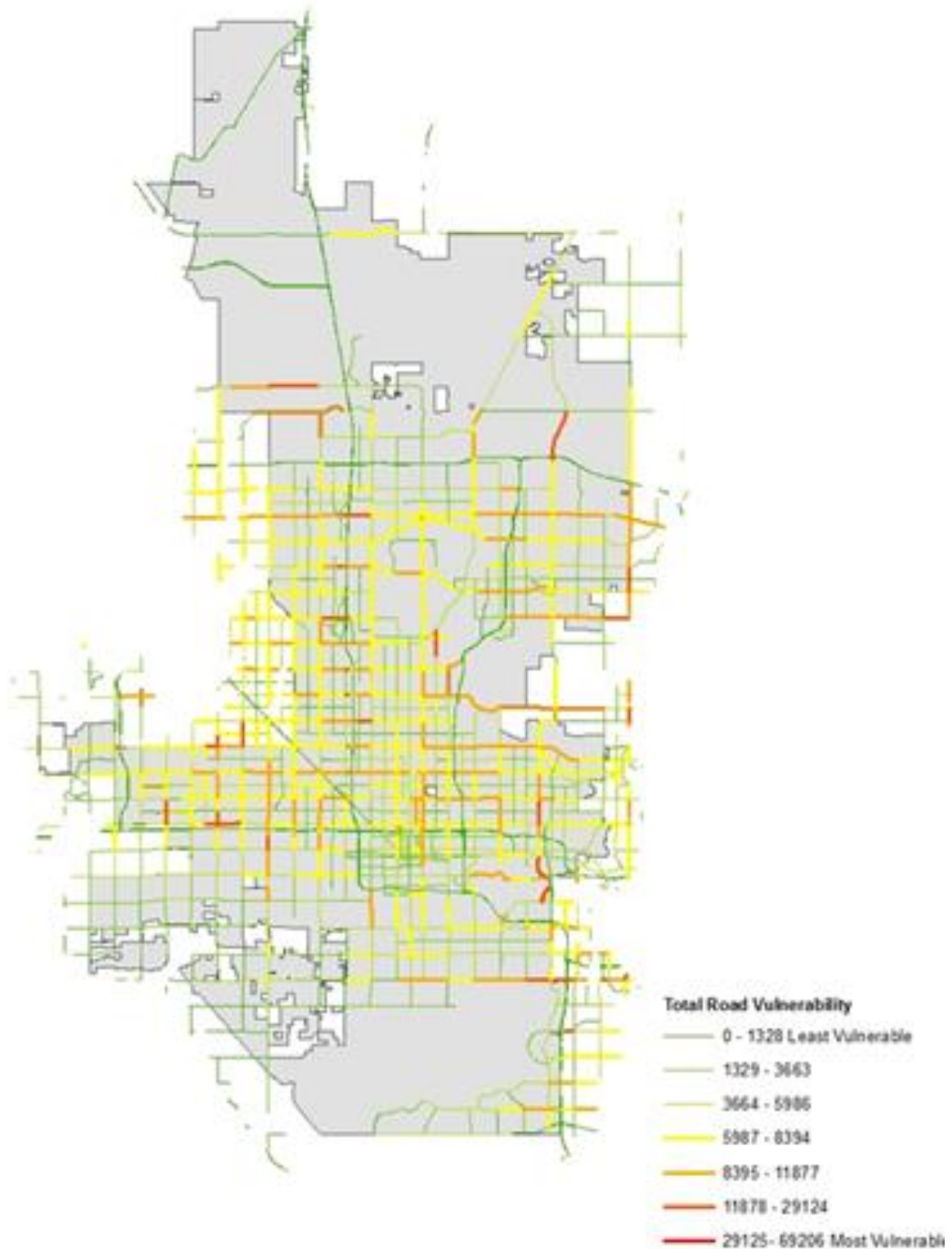


Figure 23: Total Road Vulnerability

5.3. Vulnerability Outcomes:

To identify solutions and adaptation strategies we must first understand who and what are vulnerable to flooding. Vulnerability identified certain populations and roads that will potentially be most impacted from flooding. Strategies for flooding prevention should look closely at who and what are most vulnerable to narrow the geographic area, i.e. road, intersections or neighborhood, as well as the types of solutions to implement. Though the analysis did identify who and what were most vulnerable, there were many limitations with this analysis and wish to make recommendations for future research. Some of the greatest limitations for the analysis were lack of data on flooding and vulnerability analysis. Though Cutter's work gave a basis of where to start her work looked at a very broad perspective, which may not be completely accurate. For future research it would be pertinent to create indices and weights specific to flooding events using factor analysis. We also recommend that weights and indices should be narrowed to a specific geographic location, in this city of Phoenix. We also recommend that for social vulnerability should look at education and type of employment. For infrastructure vulnerability we recommend to look at more factors for what makes infrastructure vulnerable.

The final recommendation is to look at the entire Phoenix metro region in terms of vulnerability. Although we were unable to complete this analysis on a region wide scale doing an analysis on the entire region would give more information on which roads and which populations are most vulnerable. Fortunately, this data provides clear information about who and what is most vulnerable and that agencies will be able to use this data to strategically implement solutions for certain area.

6. ADAPTATION STRATEGIES:

The planning and engineering communities must consider how to adapt infrastructure to more frequent standing and moving water events that are expected in the future due to climate change in order to mitigate impacts of flooding on infrastructure and vulnerable populations. This research explores adaptable solutions that incorporate design philosophies from both Fail-Safe and Safe-to-Fail designs.

This study defines infrastructure strategies as Fail-Safe when they are unlikely to fail, but which tend to fail in an irreparable manner, which causes harm to other components of the system. The failure of Fail-Safe infrastructure frequently results in significant interruption of service. Fail-Safe strategies are associated with more traditionally used infrastructure practices, such as a bridge designed to withstand a one-hundred year flooding event. Safe-To-Fail infrastructure strategies tend to fail more frequently, however these systems tend to be more resilient and result in shorter-term loss of functionality. Existing Safe-To-Fail strategies include Green Infrastructure and Low Impact Development (LID) strategies.

This study informs how road infrastructure design and maintenance strategies can protect the Phoenix Metro Area against more frequent flooding events that create new vulnerabilities in the system. This research makes key assumptions:

- Phoenix will experience increased road flooding in the future. Phoenix has had some significant flood events throughout its history, and there will be more in the future due to climate change.
- Climate adaptation is important, but cities have only implemented adaptation strategies on a limited basis. Instead, they continue to use risk analysis strategies to adapt, and have primarily used Fail-Safe solutions. In order to protect the infrastructure that has already been heavily invested in, solutions need to consider water safe

design that is ecologically sound (Safe-to-Fail). This presents a new paradigm for urban water and road design.

A literature review was conducted in order to collect case studies for further review. The purpose of the review was to document the suite of proposed roadway solutions that mediate the effects of flooding. Different solutions are more or less relevant to different scales of roadway types. This paper assigns each solution a rating on applicability to social, economic, or environmental vulnerabilities for three major categories of roadways: link, route, and network. Finally, results detail the attributes each solution type provides for fail-safe and safe-to-fail system responses. The final result was the creation of a suite of solutions that can be applied to any location vulnerable to flooding.

6.1. Background

Federal policy and academic research focus largely on vulnerability and use risk assessment methods that include climate change projections to develop associated adaptation strategies with known solutions (e.g., more bridge scouring needs riprap). They rarely consider or use adaptive strategies which question the underlying assumption that current infrastructure ought to be maintained for the next 100 years. Very few strategies consider how to change practices to more adaptively engage in road construction, road network design, and maintenance or scheduling. The majority of work seems to ask the question, “what is going to happen with climate change?” versus, “how can we adapt our practices to account for climate change?” An important yet overlooked question is: “are existing mitigation strategies sufficient?”

Resilience strategies for flood management, for example, focus less on trying to “control” water and more on building adaptive capacity to manage unpredictable ecological responses. This perspective seems to

be lost in the transport literature. Moreover, research needs to reflect and encourage a stronger relationship between the Safe-To-Fail solutions identified in one body of literature (flood management) and design decisions made in another (road adaptation). What are the current best practices for Fail-Safe and Safe-To-Fail climate change adaptation strategies? This paper assesses existing case studies that focus on implementing Fail-Safe and Safe-To-Fail road infrastructure strategies for flooding or climate change adaptation.

The following research questions were designed:

- How can municipal and regional governments implement these strategies at link/route/network levels for roads? (and identify economic, environmental, and social factors that relate to each road and vulnerability scale?)
- What are the tradeoffs to using Fail-Safe versus Safe-To-Fail infrastructure? (Due to the spectrum of Fail-Safe and Safe-To-Fail solutions, discussion about trade-offs should occur in the context of tangible case studies.)

6.2. Methodology

The methodology was designed to develop a tool to help policymakers make decisions about Fail-Safe and Safe-to-Fail design strategies to manage climate-change-induced flooding of roads. Existing literature was used to characterize Fail-Safe and Safe-to-Fail design strategies employed, and factoring vulnerability and infrastructure scales. Special focus was given to researching Safe-to-Fail strategies, which are frequently more cost effective than traditional Fail-Safe strategies and are easier to implement in times of budgetary limitations. Safe-to-Fail strategies are also more efficient as long-term solutions based on maintenance and repair.

Note: Appendices A-D include references and detailed descriptions of tools used for analysis.

6.2.1. CASE STUDY LITERATURE COLLECTION

Research collected existing case studies that address future flooding impacts of roads and which pertain to hazard mitigation, flood control, roadway vulnerabilities, and climate change adaptation strategies. Due to a lack of depth in the research, an initial focus on desert climates or the Phoenix area broadened to include case studies from any region. A few of the case studies came from more specialized research databases including resources such as "Environment Complete," "GeoRef," "Web of Science," "Ecological Society of America Publications," "EDP Sciences," and "GreenFILE." The study did not exclude any peer-reviewed results, and all scholarly case studies found using this method were included in the study. The study also explored municipal websites if a particular case study was in the United States. Via these sites, collection of more detailed reports was conducted, yet the study recognized that they are not scholarly, peer-reviewed publications. The search resulted in twenty four case studies and location-nonspecific adaptation strategies. Appendix A contains the full list of case studies and other solutions.

6.2.2. CASE STUDY ASSESSMENT

In addition to collecting basic information on each case study (e.g., authors, year of publication, year of study, location of study, etc.), the study collected several types of information to determine Fail-Safe and Safe-to-Fail best practices. The study collected the scale and types of infrastructures considered in the study, the types of vulnerabilities considered in the study, the relationship between design practices employed, Fail-Safe literature and Safe-to-Fail literature. Some of the information is qualitative in nature, therefore the study established inter-coder reliability by assessing each study with two separate individuals.

Major discrepancies were discussed and resolved between scorers. All score-based results obtained through the work were averaged over each coder.

6.2.2.1. Infrastructure Scales

An assessment of each case study was done in order to determine the scale of each different roadway infrastructure adaptation strategy. The size and function of the road in question determines the materials used in roads, the types of traffic served, and the wear and tear endured. Moreover, the types of flood management infrastructure employed vary depending on road type. Functional roadway types were identified and defined across all scales. The roadway type definitions were derived from the Arizona Department of Transportation (ADOT). From these definitions, Table 1 was created and used as a tool to assess the case study solutions using binary or null terms. A one (1) was assigned if a team member identified that the solution was applied to a particular roadway type in the case study, whether mentioned or assumed. A zero (0) was assigned if the team member identified that the solution was not identified in the case study, was irrelevant to the roadway type, or could not be applied. Null values (--) were assigned to assessment criteria that were not specifically mentioned, or were deemed not applicable to a solution type as it was described in a particular document.

6.2.2.2. Vulnerability Scales

The link, route and network matrix was used to assess the social, environmental and economic impacts of these solutions identified in the case studies. The matrix became Table 2 in the assessment document. Solutions were rated on a one-to-five scale with one (1) meaning that the team member analyzed the solution as having the weakest possible correlation to the impacts and a five (5) meaning that the team member

analyzed the solution as having the strongest possible correlation to the impacts. Null values were included because there was not enough information provided to associate a correlation value. Major differences between reviewer ratings were discussed in order to resolve any discrepancies and ensure the best analysis of the data.

6.2.2.3. *Fail-Safe vs. Safe-to-Fail*

Case studies were assessed to identify whether the processes, components, or system design considerations can be classified as Fail-Safe or Safe-to-Fail. While Fail-Safe and Safe-to-Fail are new concepts for infrastructure design and climate change adaptation, their explicit differences are rarely discussed in literature. Instead, qualitative differences are discussed, in particular, Fail-Safe systems are prone to rare catastrophic failures where Safe-to-Fail systems are adaptive to manage catastrophe yet suffer more failures more often. Moreover, the same design strategies (e.g., build redundancy) are often used to characterize both Fail-Safe and Safe-to-Fail systems. Differences between Fail-Safe and Safe-to-Fail were used as a starting point, and literature was acquired that discussed similar dichotomous perspectives on infrastructure management and design. These perspectives were used to create Table 3, to which the solutions found in the case studies were assessed in binary or null terms, similar to those used in Table 1. A one (1) meant that the team member felt that solution exhibited the Fail-Safe or Safe-to-Fail characteristics, whereas a zero (0) meant that it did not.

6.2.3. *ANALYTICAL HIERARCHY PROCESS*

To produce tangible results with information output from the case studies analysis, an Analytical Hierarchy Process (AHP) was used to develop a Multicriteria Decision Analysis tool. A goal of the tool is to inform different

stakeholder groups on preferred infrastructure solutions to future climate impacts that may be unpredictable. Using the normalized scores for each individual solution type, the AHP is able to rank solutions based on different stakeholder perspectives. For the purposes of this study, these perspectives will not be elicited, but rather representative of certain viewpoints (e.g., an individual who cares more about byways versus arterial functional road types).

The analysis was directly informed by outputs from the vulnerability chapter for different regions in the Phoenix Metropolitan Area. Types of vulnerabilities that most affect the region were identified and this information was multiplied with the vulnerability score, produced by the vulnerability team, for the weight of each of the identified criteria. Each solution was weighted against and then able to ranked in order. The tool allows vulnerability and institutional information to be included in analysis.

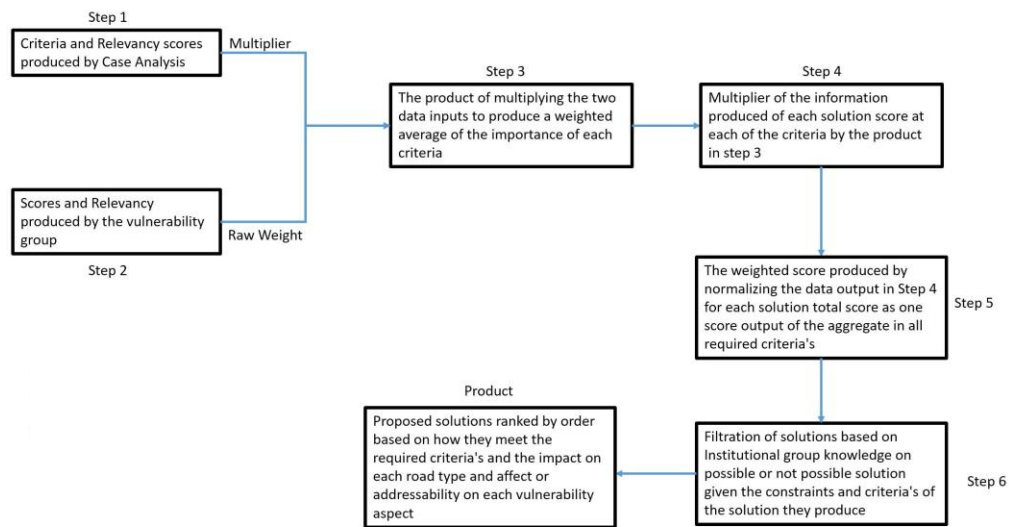


Figure 24: The Analytical Hierarchy Process for the Adaptation Process

6.3. Outcomes

To efficiently conduct this chapter, twenty-six documents were collected for literature review and were assessed by the Authors to identify the functional roadway types, vulnerabilities, and Fail-Safe or Safe-to-Fail

attributes of solutions to climate change induced flooding. Of the twenty-six documents, only twenty contained flooding solutions, and these twenty documents contained a total of thirty-one case studies. The case studies analyzed are from various geographic regions within the United States and around the world, and therefore consider a wide range of climate impacts and variables. From the thirty-one case studies, the readers identified thirty-one infrastructure solutions (listed in Appendix E) that could be implemented in Southwestern urban environments. Whereas some case studies focused only on a single flooding solution, others had between four and five solutions that were either proposed or implemented. The single most used solution was vegetation management, which was identified in ten separate case studies. Other frequently used solutions included a mixture of new and old technologies; including bioswales, cisterns, and porous or permeable paving materials. On the other hand, solutions proposed only once among all case studies included common water management technologies, such as open channel conveyance and flood storage, new technologies such as curvilinear streets, and social responses to reduce road impacts such as permanent traffic diversion and relocation of critical services. Overall, the case studies analyzed focused on the mitigation of climate change induced flooding from roads focused on environmentally friendly and cost-effective technologies, such as low-impact development strategies.

After relating different solutions or technologies to relevant resilience criteria, the values of each assessment criteria were aggregated across all solution types identified from the literature review. The averages of those aggregated values were then calculated interpreting null values as zeros.

6.3.1. WHICH ROADS HAVE SOLUTION?

Each infrastructure solution is only capable of providing flood management services for specific roadway types. For example, a curb cut is useful only on byways where sidewalks are readily available, versus arterial or backcountry roads that may be too large for a small curb cut to impact major flooding, or may not have paving, or curbs altogether. For each solution, the average scores received were used to calculate a normalized score for each functional roadway type across case studies.

Table 5: Average Results for Functional Roadway Types for All Solution Types

Backcountry Road	Byway	Living Streets	Collector Roads	Arterials	State / US Highway	Interstate Highway
0.28	0.89	0.79	0.78	0.61	0.48	0.31

Table 5 demonstrates the total scores for the entire set of solutions for all case studies. Overall, climate change flood management solutions are most useful for byways, living streets, and collector functional roadway types. This is most likely due to the fact that case studies focused on LID technologies that may not scale well to managing large amounts of flowing or standing water that impact larger roads.

The functional roadway type that received the least attention across case studies was back country roads. This seems counter intuitive, since many of the environmentally friendly LID technologies that do not require road paving (e.g., trees and cisterns) should be feasible for these roads. The lack of focus on backcountry roads may be due to the high capital cost for installing many of these technologies. Unpaved roads are mostly found outside the urban core, serve less people and thus are in places with lower infrastructure budgets than major cities.

6.3.2. WHICH VULNERABILITY WERE ADDRESSED?

Each infrastructure solution is capable of providing flood management services for multiple scales of vulnerability. For example, bioswales address social vulnerability by improving air and water quality and quality of life, while at the same time mitigate environmental vulnerability by providing abiotic and biotic ecosystem services. For each solution, the averaged scores received were used to calculate a normalized score for each scale of vulnerability across case studies. Table 6 presents the total scores for the entire set of solutions for all case studies.

Table 6: Average Results for Social, Economic, and Environmental Vulnerability for All Solution Types

	Social	Economic	Environmental
Link	2.48	2.06	2.52
Route	1.86	1.79	1.81
Network	1.39	1.5	1.42

Note: Color-coding is provided only to emphasize relative values and simplify reading the table. Highest and lowest values receive green and red coding, respectively, where median values receive yellow coding.

Overall, solutions provide modest protection to environmental and social vulnerabilities at the link level, and only limited protections to economic vulnerability. This could be problematic since the primary function of roads is economic: to transport goods and people across space. Furthermore, it is clear that vulnerability at the link level received the most attention, while route and network levels were largely ignored. The results demonstrate a drawback to using existing LID technologies, which may not be useful for relevant vulnerabilities across entire cities, and instead be most effective at the local level. It may be more challenging and cost-prohibitive to deploy LID strategies on roads that connect principal metropolitan areas,

cities, and industrial centers, including important routes into, through, and around urban areas. Taken together, the solutions strategies are largely seen in lower-traffic, high-pedestrian areas that are not necessarily part of the larger network, and cannot sufficiently meet the economic needs of a city or region.

6.3.3. FAIL-SAFE VS. SAFE-TO-FAIL

Each solution met different Fail-Safe or Safe-to-Fail criteria, depending on the context in each case study. For example, permeable pavers used in Phoenix may have been linked to increasing the redundancy of system responses to flooding, where this was not discussed or considered in Los Angeles or Chicago case studies. For this reason, binomially ranking each solution was done in each case study, and scores were normalized across all case studies to give an average score for each Fail-Safe or Safe-to-Fail attribute.

Table 7: Average Results for Safe-to-Fail and Fail-Safe Criteria for All Solution Types

Multifunctionality / Flexibility	0.53
Redundancy and Modularization	0.44
(Bio and Social) Diversity / Diversity	0.47
Multi-Scale Networks and Connectivity / Cohesion	0.67
Armoring	0.37
Strengthening	0.37
Oversizing	0.39
Isolation	0.17
Adaptability / Adaptation / Adaptive Capacity	0.40
Efficiency	0.63

Renewability / Regrowth / Engineering Resilience	0.36
Sensing	0.10
Anticipation	0.13
Learning / Learning-by-doing	0.08
Fail-Silence	0.10
Fail-Operational	0.38
Transformability / Transformation	0.16
Adaptive Design / Adaptive Planning and Design / Innovation	0.59
Transdisciplinarity / Designed Experiments	0.47

Note: Color coding is provided only to emphasize relative values and simplify reading the table. Highest and lowest values receive green and red coding, respectively, where median values receive yellow coding.

Table 7 presents average results across all case study solutions to determine which Fail-Safe or Safe-to-Fail attributes were most prevalent among the thirty-one solutions proposed. Surprisingly, Safe-to-Fail criteria dominated the solution set, where the most common Fail-Safe or Safe-to-Fail attributes found across all solutions included multi-scale networks, efficiency, adaptive design, and multifunctionality.

The Fail-Safe or Safe-to-Fail attributes with fewest relevant solutions included both Safe-Fail (fail-silence and isolation) and Safe-to-Fail attributes (sensing, anticipation, and learning). The result demonstrated that case studies are implementing Safe-to-Fail technologies to combat climate change induced flooding, which may lead to more Safe-to-Fail system responses to future flooding events. However, these solution types focused less on process-based Safe-to-Fail attributes, and focused primarily on linking environmental networks to manage incoming water versus developing human response systems to uncontrollable future floods. Unless more solutions are proposed to include process-based

features, novel solutions may still lead to brittle system failures by having maximum volumes of flows and standing water that they realistically cannot manage. Moreover, if stakeholders prefer solutions that provide these features, they currently have a limited set of options available.

6.4. Proposed Solution Types

Reflecting on the weights of design concepts discussed in section 4.3 for the city of Phoenix, the solutions were ranked accordingly, where it is noted that the solutions that ranked the highest had the aggregate highest weighted average in those design concepts. The Analytic Hierarchy Process (AHP) compares each criteria score for each solution to quantify how much better one solution may be over another. Then it uses weightings on all criteria and sub criteria to relate stakeholder opinion on which criteria matter with the solution set that best fits this viewpoint. We developed weightings for the Phoenix case study based on data provided by the Vulnerability, Historical Extremes, and Institutions groups to develop a list of potential adaptation strategies for future flooding of Phoenix roads. In particular, Vulnerability chapter data demonstrate social and infrastructure vulnerabilities in Phoenix affected the entire road network. Following this data, we weighted link, route, and network vulnerability to preference adaptation strategies at the network scale. In addition, Historical Extreme data emphasized the management of social vulnerabilities over environmental and economic, and Institutional data showed that building level solutions such as green roofs were infeasible for Phoenix roadway organizations to fund. Taken together, adaptation strategies were weighted to emphasize those that manage social vulnerabilities, and building-based adaptation strategies were removed from the solution set.

Without specific stakeholder data on Fail-Safe and Safe-to-Fail criteria, we developed characteristic weighting sets based on academic literature. In particular, 5 different weighting schemes were developed that can yield two similar sets of solutions (Table 8 and 9). Four out of 5 weighting schemes produced the same top five adaptation strategies (Table 8), but with different rankings and ordering. However, one weighting scheme focused on process-based solutions yielded two different adaptation strategies in the top five. Taken together, to maximize the effectiveness of Phoenix adaptation strategies, all seven-adaptation strategies should be considered by local stakeholders for future modeling and development.

Table 8: Process-Based Proposed Solution Types

Solution Name	MCDA Score
Vegetated Bioretention Basin	0.0664
Road weather information systems (RWIS)	0.0659
Floodway	0.0651
Open Channel Conveyance	0.0552
Relocate Service Buildings	0.0544

Table 9: General Proposed Solution Types

Solution Name	MCDA Score
Vegetated Bioretention Basin	0.0664
Floodway	0.0659
Open Channel Conveyance	0.0552
Vegetation Management	0.0540
Flood Storage	0.0407

6.5. Limitations

Over the duration of the report, several limitations of the research have been identified. Parts of the literature review analysis were subjectively determined. In order to overcome any major differences in scores, two readers reviewed each of the case studies and discussed any discrepancies, which were amended to reflect the general consensus.

Due to the time restrictions for this report, costs of implementing the proposed solution types were not considered when creating the Multi Criteria Decision Analysis tool. Furthermore, an assessment indicating the precise amount of water each solution type could be expected to remove from existing, vulnerable roadways was not conducted.

Moreover, the Analytical Hierarchy Process we used for the Multi Criteria Decision Analysis incorporated only subjective weights for the importance of each design concept from the stakeholders' point of view. While subjective weighting is important to include the requirements of the stakeholders, objective design aspects, such as the cost and performance metrics for each solution are just as important to produce a well-rounded solution. However, as pointed out earlier, due to the scope and time allowed for the project, we excluded objective metrics.

7. IMPLEMENTATION:

As climate change has continued to be more volatile the potential for more weather extremes events will rise. This chapter will assess institutional barriers — including social, knowledge, economic, and political — in adapting resilient strategies for redevelopment of the existing vulnerabilities in the transportation-infrastructure system, and provide recommendations on how to overcome such barriers. Alternatives to fail-safe design such as safe-to-fail designs and low-impact development (LID) are discussed, and Scottsdale's Indian Bend Wash is evaluated as a case study of safe-to-fail design.

7.1. Stakeholders

In the development of safe-to-fail and fail-safe infrastructure designs, it is important to consider the perspectives of potential stakeholders. Stakeholders are an integral part of the design, construction, funding and maintenance of transportation-infrastructure systems. Potential stakeholders at the federal, state, regional, and local levels should be considered before the design and implementation of infrastructure systems. Identifying and integrating stakeholders is crucial in identifying the potential barriers that future infrastructure designs may have to overcome when implementing new design strategies.

7.1.1. FEDERAL-LEVEL STAKEHOLDERS

The municipalities in Maricopa County are held to federal standards when it comes to the design and construction of large infrastructure systems. Federal institutions such as the Federal Emergency Management Agency (FEMA), the National Flood Insurance Program (NFIP), the Environmental Protection Agency (EPA), the Department of Transportation (DOT), and the Federal Highway Administration (FHWA) outline standards,

procedures, recommendations and funding options that are available to state officials. Depending on the project at hand, procedures and guidelines must be followed when constructing new infrastructure systems in order for projects to be approved and/or receive funding.

7.1.2. STATE- AND REGIONAL-LEVEL STAKEHOLDERS

On a state level, stakeholders include the Arizona Department of Transportation (ADOT), the State Transportation Board, and the Arizona Department of Emergency Management (ADEM). On a regional level, the Maricopa Association of Governments (MAG) is a key stakeholder in the development of large roadway-infrastructure projects. These agencies, along with contracted engineers, planners, maintenance and other necessary entities, work together to research, design and construct large infrastructure projects to meet the needs of federal, state and local agencies. Working with these organizations will ensure all projects comply with all codes and regulations that are required by the state of Arizona.

7.1.3. LOCAL-LEVEL STAKEHOLDERS — PHOENIX

Phoenix stakeholders include business owners, residents, commuters and others involved in local community efforts. These are the people who live and work within local communities, and whose lives are directly affected by new local infrastructure projects. Although many new infrastructure projects are advertised to benefit local residents by providing increased efficiency and safety, public opposition is often seen “concerning large construction and infrastructure projects” [55]. This is especially apparent among vulnerable residents living within Phoenix, which include young, old and low-income populations, and people living within FEMA-designated floodplains.

Allowing local stakeholders to gain access and be involved in new infrastructure plans and designs during the early stages of development is

an integral part in maintaining the local communities' individual cultural integrity and vision. This can be done through town meetings, local workshops and project information that can be easily accessed through a city's website. Ensuring that a project meets the wants and needs of residents will help limit backlash from the community.

7.1.4. PUBLIC-PRIVATE PARTNERSHIPS

Public-private partnerships (PPPs) are a great strategy to increase support for projects ranging from large infrastructure systems to local low-impact-development strategies within Phoenix. Public-private partnerships bring a wide range of stakeholders together to work towards a common goal. These partnerships bring attention and ideas to a project and can help to create projects that benefit both people and the community. ADOT has a PPP program called P3 that brings together stakeholders on small and large infrastructure projects [56]. Adapting PPPs can help projects gain financial support, which may allow more projects to be completed in a timely manner. ADOT has a limited amount of funds to divide among communities and infrastructure projects. PPPs can help to eliminate the financial dependence on ADOT, while strengthening local bonds with residents and businesses. This program may be useful in the implementation of LID strategies, which otherwise may struggle in receiving funding from local municipalities.

7.1.5. INTEGRATING STAKEHOLDERS

Ensuring that all stakeholders know their input is considered a difficult task to accomplish, especially involving large-scale projects. Martin J. Goodfellow, Jonathan Wortley, and Adisa Azapagic's "A system-design framework for the integration of public preferences into the design of large infrastructure projects" outlines the following four criteria for

incorporating stakeholders into the design and implementation of infrastructure systems [55]:

- “Allow different system design requirements to be considered by all relevant stakeholders”
- “Cope with varied requirements, some of which would be technical and quantitative and some of which could be qualitative and ambiguous”
- “Provide simple traceability of the integration of the requirements of different stakeholders so that it could be demonstrated to all stakeholders that their input was considered seriously; and
- “Allow for the weighting of different requirements to reflect their technical (design) importance as well as their significance to different stakeholders”.

These four criteria can be used as a basic guideline to incorporate stakeholders into the design phase of a project. Stakeholders are key in both large and small-scale developments. The more involved stakeholders can be in the design process, the more support a project will gain.

7.2. Knowledge Barriers

The knowledge barriers in place for the institutional aspect of roadways are concerned with standards that are no longer valid but nonetheless remain in force. Stakeholders are often unaware that this is the case. Current standards are based on two-hour, 100-year storms [57]. These storms are the extreme events and viewed as outliers. Roadway design has its foundation in these aspects and, therefore, should have the capacity to handle events below this standard. Recent Phoenix-area extreme storms, for instance the storm that happened in September 2014, have exceeded these outdated design codes. As climate change continues, roadway standards need updating. The education required for

roadway designers needs to expand to adopt a safe-to-fail approach in order to improve the overall transportation-infrastructure system. However, with all of the long-standing expertise and proven standards the field developers, construction companies, and governing bodies are set in their ways about how roadways should be designed and implemented, leading to institutional inertia. Recent improvements in technology have the ability to spur policy makers and designers to rethink their implementation methods and expand their roadway standards.

Knowledge-based decisions have a backing and analysis that provide an accurate response to a given situation. By just applying concepts with a lack of communication, the roadway system has limited its resources and innovation. Low-impact development is a method that has shown much progress throughout all aspects of a project. The integration of this strategy has proven to reduce the impacts of a project. This process is not being mitigated, as communication between stages of design and construction are minimal in regards to potential variances. LID allows for safe-to-fail flood mitigation as it allows floodplains to be maintained within the infrastructure area. The given standard and regulations are being updated progressively, but the rate is much slower than that of the advancement of technology. There are two institutions that determine the standards for roadway design: the American Society of Civil Engineers (ASCE) and the American Association of State and Highway and Transportation Officials (AASHTO). Both of these organizations have testing sites, and they have spent many hours investigating limitations on variations of roadway infrastructure [58]. The specifications set by these organizations set standards and limitations for roadways including turning radiuses and grade of roadway. This knowledge is publicly available. The AASHTO website has access to the standards through books and

reference manuals. These are all a part of standards and regulations that go into plan drawings.

Construction crews and designers are set in their ways as to how to accomplish certain tasks. Despite the availability of a variety of options, current operators are accustomed to a way of doing things and are reluctant to change techniques. It is difficult to inspire stakeholders to use a new technique when they do not see any problems with the way things have been done for the last 20 years. It is vital to the growth of the system to ensure the highest quality of infrastructure. There are new designs being produced that may be more resilient than its predecessors' designs. Fail-safe and safe-to-fail techniques are available. They are used in examples such as flood-designed parking lots that receive diverted excess water [59]. This technique uses areas that are designed to work as both a parking lot and an urban retention pond. This extra area is available and can divert excess water. It is required for developed areas to be able to retain the amount of water accumulated during a two-hour 100-year storm [58].

Technological innovations are shifting from fantasy to reality. The progression of smart-car technology has increased the demand for smart roads. A roadway system is considered "smart" when it has technological innovations that allow for monitoring and improved durability. An example of this would be roadways that have pressurized sensors to see where weight displacement is located and control systems for different weather conditions. This includes improved drainage and lighting. The integration of knowledge between areas increases efficiency of streetlights and traffic diversion. It also regulates the maintenance and upkeep of roadways. The increase in data will allow for a more accurate portrayal of what is actually happening on the road. This data will be useful to engineers, architects, policy makers and anyone else who is interested in

roadway infrastructure and implementation. "A major concern in the development of such Smart Roads...is the provision of decision support for traffic management center personnel, particularly for addressing non recurring congestion in large or complex networks. Decision support for control room staff is necessary to effectively detect, verify, and develop response strategies for traffic incidents" [60]. Innovations come with a new set of problems that are not yet to be determined. The need for personnel to monitor the new technology creates a stitch. Policy makers may enjoy this aspect as it increases the demand for jobs. This is just one example of how knowledge and communication across fields need to be expressed. The progression and advancement of the roadway system demands a mixed audience. Only through this will the best available option be chosen.

7.3. Economic And Financial Barriers

The institutional economic barriers of adopting a resilient system relate to the availability of funds in different government sectors implementing the projects; barriers in generating new sources of funds; and in the availability of financial incentives in adopting a safe-to-fail process instead of fail-safe. According to a recent report from the Arizona Office of the Auditor General, driving on poorly maintained roads costs Arizona motorists about \$1.5 billion annually in vehicle repairs and operating costs [61]. This does not include the loss of employee time and resources that businesses accrue due to bad road conditions. Current financial sources available to the public sector for transportation projects are controlled primarily through Arizona Department of Transportation (ADOT), as well as projects carried through federal organizations such as the Federal Emergency Management Agency, the National Flood Insurance Program (NFIP), the Environmental Protection Agency, Federal Highway

Administration, Cities in Phoenix Metropolitan Area, and Maricopa County.

The Arizona Department of Transportation carries out preservation, expansion and modernization projects of highways, freeways, and interstates in the state of Arizona [62]. ADOT has a detailed budget plan for their current and future projects up to five years. It covers all ADOT ongoing and future projects until 2020 [62]. Furthermore, ADOT has a broader economic plan that explains the agency's financial needs and planned expenditure up to the year 2035 [61]. On its current course, ADOT will only receive \$26.2 billion in revenue from various federal and state taxes until 2035. The department needs about \$88.9 billion to maintain operations and develop new infrastructure in order to meet the public demand [63]. As it stands, over the next five years, ADOT needs to spend \$13 billion to preserve what now exists. With congressional stalemates and an uninterested state legislature, ADOT has only been allocated a fraction of that to spend by 2020 [63].

Eighty percent of the funding available for the roadway systems comes from fuel and motor-carrier taxes, vehicle-registration fees and capital grants [64]. ADOT highway funding, along with federal highway funding, is based on taxes collected on the number of gallons sold rather than on a percent of sales revenue. Fuel-conservation programs and the bad economy combined to reduce the number of gallons purchased, undermining revenue growth [63]. The legislature continued its recession-era fiscal activity, sweeping highway-user trust-fund money into the state's general fund to balance the budget. Bill Pederson, ADOT's partnering project manager, said that the Arizona fuel tax has been 18 cents per gallon for gasoline and 26 cents per gallon for diesel since 1991 [62]. However, fuel efficiency in vehicles has increased by five miles per gallon on average over that timeframe. Additionally, the population in the

Phoenix Valley has almost doubled since 1990, and inflation has been about three percent annually throughout the past two decades — all combining to effectively shrink the department's budget by almost half [62]. The 18-cents-per-gallon tax set in 1991 has the buying power of only 10 cents today after adjusting for inflation [65].

Pederson explained that the department used to be able to upgrade pavements and upgrade roads from two lanes to four. Now the agency does not have the funds to upgrade pavements or redo guardrails, even if it is necessary. The agency is using highway-revenue funds to pay for maintenance. In order to cope with the budget cuts, ADOT has allocated about 60 percent of its five-year planned budget for preservation projects, about 20 percent for modernization and about 20 percent for expansion. This means the agency has very little room in its budget for work that is not already in the plan. For any proposed resilient project to take place, it should fit in ADOT's current agenda, and should propose front-end cost-saving strategies.

ADOT and Maricopa County already have allocated their budgets and work plans for the next several years. Given the financial barriers, it is important not to propose costly new project ideas outside of ADOT and Maricopa County's current scope, as they might never be implemented. Instead, the recommendations should increase resilience and cost efficiency in current ADOT preservation projects and Maricopa's modernization projects. They also should propose strategies to adopt safe-to-fail options on the existing projects as an alternative to cost-efficient resilient fail-safe projects. It is in fact very difficult to address if one system is more cost efficient than the other. The research on safe-to-fail designs is only a few decades old. Moreover, civil engineers are accustomed to building fail safe, rugged infrastructure—such as roads, bridges, culverts and water treatment plants—that is designed to last for decades [64].

However, building rugged, tall, and strong requires excessive resources and funding that ADOT, MAG, and responsible agencies in the Phoenix metropolitan area currently lack.

Paul Kirshen of the University of New Hampshire argues that designing projects so they are safe to fail is often cheaper and more efficient. Flexible adaptation strategies can be retrofitted into existing facilities in stages, as funding sources become available and the level of risk at the infrastructure increases. Examples of these are prefabricated highway bridges that can be elevated as peak flows beneath them rise, or modular seawalls that can be raised as needed [64]. The additional remaining budget from flexible adaptation projects could be restructured on maintenance and preservation work throughout various responsible agencies. Implementing all these changes is not easy and will require serious legislative action and/or take several years to execute. The agencies cannot afford to spend their entire budget on a selected few set of projects, as the maintenance is needed throughout the entire roadway system. Added to these issues, Arizona's transportation infrastructure also will continue to deteriorate due to climate change and natural causes. It will be difficult for the state to repair the roadway infrastructure, as it will require a funding source in excess of \$200 billion.

One way to look at the problem is that the roadway infrastructure needs a new and serious funding formula. Motorists may need to pay more at the pump, pay tolls, or see an increased county sales tax. The federal fuel taxes and state-highway-fund taxes that have been in place for the past two decades need to increase to at least its current buying power rate of 32 cents from 18 cents per gallon to adjust for the past two decades of inflation [65]. The Regional Area Road Fund in Maricopa County should be doubled from a half-cent sales tax. The agency's budget is hurting from fuel-efficient, hybrid and electric cars. A new sales revenue-based taxing

system will eventually be needed for electric cars in order to make up for the loss of gasoline sales. Meanwhile, the agencies should look into alternative sources of funding, such as private contributions, capital grants and public-private partnerships to fund major projects [62]. In successful developing of almost any other infrastructure sectors (such as energy, buildings and agriculture) private entities play a key role. Perhaps it is time that transit corporations, trucking companies, goods manufacturers, and businesses become more involved in the development of transportation infrastructure.

As discussed previously, it might be difficult to implement a new funding formula throughout the agencies in a short duration. Therefore, it is very important for the different organizations at the state and federal level to collaborate and allocate the currently funds available into preservation and maintenance projects that will create resilience. According to a recent study by Levinson and Kahn, the sooner repairs are made on roadways and bridges; the cheaper they are throughout their lifecycle. Every dollar spent on preservation and preventive maintenance saves \$4-\$10 in future repairs. Other benefits of focusing on preservation and maintenance projects is that by not expanding roads, metro areas gain an incentive to charge drivers for congestion, generating additional revenue for the cities. Relocating funds between agencies has its own challenges; collaboration between various stakeholders is discussed in the stakeholder-perspectives section of this report. The legislation in Arizona allows for public-private partnership projects as well as relocation of available funds between agencies during emergency and other crucial situations. In order for the roadway system to become more resilient, all stakeholders must work together to focus on preservation projects for the next several years, and relocate most of the available budget from the modernization and expansion projects currently in plan.

7.4. Political Barriers

Even if the financing for new roadway design alternatives were available, there is still the matter of building new policies to overcome political barriers and institutional inertia in opposition to change. In considering the political barriers to adopting new safe-to-fail roadway designs, the institutional chapter researched the institutional policies and barriers pertaining to the federal, state, and regional transportation policies for the highway, collector, and arterial roads in the city of Phoenix. The State of Arizona government has the final approval in roadway design policy, following suit in matching federal standards in order to maintain federal funding for road projects.

The Federal Highway Administration (FHWA) enacted pilot programs from 2013-2015 with State Departments of Transportation (DOT) and Metropolitan Planning Organizations (MPOs) to perform climate change and extreme weather vulnerability assessments of transportation infrastructure. The Arizona Department of Transportation (ADOT) is fortunate to join with the FHWA to study its infrastructure's vulnerability to various extreme weather events including extreme precipitation. The federal study found that the precipitation magnitude of a 100-year, 24-hour rainfall event to increase modestly to a range from 3.3 to 4.8 inches. Additionally, the depressed highways in the Phoenix urbanized area will be the most susceptible to flooding [66]. This resilient-thinking partnership is the most promising avenue in overcoming institutional inertia that seeks to preserve the status quo of fail-safe highway design in the Phoenix metropolitan area. The federal study's findings also corresponded to the forecasting chapter's results for the predicted climate in the Phoenix metropolitan area.

In 2015, Congress passed the Fixing America's Surface Transportation (FAST) that not only maintains transportation funding levels for the next five

years, but it also allows for a slight increase in funding for priority road projects to metropolitan regions over 200,000 people. Coupled with a new lower threshold of \$10 million to apply for a Transportation Infrastructure Finance and Innovation Act (TIFIA) loan, the federal government is providing more opportunities for local communities to decide which transportation projects to undertake. In the past, the state DOT solely decided on which projects to carry out [68]. Now with FAST, ADOT can work in conjunction with the city of Phoenix and Greater Phoenix's regional governing body, the Maricopa Association of Governments (MAG) in determining the best usage of the streamlined federal transportation funding.

On the municipal level, the City of Phoenix published its new Floodplain Management Plan in 2016. This replaces the former plan, which was adopted in 1992, in order to meet the 2013 Federal Emergency Management Agency (FEMA) National Flood Insurance (NIP) standards. The strengths of the city's new plan are the prioritization of flood management activities, identification flood-reducing improvement projects, the creation of intergovernmental partnerships, and education of the public regarding local flood potential. This new City of Phoenix plan puts into effect policies that tear down political barriers that inhibit the implementation of resilient strategies for flood events and safe-to-fail roadway designs [69].

On the state and regional levels, ADOT and MAG have already worked together in establishing the 2035 Regional Transportation Plan (RTP), which was enacted in 2012 prior to the new federal FAST Act. This means that the RTP for the Greater Phoenix metropolitan area operates under the SAFETEA-LU federal transportation funding law of 2005. The current RTP follows the structure of ADOT as decision-maker for the allocation of federal funds [64]. In updating the RTP to follow the FAST Act guidelines,

ADOT, MAG, and Phoenix can work on equal footing to distribute the federal monies. Luckily, ADOT has shown that it is willing to investigate the vulnerability of its roadways with federal support. ADOT has also demonstrated that it can coordinate with the other governing bodies of the metropolitan region, which lays the foundation for a promising partnership in developing more resilient highway systems in Phoenix that meets the needs of the community.

ADOT has already implemented plans for resiliency to the highways in Phoenix to some extent. The flooding of Interstate 10 that occurred during the extreme precipitation event on September 8, 2014 was a direct result of some of the water pumps on the interstate failing to activate because of overheating (due to their over usage from the storm), thereby, causing massive flooding on the busy freeway. ADOT recognized I-10's vulnerability to flood events and installed the water pumps as a fail-safe solution. However, when the water pump system failed in the extreme flood event, commuters were stranded on the flooded interstate causing much damage and lost economic productivity [70].

At the state and regional level, ADOT and MAG have a good framework for coordination between them to construct highways with safe-to-fail designs for extreme flood events. Moving beyond governmental agency coordination, ADOT must adopt policies for roadway infrastructure adaptation to future climate change. Rather than enact a top-down approach, the policies should focus on incentivizing people and individual organizations to incorporate climate adaptation plans in their daily activities. A good example of this would be to integrate climate impact provisions in environmental impact assessments that firms and individuals complete when undertaking potentially harmful activities. This is especially important as both the federal government study and this project's forecasting chapter predicts Phoenix's climate to become drier and

experience more intense precipitation events, leading to an increased susceptibility to flooding. Currently, the FHWA is reviewing implementing climate change impacts under the congressional transportation funding and authorization bill [71]. Finally, there needs to be improved communication from government agencies of the results of climate impact studies. The increase in awareness of the need for adaptation that follows could spur the public to elect officials that will enact policies that prepare the infrastructure, including allowing for safe-to-fail designs, for the extreme precipitation events of climate change.

7.5. Design Standards: Alternatives To Fail-Safe Strategies

While fail-safe designs may be appropriate in some places, such static designs cannot be sustainable “in the context of unpredictable disturbance and change” [72]. Yet alternatives to fail-safe designs exist. As it pertains to flooding, both low impact development and “safe-to-fail” designs offer strategies and designs aimed at minimizing the impact of development on natural hydrological systems. More specifically, “the goals of low impact development (LID) are to replicate the natural hydrological landscape and create flow conditions that mimic the predevelopment flow regime through the mechanisms of microscale stormwater storage, increased filtration, and lengthening flow paths and runoff time” [73]. Examples of LID infrastructure include pervious pavement, infiltration swales, bioretention areas, and retention ponds, as well as building designs such as green roofs. In a review of several LID case studies, Michael Dietz and his team found “generally that LID practices are effective at preserving the natural hydrological function of a site, and retaining pollutants” [74].

Similarly, safe-to-fail plans “anticipate failures and design systems strategically so that failure is contained and minimized” [72]. According to

Ahern, strategies, or more appropriately, characteristics, of safe-to-fail design include multifunctionality, redundancy and modularization, bio and social diversity, multi-scale networks and connectivity, and adaptive planning and design. Examples of safe-to-fail designs, more commonly referred to as green infrastructure, overlap with LID, but are applied on larger planning scopes, such as highways and greenways. Yet despite initial studies finding positive effects of safe-to-fail and LID on hydrological systems, few long-term studies of both design strategies have been conducted, causing the adoption of such practices to only be adopted incrementally by municipalities and governing bodies.

7.6. Incentivizing Low-Impact Development (Lid)

Given the existing political, knowledge, social, economic, and financial barriers, adopting codes and ordinances mandating low-impact development (LID) can be a challenge for governing bodies. Resistance can also “be related to other common concerns such as perceptions of risk. One problem is that only a small percentage of assessments include the economic benefits of LID technologies” [75]. Yet several incentive mechanisms exist that, when deployed by municipalities, can help integrate LID practices into future and retrofit development projects. As the EPA explains, “incentive mechanisms allow municipalities to act beyond the confines of their regulatory authorities to improve wet weather management on properties that may not fall under updated stormwater requirements or other state and municipal policies, codes and ordinances” [76].

The EPA Managing Wet Weather with Green Infrastructure: Municipal Handbook – Incentive Mechanisms outlines five key incentive mechanisms for municipalities: stormwater fee discounts, development incentives, grants, rebates, installation financing, and awards and other recognition

programs. While they all target private property owners or developers, each incentive is more effective for certain circumstances. For example, stormwater fee discounts “require a stormwater fee that is based on impervious surface area. If property owners reduce need for service by reducing impervious area and the volume of runoff discharged from the property, the municipality reduces the fee” [76]. As such, stormwater fees are largely aimed at retrofit or rehabilitation projects. However, new developments that include minimal impervious area can receive reduced stormwater fees, as well as collect the benefits of development incentives, if a municipality offers them. Development incentives are often designed to streamline permitting processes or offer a zoning upgrade if the development includes a certain percentage of LID features.

On the other hand, grants, rebates, and installation financing provide direct funding to developers or property owners who implement green infrastructure projects. Financial assistance for implementing such projects can also take form in low-interest loans. Typically, this funding structure requires specific LID practices to be located in designated areas. For example, “Philadelphia provides grants through its Stormwater Management Incentives Program, which is designed to encourage developers to reduce stormwater by helping them pay for LID practices on commercial properties that generate large volumes of stormwater runoff” [77].

Finally, awards and recognition programs “provide marketing opportunities and public outreach for exemplary projects [and] may include monetary awards” [76]. Though awards and recognition programs do not directly fund the LID projects, they can play an important role in encouraging local participation and innovation. More often, awards and recognition programs feature qualified property owners in newspaper articles, on websites, and/or in utility bill mailings [77]. Furthermore, the

economic benefits of LID impact the real estate community, as, “recognition programs can help to increase property values, promote property sales and rentals, and generally increase demand for those properties” [77]. At the same time, awards and recognition programs are effective tools for educating the public about LID as well.

Notably, while the most popular incentives were covered above, there are other incentives, such as LID point systems or credit systems, which municipalities can create as well. San Luis Obispo County, California, for example, outlines potential LID incentive programs including tree canopy credit, managed conservation area credit, stream and vegetated buffer credit, and more (San Luis Obispo County). According to the EPA, “the goal of the credits is to reduce the required capacity (and therefore the cost) of stormwater treatment practices (STPs) by using nonstructural site design and conservation measures. These credits can also decrease a utility fee, if applicable” [78].

Utilizing any combination of these strategies enables local governments to encourage the use of alternative infrastructure practices on private property. In turn, public infrastructure is “less burdened when private property owners manage their own stormwater runoff on-site” [75]. Beyond benefiting private property owners and developers financially, and the environment ecologically, the use of incentives benefits the governing body as well. Incentives mechanisms and programs can be “easy to implement and afford local decision makers the flexibility and creativity to tailor programs to specific priorities or to particular geographic areas in a community” [76]. By tailoring programs to geographically specific locations, municipalities are also able “to focus resources and program efforts on a more manageable scale” [76]. At the same time, municipalities can use the program as a pilot to determine the potential for a wider application or to be officially adopted into the city

codes [76]. This is largely because incentive programs are voluntary, “which creates less resistance from stakeholder groups and allows policy makers to test and refine program” [76].

Overall, implementing LID incentives benefits multiple parties. More importantly though, by “implementing LID principles and practices, water can be managed in a way that reduces the effects of built areas and promotes the natural movement of water in an ecosystem or watershed” [76]. LID is thus intimately tied to land use strategies, and it will be essential for communities to incorporate “a wide range of environmentally sound land use strategies – such as maintaining natural resource areas, preserving critical ecological buffer areas, minimizing land disturbance, minimizing impervious cover, and following smart growth principles” [78]. Approaching land development and ecological health using a holistic approach will be essential for communities, cities, and regions to head toward a sustainable future. LID incentives should be used as an intermediary step until economic and financial, political, and knowledge barriers are overcome. This requires long-term studies demonstrating the benefits of LID, new financing structures, public education, and institutional reform. Once these criteria are met, municipalities should mandate LID and green infrastructure into city codes, if not take a “risk” and implement LID even beforehand.

Of importance, widespread adoption of LID could have tremendous effects on efforts to restore natural hydrological cycles. Yet LID practices are primarily for small-scale projects and depend on interests of developers and private property owners to be adopted (at least currently). Furthermore, it is not the intention of LID to handle 100-year storm volumes and large-scale stormwater management is still required. Safe-to-fail designs, with a similar objective as LID to reduce the social, economic, and environmental impacts of flooding, require municipal or

state-led efforts for implementation. While currently not standard practice, the implementation of green infrastructure projects is on the rise and examples can be seen worldwide, including in Phoenix, Arizona.

7.7. Case Study: Indian Bend Wash

Possibly the best example of safe-to-fail flood infrastructure in the Phoenix metropolitan area is the Indian Bend Wash, located in the city of Scottsdale. Constituting a length of 11 miles of parks, lakes, walking paths and golf courses, Indian Bend Wash is a greenbelt for the city that absorbs excess stormwater that otherwise would flood the city [79]. Most of the year Indian Bend Wash serves as a place of recreation for city residents, and when it rains, it mitigates flooding from damaging the city.

Whatever infrastructure is lost within the greenbelt is both minimal and relatively affordable when compared to the fiscal damages from flooding in neighborhoods [80]. Had Indian Bend Wash not been developed as a greenbelt, it likely would have taken the form of a 170-foot-wide, 23-foot-deep concrete culvert, similar to the one that holds much of the Los Angeles River in California [79].

But the path to development of Indian Bend Wash as a greenbelt was not easy. It took more than 20 years for Indian Bend Wash to go from concept to reality. Any safe-to-fail flood infrastructure being planned today may take a similar amount of time.

Plans for Indian Bend Wash were originally drawn up in 1963 by the U.S. Army Corps of Engineers and Maricopa County's Flood Control District. One might think that the project's delays were because of federal holdups, but the plan received Congressional approval in July 1965. Instead, the bigger problem was Scottsdale southern neighbor, the city of Tempe. The plan for Indian Bend Wash — in either its concrete or greenbelt form — ultimately would channel floodwaters into the Salt River,

and Tempe officials feared that a simultaneous flooding of Indian Bend Wash and the Salt River would inundate their city [81]. The root of the problem, however, was that rather than dealing with the Salt River as a whole system, the U.S. Army Corps of Engineers and Maricopa County's Flood Control District were tackling each component independently. (The Corps of Engineers responded to Tempe officials by saying that Indian Bend Wash flooding and Salt River flooding would not coincide since they were projected to occur at different times of year [81]). Today, a safe-to-fail flood infrastructure project could be delayed by a similar approach that is too local while ignoring the system as a whole. Particularly, the development of Indian Bend Wash proved that ignoring the political interests of neighboring jurisdictions could delay a project.

Still, the greenbelt plan faced more obstacles. A safe-to-fail flood plan would require more land than the concrete-culvert plan. Consequently, Scottsdale faced challenges of zoning and land acquisition. To address the zoning issue, Scottsdale had to change its charter to allow it to designate flood areas. The land represented a bigger challenge, as developers already possessed some of what would be flooded. The city negotiated with the developers to obtain the necessary flood easements, and in some cases bought land outright. For example, the city bought 55 acres of land that would become El Dorado Park for \$150,000 (\$1 million in 2016). There also was the issue of homes already built within the floodplain. The city bought 53 homes and moved their residents to new homes elsewhere in the city. Funding for the project was a major issue. It was not until 1973, when Scottsdale voters approved a \$10 million bond (\$53.4 million in 2016), that work on the greenbelt could proceed in earnest [82]. The greenbelt opened to the public in 1984 [79].

Today, it is important to recognize that while safe-to-fail plans sometimes may be more affordable than conventional failsafe plans, sometimes

safe-to-fail plans may require more resources — such as land and money — and that a safe-to-fail plan, no matter how good, can fail to launch without those resources.

7.8. Outcomes

As our climate continues to change at record rates, we will face increased challenges concerning the local roadway infrastructure systems and, in the context of this analysis, the city of Phoenix, Arizona. Higher levels of rainfall and storm water runoff will necessitate updates to the existing infrastructure systems in the Phoenix metropolitan area, which may require a shift in how designers and policy makers approach future roadway issues. Regulations, funding and design standards are some of the causes that could facilitate embracing safe-to-fail designs. Infrastructure projects in urban areas are complex issues that require the collaboration and pedagogy of all parties involved.

Pushback is expected whenever new solutions to old problems are introduced, so it will be imperative to educate all stakeholders on new methodologies and design strategies prior to implementation. Using the Indian Bend Wash in Scottsdale, Arizona as a case study, professionals can analyze and understand the benefits and difficulties of a successful Safe-to-Fail, Low Impact Development (LID) project.

8. CONCLUSION:

Due to that frequent extreme precipitation events are expected for much of the southwest U.S. and there is a pressing need to assess how the design of infrastructure can make people vulnerable and eventually solutions to mitigate this vulnerability. Anticipating the occurrence of such extreme events is merely the first step to its solution, yet providing innovative proposals that mitigating the impacts remains vital while embracing such proposals is the real challenge. This research has shed light to coupling the safe-to-fail designs that are widely used in landscape into being the robust approach in designing our roadways infrastructure. Adopting the novel safe-to-fail design approach rather than fail-safe traditional designs demonstrate prudent, cost effective and intelligent. This research was based on studying the historical extremes that stroke Arizona then precisely forecasting the probability and locations of flooding, which serve identifying social and infrastructure vulnerabilities that are contemplated to propose safe-to-fail adaptations strategies for the infrastructure of Maricopa County. Finally, local laws and regulations, budgets, and design standards are only a handful of the factors that make implementing these projects such a huge undertaking, but success is obtainable through proper education, planning, and a thorough understanding of current methodologies.

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9.1. Personal Communication

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10. APPENDICES:

10.1. Appendix A - Case Studies Collected For Literature Review

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10.2. Appendix B - Infrastructure Scales And Definitions

Table 10: Functional Roadway Types

	Definition
Backcountry Road	A road that lacks an all-weather surface treatment, safety devices (road markings, signs or signals), and/or design features, usually located in undeveloped rural areas.
Local Byway	A local road with an all-weather surface suitable for year-round automobile travel.
Living Streets	Living streets are specifically designed for pedestrian and bike use in combination with auto use. Automobile use is not the primary use.
Collector Roads	Collector roads move traffic from local roads to arterial roads. They do provide access to/ from private properties. Speed limits are typically 25-35 mph. Collector roads are also referred to distributor roads.
Arterials	Arterial roads connect collector roads to freeways and between urban centers. They are often limited access.
State Highway (State Route) / U.S. Highway (U.S. Route) / County Road	A public road maintained by a state or county that carries a number assigned by that state, county, or the American Association of State Highway and Transportation Officials (AASHTO).
Expressway / Freeway (Motorway) / Interstate Highway	A type of highway that has partial or limited access from adjacent and parallel roads and may be separated. They "connect, as directly as practicable, the principal metropolitan areas, cities, and industrial centers, including important routes into, through, and around urban areas, serve the national defense and, to the greatest extent possible, connect at suitable border points with routes of continental importance in Canada and Mexico."

10.2.1. REFERENCES FOR APPENDIX B

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10.3. Appendix C - Vulnerability Scales And Definitions

Function	Scale	Definition
<p>Social: The functions that roads provide that affect infrastructure users included in our work are access to services and amenities, safety (e.g., evacuation routes and emergency service provision), and improving quality of life (e.g., lowering traffic, emissions, noise, etc.). Infrastructure that is socially vulnerable puts these functions at risk. If the flood management solution puts these functions at risk, the solution is considered socially vulnerable.</p>	Link	A road or road part that connects intersections or exits.
	Route	A larger section of road that connects services or cities. Often a single stretch of road with either the same name, limited intersections, limited turns, the same speed limit across it. Multiple roads can serve the same routes.
	Network	A collection of multiple roads and intersections/exits, often delimited by service area (e.g., city districts) or jurisdictional boundaries (e.g., cities and counties).
<p>Economic: By providing access to new services, increasing population, and impacting all aspects of urban development, roads have a large impact on the economy of an urban system. Economic functions roads provide included in this study are access to services, shipping lanes, redistribution of wealth, relieving congestion, and supporting growth. Thus, an economically vulnerable infrastructure is one where the infrastructure does not support these functions or falls short of providing them.</p>	Link	A road or road part that connects intersections or exits.
	Route	A larger section of road that connects services or cities. Often a single stretch of road with either the same name, limited intersections, limited turns, the same speed limit across it. Multiple roads can serve the same routes.
	Network	A collection of multiple roads and intersections/exits, often delimited by service area (e.g., city districts) or jurisdictional boundaries (e.g., cities and counties).
<p>Environmental: Road infrastructure and flood management infrastructure provide abiotic and biotic ecosystem services. Infrastructure that is environmentally vulnerable puts these services at risk, or does not even consider them in design (e.g., grey vs. green infrastructure).</p>	Link	A road or road part that connects intersections or exits.
	Route	A larger section of road that connects services or cities. Often a single stretch of road with either the same name, limited intersections, limited turns, the same speed limit across it. Multiple roads can serve the same routes.
	Network	A collection of multiple roads and intersections/exits, often delimited by service area (e.g., city districts) or jurisdictional boundaries (e.g., cities and counties).

10.3.1. REFERENCES FOR APPENDIX C

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10.4. Appendix D - Comparison Tables Of Fail-Safe And Safe-To-Fail In Literature

Design Strategies	Fail-Safe or Safe-to-Fail	Definition
Multifunctionality (Ahern) / Flexibility (Park)	Safe-to-Fail	Multifunctionality: "Multifunctionality can be achieved through intertwining/combining functions, stacking or time-shifting. It is inherently efficient spatially and economically, and benefits by support from the social constituents and stakeholders associated with the multiple functions provided. Multifunctionality supports response diversity in the functions provided." Flexibility: "Systems and components with extensible functionality that enable multi-use and reconfiguration"
Redundancy and Modularization (Ahern)	Safe-to-Fail	"Redundancy and modularization are achieved when multiple elements or components provide the same, similar, or backup functions. Redundancy and modularization spread risks – across time, across geographical areas, and across multiple systems."
(Bio and Social) Diversity (Ahern) / Diversity (Fiksel)	Safe-to-Fail	(Bio and Social) Diversity: "Response diversity in biological systems refers to the diversity of species within functional groups that have different responses to disturbance and stress... Thus with a greater number of species performing a similar function, the ecosystem services provided by any functional group...are more likely to be sustained over a wider range of conditions, and the system will have a greater capacity to recover from disturbance." Diversity: "Diversity is the existence of multiple forms and behaviors"
Multi-Scale Networks and Connectivity (Ahern) / Cohesion (Fiksel)	Safe-to-Fail	Multi-scale Networks and Connectivity: "Networks are systems that support functions by way of connectivity... Complex networks build resilience capacity through redundant circuitry that maintains functional connectivity after network disturbance(s)." Cohesion: "Cohesion is the existence of unifying forces or linkages."
Armoring (Park / Seager)	Fail-Safe	"Protecting a system or component by hardening and stiffening to exogenous shocks (i.e., take more physical and functional load with less deformation) via the addition of new components or functionality. Example may be the exoskeleton / shell of a lobster. Relevant in social settings as well, e.g., "emotional armoring" can mean stoicism to most issues, yet prone to a catastrophic emotional response."
Strengthening (Park / Seager)	Fail-Safe	"Protecting a system or component by hardening and stiffening to exogenous shocks (i.e., take more physical and functional load with less deformation) via the improvement and upgrade of existing system components and functionality. Example would be making the weak internal body of a lobster stronger. Strengthening often comes at the cost of flexibility and increases the chance of technological and structural lock-in."
Oversizing (Park /	Fail-Safe	"Increasing existing system and component tolerance, capacities, robustness, functionality, etc. - hardening of

Seager)		existing components. Known colloquially as the addition of a "fudge factor".
Isolation (Park / Seager)	Fail-Safe	Reducing connectivity, interdependence, functionality, and (in general) interactions among system components and between systems where those interactions already existed.
Adaptability (Fiksel) / Adaptation (Park) / Adaptive Capacity (Walker/Folke)	Safe-to-Fail	Adaptability: "Adaptability flexibility to change in response to new pressures" Adaptation: "Adaptation is the response taken after information from sensing and anticipation are incorporated into understanding." Adaptive Capacity: "Capacity of actors in the system to influence resilience in a social-ecological system, essentially to manage it"
Efficiency (Fiksel)	Safe-to-Fail	"Efficiency is performance with modest resource consumption"
Renewability (Park) / Regrowth (Park) / Engineering Resilience	Safe-to-Fail	Renewability: "recovery of system or component function from endogenous driven processes" Regrowth: "recovery of system or component function from an exogenous forcing " Engineering Resilience: "Return time to a steady state following a perturbation"
Sensing (Park)	Safe-to-Fail	"Sensing is the process by which new system stresses are efficiently and rapidly incorporated into current understanding."
Anticipation (Park)	Safe-to-Fail	"Anticipation is the process by which newly incorporated knowledge gained by sensing is used to foresee possible crises and disasters. Anticipation permits the development of adaptation strategies and leads to further enhancement of sensing for the anticipated disturbance regimes. However, it does not necessarily involve forecasting, or estimation of probabilities."
Learning (Park) / Learning-by-doing (Ahern)	Safe-to-Fail	Learning: "Learning is the process by which new knowledge is created and maintained by observation of past actions—that is, understanding of how various adaptive strategies have succeeded to buffer, delay, or attenuate the variability arising from both internal and external factors. After adaptation, the level of appropriateness of adaptive actions can be assessed and future iterations can incorporate this knowledge." Learning-by-doing: "...facilitated by conceiving uncertainties not as obstacles to overcome but opportunities to learn from, and by including feedback loops to ensure that decision makers receive the monitoring results in time to develop appropriate policies, or to alter plans or management practices accordingly"
Fail-Silence (Moller and Hannson)	Fail-Safe	"Safe fail. There are many ways a complex system may fail. The principle of safe fail means that the system should fail "safely"; either that internal components may fail without the system as a whole failing, or that the system fails without causing harm. One common example is fail-silence mechanisms—fail-silence (also called "negative feedback") mechanisms are introduced to achieve self-shutdown in case of device failure or when the operator loses control. A classical example is the dead man's handle that stops the

		train when the driver falls asleep. One of the most important safety measures in the nuclear industry is to ensure that reactors close down automatically in critical situations."
Fail-Operational (Moller and Hannson)	Fail-Safe	"Fail-operational means that the system will continue to work despite the fault. (Sometimes a distinction is made between partial operational ("fail-active") and fully operational. In aviation, fail-operational systems are paramount; airborne failures may lead to partial operational restrictions, but system shutdown is normally not a particularly safe option. A safety-valve is another paradigmatic fail operational device; if the pressure becomes too high in a steam-boiler, the safety-valve lets out steam from the boiler (without shutting down the system)."
Transformability (Blackmore & Plant) / Transformation (Mu / Walker)	Safe-to-Fail	Transformability: "Capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable" Transformation: "The capacity to create or move to a fundamentally new system (described as a new landscape) is called transformability."
Adaptive Design / Adaptive Planning and Design / Innovation (Seager)	Safe-to-Fail	Adaptive Design: "A process/approach where selected urban plans and projects explore innovative practices and methods, informed by landscape ecology knowledge and research design, open to design innovations and creativity, and monitored and analyzed to learn from the experiment—with the goal of gaining knowledge to apply to future projects" Adaptive Planning and Design: "Adaptive planning and design conceives the "problem" of making decisions with imperfect knowledge about change and uncertain disturbances as an "opportunity" to "learn-by-doing." Under an adaptive model, urban plans and designs can be understood as hypotheses of how a policy or project will influence particular landscape processes or functions and implemented planning policies or designs become "experiments" from which experts, professionals, and decision makers may gain new knowledge through monitoring and analysis." Innovation: "Technological innovation is both threatening and promising. Depending upon how one balances technological optimism and pessimism, technological innovation can be viewed as enabling either unsustainable practices (such as industrial pollution and ecological habitat destruction) or greater human well-being (such as agriculture, industrial production and leisure)."
Transdisciplinarity / Designed Experiments	Safe-to-Fail	Transdisciplinarity: "In contrast with interdisciplinarity, transdisciplinarity involves stakeholders and decision makers with scientists and professionals, throughout a project, with all parties contributing to, and benefiting from, a mutual knowledge and experience base" Designed Experiments: "Interdisciplinary partnerships of scientists, planners and designers collaborating to insert experiments into the urban mosaic, balancing ecological goals with context, aesthetics, amenity and safety"

10.4.1. REFERENCES FOR APPENDIX D

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10.5. Appendix E – List Of Adaptation Strategy / Infrastructure Solution Types Identified

- Standard curb cut; stormwater curb extensions
- Grated curb cut
- Curb cut sediment capture; percolation curb inlet
- Meandering or linear swale; bioswale; vegetated/grass swale; traffic circles/medians
- Vegetated bioretention basin; large retention basins/parks; wetland; created wetland
- Bioretention cell; bioretention curb inlet; raingardens
- Planter; flow through planters; infiltration planters
- Porous asphalt; pervious asphalt
- Porous concrete; pervious pavement; porous pavement; green concrete
- Structural grids; vegetated grass pavers; grasscrete; reinforced grass grid paver system
- Permeable pavers
- Infiltration trench; infiltration drainfield
- Underdrains; drainage pipes
- Floodway; floodplains
- Green roofs
- Cisterns; street storage and catch basins
- Open channel conveyance
- Road weather information systems (RWIS); automatic monitoring systems; environmental sensor station; drainage management software; water sensors (shaft encoder float, pressure transducer, tipping gauge)
- Vegetation management; natural drainage system; trees
- Flow regulation devices; flow splitters
- Curvilinear streets
- Raised subgrade
- Chicanes/bump-outs
- Dual culvert cells
- Multi-span bridge
- Discouraging land subsidence
- Traffic diversion
- Infrastructure maintenance; infrastructure monitoring; maintenance agreement
- Relocate service buildings
- Flood storage
- Street width reduction