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Wildfire risk, post-fire debris flows, and transportation infrastructure vulnerability

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ABSTRACT

Wildfires have grown in number, size and intensity in the American West and forecasts predict worsening trends. Evidence mounts that post-fire debris flows pose a major hazard to infrastructure, particularly roadways. Vulnerabilities of assets to post-fire flows requires consideration of geologic, vegetative, and hydrologic conditions. A model that considers environmental conditions, post-fire effects, and transportation asset use is developed, and applied to a fire prone region in Arizona. 17% of watersheds have a greater than 20% chance of post-fire debris movements and flooding under a minor precipitation event. Additionally, there is a greater than 50% probability of post-fire debris flows where recent fires have occurred, validating the underlying model. The model shows the vulnerability of infrastructure to environmental and technological variables, drawing attention to the need to manage the risk as a broader system.

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1. Introduction

Annual wildfire frequency, severity, and total area burned have been steadily increasing over the last three decades in the western United States and caused billions of dollars in damage and economic losses. (Calkin et al., 2015; Dennison et al., 2014; Thomas et al., 2017). To develop cost-effective strategies that mitigate these impacts the U.S. Forrest Service (USFS) utilizes and advocates for a framework that characterizes wildfire likelihood and intensity, fire effects, and the relative importance (or value) of assets (Scott et al., 2013). In this context, the USFS considers 'risk' a combined measure of wildfire probability and its associated consequences. The assessment is based on the exposure of resources and assets to wildfire largely resulting from their co-location. This viewpoint, however, only partially considers the total risks associated with wildfire. In reality, the risks are significantly more complex and often extend well beyond both the location and time of the fire. Severe wildfires fundamentally alter watersheds for years and significantly increase the risks of other hazards, especially flooding and debris movement (Ice et al., 2004). Wildfires reduce surface litter and create water-repellant soils resulting in increased surface runoff, rill, and gully erosion. Accounting for these impacts should be part of any wildfire risk assessment and resilience analysis.

With increasing recognition that climate change hazards will produce complex impacts on natural and built environments, it is critical that resilient infrastructure strategies embrace this complexity. One challenge that illustrates this complexity is the combined effect of an extreme wildfire (i.e., strand-replacing fires, crown fires, or fires with high fireline intensity) followed by common precipitation events and the impact on downstream infrastructure. Wildfires followed by common precipitation events often produce water and debris flows several orders of magnitude greater than the precipitation event alone (Neary et al., 2012). Such flows are potentially outside the safety tolerance for infrastructure. For example, peak flow rates following the Rodeo–Chediski fire in Arizona were found to be as high as 2350 times the rates measured under pre-burned conditions (Ffolliott & Neary, 2003). Worse still, engineers lack the science to understand these interactions and in some cases are ill-equipped to design against them.

Transportation infrastructure is often some of the highest valued built assets in wildfire regions and is critical to person mobility, goods movement and in

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the event of disasters the rescue of people and access to critical services. Water and debris flow in excess of design standards increase the likelihood of functional or structural failure for roadway infrastructure elements including culverts, bridges, and drainage systems. Dependent on the severity, the combined events of wildfire and precipitation will likely force road closures, increase maintenance requirements, and costly reconstruction of failed elements. With regard to individual mobility and accessibility to necessary goods and services, failures within the transportation system may have larger consequences in rural areas, relative to urban settings, where mode choice and route alternatives are unrealistic or do not exist.

1.1. Wildfire and transportation

To date, much of the research assessing the impacts of wildfires on the transportation system has focused on the immediate and observable impacts of the fire itself. Within the literature, there are two common research threads. The first focuses on the impacts and challenges associated with wildfire evacuation. In wildland areas or at the wildland–urban interface (WUI), transportation system redundancies are limited, and individuals are sometimes left with few options when faced with evacuation. Research in this area has helped to identify the links and nodes where congestion and gridlock are likely to occur and how emergency personal and fire managers should manage evacuation orders (Cohn et al., 2006; Cova et al., 2013; Wolshon & Marchive, 2007).

The second area of research largely deals with the impacts on the transportation system during an active wildfire. Among the most common impacts noted in the literature is the temporary closure of roadways due to direct threat or loss of visibility (Camp et al., 2013; Dijst et al., 2013; Evans et al., 2009; MacArthur et al., 2012; Mitsakis et al., 2014; Morton et al., 2003; Peterson et al., 2008; Walker et al., 2011; Wu & Usher, 2001). Rarely mentioned is the potential direct or indirect degradation the fire causes to transportation infrastructure. Perhaps this is because, as MacArthur et al. (2012) note, direct impacts to infrastructure are unlikely and that only in the most extreme cases of excess heat will wildfires cause material damage to roadways and bridge structures. An exception is the direct threat wildfires pose to wooden vehicle and rail bridges (Camp et al., 2013). Others note the potential indirect impact wildfires may have on the transportation system including the increased likelihood for future landslides, rockslides and avalanches, loss of control systems (e.g., traffic lights) and traffic signage (De Graff et al., 2015; MacArthur et al., 2012; MacDonald & Larsen, 2009; Wu & Usher, 2001). With the exception of Sosa-Perez and MacDonald (2016) who evaluated the potential for erosion on unpaved forest roads, there are no identified studies that consider the vulnerability to the transportation infrastructure to post-fire flooding.

1.2. Wildfires, precipitation, and climate change

There are several factors that have contributed to the steady increase in wildfire frequency, severity, and total burned area in the western United States. Wildfire prevention and suppression began as one of the primary focuses of the USFS in the early part of the twentieth century with the stated goal of preventing losses in mountain towns and other areas where individuals had settled. These efforts were very successful with total acreage burned falling from 40 to 50 million acres annually in the 1930s to about 5 million by the 1970s (Cohen, 2008). The exclusion of fire from forest ecosystems has had a significant impact on vegetation structure and fuel load. The proliferation of small in-growth trees and the accumulation of dead and dry woody fuels give rise to extreme wildfire behavior and are at least partially responsible for the increase in extreme wildfires from the 1980s to the present. (Dennison et al., 2014; Finney & Cohen, 2003). Other factors include drought, disease, and increased interaction between humans and forests leading to accidental as well as purposeful ignition (Garfin et al., 2014).

The causal relationship between wildfires and post-fire flooding and debris flows is well understood. Burned areas are susceptible to a number of reasons including decreased vegetation, decreased soil infiltration capacity and stability, and the potential for hydrophobic layers created by extreme heat (Moody et al., 2013). The events are most common in the first 1 to 2 years following a fire with the risks significantly declining after that period. Hydrologic conditions of a watershed typically return to pre-fire conditions within 5 years (Ice et al., 2004). While a severe and rare storm event (return period >100 years) following a wildfire can cause catastrophic flooding, the hydrologic changes induced can cause precipitation events with return periods of only 1 to 2 years to trigger significant flooding and debris flows (Cannon et al., 2008). These common precipitation events (defined here as a return period between 1 and 10 years) are capable of producing 1000-year floods when associated with high-intensity fires (Ice et al., 2004). This potential for damage is recognized by the US Forest Service, which provides resources to mitigate the impacts (USDA Forest Service, 2019).

The climate and changing patterns of this climate have a role in this process as well. While wildfire forecasts across the U.S. show increasing frequency and intensity, predictions for the Southwestern U.S. – which is forecast to get hotter and drier – show an extended annual fire season with increases in the total number of fires and area burned (Abatzoglou & Williams, 2016; Dennison et al., 2014; Spracklen et al., 2009; Westerling et al., 2006). Along with the increasing risk of severe wildfires, there are also predicted to be significant changes in precipitation patterns. While drought may become a persistent problem for much of the southwest, climate models predict that the future will also be punctuated by an increase in heavy rainfall events (Cook et al., 2015; Min et al., 2011). Changes in these factors have the potential to trigger significant flooding and debris flows that may damage infrastructure and endanger human life.

1.3. Arizona wildfires and flooding case study

In Arizona, the Apache-Sitgreaves, Coconino, Kaibab, and Tonto forests are an interesting case study to assess the interactions between climate, wildfires, and transportation, because they contain a range of different types of transportation infrastructure (from forest roads to interstates), they connect large portions of the state together, and contain a confluence of troublesome variables (namely heat, drought, monsoon rains, and severe climate forecasts). The confluence of these variables and the devastation they can create together are exemplified by the 2010 Shultz Fire. This fire burned 15,000 acres, small by wildfire standards, in the Coconino Forest on the eastern slopes of the San Francisco Peaks in Northern Arizona. Though the fire itself was relatively small, it led to a series of major flooding events that were extreme in terms of peak water flow, sediment, and debris movement for the area. These floods, estimated to be one to two orders of magnitude larger than those produced by similar pre-fire precipitation events, resulted from the confluence of ecological, geomorphic, and climatic conditions that produced an extreme wildfire and were followed by the fourth largest monsoon season precipitation on record (Neary et al., 2012). The precipitation events following the wildfire were all less than or equal to 50-year return period events but subsequent flooding and erosion were on the scale of a 1000-year return period. It caused considerable damage in nearby communities destroying homes, rupturing water mains, and inundating roads and drainage structures with sediment and debris (Klassen, 2011; NOAA, 2019; Youberg et al., 2011). While there were no structures or infrastructure lost to the wildfire, the total official costs attributed to the fire were nearly 60 USD million, largely due to the subsequent flooding (Petterson, 2014). With additional economic costs of the fire and flooding – which includes losses in property value and structural damage to homes – the total impact was estimated at 130–150 USD million dollars. In contrast, the pretreatment costs to prevent extreme wildfire in that areas were estimated at 15 USD million ($1000/acre) (Combrink et al., 2013).

The Four Forest Restoration Initiative (4FRI) was launched in 2010 to accelerate efforts to return Arizona Forests to ecological conditions found in the early twentieth century through mechanical thinning and prescribed burns. One of the goals is to reduce the incidents and the size of severe wildfires. Covering 2.4 million acres across portions of Apache-Sitgreaves, Coconino, Kaibab, and Tonto national forests, 4FRI is a multi-decade project with an annual goal of the treatment of 20,000 acres (Four Forrest Restoration Intitaive, 2017) (Figure 1). The project is a collaboration across several agencies and considers input from various stakeholders to identify specific areas as priority treatment zones. The prioritization scheme for restoration efforts emphasizes areas of 'high fire hazard and where fire immediately threatens communities' (U.S. Forest Service, 2009). While it may be implicit in some of the recommendations made by agencies and stakeholders, the potential for post-fire flooding is not explicitly mentioned as a metric for assigning priority in the 4FRI strategic plan nor are specific transportation assets identified (Four Forrest Restoration Intitaive, 2017).

2. Methods

New approaches are needed to understand how wildfire may impact infrastructure and WUI communities beyond the immediate effects of the fire itself. Towards this end, a novel method has been developed that combines post-fire debris flow risk, hydrologic assessment, and roadway network analysis to better understand where and how transportation infrastructure is at risk. The 4FRI region is used as a case study and the analysis approach involves; (i) identifying stream flows that drain into or across transportation infrastructure (roads), (ii) characterizing each contributing watershed by wildfire hazard and post-fire flooding vulnerability factors (intrinsic system characteristics that increase the likelihood of severe flooding

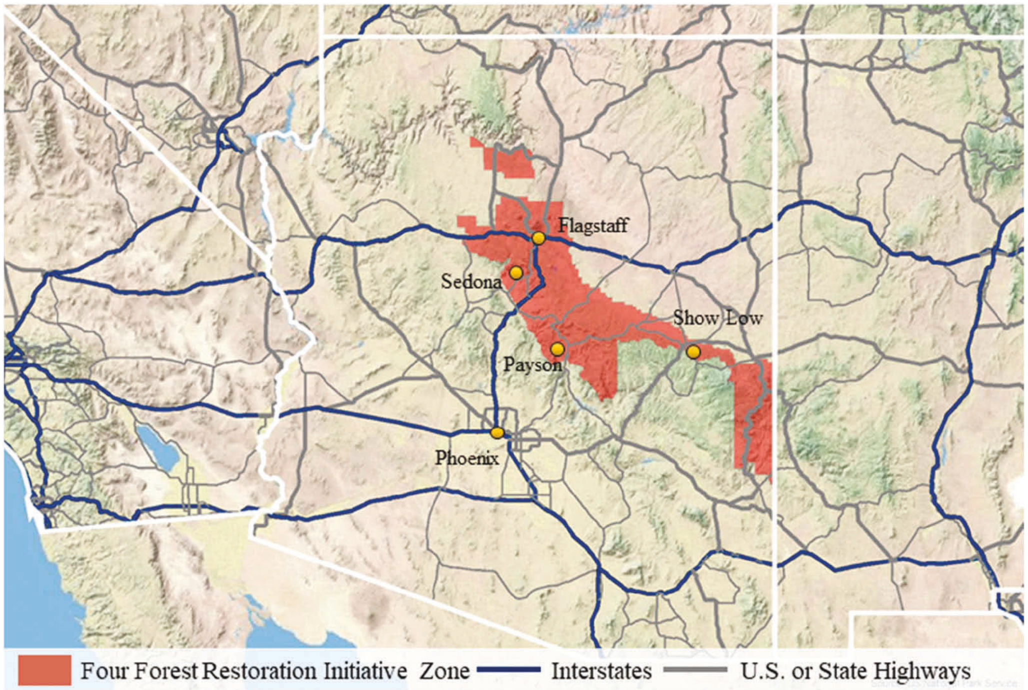

Figure 1. Four Forest Restoration Initiative.

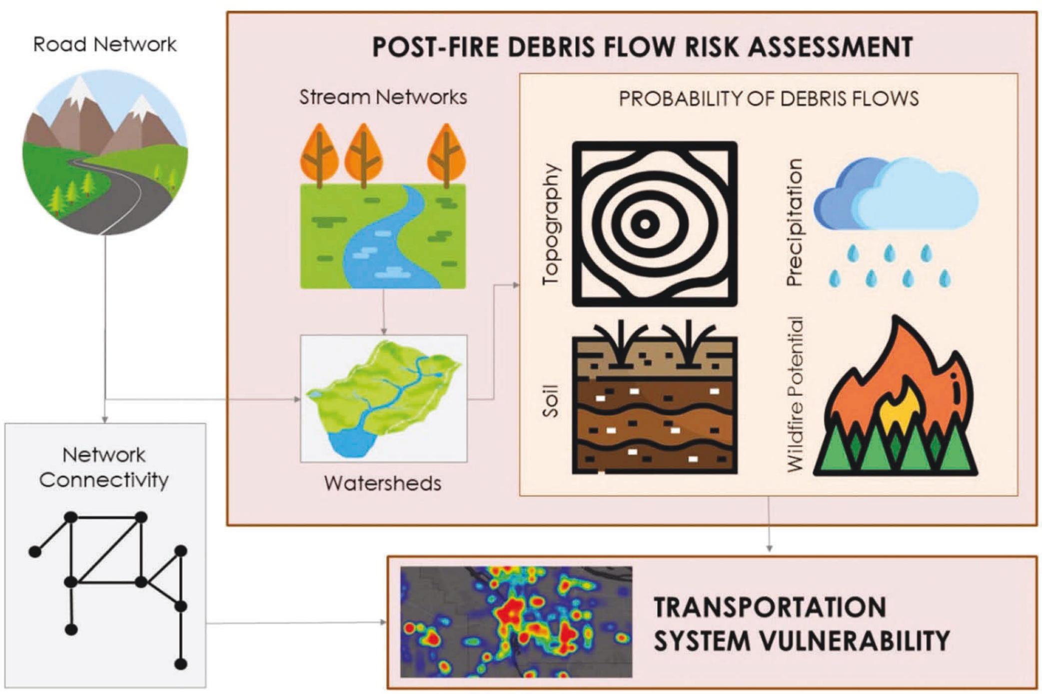

Figure 2. Methodology for characterizing the vulnerability of transportation infrastructure to post-fire debris flows.

and debris movement), and (iii) characterizing the relative importance of impacted transportation links to regional mobility (Figure 2). This approach highlights that the threats posed by climate change are more complex than the co-location of infrastructure and single hazards. The combined effects of multiple hazards can create vulnerabilities well beyond the locale where they occur.

2.1. Stream flows and watershed delineation

The national hydrology dataset was used to determine potential intersections between streams, rivers, and paved roadways within the 4FRI region (USGS, 2017b). The road network analyzed includes interstates, highways, arterials, collectors, and local roadways. ArcHydro tools were then used to establish the spatial geometry of watersheds for each point of conflict. These watersheds represent the total surface area which would be expected to contribute to flows crossing specific points along with the roadway network.

2.2. Watershed characterization

All watersheds were characterized by factors known to increase the probability of post-fire debris and water flows. The factors include the wildfire hazard potential, surface area characteristics, soil characteristics, and storm rainfall intensity and utilizes a predictive model developed by Cannon et al. (2010). While several models are presented by Cannon et al. (2010), Model A was selected for both its predictive performance and the availability of input data to force the model. The model establishes probability (P) of debris flows occurring following a wildfire by the following:

$$P = \frac{e^x}{1 + e^x}$$

and

$$x = -0.7 - 0.03(\%A) - 1.6(R) + 0.06(\%B) + 0.07(I) + 0.2(C) - 0.4(LL)$$

where $\% A$ is the percentage of watershed area with gradients greater than or equal to 30%, R is a measure of basin ruggedness, $\% B$ is the percentage of the watershed burned at high or moderate severity, I is the average storm rainfall intensity (in mm/h), C is clay content in percent, and LL is the liquid limit. Table 1 further defines these variables and respective sources. Cannon et al. (2010) developed the model using regression analysis of post-fire debris movement events based on characteristics of watersheds. In order to use the model in a predictive capacity, the fractional area burned at high or moderate severity is assumed equivalent to the fractional area where the wildfire hazard potential is high or very high. Similarly, the assumed rainfall intensity is associated with 2 year-10 min and 10 year-10 min storms based. These values were selected based on the recommendation that the model is used with high-frequency – low-duration storms. Mean values for I, C, and LL were assumed for individual watersheds.

2.3. Betweenness centrality

In wildfire risk assessment frameworks, the risk value associated with an event occurring is the product of the probability of an event occurring and the value or relative importance of infrastructure that would be threatened if the event was to occur. The importance of a roadway link or node is most easily described by the number of vehicles passing through it over a given time interval. However, average daily traffic counts are typically unavailable for large portions of rural road networks. When such information is unavailable, network science has been used to approximate the importance of roadway links and nodes. Although it is not the only metric that can be derived by graph theory to describe a network, betweenness centrality has been routinely used to describe the relative importance of a node and/or link within transportation networks as well as the vulnerability and resilience of the network (Derrible, 2012; Issacharoff et al., 2008; Kermanshah & Derrible, 2016; Mattsson & Jenelius, 2015; Pregnolato et al., 2016; X. Zhang et al., 2015; Zhang & Virrantaus, 2010). Betweenness centrality is a measure of the total number of shortest paths connecting all node pairs within a network that pass through a node or traverse a link

Table 1. Factors predicting post-fire debris flow occurrence.

Variable	Description	Source
Percent area (%A)	Percentage of watershed area with slopes greater than or equal to 30%	10-meter Digital Elevation Model (USGS, 2017a)
Ruggedness (R)	Change in basin elevation divided by the square root of the basin area	10-meter Digital Elevation Model (USGS, 2017a)
Wildfire hazard potential (%B)	Relative potential for wildfire that would be difficult for suppression resources to contain resulting in extreme fire behavior. Hazard potential is based on landscape conditions.	Wildfire Hazard Potential (Dillon et al., 2014)
Storm rainfall intensity (I)	Rate of precipitation associated with specific storm lengths and reoccurrence intervals.	NOAA Atlas 14 (Bonnin et al., 2006)
Clay content (C)	Mineral particles less than 0.002 mm in equivalent diameter as a weight percentage of the less than 2.0 mm fraction.	Digital General Soil Map of the United States (STATSGO2) (National Resource Conservation Service, 2017)
Liquid limit (LL)	The water content of the soil at the change between the liquid and plastic states.	Digital General Soil Map of the United States (STATSGO2) (National Resource Conservation Service, 2017)

(Demšar et al., 2008; Lämmer et al., 2006). Links or nodes exhibiting high measures of betweenness centrality are generally understood to be important elements of transportation networks. The loss of a link or node with a high measure of betweenness centrality would break many shortest paths disrupting flow on the network and forcing potential trips through longer detours. In the context of sparse rural roadway networks, the loss of network elements with high betweenness may be especially problematic where redundant routes are limited and detours may add substantial travel time between origin-destination pairs (Wang et al., 2017). To calculate betweenness centrality for the 4FRI paved road network, which is comprised of nearly 43,000 links, City Form Lab's Urban Network Analysis Toolbox for ArcGIS was used (Sevtsuk et al., 2012).

3. Results

Across the 4FRI region, there are more than 7,100 potential interactions between stream flows and roadways. By roadway classification, 3% are on interstates, 3% are on U.S. highways, 9% are on state highways and major arterials, and 85% on local, neighborhood, or rural roads. Only 27% of these points fall within census-designated populated areas (U.S. Census Bureau, 2016) such as the communities of Flagstaff, Payson, Show Low and Williams. The majority of the points are found in rural areas on links connecting WUI communities, remote residences, and serving as routes to outdoor recreation opportunities, historical places, national and state parks, and landmarks. Hazard variable value distributions for watersheds are shown in Figure 3. A major contributor to damaging post-fire debris flows is steep and rugged terrain. Compared with other forested regions in the western United States such as those in the Sierra Nevada, Rocky, and Cascade mountain ranges, the terrain across the 4FRI region is relatively moderate and characterized generally by gradual elevation changes (USGS, 2018). Only 9% of the total land area within the 4FRI region has hill slopes greater than 30°. However, these areas are clustered within discreet sections of the initiative zone and are found near roadway infrastructure and communities in several places including near Flagstaff, Payson, and Sedona. This includes the region where the Schultz Fire and flooding occurred. More than 60% of the 4FRI region is considered at high to very high risk for extreme wildfire behavior under conducive weather conditions (Dillon et al., 2014). The risk is evenly distributed throughout the 4FRI region with the exception of the Kaibab National Forest north of the Grand Canyon where wildfire hazard potential is relatively moderate. Precipitation potential is highest in the Tonto National Forest and portions of the Apache-Sitgreaves National Forest stretching from Payson to Show Low, AZ, and lowest in the northern portions of the Coconino and Kaibab national forests. High and low values for soil clay content and liquid limit tend to be coincident with the highest values occurring in the Coconino and Kaibab national forests and in a small portion of the Apache-Sitgreaves National Forest located near Show Low.

While each variable contributes to the hazard potential of post-fire flooding, it is the coincidence of these factors that dictates the probability of post-fire flooding and debris movement. Across the 4FRI region, the probability for post-fire debris flows and flooding is relatively benign. Only 12% and 17% of all watersheds have a greater than 20% chance of producing post-fire debris movements and flooding under 2 year – 10 min and 10 year – 10 min precipitation events. Furthermore, these areas are concentrated in a few areas within the region (Figure 4). These watersheds are located along the western edge of both the Coconino and Apache-Sitgreaves National Forests. The Kaibab and eastern portions of the Apache-Sitgreaves are the least likely areas within the 4FRI region to experience post-fire debris flows and flooding. Due to the recent fire and decreased fuel loads, the Schultz Fire region exhibits low probability of future wildfires and post-fire flooding. However, assuming the Shultz fire had not happened, all watersheds within the fire's boundary exhibit a greater than 50% probability of post-fire debris flows and flooding following a 10-year, 10-min precipitation event validating the underlying model.

The relative vulnerability of the transportation system to post-fire debris flows and flooding can be understood by comparing the probabilities of these flows with the betweenness assessment of roadway links they intersect. Figure 5 illustrates this comparison. The portions of the transportation system that have the highest probability (>75%) of post-fire flows are characterized by rural roadways that likely play a minor role in overall mobility within the region. In contrast, many of the major roadways in the region have a low probability of experiencing post-fire flooding. However, there are small number of watersheds that feed streams that cross major roadways that have a relatively high probability (>40%) of post-fire flows (Figure 5, red square). If a wildfire occurred in these watersheds followed by a fairly common precipitation event (e.g., a 2 year-10 min or 10-year-10 min); then, it could be reasonably expected that flows would create serious disruptions within the regional transportation system. These 13 watersheds contribute to stream flows that cross a rural stretch of State Route 260 between Payson and Show Low, AZ. State Route 260 is a major

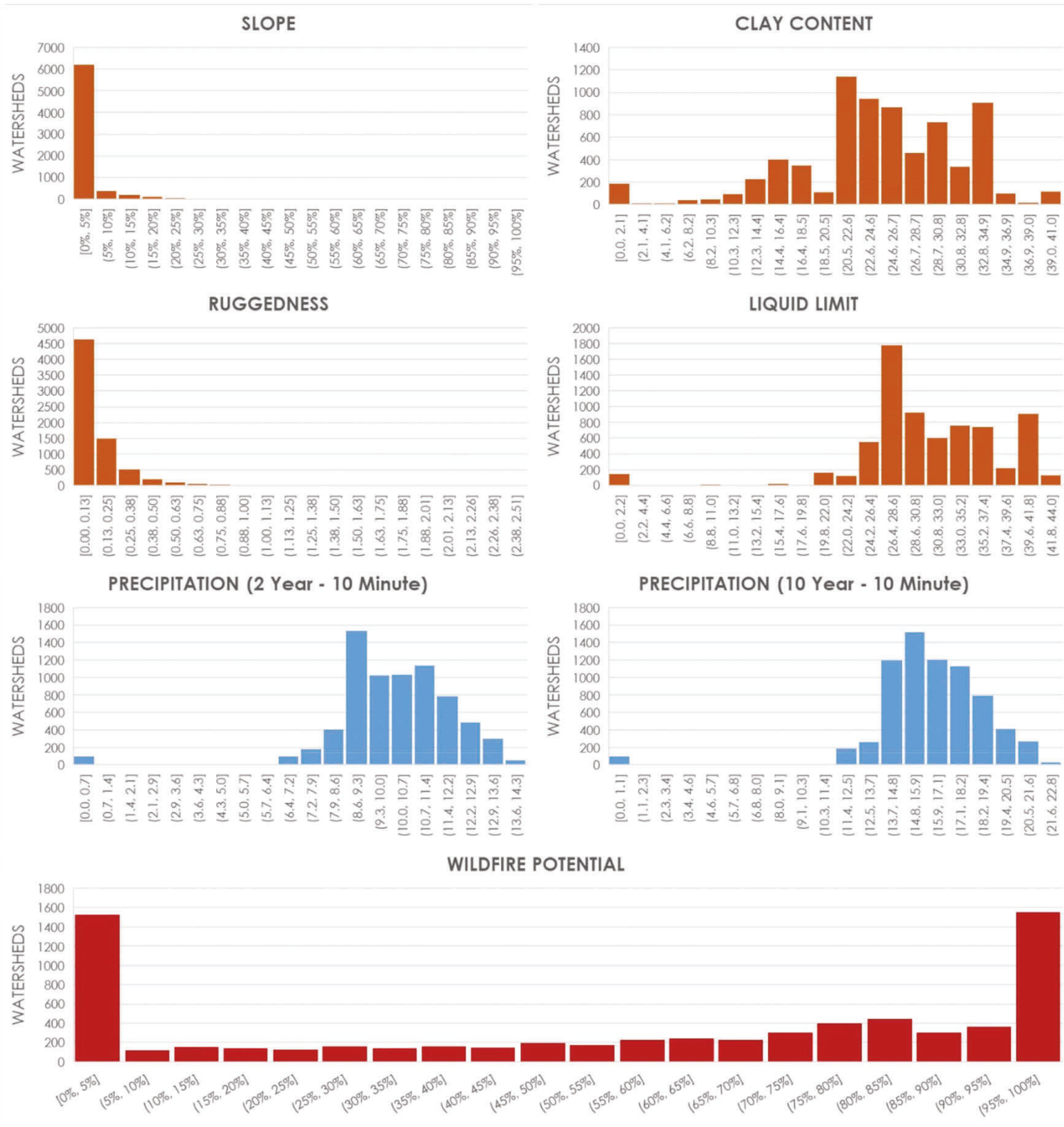

Figure 3. Results for distribution of hazard variables.

east-west state highway in the north-central part of Arizona and is the direct route for many rural communities east of Payson to reach the metropolitan area of Phoenix as well as northern areas of the state including Flagstaff. Road closures resulting from post-wildfire flows along this route would likely have significant impacts on mobility and commerce for communities east of Payson. Wildfire mitigation initiatives that emphasize human life and communities might overlook this area as a priority due to a lack of significant development. The results, however, indicate that a wildfire in this area could lead to significant transportation disruptions. In addition to protecting human life and communities, wildfire mitigation efforts need to also consider areas like these where critical infrastructure is vulnerable to wildfire and post-fire impacts.

4. Limitations

The factors evaluated in this analysis were selected because of the validated model developed by Cannon et al. (2010) and because they are readily available at a scale sufficient to characterize every potential watershed within the 4FRI region. There are other factors that also play a role in post-fire flows including the availability of hillslope and channel materials, the presence of existing material within channels, and the frequency of fire-flood occurrences which may limit

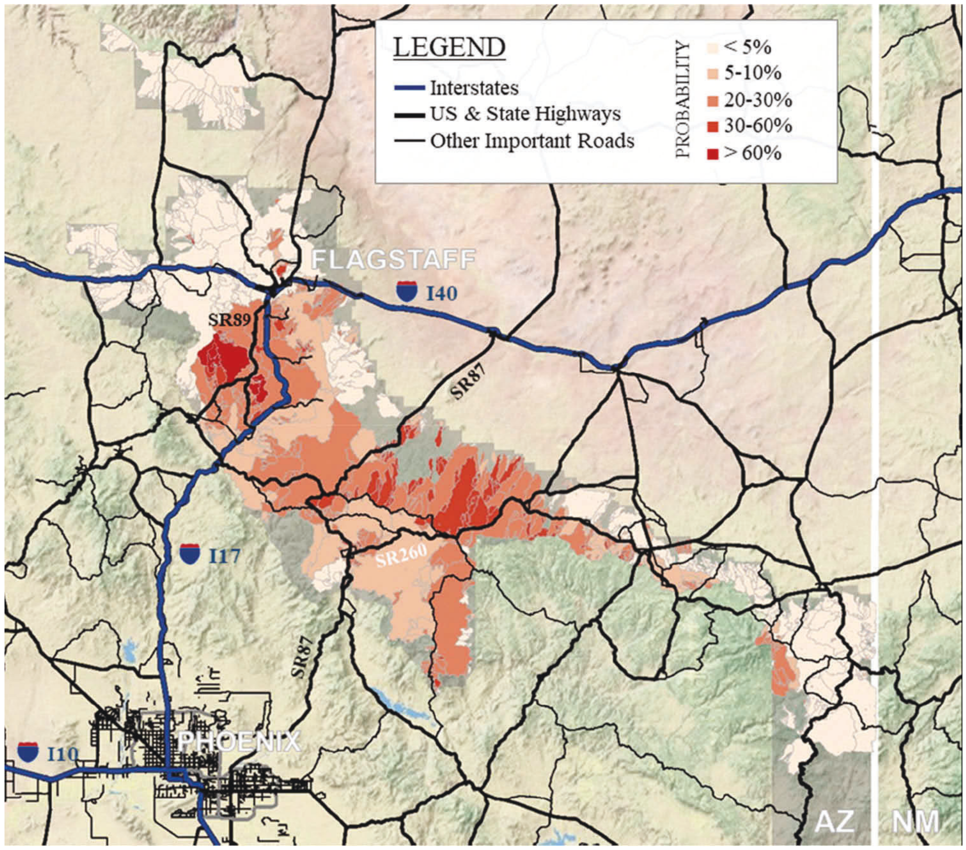

Figure 4. Probability of post-fire debris flows and flooding following a wildfire and precipitation (10 year – 10 min) event.

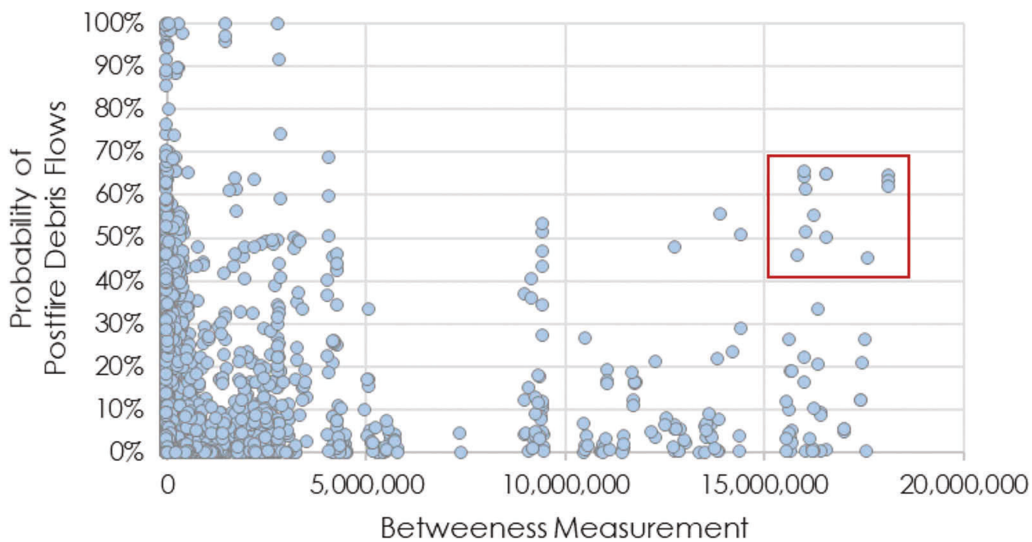

Figure 5. Comparison of probability of post-fire flows and potential impact on regional mobility.

material availability (Cannon et al., 2010). Though the described methods successfully identify where streams and roads intersect, they are not predictive of the kinds of drainage infrastructure in place at these locations. Also, while design standards exist, they are not always consistent across individual pieces of infrastructure (for example, drainage areas judged by the field engineer to require a small pipe might not have a full hydrological design applied, while large culverts do) and also engineers exercise their own judgment at the construction stage as to how much their design will exceed the minimum limits set by the owner agency. Collectively these factors impart a level of uncertainty and inconsistency with respect to an individual piece of infrastructure's robustness against unexpected flow volumes and return periods. To fully assess the probability of failure, rather than the probability of experiencing post-fire flooding, knowledge of the drainage infrastructure present is required. Additionally, a long-term effect of wildfires that is not evaluated here is the decay of tree-root systems result in the generation of landslides and debris movement that could also result in downstream infrastructure failure (Meyer et al., 2001).

5. Discussion

There has been a growing trend in the number of devastating wildfires in the American West and the destruction caused by post-fire flooding and debris flows can be equally devastating. In January 2018 heavy rains triggered catastrophic flooding and mudflows in Montecito, CA that claimed lives, destroyed communities, and closed a major U.S. highway for nearly 2 weeks less than 1 month after the Thomas Fire burned the hillsides above (Dolan, 2018; Mejia et al., 2018). Understanding the risks for flooding and debris, crews immediately went to work following the fire to stabilize the charred hillsides, but there simply was not enough time to effectively treat the entire area. This example demonstrates how existing efforts to mitigate and adapt to the potential devastating impacts of post-fire flooding and debris movement are largely reactive and are extremely time sensitive. The reality of damaging post-fire flooding and debris flows in the West show that existing mitigation programs are limited in their ability to respond and prevent these events and their follow-on impacts. Without additional resources, the increasing severity and expansiveness of forest fires in the west will further hamper the ability of these programs to respond. There are, however, initiatives and efforts like 4FRI that are taking a proactive approach to limiting the rise and spread of extreme wildfires. The primary focus of these initiatives in many cases is preventing the loss of life and damage to WUI communities from the wildfire. These are necessary pursuits, but the results show that critical infrastructure, in this case, transportation, exists outside these communities that are also vulnerable to post-fire effects. In particular, the methodological advances and corresponding results point to specific regions where critical roadway vulnerabilities exist, and as such should be prioritized with proactive efforts.

Another option to limit post-fire consequences is adapting existing infrastructure to withstand these events. Traditional risk-based approaches to designing infrastructure consider the potential threats, their probabilities, and potential consequences when selecting design parameters. This approach focuses on the robustness (i.e., armoring and strengthening) of infrastructure relying on historical (e.g., precipitation) data to determine the size of structural elements, leading to the current paradigm focused on fortified grey infrastructure. Risk is generally based on historical data that corresponds to 50 or 100-year single hazard events (2% or 1% probability of annual exceedance, respectively). This approach is known as 'fail-safe' and seeks to prevent failure of infrastructure, without consideration in design of what happens when infrastructure fails. In the case of post-fire flooding, utilizing this approach is problematic for a number of reasons. First, understanding these threats and their potential probability in any location is difficult as these events require the occurrence of two hazards where one follows in short order after the other. Second, because common precipitation events can lead to water and debris flows that are consistent with 1000-year events (0.1% probability of annual exceedance), the engineering community's understanding of the potential consequences, based on historical observation, is also limited. The methods developed here that join precipitation with post-fire risk and transportation infrastructure provide necessary first steps towards understanding multi-hazard risk. They provide a foundation for how design standards can consider some of the complexity inherent in multi-hazard events. However, designing infrastructure to be capable of handling high volume, high velocity, debris-laden water flows associated with 1000-year events is potentially physically, economically, or socially infeasible. Lastly, climate change is expected to introduce uncertainty in environmental hazards, that is the unpredictability of the frequency or intensity of extreme events (known as non-stationarity). This means that the traditional design approaches that rely on historical patterns and assume that those patterns will be consistent in the future are no longer valid (Kim et al., 2019; Lopez-Cantu & Samaras, 2018). The confluence of these factors calls for a reassessment of risk-based approaches.

Further adding to the complication of this issue, the emergence of a non-stationary climate has added more uncertainty to the entire process and led to a significant discussion about whether the traditional risk-based approach is still appropriate for designing and managing civil infrastructure. Civil infrastructure is often capitally intensive projects and is designed to last decades and the uncertainty associated with climate variables creates significant challenges for designing cost-effective implementations. Our understanding of the global climate has improved significantly in recent decades and models exist that predict future climate outcomes under various scenarios. These models, however, are far too coarse in their spatial and temporal resolutions to provide reliable support for making decisions about how infrastructure should be designed. Additionally, uncertainties within the models are likely to compound over time further dampening the ability to rely on them for infrastructure designed to last decades. Resilience engineering approaches accept the uncertainty associated with non-stationarity and recognize that the ability to develop 'fail-safe' designs is unlikely. Therefore, the potential for failure and the associated consequences are assumed. A resilience approach that considers how these failures are managed and what approaches and designs can be used to reduce such consequences has been dubbed 'safe-to-fail'. In the context of post-fire flooding and transportation infrastructure, this would include managing the consequences of failure to regional mobility, which has implications for social and economic systems. Adapting resilient practices to manage these consequences are context dependent but might include low-cost infrastructure that is easy and quick to replace, increasing redundancies in the transportation network in vulnerable areas, and strategic abandonment of infrastructure where reoccurring failure is likely.

6. Conclusion

Climate hazards interact with infrastructure in many ways and the current risk assessment techniques focus heavily on the co-location of the hazard and infrastructure. As this work illustrates, the impacts associated with climate hazards can occur well downstream from their physical location. Additionally, the ability of some hazards to amplify the impacts associated with others adds additional complexity. The specific conclusions drawn from the analysis in this paper are:

- Current research on the impacts of wildfires to transportation focuses on evacuation and mobility during the event, with only limited consideration of direct physical impacts;
- Transportation infrastructure is vulnerable to post-fire flooding, which can be many times larger than the level of flow that the original engineer considered when designing the infrastructure;
- The vulnerability of infrastructure to post-fire flooding varies according to physical factors of the associated drainage area including size, slope, and its variation throughout the drainage area, and the severity of the fire;
- When post-fire flooding overwhelms the transportation infrastructure failures inevitably occur and communities have varying levels of risk depending on the nature of the infrastructure that exists, its vulnerability to post-fire flooding, and the level of redundancy in the transportation infrastructure for that community; and
- In addition to protecting human life and communities, wildfire mitigation efforts need to consider areas that are at high risk to post-fire impacts due to losses in critical infrastructure.

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Notes on contributors

Andrew M. Fraser is currently a project engineer with the Maricopa Water District in the Phoenix metro area but led this work during his tenure as a Research Assistant Professor in Arizona State University's School of Sustainable Engineering and the Built Environment. As a research professor he led several studies to understand the impacts of climate change driven extreme events on infrastructure, the services they deliver, and the people who rely on them.

Mikhail V. Chester is the Director of the Metis Center for Infrastructure and Sustainable Engineering at Arizona State University where he maintains a research program focused on preparing infrastructure and their institutions for the challenges of the coming century. His work spans climate adaptation, disruptive technologies, innovative financing, transitions to agility and flexibility, and modernization of infrastructure management. He is broadly interested in how we need to change infrastructure governance, design, and education for the Anthropocene, an era marked by acceleration and uncertainty. He is co-lead of the Urban Resilience to Extremes research network composed of 19 institutions and 250 researchers across the Americas, focused on developing innovative infrastructure solutions for extreme events.

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