Resilient Analytics: ADOT SR 88 Vulnerability Assessment and Design Recommendations

Introduction:

ADOT indicates that the history of State Route 88 (SR 88) shows continued flooding events where storm water damaged the road and repairs were required. The latest event, in September 2019, damaged the road enough to make it impassable and as such a section of the road from MP 222 to 229 currently remains closed for public safety reasons. In this event, the Woodbury Fire consumed almost 124,000 acres of the Tonto National Forest followed by a storm event in September 2019 where a storm dumped up to approximately six inches of rain onto the fire scar causing the runoff to severely damage large portions of the road. The damage included a large rockslide that left a critical section of the road unpassable. The runoff from the Woodbury fire burn scar is considered an ongoing risk with future storms.

Given the history of the location, ADOT is undertaking a study to determine the feasibility of repairing and re-opening the closed section of SR 88. A core part of this assessment is the potential to include resiliency in the design to mitigate future damage from storm events. Of particular interest is the potential impact of future storm events to drainage, slope stabilization, and wildfire mitigation designs.

Historical Conditions:

SR 88 is located in the NWS Fire Weather Zone 133 named Southern Gila County/Tonto National Forest Foothills. The Fire Weather Zone 133 boundary can be seen in Figure 1. Wildfires are a common occurrence in this area, with multiple fires impacting SR 88. However, he number of wildfires and the area of the wildfires have increased signifgicantly in this area over the last 10 years.

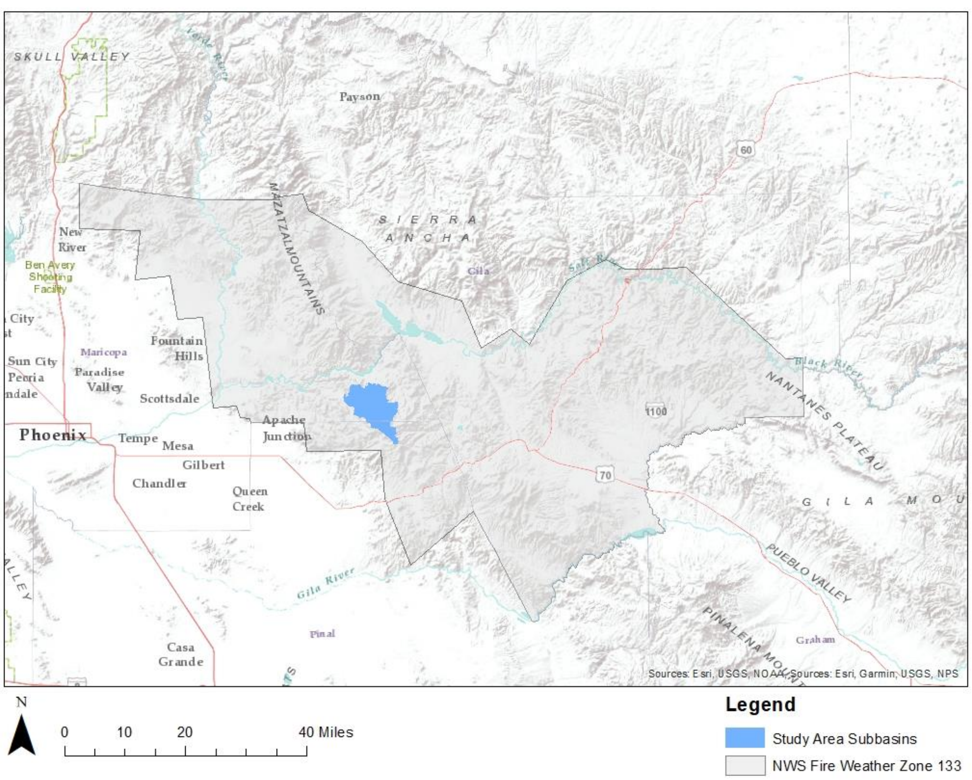

FIGURE 1: NATIONAL WEATER SERVICE (NWS) FIRE WEATHER ZONE 133. STUDY AREA SUBBASINS INCLUDED FOR CONTEXT.

From 1980 to 2000 the average number of wildfires and burn area within zone 133 were 2 wildfires and 10,783 acres respectively. From 2001 to 2021 the average number of wildfires increased to 13 which represents a 7.5X increase. Similarly, average annual wildfire area increased to 60,372 which represents a 5.5X increase. This shows a strong trend in increasing wildfire activity which could be caused by a combination of factors including increasing temperatures, drought conditions and an increase in population to the area.

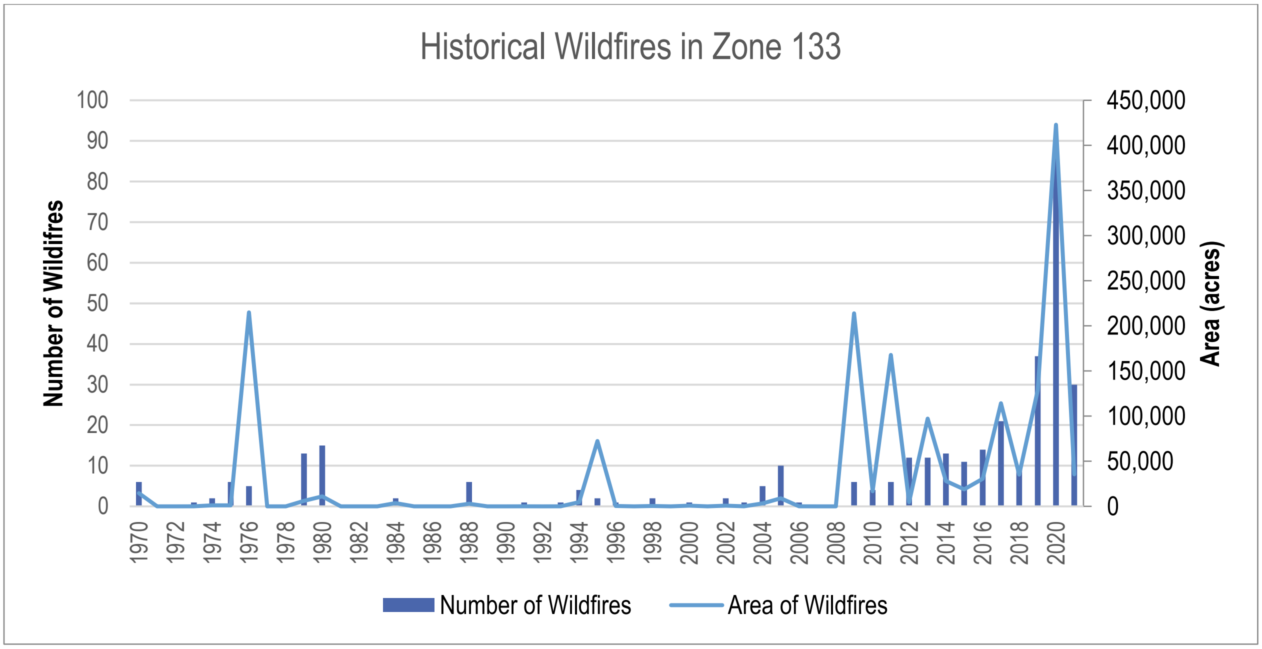

FIGURE 2:HISTORICAL WILDFIRES IN WEATHER ZONE 133

The increase in wildfires results in associated damages to vegetation and soil which in turn leads to an increased risk of flash flooding and debris flows. Prior to the Woodbury fire there have been numerous instances of such flooding on SR 88.

In 2013, the Doce Fire burned over 10,000 acres of land near State Route 89 and State Route 88, increasing the risk of flooding and debris flows. A few years later in 2015, heavy rain and flooding caused by the remnants of Hurricane Norbert resulted in closures of SR 88 due to debris flows from the Doce Fire burn scar.

Similarly, in 2019, the Woodbury Fire consumed almost 124,000 acres of the Tonto National Forest. The Woodbury Fire took place between June 8 and July 15, 2019, and was the fifth largest wildfire in Arizona's history. The fire was human caused and started in the Tonto National Forest near the Woodbury Trailhead. Six days later, on June 14, the Woodbury Fire had doubled in size to 25,716 acres (U.S. National Park Service, 2019). Due to the rugged terrain and limited access to the area, firefighters struggled to put out the fire. By the time the fire was 100% contained on July 15, the Woodbury Fire had burned 123,875 acres[1].

The conditions preceding the fire had a large impact on the fire's spread. First, the winter months experienced increased moisture levels, which led to many non-native grasses and other plants thriving[1]. Second, the state had been in a long-term drought leading up to the fire[2]. The dry conditions caused the plants to dry out, and essentially turned the plants into fuel for the fire. Furthermore, the temperatures during the fire reached over 100°F, making it even more difficult for the firefighters to battle the fire. Finally, Arizona's monsoon season was delayed that summer, which did not help the firefighters[1].

[1] U.S. National Park Service. (2021, January 24). Woodbury Fire 2019—Tonto National Monument. U.S. National Park Service. https://www.nps.gov/tont/learn/historyculture/woodbury-fire.htm

[2] State Drought Monitoring Technical Committee. (2019). Drought Status Report (p. 1). State Drought Monitoring Technical Committee.

Date	Weather Event	Details	Link
8/19/2022	Flooding	The Arizona Department of Transportation closed State Route 88 (Apache Trail) between Roosevelt Dam and the Apache Lake Marina due to the threat of storms that have the potential to damage the roadway and create hazardous conditions for drivers	https://www.yourvalley.net/stories/sr88-closed-aug-19-from-roosevelt-dam-to-apache-lake-marina,322247
7/28/2022	Flooding	Monsoon rain has caused severe flooding and road closures	https://www.abc15.com/news/region-southeast-valley/apache-junction/heavy-flooding-reported-in-apache-junction-during-monsoon-storm-thursday
9/5/2021	Flooding	A portion of State Route 88 near Apache Junction is closed indefinitely due to extensive flood damage	https://www.fox10phoenix.com/news/portion-of-state-route-88-near-apache-junction-closed-indefinitely-due-to-flood-damage
11/19/2019	Flooding	Road closure before storm	https://www.pinalcentral.com/florence_reminder_blade_tribune/news/section-of-sr-88-vulnerable-to-flash-floods-to-close-in-advance-of-storm/article_ac068e8a-d553-51ad-8b64-0bd0966379c4.html
10/1/2019	Flooding, Mud/Rockslide	The Arizona Department of Transportation has closed a portion of State Route 88 between Tortilla Flat and the Roosevelt Lake turnoff	https://kjzz.org/content/1199216/stretch-arizona-sr-88-along-woodbury-fire-scar-closed-traffic
7/29/2019	Flooding	Seven-mile stretch of SR 88 was closed due to flooding risk	https://dot.az.gov/content/seven-mile-stretch-sr-88-remains-closed-due-flooding-risk
6/8/2019 – 7/15/2019	Woodbury Fire	Seven-mile stretch of SR 88 closed post Woodbury fire	https://data.redding.com/fires/incident/6382/woodbury-fire/

TABLE 1: LIST OF FLOODING EVENTS AND CLOSURES POST WOODBURY FIRE. NOTE THIS MAY NOT INCLUDE ALL CLOSURES AND FLOODING EVENTS.

Since the 2019 Woodbury Fire, SR 88 has incurred multiple flooding events and closures (Table 1). Just three months after the Woodbury fire, a flooding and mudslide event occurred causing a closure between Apache Junction and Tortilla Flat. The remnants of Tropical Storm Lorena poured six inches of rain onto the burn scar, causing millions of dollars in damage between the Fish Creek Hill overlook and the Apache Lake Marina. The storm created substantial damage and left debris on the roadway, including large rocks and boulders. These damages caused it to close for repairs for more than a week.[3] A little over a month following event another flooding event occurred causing a closure on an unpaved section of SR 88 between Roosevelt and the Apache Lake marina.

In September of 2021 Officials stated that heavy rain from the remnants of Hurricane Nora fell onto a burn scar from the 2019 Woodbury Fire of the Tonto National Forest. This caused the unpaved part of the highway to close indefinitely from milepost 214 to 228, until new vegetation grew to help stabilize the area[4].

[3] Moore, Holliday. 2019. "Stretch Of Arizona SR 88 Along Woodbury Fire Scar Closed To Traffic." KJZZ. October 1, 2019. https://kjzz.org/content/1199216/stretch-arizona-sr-88-along-woodbury-fire-scar-closed-traffic.
[4] Phan, May. n.d. "Portion of State Route 88 near Apache Junction Closed Indefinitely Due to Flood Damage." Accessed March 27, 2023. https://www.fox10phoenix.com/news/portion-of-state-route-88-near-apache-junction-closed-indefinitely-due-to-flood-damage.

In 2022, the area saw two more flooding events in the span of a single month. The first event occurred in July where 1-3" of rain fell in 1-2 hours. At least one person had to be rescued from a vehicle stuck in a wash in the area of Cortez Road and Superstition Boulevard[5]. The second event occurred in late August which caused a closure that lasted three days between milepost 242 at Roosevelt Dam to milepost 229 at Apache Lake Marina[6].

Although the Woodbury fire increased the flooding and closure risk, SR 88 was vulnerable to extreme weather events before the fire. Extreme precipitation events driven by monsoons are common and have been damaging SR 88 long before the Woodbury fire. In July of 2017 a flash flood overwhelmed highway drainage causing a road closure[7] and there have been a number of other examples.

Given the history of the location, it is important to evaluate how future weather related events will impact SR 88. Future weather events will have a substantial impact to drainage, slope stabilization, and wildfire mitigation designs. Specifically, this analysis focuses on changes in runoff events and wildfire risk.

Climate Data:

The potential future climate hazards are evaluated using future climate projections from the Climate Model Intercomparison Project – phase 5 (CMIP5) Global Climate Models (GCMs). The GCMs are useful tools that can expand our understanding of the future evolution of the climate system, however, they are usually developed and run using coarse spatial resolutions (in the order of 100km for example) which are not conducive to providing information for localized impacts evaluations. To bridge the gap between the larger scale climate changes projected by the GCMs and the local or regional scale information needed for planning and adaptation a variety of methods are employed to downscale the GCM data. The current study used the CMIP5 GCM dataset which was downscaled using the Localized Constructed Analogs (LOCA) method[8] to a 1/16th degree (3.7 mile) resolution. The LOCA downscaled dataset has been used for evaluation of potential future climate change impacts in many applications including the 4th National Climate Assessment[9].

The LOCA downscaled climate projections used in our analyses were obtained from 32 CMIP5 GCMs for the following periods – historical 1950-2005, and 2005-2055 (centered on 2030), 2025-2075 (centered on 2050) future periods under two Representative Concentration Pathways (RCP), specifically RCP4.5 and RCP8.5. The two RCPs are emission and concentration scenarios that drive the global climate models. RCP4.5 is a moderate scenario in which emissions peak around 2040 and then decline. RCP8.5 is the highest emissions scenario in which emissions rise throughout the 21st century.

LOCA statistically downscaled data was used to force the Variable Infiltration Capacity land surface model, which provided the runoff data at the same 1/16th degree (3.7 mile) resolution used in the analysis.

The agreement of the models was estimated using the number of GCMs (out of 32) indicating the same direction of change and was characterized using the terminiology proposed by the IPCC[10,11] where:

- "Likely" is used when > 66% agree in the direction of change
- "Very likely" is used when > 90% of the models agree in the direction of change

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[5] ABC15 Arizona in Phoenix (KNXV). "VIDEOS: Heavy Flooding Reported in Apache Junction during Monsoon Storm Thursday," July 28, 2022. https://www.abc15.com/news/region-southeast-valley/apache-junction/heavy-flooding-reported-in-apache-junction-during-monsoon-storm-thursday.

[6] ADOT. E. I. N. 2022. "ADOT Closes SR 88 from Roosevelt Dam to Apache Lake Marina." EIN News. August 22, 2022. https://www.einnews.com/pr_news/587138375/adot-closes-sr-88-from-roosevelt-dam-to-apache-lake-marina.

[7] Declaration of Emergency. "State Route 88 Flood Damage". https://azdot.gov/sites/default/files/news/Declaration-of-Emergency-SR88.jpg

[8] Pierce, D. W., D. R. Cayan, and B. L. Thrasher, 2014: Statistical downscaling using Localized Constructed Analogs (LOCA). Journal of Hydrometeorology, volume 15, page 2558-2585.

[9] USGCRP, 2017: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp, doi: 10.7930/J0J964J6.

[10] Hennemuth, B., Bender, S., Bülow, K., Dreier, N., Keup-Thiel, E., Krüger, O., Mudersbach, C., Radermacher, C., Schoetter, R. (2013): Statistical methods for the analysis of simulated and observed climate data, applied in projects and institutions dealing with climate change impact and adaptation. CSC Report 13, Climate Service Center, Germany.

[11] Mastrandrea, M. D., Field, C. B., Stocker, T. F., Edenhofer, O., Ebi, K. L., Frame, D. J., ... & Zwiers, F. W. (2010). Guidance note for lead authors of the IPCC fifth assessment report on consistent treatment of uncertainties.

Projected Wildfire Conditions:

To project potential wildfire risk, the Keetch-Byram Drought Index (KBDI) was utilized. The analysis was conducted across the Southern Gila County/Tonto National Forest Foothills NWS Fire Weather Zone 133 (Figure 1).

The KBDI is used in this study as it is the most widely used index for wildfire monitoring and prediction to remain consistent with industry practices. The KBDI index is categorized into four different severity levels indicating the amount of risk for forest fires that exists for a given area (Table 1) . The index represents the net effect of evapotranspiration and precipitation in producing cumulative moisture deficiency in deep duff and upper soil layers.

KBDI Range	Fire Potential
0-200	Low
200-400	Moderate
400-600	High
600-800	Extreme

TABLE 2: KBDI SEVERITY LEVELS

Historically (based on the observational dataset Livneh et al. 2015), Fire Weather Zone 133 experiences approximately 67 days of extreme wildfire risk, with KBDI > 600. The majority of those days are in the summer when fire risk is the highest. During these days, the area is more vulnerable to wildfire ignition and spread. The average KBDI value for summer is representative of the average seasonal fire risk in Fire Weather Zone 133. Historically, the average summer KBDI value is approximately 478. Increases in the average seasonal fire risk or the number of extreme fire risk days (days with KBDI > 600) is indicative of greater wildfire risk which could lead to a larger number of wildfires in the area.

Year	Scenario	Extreme Days Mean Value	Extreme Days Ensemble 17th and 83rd percentile range
2030	RCP 4.5	81	60 – 107
	RCP 8.5	82	59 – 107
2050	RCP 4.5	93	71 – 113
	RCP 8.5	102	79 – 121

TABLE 3: ENSEMBLE MEAN NUMBER OF EXTREME FIRE DAYS ACROSS THE WILDFIRE STUDY AREA, INCLUDING ALSO THE 17TH AND 83RD PERCENTILE OF THE ENSEMBLE RESULTS WHICH ENCOMPASS 66% OF THE PROJECTIONS

Year	Scenario	Mean Summer KBDI Value	Mean Summer KBDI Ensemble 17th and 83rd percentile range
2030	RCP 4.5	509	481 – 538
	RCP 8.5	514	477 – 546
2050	RCP 4.5	554	521 – 590
	RCP 8.5	566	533 – 610

TABLE 4: ENSEMBLE MEAN SUMMER KBDI ACROSS THE WILDFIRE STUDY AREA, INCLUDING ALSO THE 17TH AND 83RD PERCENTILE OF THE ENSEMBLE RESULTS WHICH ENCOMPASS 66% OF THE PROJECTIONS

In 2030 under RCP4.5 and RCP8.5 we see the mean number of extreme wildfire risk days and the average summer KBDI increasing. The 17th percentile of models shows a slight decrease in extreme fire days. This decrease in extreme days may be driven by increases in summertime precipitation. In 2030 under both RCPs, 66% of models show an increase in the number of extreme fire days, while 88% and 81% of models show an increase in the average summer KBDI. The direction of change indicating an increase in wildfire risk in 2030 is estimated to be LIKELY given that more than 66% of the GCMs are in agreement regarding the rise in average summer KBDI and the number of extreme fire days.

In 2050 under RCP4.5 and RCP8.5 we see the mean number of extreme wildfire risk days and the average summer KBDI increasing further. In 2050, the number of extreme fire days and the average summer KBDI are projected to increase across the ensemble as showcased by the 17th and 83rd percentiles which comprise the LIKELY ensemble range. In 2050 under RCP4.5 and RCP8.5, 100% of models show an increase in the average summer KBD, while 91% and 94% (respectively) of models show an increase in the number of extreme fire days. The model agreement regarding the direction of the future changes indicates that a potential increase in wildfire risk is VERY LIKELY in the area of interest.

As illustrated by the Woodbury fire in 2018, wildfires have a large impact on SR 88. Wildfires affect runoff processes within a watershed and generally result in more rapid runoff and larger runoff volumes which can result in increased maintenance, road damage or road failure.

Projected Runoff Changes:

SR 88 will be impacted by projected changes in runoff. Using max annual (a water year was used for the calculations which starts in October and ends in September) 1-day, 2- and 3-day accumulated daily runoff values (inches) the changes in 25-year, 50-year and 100-year runoff events were calculated to inform how peak discharge in the sub-basins could change under future conditions.

Due to duration limitation, peak runoff was calculated for the 1-day, 2-day and 3-day duration. It is assumed that the ratio of durations will remain constant into the future. Due to limitation in daily extremes estimation the 3-day accumulated runoff is utilized in this analysis. It is assumed that runoff is directly proportional to peak discharge. RI runoff depth is calculated using maximum annual 3-day runoff values to capture changes in the most extreme runoff events. Only the 25-year event will be considered as drainage features for SR 88 are designed to the 25-year event.

Due to the relatively small size of the subbasins in relation to the 1/16th degree climate grids, changes in runoff were calculated over the entire study area and not by sub basin (Figure 3).

Runoff changes vary widely by model, scenario and timeframe, but for planning purposes the mean percent change in runoff across climate models (32 models in total) for two Representative Concentration Pathways (RCPs) and for two future periods centered on 2030 and 2050 will be presented.

Year	Scenario	25-Year Event Ensemble Mean Value	25-Year Event Ensemble 17th and 83rd percentile range
2030	RCP 4.5	55%	-9 – 113%
	RCP 8.5	51%	-11 – 87%
2050	RCP 4.5	68%	-2 – 155%
	RCP 8.5	83%	7 – 138%

TABLE 5: ENSEMBLE MEAN CHANGE IN RUNOFF COMPARED TO BASELINE (1950-2005) ACROSS THE STUDY AREA, INCLUDING ALSO THE 17TH AND 83RD PERCENTILE OF THE ENSEMBLE RESULTS WHICH ENCOMPASS 66% OF THE PROJECTIONS (NEGATIVE PERCENT CHANGE INDICATES A DECREASE)

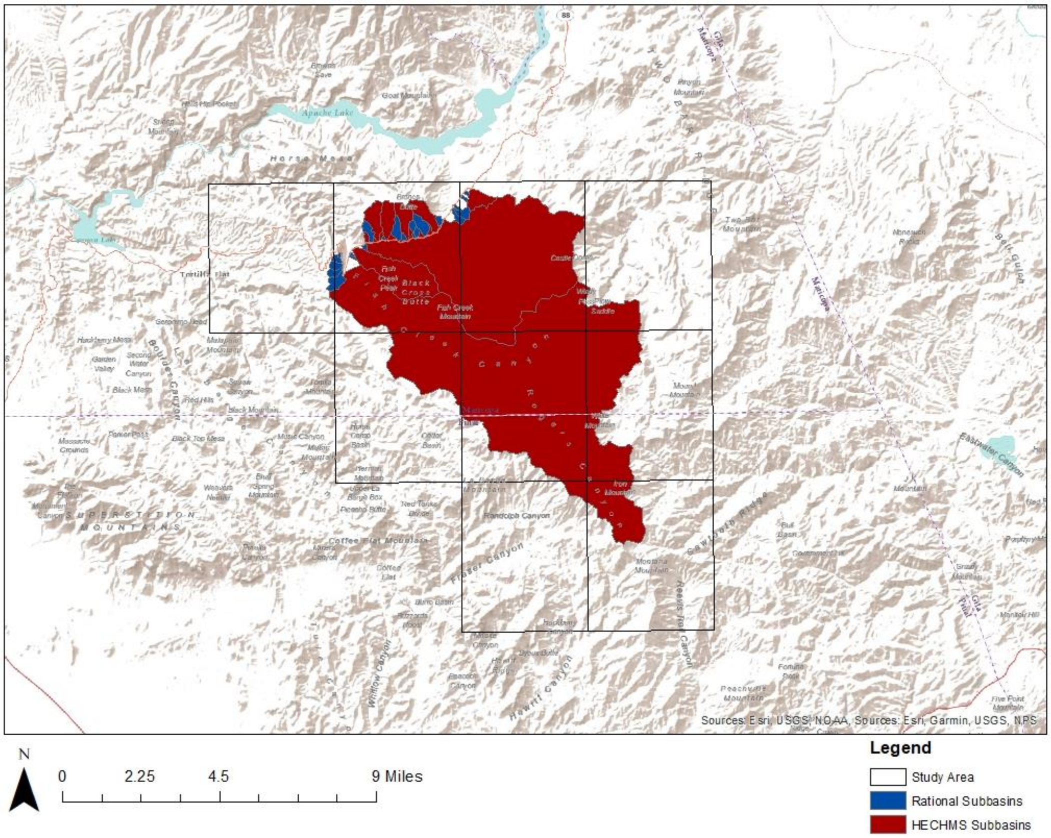

FIGURE 3: RUNOFF ANALYSIS STUDY AREA AND SUBBASIN BOUNDARIES

Across the study area, average runoff across the suite of climate models is expected to increase. The projected increase in extreme runoff is attributed to the projected increase in frequency and intensity of extreme rainfall events. The representation of the results as an average over the 9 grid points (at 3.7 mile resolution) overlapping with the sub-basins of interest leads to some smoothing of the extremes expereinced within the area.

In 2030 the 25-year event is projected to increase by 55% under RCP 4.5 and 51% under RCP 8.5. 75% and 69% of models show an increase in the 3-day 25-year runoff event under RCP 4.5 and RCP 8.5 respectively. The model agreement regarding the direction of the future changes indicates that a potential increase in extreme runoff events is LIKELY in the area of interest.

In 2050 the 25-year event is projected to increase by 68% under RCP 4.5 and 83% under RCP 8.5. 81% and 88% of models show an increase in the 3-day 25-year runoff event under RCP 4.5 and RCP 8.5 respectively. The model agreement regarding the direction of the future changes indicates that a potential increase in extreme runoff events is LIKELY in the area of interest.

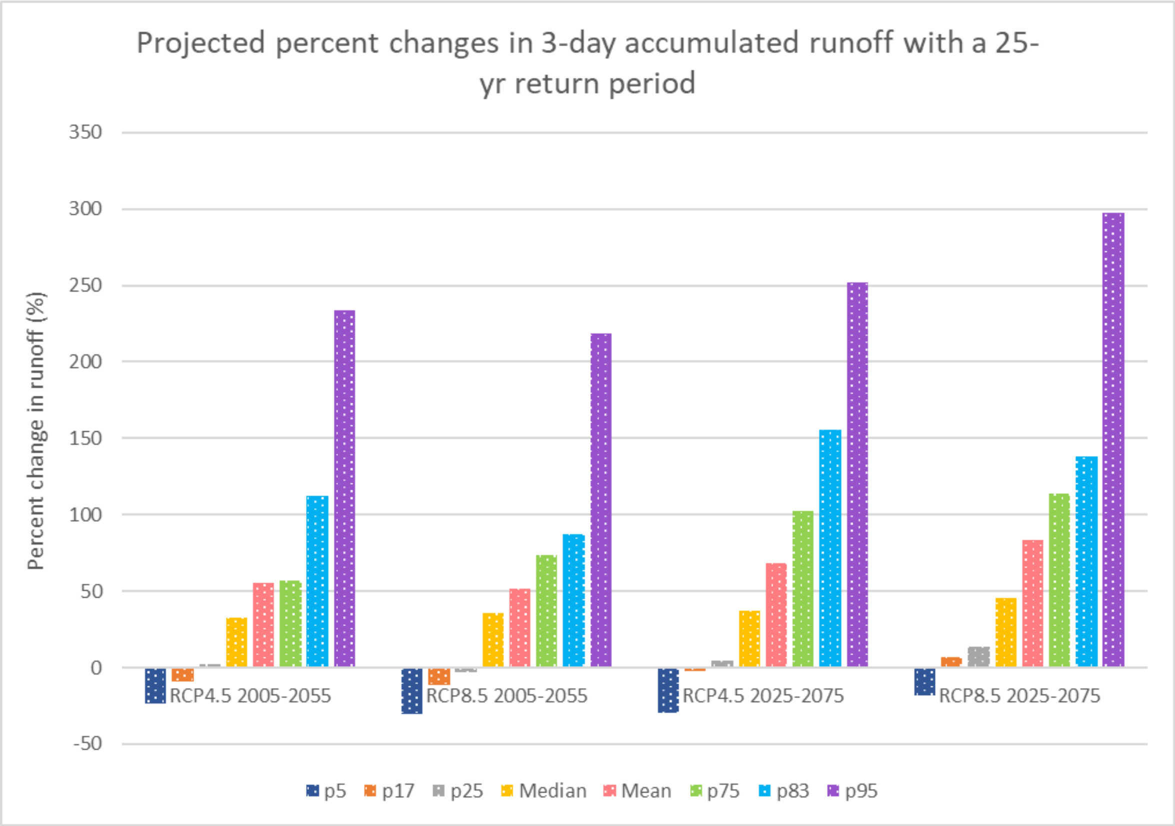

FIGURE 4: ENSEMBLE UNCERTAINTY OF PROJECTED PERCENT CHANGES IN 3-DAY ACCUMULATED RUNOFF WITH A 25-YR RETURN PERIOD AVERAGED OVER 9 GRID POINTS COVERING THE SUB-BASINS OF INTEREST. THE COLUMNS REPRESENT THE PERCENTILES CALCULATED USING THE PROJECTED PERCENT CHANGES FROM AN ENSEMBLE OF 32 CMIP5 GCMS DOWNSCALED USING THE LOCA STATISTICAL METHOD (PIERCE ET AL. 2014). THE P17 TO P83 PERCENTILES OF THE ENSEMBLE ENCOMPASS THE LIKELY RANGE OF THE PROJECTIONS (66% OF THE PROJECTIONS FALL WITHIN THIS RANGE). THE PERCENT CHANGES ARE CALCULATED AS ((FUTURE MODEL RUNOFF – HISTORICAL MODEL RUNOFF) / HISTORICAL MODEL RUNOFF)* 100%

The percent changes show the increase or decrease from the historical (1950-2005) runoff modelled by the GCMs. The ensemble results from the two RCPs do not vary greatly during the earlier period (2005-2055, centered on 2030) when natural variability and a choice of a GCM have greater impact on the projected changes. The influence of the concentration scenarios (RCP4.5 and RCP8.5) increases a bit during the later period (2025-2075, centered on 2050). The ensemble mean is often used in adaptation recommendations as it represents a more robust change compared to the projections from a single model. While the median for the area of interest does not increase greatly (below 50% above the historical 3-day runoff amounts), the ensemble mean reflects to a greater extent the uncertainty of the ensemble. Due to the skewed nature of the projected changes the ensemble mean highlights this larger uncertainty as illustrated by the upper quartile (p75 and above) of the projections. We are using the ensemble mean in our recommendations to highlight this greater uncertainty.Additional information on runoff validation and uncertainty can be found in the appendix.

Specific evaluation of landslides/mudslides is outside of the scope of this study, however we can make some high level conclusions. Wildfires and increasing extreme precipitation events make the landscape more susceptible to landslides. Given the increase in wildfire risk and increase in extreme runoff, it is possible that an increase in landslide events will occur as well.

Recommendations:

Based on the projected changes in runoff and wildfire activity the following design recommendations are presented.

Alternative 1: Upsize culverts by increasing the 25-year design peak discharge by 83% to pass projected 2050 storms

83% represents the mean projected increase for the 25-year storm event in 2050 for RCP 8.5 (high emissions scenario). The higher emissions scenario is presented for this alternative to highlight an option to increase resilience against what could be considered a "worst case scenario". For reference, that upsize would be equivalent to upsizing both the R and H sub basin culverts to above the current 100-year peak discharge event. Reference based on percent difference in 25-year peak discharge to the 50-year and 100-year discharge from the SR 88 – Preliminary Drainage Report. The mean value was chosen to account for extremes in the tail end of the runoff distribution and for wildfire risk which could exacerbate runoff conditions.

Alternative 2: Upsize culverts by increasing the 25-year design peak discharge by 55% to pass projected 2030 storms

55% represents the mean projected increase for the 25-year storm event in 2050 for RCP 4.5 (moderate emissions scenario). For reference, that would be equivalent to upsizing the R sub basin culverts to above the current 100-year peak discharge events and upsizing the H sub basin culverts to above the current 50-year peak discharge events. Reference based on percent difference in 25-year peak discharge to the 50-year and 100-year discharge from the SR 88 – Preliminary Drainage Report. The mean value was chosen to account for extremes in the tail end of the runoff distribution and for wildfire risk which could exacerbate runoff conditions.

Alternative 3: Do not upsize culverts to pass projected storms

Although these findings do not impact other specific design standards, they can also help to prioritize and evaluate the alternatives.

Projected increases in runoff and wildfire activity could lead to an increase in road damage and maintenance events. Resilience strategies presented in the alternatives could lead to lower maintenance costs and reduce the chance or future road closures. Slope treatment, erosion protection and roadway surface treatments should be prioritized based on the increase in runoff events and wildfire risk in order to limit potential future damage and maintenance.

Appendix

Runoff Validation:

In order to validate the runoff data an evaluation was performed on the precipitation data that drives the VIC model. The 25-year, 50-year and 100-year 3-day precipitation event calculated for the baseline (1950-2005) fell within the 90% confidence intervals of the PDS-based point frequency estimates used in the drainage calculations. Precipitation projections follow a very similar pattern to runoff and show an overall increase in event intensity. It is important to note the wide uncertainty in this variable. While the minimum of the ensemble of projected changes indicates a decrease in both precipitation intensity and runoff the maximum of the ensmemble of projected changes indicates a very large increase in precipitation intensity and runoff. Overall, the suite of models show a shift towards more intense precipitation and runoff events. Approximately 75% of the projections indicate an increase in intense precipitation and runoff events.

This finding is in line with similar studies from Arizona. Zhang et al[13] found annual runoff in Southeastern Arizona is expected to increase by 79% to 92%. That increase was driven by extreme precipitation events as average annual rainfall in that area was projected to decrease. Vano et al[14] evaluated the LOCA CMIP5 hydrology dataset and show similar findings in Arizona. Annual maximum precipitation and runoff are projected to be increasing in the study area. It is important to note that the LOCA dataset produced larger than average runoff values in a few regions of the country, and one of those is Western Arizona. The study area in this analysis does not overlap with these runoff anomalies but should be noted due to its general proximity to this phenomenon. This anomaly is likely caused by the VIC hydrologic model parameters in those regions.

Uncertainty:

We are considering several types of uncertainty in our analyses, namely, natural variability of the climate system (natural variability uncertainty), future socio-economic developments leading to different emissions and concentrations scenarios (scenario uncertainty), and current understanding and modeling of the climate system (model or structural uncertainty). We are addressing these different types of uncertainty through the use of a multi-model ensemble of 32 Global Climate Models (GCMs) from the Climate Model Intercomparison Project Phase 5 (CMIP5) which are intended to represent the natural variability and model uncertainty, and the incorporation of two Representative Concentration Pathways (RCP4.5 and RCP8.5) for the future projections which represent the scenario uncertainty.

The drainage analysis is focused on maximum runoff accumulations during 1, 2- and 3-day intervals for each year of the 50-year historical and future periods of analyses. These maximum runoff totals for each of the 1, 2- and 3-day accumulation periods are then subjected to stationary Generalized Extreme Value Analysis using a block maxima approach to obtain return values of runoff accumulations with 25-, 50- and 100-year return periods. These extreme runoff accumulations represent events from the tails of the runoff distribution and modeling these extremes through the model chain of GCMs with coarse resolution, application of a downscaling method to obtain finer scale outputs subsequently used as inputs in a hydrological model, and then modelled with EVA is a complex process for which uncertainty increases at each step. The uncertainty can be visualized by the wide range of model projections of return values for given return periods for each of these runoff extremes and can be represented by the ensemble minimum and maximum values or by chosen lower and upper percentiles of the ensemble results, for example. Given the large uncertainty in ensemble results showing increasing as well as decreasing magnitudes of extreme runoff amounts for given return periods, we also assessed the level of agreement of the models for a specific direction of future change as mentioned above.

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[13] Zhang Y., Hernandez M., Anson E., Nearing M.A., Wei H., Stone J.J., Heilman P.. 2012. Modeling climate change effects on runoff and soil erosion in southeastern Arizona rangelands and implications for mitigation with conservation practices. Journal of Soil and Water Conservation 67(5):390-405, doi:10.2489/jswc.67.5.390.

[14] Vano, J., J. Hamman, E. Gutmann, A. Wood, N. Mizukami, M. Clark, D. W. Pierce, D. R. Cayan, C. Wobus, K. Nowak, and J. Arnold. (June 2020). Comparing Downscaled LOCA and BCSD CMIP5 Climate and Hydrology Projections - Release of Downscaled LOCA CMIP5 Hydrology. 96 p.