Title

Vulnerability of California Roadways to Post-Wildfire Debris Flow

Permalink

https://escholarship.org/uc/item/60d0k700

Authors

Chester, Mikhail V.
Li, Rui

Publication Date

2020-07-01

RESEARCH REPORT

Institute of
Transportation
Studies

UNIVERSITY
OF
CALIFORNIA

Vulnerability of California Roadways to Post-Wildfire Debris Flows

Mikhail V. Chester, Ph.D., Visiting Scholar on Sabbatical, Institute of Transportation Studies, University of California Los Angeles

Rui Li, Doctoral Student, Civil, Environmental, and Sustainable Engineering, Arizona State University

July 2020

UCLA Institute of Transportation Studies

Report No.: UC-ITS-2020-38 | DOI: 10.17610/T60W35

Technical Report Documentation Page

1. Report No. UC-ITS-2020-38	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.** N/A
4. Title and Subtitle Vulnerability of California Roadways to Post-Wildfire Debris Flows.		**5. Report Date** July 2020
		6. Performing Organization Code ITS-UCLA
7. Author(s) Mikhail V. Chester, Ph.D. https://orcid.org/0000-0002-9354-2102 Rui Li, https://orcid.org/0000-0001-8385-763X		**8. Performing Organization Report No.** N/A
9. Performing Organization Name and Address Institute of Transportation Studies, UCLA 3320 Public Affairs Building Los Angeles, CA 90095-1656		**10. Work Unit No.** N/A
		11. Contract or Grant No. UC-ITS-2020-38
12. Sponsoring Agency Name and Address The University of California Institute of Transportation Studies www.ucits.org		**13. Type of Report and Period Covered** Final Report (July 2019-July 2020).
		14. Sponsoring Agency Code UC ITS
15. Supplementary Notes DOI: 10.17610/T60W35		
16. Abstract A vulnerability assessment of California roadways to post-wildfire debris flows is developed. The work examines current and future conditions, considering climate change scenarios and how they affect fire risk and precipitation. Results show how post-fire debris flow risks change from today into the future. A discussion is presented on how to prioritize investments considering the criticality of roadways within the broader network.		

17. Key Words Wildfires; Debris Flows; Roadways; Infrastructure; Climate Change; Resilience		**18. Distribution Statement** No restrictions.		
19. Security Classification (of this report) Unclassified	**20. Security Classification (of this page)** Unclassified	**21. No. of Pages** 44	**22. Price** N/A	
Form Dot F 1700.7 (8-72)		Reproduction of completed page authorized		

About the UC Institute of Transportation Studies

The University of California Institute of Transportation Studies (UC ITS) is a network of faculty, research and administrative staff, and students dedicated to advancing the state of the art in transportation engineering, planning, and policy for the people of California. Established by the Legislature in 1947, ITS has branches at UC Berkeley, UC Davis, UC Irvine, and UCLA.

Acknowledgments

This study was made possible through funding received by the University of California Institute of Transportation Studies from the State of California via the Public Transportation Account and the Road Repair and Accountability Act of 2017 (Senate Bill 1). The authors would like to thank the State of California for its support of university-based research, and especially for the funding received for this project.

Disclaimer

Vulnerability of California Roadways to Post-Wildfire Debris Flows

Mikhail V. Chester, Ph.D., Visiting Scholar on Sabbatical, Institute of Transportation Studies, University of California Los Angeles

Rui Li, Doctoral Student, Civil, Environmental, and Sustainable Engineering, Arizona State University

July 2020

UCLA Institute of Transportation Studies

Report No.: UC-ITS-2020-38 | DOI: 10.17610/T60W35

Table of Contents

Table of Contents

List of Tables

List of Figures

List of Equations

Executive Summary

Executive Summary

Wildfires represent a major challenge for ensuring the reliability or transportation services into the future. While many infrastructure are vulnerable to wildfires, roadways in particular are perhaps the most pervasive assets in wildfire prone regions. As such, there is a rich history in California and across the US West of roadway disruptions to wildfires. Climate change represents a potential exacerbating force, threatening to change wildfire dynamics. Yet there remains little work examining how wildfires make roadways vulnerable, and how vulnerability could change into the future. This insight is critical to long-term planning, strategic investment, and creation of resilience strategies.

Post-wildfire debris flows represent a major challenge for roadways in California and the West. While wildfires themselves disrupt traffic and create evacuation challenges, precipitation events that occur after wildfires have the capacity to overwhelm roadways and their stormwater infrastructure, in extreme circumstances causing total failure of the asset. This dynamic has recently occurred following Thomas Fire (Kean et al., 2019), San Bernardino Fire, and Camp Fire (Kean et al., 2011). Wildfires change soil chemistry making the soil prone to less absorption and more runoff, producing debris, and denuding the landscape (De Graff et al., 2015; Elliott et al., 2004; Moody et al., 2013). A subsequent rain event can have orders of magnitude greater runoff than pre-wildfire conditions (Cannon et al., 2008, 2011; Elliott et al., 2004; Kean et al., 2011). Yet our understanding of the vulnerability of roadways to wildfires still largely focuses on spatial overlays of where fires are or will occur, and which assets are there (Wolshon et al., 2007). This approach is useful but aligns more with hazard analysis than vulnerability analysis. What is needed are new approaches for characterizing roadway vulnerability to post-wildfire debris flows that capture fire risk (including vegetation, precipitation, soil, and geologic conditions) and roadway criticality. This work addresses this challenge for California assessing both current and future conditions.

A post-wildfire debris flow roadway vulnerability assessment is developed for the entire state of California for both current and future conditions. The vulnerability assessment considers soil conditions, vegetative conditions, geologic conditions, precipitation (current and future), and fire risk (current and future), in addition to roadway criticality. Post-fire debris flow models developed by Canon et al. (2010) and Staley et al. (2017) are used to characterize post-fire debris flow risk by watershed. The model is forced with precipitation and environmental variables from state sources including CalFire and Cal-Adapt. The watershed risk is joined with a network topological analysis of roadway criticality. Some roadways may be in regions that are high risk to post-fire flows, but may not be critical in people driving from origins to destinations. We define criticality based on betweenness centrality, a measure of the number of routes that would use a particular link to traverse the network. We do not consider traffic flows as i) many roadway links in the broader network are in remote regions without traffic counts, and ii) even if a road has a high traffic volume, that traffic may be easily shifted to a nearby route. We consider arterials and highways in our assessment. It is methodologically possible to consider lower functional classifications (such as local and collector roads) but is computationally prohibitive.

The results present the current and future watershed risk, roadway risk, and roadway vulnerabilities. Under current conditions, watershed post-fire debris flow likelihood and number of vulnerable roadways are likely to increase with long recurrence design storm events. Under a 10-year recurrence design storm, 0.06% of roadways are vulnerable to post-fire debris flow, and that increases to 0.16% to 0.47% under 50 or 100-year recurrence design storms. The percentage of watersheds under risk is greater than roadways. Many problematical basins are in the wildland where no roadways currently pass through. Climate change, which drives the regional precipitation intensity and large fire burn area to an extreme, will push more watersheds and roadways under the extremely high (more than 80% likelihood) post-fire debris flow risk category. Simulations under different climate change models (HadGEM and CanESM in this study) provide reasonable bounding cases for future conditions. Under a 100-year design storm event, in the worst-case emission scenario (RCP 8.5), 1.16% to 1.46% of roadways are highly vulnerable while in the stabilization scenario (RCP 4.5), 0.52% to 0.73% of roadways are highly vulnerable.

The results from this study provide guidance for roadway mangers to identify the potential high post-fire debris flow watersheds, roadways under extremely high post-fire debris flow threat, and the changing profile of vulnerable roadways under both current long recurrence design storm events and future climate scenarios. Currently, under a 100-year design storm, most vulnerable roadways are located in Caltrans 2, 7, and 11 districts, while extremely high post-fire debris risk watersheds appear in Caltrans districts 2, 6, and 7. It is common to see increased roadway vulnerability in regions where fires are currently occurring, indicating more frequent and intense future fires and precipitation impacting a broader portion of the transportation network. In the future climate change scenarios, districts 1 and 8 can expect an increase in their vulnerability ranking.

The vast roadway network, exacerbating conditions driven by climate change, and large expense of rehabilitating assets should give California incentive to consider a broad suite of resilience strategies. Engineered infrastructure design in the face of hazards currently emphasizes control and pushback, with robustness (armoring, strengthening, and hardening) as the predominant approach. Robustness, i.e., the upgrading of assets to be able to withstand more intense post-fire debris flows, is necessary, but given the uncertainty inherent in climate change, and the vast roadway system that has to be upgraded, other strategies should also be considered. Graceful Extensibility (extending transportation services via, e.g., virtual connectivity or mode shifting) and Sustained Adaptability (i.e., a commitment to reassessing conditions, technologies, designs, and operations for a future defined by uncertainty) may provide alternative strategies at a systemic level for reducing impacts (Woods, 2015). Furthermore, safe-to-fail, i.e., the incorporation of failure analysis into the design process to broaden the suite of strategies to reduce the negative outcomes and costs of failure, should be considered beyond current fail-safe focused approaches. It may be the case that failure is inevitable, and California should have structured approaches for infrastructure design that acknowledge this failure.

Project data are available at wildfires.resilientinfrastructure.org.

Contents

Introduction

Characterizing the vulnerability of infrastructure to climate change represents an important new frontier for theory, research, and practice. Infrastructure -- the human engineered systems that deliver basic and critical services, such as transportation, power, and water -- are caught between design processes that largely emphasize historical weather and future climate uncertainty (Chester et al., 2020). As infrastructure managers are increasingly required to confront climate change to ensure the reliability of services into the future, new methods are needed for understanding risks and vulnerabilities, and adaptation options.

Wildfires represent a particularly challenging problem for infrastructure. Their direct damaging of roadways is unlikely (MacArthur et al., 2012). Wildfires tend to present as a concurrent hazard; they manifest with heat and drought, and they tend to produce powerful post-fire debris flows. These debris flows represent significant hazards for infrastructure in general, but in particular roadways, where landslides, debris movement, and exacerbated water flows often cut across roadways. It typically takes about 5 years for a watershed to return to its pre-fire conditions (Ice et al., 2004) and common precipitation events (defined as return periods of up to 10 years) are capable of producing 1000 year floods after an intense fire (Gartner et al., 2008). Yet few rigorous methods exist for unpacking the relationships between climate change, wildfires, post-fire debris flows, and transportation infrastructure. With climate forecasts generally showing significant and relatively fast changes in extreme events, there is cause for immediate examination of how our critical services (as supported by generally long lifetime infrastructure) are vulnerable and what can be done to protect them.

When it comes to transportation and wildfires, work tends to focus on evacuation strategies and hazard mapping, and there are few efforts to understand post-fire flows risk and how that translates to roadway vulnerability. The evacuation literature is rich and has been pursued for decades. This includes evacuation order strategies (Cohn et al., 2006; Cova et al., 2013; Wolshon et al., 2007), and logistics (Camp et al., 2013; Dijst et al., 2013; Evans et al., 2009; MacArthur et al., 2012; Morton et al., 2003; Peterson et al., 2010; Walker et al., 2011; Wu, 2001). Several studies establish precedent for more rigorous vulnerability assessments. Several researchers have noted the potential for increased landslides and loss of control systems (De Graff et al., 2015; MacArthur et al., 2012; Macdonald et al., 2008; Wu, 2001). Only one existing study (by the authors) has been identified that systematically assesses the relationships between fires, precipitation, geological and vegetative conditions, hydrology, and roadway infrastructure. Fraser et al. 2020 developed a model using Arizona’s forested region to assess post-fire debris flow risk to roadways. The study combined soil, topography, precipitation, and current wildfire potential, watersheds, and hydrologic analysis, with roadway infrastructure, also considering the importance of various links in the network (betweenness centrality). The study’s findings were confirmed as they showed high risk assets where recent fires and subsequent post-fire debris flows and roadway washouts had occurred. However, the work did not consider future climate change (and its fire and precipitation uncertainty). Also, it was conducted for a relatively small region, raising questions around how state or regional variations in geological, vegetative, hydrological, climate, and infrastructure affect a large infrastructure system and an agency’s prioritization for mediating risk.

We develop a roadway vulnerability assessment for the state of California considering climate change (and its uncertainty). In doing so, several important methodological advancements are made over the approaches developed by Fraser et al. 2020. First, the inclusion of climate forecasts (for wildfires and precipitation) requires assessment of current and future risk using consistent methods. We develop these methods. Second, statewide assessment at the scale of California presents several major computational challenges in terms of commensurate data inputs (data are sometimes regionalized and inconsistent) and scalability of computation. Third, the relationship between post-fire flows and roadways is complicated. Flows are expected to impact roads following stream paths. We develop new hydrologic methods to characterize how individual roadway links (as they intersect stream paths) are vulnerable. The methods embrace the uncertainty inherent in the work, in terms of climate change scenarios, wildfires, precipitation, and post-fire debris flows.

Following, we describe our data processing, methodological assessments, and results. We conclude with a discussion focused on the significance of the work for decisionmakers, with an emphasis placed on helping infrastructure managers prioritize limited resources towards high risk areas. We make the code available with documentation to the general public through our project website (wildfires.resilientinfrastructure.org).

Methodology

This study analyzes roadway vulnerability to post-fire debris flow hazards, which associates roadway debris flow risk with network topography. The work by Fraser et al. (2020) introduced a framework of vulnerability analysis using empirical post-fire debris flow models (Cannon et al., 2010) with network criticality assessment for roadways in Arizona. Opportunities exist for improving this framework with climate change scenarios to include future uncertainties, scaling the methods to the entire California state, and updating the debris flow model given emerging methods. This work advances the assessment of roadway vulnerability to post-fire debris flows by building upon the work of Fraser et al. (2020) to incorporate these opportunities. An updated vulnerability assessment framework included the roadway post-fire debris flow estimation with a state-of-the-art debris flow assessment (Staley et al., 2017) and burned area simulation (Staley et al., 2018), with downscaled future precipitation and fire projections (Pierce et al., 2018a; Westerling, 2018a).

Major steps of the analysis involved: 1) defining the hydrological system and principles to identify the risk profile of infrastructure, 2) quantifying the post-fire debris flow likelihood in watersheds and at roadways for current and future climate conditions, 3) analyzing the post-fire debris flow risk and 4) analyzing the roadway network's vulnerability and identifying the most vulnerable roadways. The model components are shown in Figure 1 and discussed in detail in the subsequent sections.

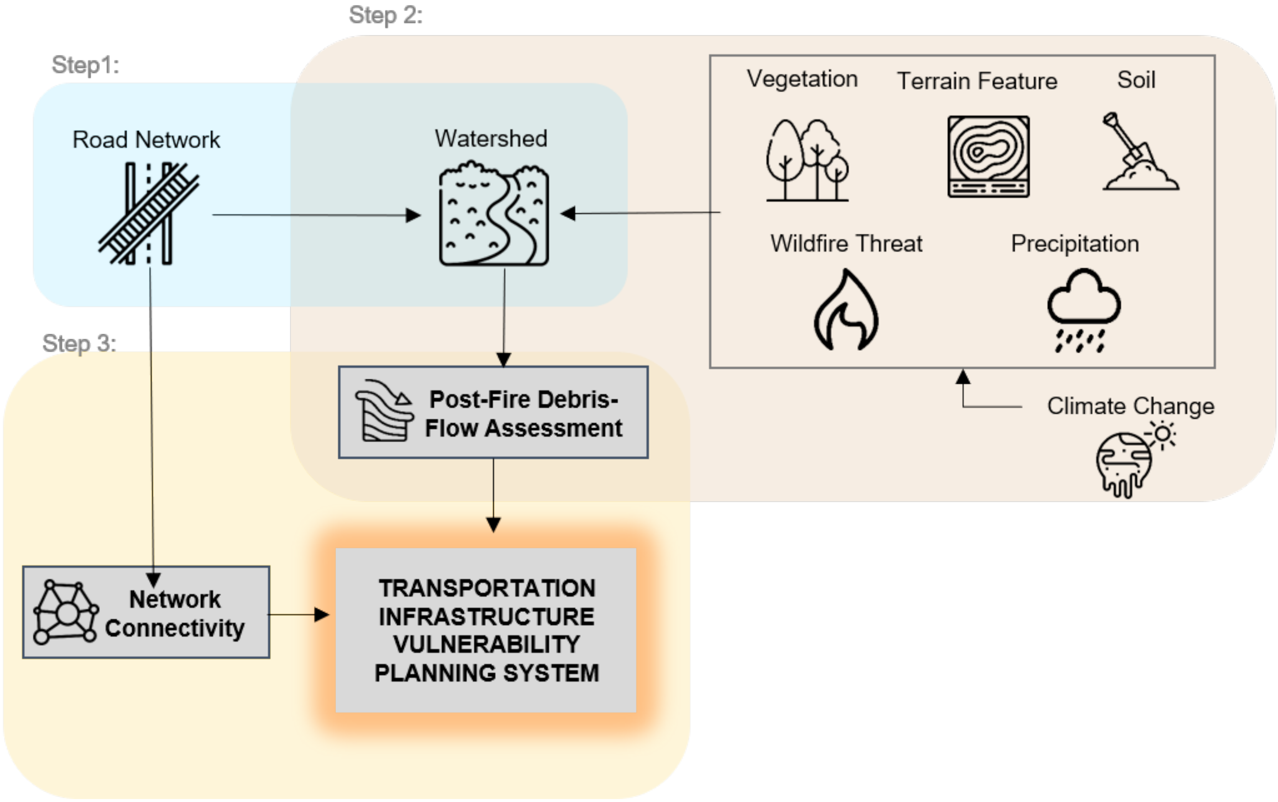


Figure 1. Methodology Overview

Hydrological System Definition

The post-fire debris flow assessment calculates the potential of debris flow based on soil, precipitation intensity, fire burned area, vegetation type, and geological characteristics in watersheds. The size, shape, and correct delineation of watersheds significantly influences the estimation result. In Fraser et al. (2020)'s model, the watershed boundary is delineated from 10-meters digital elevation models in Arizona (DEM). Calculating the boundary of watersheds for the whole of California is both computationally intensive and error-prone. As such, watersheds from the NHDPlus High Resolution (NHDPlus HR) dataset (Viger et al., 2016) are used in the calculation. The NHDPlus HR datasets are built with the ⅓ arc-second 3D Elevation data, which consists of small size catchments (area ranges from 10^{-2} to 10^{2} km^{2}), and a stream network at a refined scale to inform the post-fire debris flow estimation. The NHDPlus HR datasets, which were sourcing with the HUC 4 indexes, were obtained from the USGS National Geospatial Program. In total, 1.7 million watersheds in California were used in the estimation, and Figure 2.a shows the coverage in HUC 4 unit. HUC 1807 and 1810 are defined as the Southern California region while the rest are considered as the Northern California region. The Caltrans district map (Figure 2.b) was introduced to describe the analysis results.

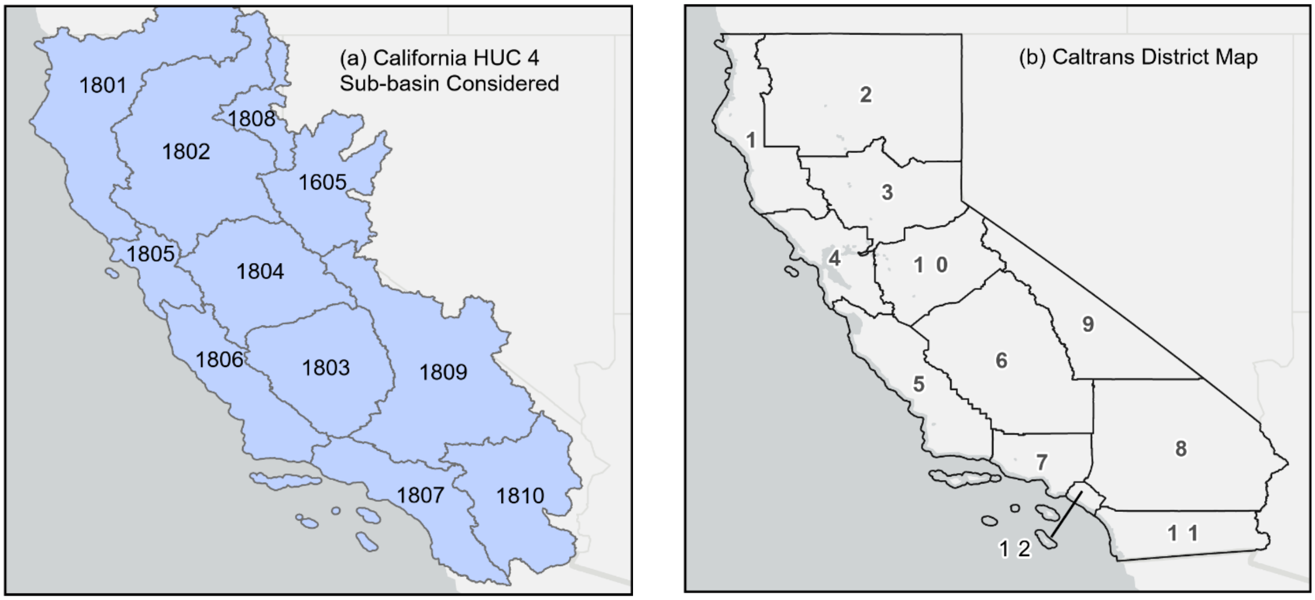


Figure 2. Watershed (NHDPlus HR) and Caltrans Districts Overlays.

Roadway Network Definition

Roadway post-fire debris flow risk is calculated from watershed characteristics where roadways pass through. Mapping of the watershed debris flow risk in the roadway network is done by assigning the value of the watershed debris flow to the roadway and stream interactions in the watershed (Figure 3.a). The streamflow is obtained from NHDPlus HR data. In doing so, it is assumed: 1) roadway sections with no streamflow interactions would not have debris flow occurring, and 2) roadways would have the same degree of risk as the catchment at the roadway and streamflow intersections. The roadway network is retrieved from OpenStreetMap (“Researcher Information - OpenStreetMap Wiki,” 2017). Functional classifications of Interstates, Highways, and Arterials are considered. While the methodology is applicable to lower classification roads (such as Local links), the computational requirements are significant and therefore excluded. In total, 95,173 roadway and streamflow intersections were identified with the majority located in the Great Valley and West Coast (Figure 3.b). The datasets used in the hydrological system and roadway network definition are listed in Table 1.

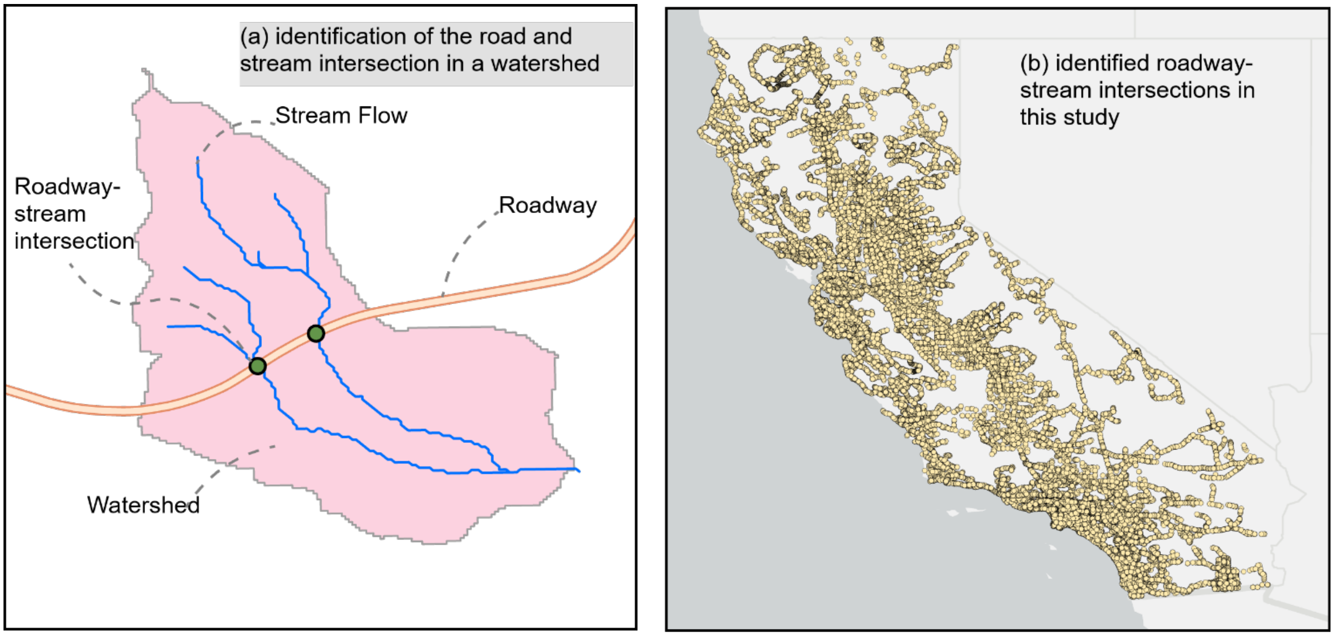


Figure 3. Roadway and Streamflow Intersections.

Table 1. Watershed and Roadway Network Data Description

Variables	Description	Source
Watersheds, streamflow network	The watershed used to carry out the debris-flow likelihood calculation	NHDPlus HR Hydrology Model (https://viewer.nationalmap.gov/basic/)
Roadways network	The roadway network used in this study, which includes restricted access to major divided highways, arterials, and partial of the non-major routes.	OpenStreetMap (OSM, 2019)

Current Post-fire Debris Flow Risk

Post-fire debris flow risk has been studied for decades using empirical models to estimate flow volume, predict the likelihood of debris flow, and evaluate the rainfall threshold for debris flow in fire burned areas (Cannon et al., 2010; Gartner et al., 2014). These models consider watershed terrain features, wildfire burn area, vegetation burn severity, soil characteristics, and rainfall intensity. For California, models developed by Cannon et al.(2010) and Staley et al. (2017) were used to analyze the post-fire debris flow risk. While the work by Staley et al. (2017) represents the state-of-the-art for post-fire debris flows analysis, one important variable, simulated Difference Normalized Burn Ratio (dNBR), used in the model is only regressed for Southern California (Staley et al., 2018). To complete the analysis for all of California, models from Cannon et al.(2010) are used which don't consider vegetation conditions for Northern California in the risk analysis. The post-fire debris flow likelihood(*P*) is calculated using Equation 1:

$$P = e^{x}/(1 + e^{x})$$

Equation 1

The likelihood of post-fire debris flow is a fraction between 0% to 100%, and classifying it by severity bins helps to discuss risk level. The debris flow risk is characterized by five bins: very low, low, medium, high, and extreme high. Each rank represents the corresponding 20% bin for debris flow likelihood. The model and the classification are used for both the current and future post-fire debris flow risk assessments.

In Southern California, x is calculated as Equation 2:

$$x = -3.63 + (0.41 \times x_{1R} \times i_{15}) + (0.67 \times x_{2R} \times i_{15}) + (0.7 \times x_{3R} \times i_{15})$$

Equation 2

x_{1R} is the area of the basin where medium to high level burn occurs on steep slopes (gradients over 23 degrees). x_{2R} is the average Difference Normalized Burn Ratio (dNBR) in the upslope area. dNBR is an index used to value the degree of disruption on the vegetation system in a burned area. x_{3R} is the average KF-factor of the upslope area, where the KF-factor indicates the potential for erosion and the rate of runoff. i_{15} is the 15 minute rainfall intensity under different recurrence intervals.

in Northern California, x is calculated as Equation 3:

$$x = -07 + 0.33 \times slp_{pct} - 1.6 \times rugged + 0.2 \times CC_{pct} - 0.4 \times LL_{pct} + 0.07 \times i_{60} + 0.06 \times HM_{pct}$$

Equation 3

slp_{pct} is the percentage of watershed area with gradients larger than 30%. $rugged$ is the average basin ruggedness. CC_{pct} and LL_{pct} are the average basin clay content and liquid limit percentage in the upstream basin. i_{60} is the 60 minutes rainfall accumulation under different rainfall recurrence intervals. HM_{pct} is the percentage of basin area burned at *moderate* and *high* severity.

The current post-fire debris flow assessment is carried out with the present soil, geological, and precipitation conditions, as well as estimations of the most recent fire threat and vegetation types. The current soil, geological, and precipitation data are retrieved from the datasets shown in Table 2. Most of the post-fire debris flows are associated with long-recurrence precipitation events (Cannon et al., 2010). As such, it's necessary to estimate the debris flow risk under short, medium and long recurrence rainfall events, to identify the risky locations under both more frequent precipitation (shorter recurrence) and more intensive rainfall (longer recurrence) events. Rainfall events with 10, 50, and 100-year recurrence intervals are used to simulate the short, medium, and long-recurrence events.

Table 2. Variables Used in Predicting Post-fire Debris Flow

Variables	Description	Source
Watersheds	The watershed used to carry out the debri-flow likelihood calculation	NHDPlus HR Hydrology Model (Viger et al., 2016)
Land Gradient	The proportion of upslope area burned at high or moderate severity and with gradients in excess of 23 degrees.	30-meters Digital Elevation Model (USGS, 2017)
slope	The proportion of upslope area burned at high or moderate severity and with gradients in excess of 30 degrees.	
K-Factors, CC, and LL	Soil erodibility factor which represents both susceptibility of soil to erosion and the rate of runoff, as measured under the standard unit plot condition.	Digital General Soil Map of the United States (STATSGO) (Schwartz et al., 1995)
MCPc	The percentage of a watershed area that is burned medium to high level in a wildfire event.	Fire Threat Map (FRAP, 2017)
Rainfall Intensity	Rate of precipitation associated with specific storm lengths and occurrence intervals.	NOAA Atlas 14 (Peterson et al., 2010)
Vegetation	The existing vegetation type (EVT) which used to simulate dNBR prior to wildfire.	2016 EVT map (LANDFIRE, 2016)

Basin burn severity and vegetation dNBR was estimated from recent fire threat and existing vegetation type data. In this study, the area of a basin with medium to high level burn severity is derived from the Cal Fire 2014 threat map (FRAP, 2017). The map classifies fire risk in five levels: very low, low, medium, high, and very high, based on vegetation, soil, and meteorology data. It is assumed that regions with high to extreme fire risk are going to be burned with medium to high severity. Staley (2018) proposed a simulation method to estimate the dNBR prior to future fires occurring. The simulation function, as shown in Equation 4, is based on the vegetation type and the historical dNBR records in the burnt area.

$$dNBR_{sim} = \lambda[-ln(1 - P_{dsim})]^{1/k} \times 2000 - 1000 \quad \text{Equation 4}$$

Here, k and λ are the shape and scale parameters of the historical dNBR fitting Weibull CDF for each Existing Vegetation Type (EVT). P_{dsim}, which is the cumulative percentile of the Weibull CDF, simulates the frequency of fire severity. For instance, P_{dsim} = 0.50 represents a moderately frequency fire burn severity. This study simulates a very high severity wildfire, where P_{dsim} equals 95%, to cover 95% of the possible fire burnt scenarios.

Future Post-fire Debris Flow Risk

Climate change has the potential to shift regional precipitation and wildfire patterns. Post-fire debris flow is a combined hazard from both fire and rainfall, and evaluating post-fire debris flows under climate change scenarios would help stakeholders to identify the changing future hotspots that may be overlooked by a present-day analysis. Localized Constructed Analogues (LOCA) downscaled climate change prediction offers regional fire burn area and precipitation volume which is used in estimating the future post-fire debris flow risk.

Future scenarios considered in this study were defined by two greenhouse Representative Concentration Pathways, RCP 4.5 and RCP 8.5, and two climate models. RCP 4.5 represents a scenario where greenhouse gas (GHG) emissions are stabilized and begin to decline in the middle of the 21st century. RCP 8.5 describes a scenario where GHG emissions increase rapidly until the end of the century. Many climate models and scenarios exist and the California Energy Commission (CEC) provides guidance on selecting representative cases (Pierce et al., 2018a). Following CEC guidance, the CanESM2 and HadGEM2-ES models are chosen and corresponding data from Cal-Adapt are used (Pierce et al., 2018a; Westerling, 2018a). CanESM2 is identified by the CEC as an average future while HadGEM2 is characterized as a warmer and drier future. The combination of two models and two RCPs results in four future scenarios.

The climate scenarios, as well as their influence on wildfire and precipitation, are considered in the future post-fire debris flow risk estimation. Variables including vegetation, soil, and terrain in the post-fire debris flow model are assumed to be constant given that there are no fine scale data indicating change. Figure 4 shows the critical variables considered and the corresponding climate scenarios they are applied to.

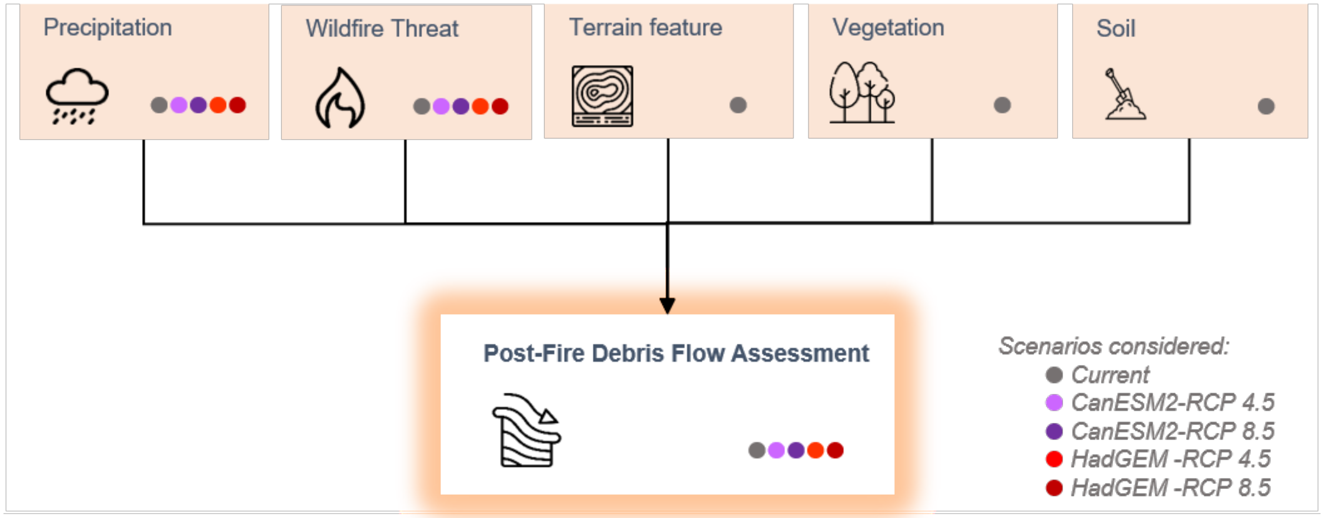


Figure 4. Key Factors Considered Across Current and Future Climate.

Future extreme precipitation is based on LOCA downscaled 6×6 km^2 resolution recurrence precipitation projections available from Cal-Adapt, described in Table 3 (Pierce et al., 2018a). The LOCA downscaled predictions give the daily 24-hour duration precipitation from 2006-2100. To use the downscaled precipitation data in the post-fire debris flow assessment model, the 24 hour rainfall intensity must be converted to shorter duration 15 minute design storms. The conversion assumes that the precipitation under different events would change at the same scale. The precipitation event is estimated as: 1) climate prediction records for every 6×6 km^2 area in

California are retrieved, 2) a Peaks-Over-Threshold (POT) approach (Wilks, 2011) is used to estimate the intensity of 10, 50, and 100-year recurrence design storm from the LOCA estimated rainfall data. 3) Employing φ_{rain} to represent the rainfall changing ratio between the future and current 24 hour duration design storm intensity at different recurrence intervals, the current 15-minute or 60-minute duration design storms is scaled with φ_{rain} to estimate intensity of future short duration design storms. The first and second steps were performed with the Cal-adapt API (Cal-Adapt, 2017), and the third and fourth steps are completed in Python following:

$$\varphi_{rain} = (i_{24pre} - i_{24cur})/i_{24cur}$$ *Equation 5*

$$i_{15pre} = (\varphi_{rain} + 1) \times i_{15cur}$$ *Equation 6*

where $\varphi_{rain}$is the rainfall change ratio. $i_{24pre}$and i_{24cur} represent the predicted and current 24-hour rainfall intensity. $i_{15pre}$and $i_{15cur}$are the predicted and current 15-minute intervals of rainfall intensity.

Table 3. Variables Used in Predicting Future Post-fire Debris Flow

Variables	Description	Source
burned severity (future)	The percentage of a watershed area that is burned medium to high level if a wildfire event happens in the future scenario.	6×6 km^2 Resolution Future Burnt Area Map (Westerling, 2018b)
Rainfall Intensity (future)	Rate of precipitation associated with specific storm lengths and occurrence intervals in the future scenarios.	6×6 km^2 Resolution Future Extreme Rainfall Event (Pierce et al., 2018b)

Like the future precipitation data, the wildfire projection needs to be compiled before inputting into the post-fire debris flow calculation. As the future wildfire burned area is presented as an area burned annually in a given 6×6 km^2 size pixel (Westerling, 2018a), which could be interpreted as the burnt ratio for every pixel, the data are converted into the area expected to burn at medium to high severity. The conversion process started by calculating the total burned area changing ratio in one 6×6 km^2 pixel between the projected (2010 to 2099) and recovered (1953 to 2009) time period. This changing ratio is then applied to the current fire threat map (FRAP, 2017) to generate a new fire threat map. From the new fire threat map, retrieving regions with the fire threat larger than high level as the future burned area.

Roadway Vulnerability Assessment

The vulnerability of roadways to post-fire debris flow captures both the likelihood of debris flows and the criticality of each roadway in the broader network. The criticality of roadways can be measured as the link capacity (Li et al., 2012), the traffic delay when disruption occurs (Dowds et al., 2017), or the topological connectivity of a network. Traffic, while a useful measure of how intensely used a roadway is, does not capture dynamics related to how important a link is in the overall network, and is often unavailable for rural areas (Dowds et al., 2017; Fraser et al., 2020; Yang et al., 2018). If a high traffic link is disabled and the traffic can be accommodated on nearby links at minimal to no cost, then the link should not necessarily be considered critical. Transportation resilience studies often rely on measures of betweenness centrality -- a measure of how important each link is to being able to traverse the network -- to describe network criticality (Kermanshah et al., 2016; Zhang et al., 2015). The betweenness centrality is quantified for each link in the roadway network, as:

$$g(v) = \Sigma_{s \neq v \neq t} \frac{\delta_{st}(v)}{\delta_{st}} \quad \text{Equation 7}$$

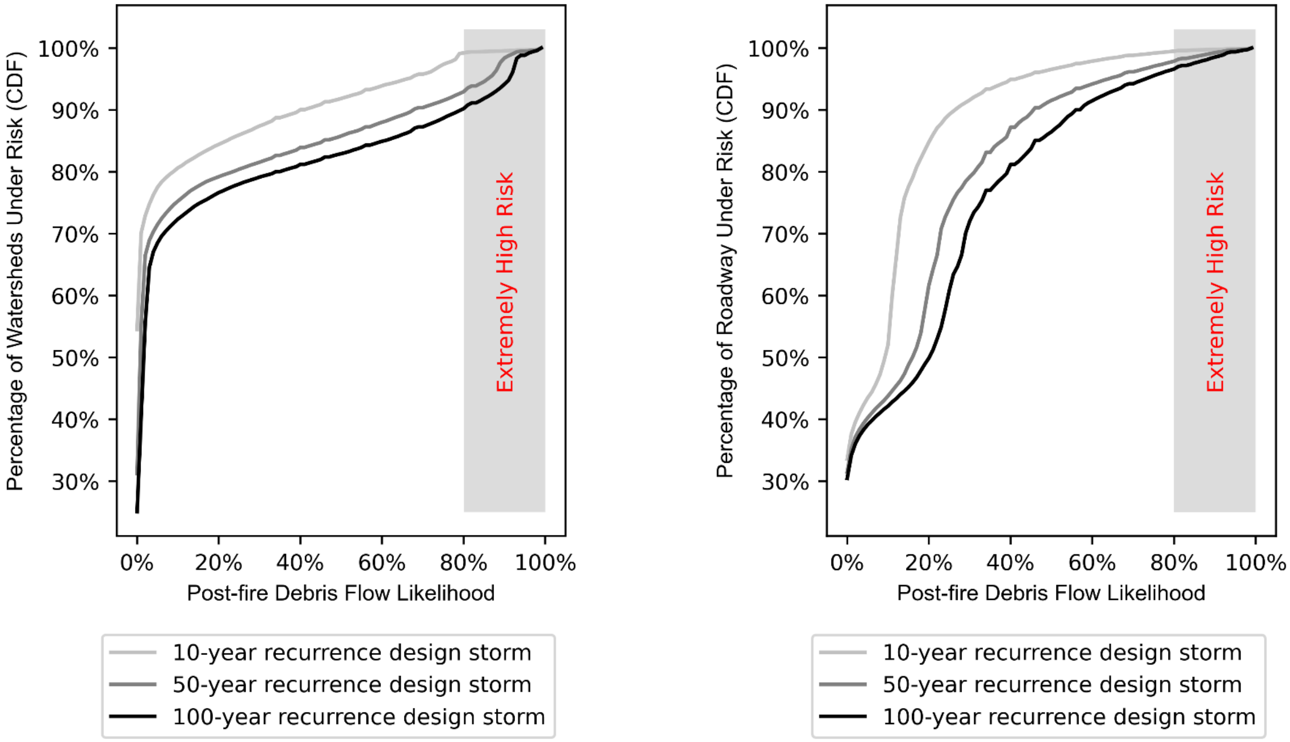
where the $\delta_{st}(v)$ is the count of paths form not 's' to 't' which go through 'v', and δ_{st} is the number of all paths that connect 's' and 't'. The calculations are performed with NetworkX (Hagberg et al., 2020) and network data from OpenStreetMap (OSM, 2019). While the whole California roadway network is too large for NetworkX to handle, we separated the whole system by county and carried out betweenness centrality analysis in NetworkX.

The vulnerability of roadways is obtained by combining the betweenness centrality and the post-fire debris flow risk for each roadway link. Each roadway link has 15 different debris flow risk values which correspond to the five distinct climate scenarios and three different rainfall recurrence intervals for each scenario. Correspondingly, the roadway can be described through 15 vulnerability values matching with the debris flow risks. The most vulnerable roadways under different climate and rainfall recurrence scenarios were identified as the critical links in the network (high betweenness centrality) with extremely high post-fire debris flow risk (post-fire debris flow risk larger than 80%).

Results

Current Post-fire Debris Flow Risk

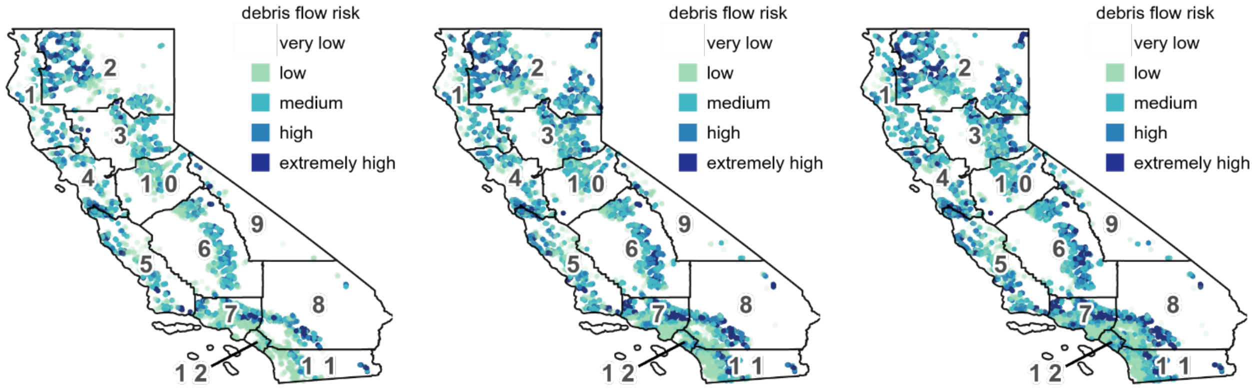
The current post-fire debris flow risk – a function of soil, vegetation, geology, and precipitation – was estimated for both the watershed and the roadways passing through based on the intensity of extreme precipitation events. In doing so problematic watersheds and roadways are identified under different storm intensities. Increasing the precipitation recurrence interval results in more watersheds and roadways with *extremely high* post-fire debris flow risk. From 10-year to 100-year recurrence design storm events, the percentage of watersheds under *extremely high* post-fire debris flow risk is anticipated to increase from 0.28% to 10.11% (Figure 5-a), an increase of 35 times. This aligns with the previous study findings that the post-fire debris flow is highly related to the extreme precipitation events (Cannon et al., 2010). The majority of the *extremely high* debris flow likelihood watersheds aligns with the current *high* to the *extremely high* fire-threat area defined by CalFire (Appendix A). However, the debris flow risk are low in the *extreme high* fire threatened northeastern California, where highway 395 and state route 139 pass between Altura and Susanville. This area has an *extremely high* fire threat but is geologically flat and with little precipitation, which when combined produces a low likelihood of debris flow.


(a) Watersheds post-fire debris flow likelihood CDF

(b) Roadway post-fire debris flow likelihood CDF

Figure 5. Watershed Debris Flow Risk by Design Storm.

Under a 10-year recurrence design storm, 0.14% of roadways are classified with an *extremely high* debris flow risk. Meanwhile, 0.5%, and 4% of the roadways have *extremely high* debris flow risk under 50 and 100-year design storms (Figure 5.b). The ratio of problematic roadways is lower than the *high* risk watersheds. The identified *extremely high* risk roadways tend to cluster near the northeast part of district 1, west district 2, southeast district 6, south of district 5, district 7, and 12 (Figure 6). The ratio of roadways under *extremely high* post-fire debris flow risk increases as the rainfall recurrence interval increases, because of the concentration of roadways near metropolitan regions in the Central Valley region where debris flows risk is low. This finding aligns with the previous post-fire debris-flow record. The 2017-2018 Thomas Fire debris flow hit Santa Barbara and Ventura county, where a 50-year recurrence storm triggered the event. The debris flow contributed to an inundation zone more extensive than the 100-year floodplain in Montecito and created a 500-m wide flow path across Highway 101 (Kean et al., 2019)



(a) 10-year recurrence (b) 50-year recurrence (c) 100-year recurrence

Figure 6. Roadways Post-fire Debris Flow Risk Under 10, 50, and 100-year Recurrence Design Storm

The current result shows that the *extremely high* debris-flow events are related to rainfall events with more than 50-year recurrence intervals. While most of the *extremely high* post-fire debris flow threatened areas align with the wildfire threat map, some regions with *high* fire threat show post-fire debris flow risk could still be low because of the flat terrain, low precipitation, and other factors that mitigate the debris-flow risk. The roadways with *extremely high* post-fire debris flow tend to be clustered.

Future Post-fire Debris Flow Risk

Changes in wildfire risk and precipitation vary across the state and climate change scenario. Under the HadGEM2-RCP 8.5 scenario, in Caltrans district 6, climate change could remarkably increase the fire burn area size to up to 45 times (4500%). Meanwhile, current low risk regions in the California Desert (Caltrans district 8) is projected to have much less fire activity with some likelihoods disappearing altogether (Figure 7.a). In the downscaled climate model, wildfire is anticipated to increase in the current high fire threat region, but not cities. Climate change affects extreme precipitation event in different patterns. Compared with the current 100-year design storm, most parts of California are going to experience an increase in rainfall intensity under the HadGEM2-RCP 8.5 scenario, as shown in Figure 7.b. Under the HadGEM2-RCP 8.5 scenario, the current sensitive areas are projected to see an increase in wildfire risk.

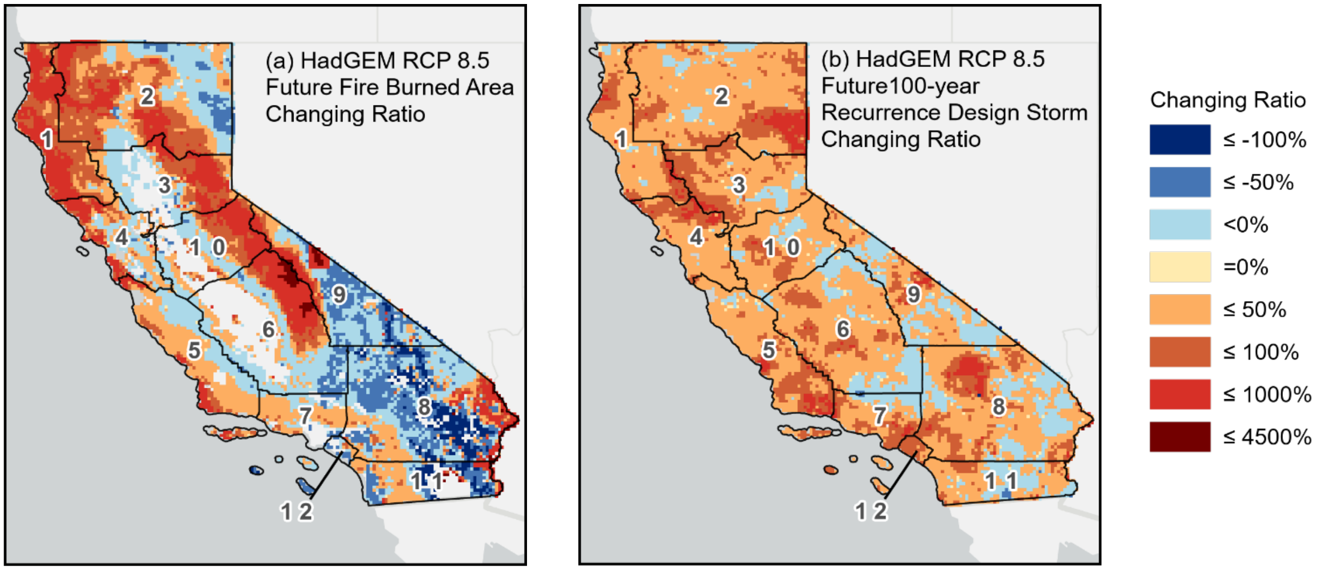


Figure 7. Change in Fire Burn Area and Precipitation for the HadGEM RCP 8.5 Scenario.

The future fire burned area and future precipitation converge in affecting roadway post-fire debris flow under different climate scenarios. When both the fire and precipitation extreme increase, the regional risk also increases, and vice versa. For example, in Caltrans district 1, both rainfall intensity (Figure 7.b) and fire burn size (Figure 7.a) are expected to increase. The two converge in increasing watershed and roadway post-fire debris flow risk in the future scenario (Figure 9). Theoretically, districts with both rainfall and fire decreasing in the future tend to have reducing post-fire debris flow risk. But in most cases, fire and precipitation would have either one or both increasing. When one region has either the fire burned area or precipitation intensity increase, regional debris-flow risk will react based also on the soil, terrain, and vegetation conditions in the region.

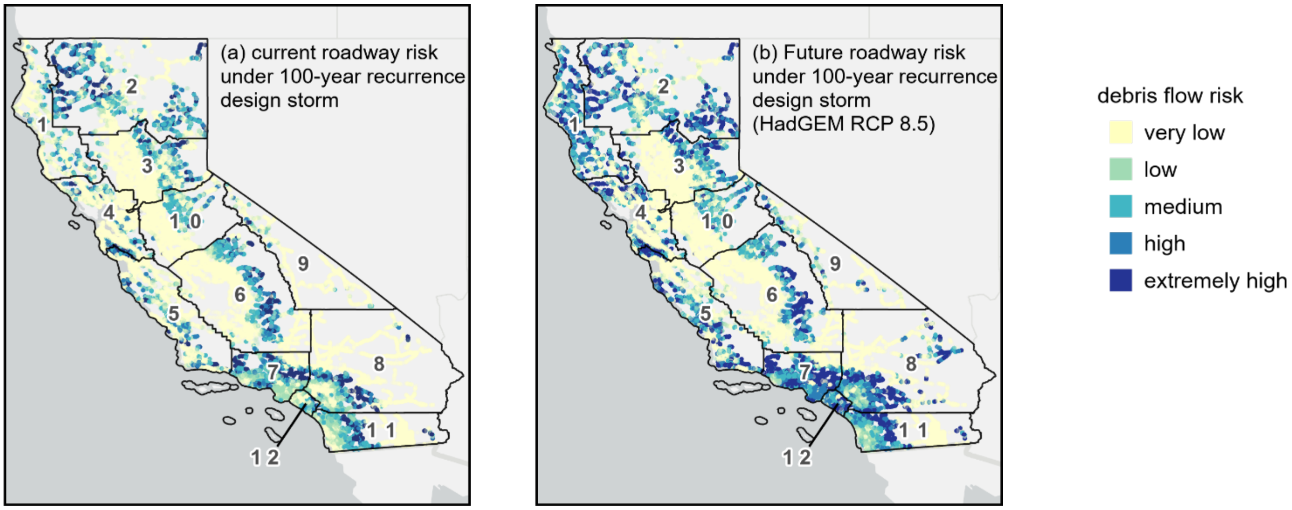
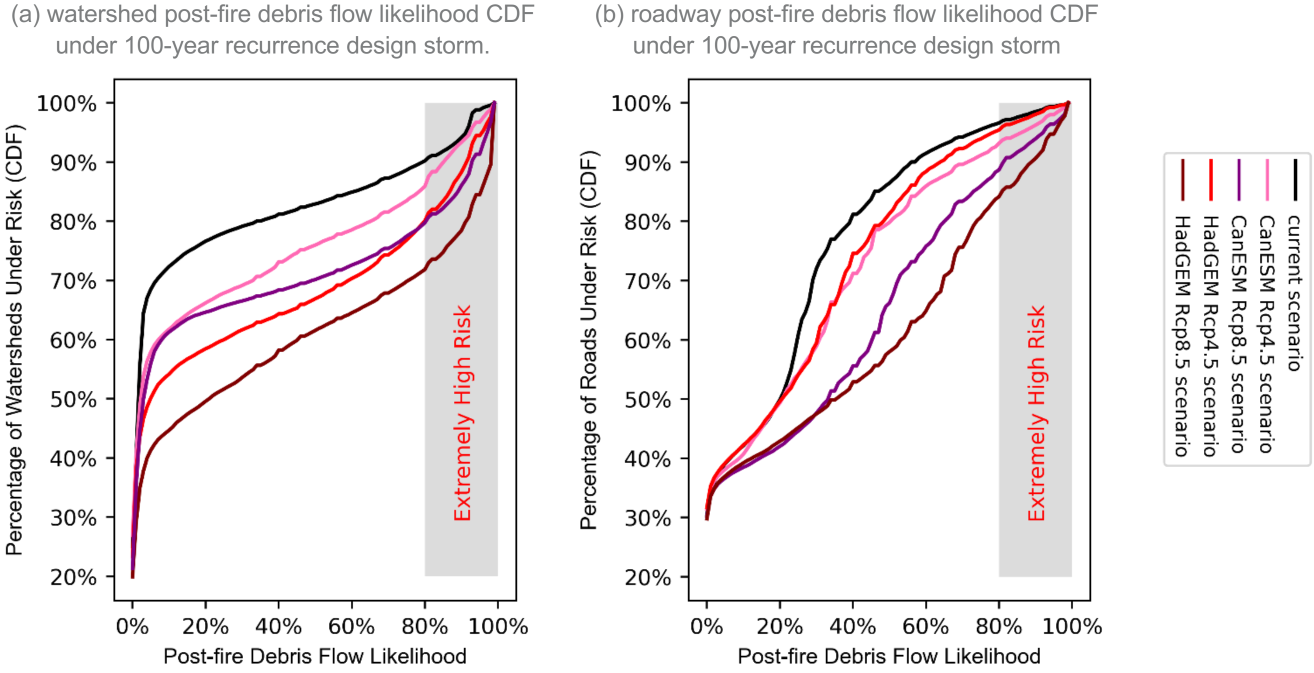


Figure 8. Current and Future Roadway Risk.

In general, the four climate change scenarios estimate an increasing number of watersheds with *extreme high* debris-flow risk (Figure 9). Currently under a 100-year rainfall event, 10% of the watersheds are exposed to *extreme high* debris flow risk. In the future, the number of watersheds under *extreme high* debris flow risk would increase by at least 14% (Can-ESM2 RCP 4.5) and at most 28% (HadGEM RCP 8.5 scenario shown in Figure 9.a). The spatial pattern of watershed post-fire debris flow risk is shown in Appendix B.


(a) watershed post-fire debris flow likelihood CDF under 100-year recurrence design storm.

(b) roadway post-fire debris flow likelihood CDF under 100-year recurrence design storm

Figure 9. Watershed and Roadway Post-fire Debris Flow Likelihood.

The shifting of debris flow risk at watersheds will influence roadway debris flow risk. That is to say, more roadways in the sensitive region would be exposed to *extreme high* post-fire debris flow risk. Currently under a

100-year rainfall event, 4% of roadways are exposed to *extreme high* debris flow risk. Under the same level rainfall event, 5% (HadGEM RCP 4.5) to 15% (HadGEM RCP 8.5) of roadways would be exposed to *extreme high* debris flow risk (Figure 9.b). Under the HadGEM RCP 8.5 scenario, which creates more *extreme high* post-fire debris flow roadways than the other climate scenarios, the number of roadways under *high* to *extreme high* debris flow risk is expected to increase around Caltrans district 1, 2, and Southern California (**Error! Reference source not found.**.b). The roadway network was assumed constant into the future but very well may grow, thereby increasing the potential for new problematic roadways.

The increase in projected burned area in current *high* fire threat territories, together with the statewide increase in precipitation intensity, worsen the post-fire debris flow risk in sensitive zones. Regional climate change patterns affect post-fire debris flow likelihood in different ways, but in general increase the risk of post-fire debris flows in sensitive areas.

Roadway Vulnerability

The vulnerability of roadways to post-fire debris flow is characterized as the co-occurrence of debris flow probability and betweenness centrality, effectively capturing roadways that have high likelihood of experiencing flows and are important for facilitating connectivity. Roadways with high betweenness centrality and high debris flow risk are the most vulnerable hotspots that deserve the attention. Currently, the most vulnerable roadways are identified as those with betweenness centrality larger than 0.4, and post-fire debris flow likelihood greater than 80%, which is shown in the red square in Figure 10. As such, the identified amenable roadways in the red box are not only spatially critical to a network with lots of nodes in the system dependent on them, but also vulnerable to *extreme high* post-fire debris flows.

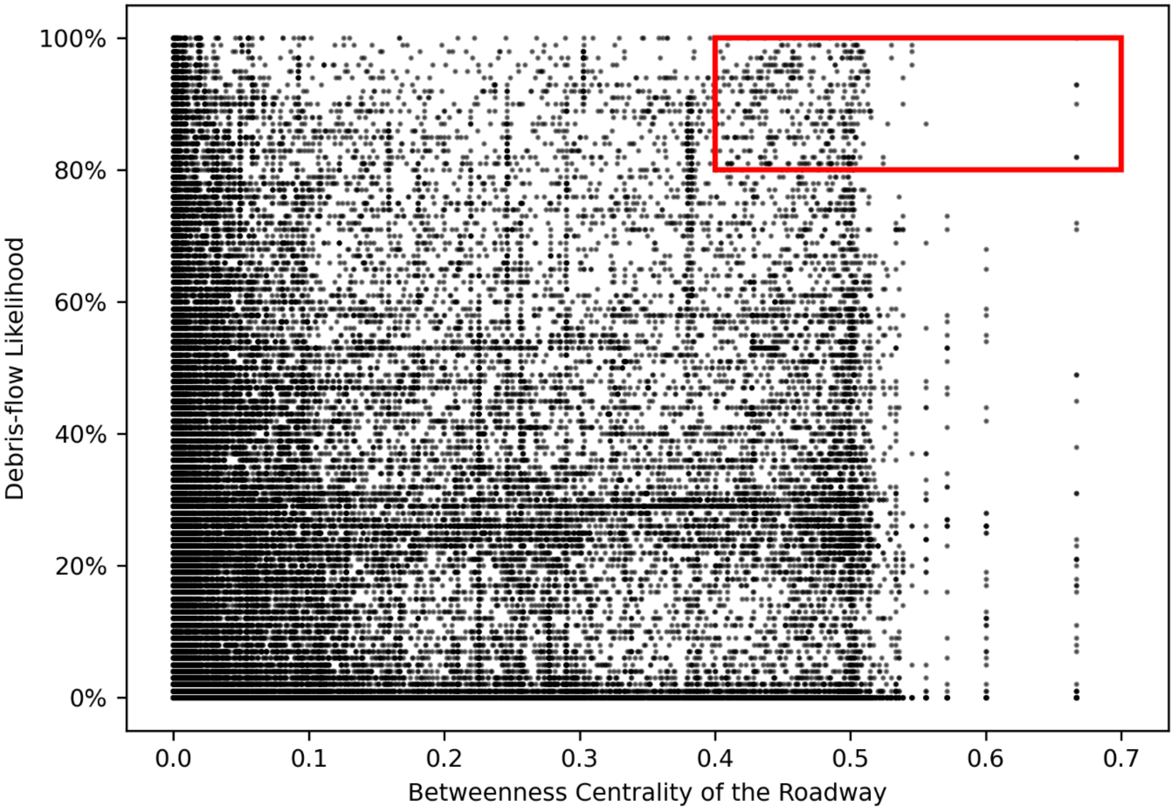


Figure 10.Roadway Vulnerability Considering Betweenness Centrality and Debris Flow Likelihood

Since the roadway network is assumed to be constant into the future, the profile of vulnerable hotspots shifts with climate change thereby affecting debris flow risk. Table 4 shows the number of vulnerable hotspots under each climate scenario and different rainfall recurrence intervals. Currently, 0.47% of the total roadways have *extreme high* post-fire debris flow risk and are critical in the roadway network. Under mild climate change scenarios (i.e., RCP 4.5), an increasing number of critical roadways are expected to face *extreme high* debris risk. In a moderate future climate model (CanESM2), 0.73% of the roadways are going to be highly vulnerable. The number of highly vulnerable roadways could rise 55% compared to current conditions. The number of hotspots is anticipated to be greatly increased in RCP 8.5 scenarios which produce larger burned areas and more intense extreme precipitation. Under the hot and dry climate model (HadGEM), 1.46% of roadways are estimated to be vulnerable, which is 210% more than the current situation. A significant number of vulnerable roads increased in RCP 8.5 versus 4.5.

Table 4. Roadway Vulnerability by Climate Scenario

Climate Scenarios	Rainfall Recurrence Intervals		
	10-year	50-year	100-year
current	60 (0.06%)	151 (0.16%)	444 (0.47%)
CanESM2- RCP 4.5	105 (0.11%)	443 (0.47%)	698 (0.73%)
HadGEM- RCP 4.5	63 (0.07%)	366 (0.38%)	492 (0.52%)
CanESM2- RCP 8.5	254 (0.27%)	729 (0.77%)	1104 (1.16%)
HadGEM- RCP 4.5	211 (0.22%)	887 (0.93%)	1391 (1.46%)

The spatial distribution of the vulnerable hotspots changes from current to future conditions (Figure 11). Currently, nearly all Caltrans districts have vulnerable roadways which are both critical in the network and are exposed to *extreme high* post-fire debris flow. It's especially problematic in district 2 and 7 which have a large concentration of hotspots. It's worth noting that in future scenarios, more vulnerable roadway hotspots are anticipated to appear in southern California and Caltrans districts along the west coast. This could signal a shift in the distribution of roadway impacts from post-fire flows, warranting consideration of how resources are invested.

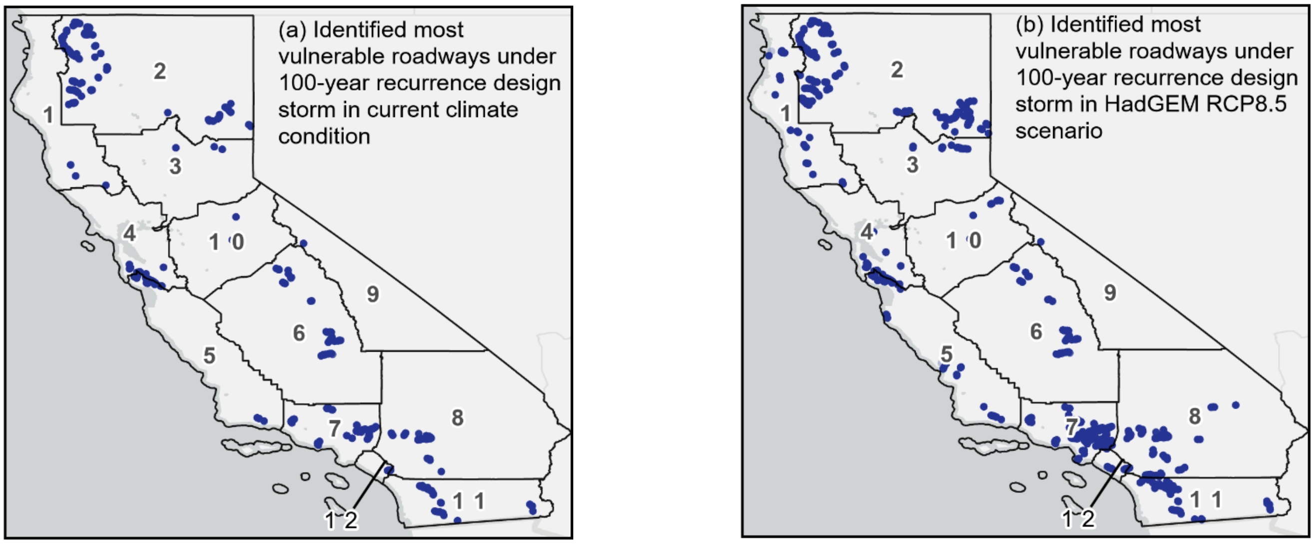


Figure 11. Most Vulnerable Roadways Under Current and Future (HadGEM RCP 8.5) Scenarios.

As climate change effects the future fire burn area and precipitation heterogeneously, the vulnerability profile of Caltrans districts changes. For comparison, Table 5 shows the ranking of the vulnerability of Caltrans districts based on the number of hotspots in each region. Across Caltrans regions, district 3 and 9 are ranked as the least vulnerable, while district 7 is expected to have the most perturbations in both current and future scenarios. Most of the districts have vulnerability profile shifts between different climate scenarios. District 8 is anticipated to have an increase in its vulnerability ranking. Relatively speaking, the risk ranking of district 2, 4, and 6 is expected to decrease. It is not that roads would become safer in these districts but that the roads in other districts would become riskier.

Table 5. Post-fire Debris Flow Vulnerability Ranking by Caltrans District

Vulnerability Ranking	Climate Scenarios				
	Current	CanESM - RCP 4.5	CanESM - RCP 8.5	HadGEM - RCP 4.5	HadGEM - RCP 8.5
1	District 7	District 7	District 7	District 7	District 7
2	District 2	District 2	District 11	District 2	District 8
3	District 11	District 11	District 2	District 8	District 11
4	District 6	District 6	District 8	District 11	District 2
5	District 8	District 8	District 6	District 12	District 6
6	District 12	District 1	District 5	District 6	District 5
7	District 4,5	District 4	District 10	District 1	District 12
8		District 5, 10	District 12	District 5	District 1
9	District 10		District 4	District 4	District 4
10	District 1	District 3	District 1	District 10	District 10
11	District 3,9	District 9	District 3	District 3,9	District 3
12		District 12	District 9		District 9

Discussion

Policy Implications

Post-fire debris flows can produce massive damages to infrastructures and paralyze post-disaster rescue. The results can assist stakeholders in identifying watersheds where post-fire debris flow is likely to occur, and roadways which are vulnerable to post-fire debris flow risk under both present and future climate change scenarios.

The result shows that more roadways would have *high* post-fire debris-flow risk under 50 to 100-year recurrence interval precipitation events. For instance, in the current climate situation, 0.14% of roads are characterized as *extreme high* post-fire debris flow threat when the burned area experiences a short recurrence interval design storm (10-year). Meanwhile, under a 100-year recurrence design storm, 4% of the roadways currently have *extreme high* debris-flow potential. In the future, 5% (HadGEM RCP 4.5) to 15% (HadGEM RCP 8.5) of roads would be exposed to *extremely high* debris-flow likelihood. The trend that post-fire debris flow is more related to longer recurrence precipitation events corresponds with the finding by Cannon et al. (2010).

Under current climate conditions, the result shows that roadways with *extremely high* post-fire debris flow likelihood are concentrated near high fire-threat areas, particularly in Caltrans districts 1, 2, 7, 6, and 11. Some of the identified *extremely high* risk roadways are consistent with recent events, such as debris flows in and near burned scars of the Thomas (Kean et al., 2019) San Bernardino, and Camp (Kean et al., 2011) fires.

The results characterize both roadway debris flow likelihood and roadway vulnerability. The number of most vulnerable roads is less than the number of *extremely high* risk roads. This is because both the roadway's post-fire debris flow risk as well as its network criticality are used when evaluating the roadway vulnerability. Corridors with high post-fire debris flow risk but low network centrality are deemed less vulnerable. Considering the network centrality of infrastructure in risk assessment could help stakeholders to prioritize their resources.

More vulnerable roadways, especially in current problematic regions, can be expected to also be vulnerable in the future. This is largely due to future regional precipitation intensity and wildfire burn area size. Specifically, within the two emission scenarios, more roadways would have *extremely high* post-fire debris flow potential in the high emission scenario (RCP 8.5) than the mild emission scenario (RCP 4.5). Meanwhile, results from the climate models indicate the potential range of hazardous roadways under each emission scenario. In RCP 4.5 scenario, 0.52% to 0.73% of the roadways are *highly* vulnerable, while in the RCP 8.5 scenario, 1.16% to 1.46% of the roadways are *highly* vulnerable. Comparing to the current climate situation, a 75% to 213% increase in the number of vulnerable roadways is simulated into the future.

In each Caltrans district, roadway post-fire debris flow vulnerability profiles change over time. Under current climate conditions, it is estimated that Caltrans districts 7, 2, and 11 rank as the top three regions with most of the vulnerable roads. Under the future climate scenario, district 8 is expected to have more vulnerable roads.

Limitations

The limitations of this study come from the model assumptions and the fact that some key datasets are unavailable. This study assumes that roadway post-fire debris flow happens at the intersection of the corridor and streamflow, and the likelihood of roadway debris flow equals the watershed's debris flow potential. While this assumption compensates for the computational challenges of using fine scale watersheds, as in Fraser et al.'s (2020) method, it overlooks roadways located in low risk watersheds, but with upstream basins that have high post-fire debris flow potentials. Introducing the debris flow volume (Gartner et al., 2014) into the post-fire debris flow risk assessment could address this problem. Another model limitation is that two empirical models from different researchers were used in the post-fire debris flow calculation. The reason for doing so was the lack of historical vegetation burned severity data to simulate the dNBR prior to wildfires, in Northern California. This problem could be solved by carrying out the statistical analysis of the dNBR distribution for each vegetation type in Northern California (Staley et al., 2018).

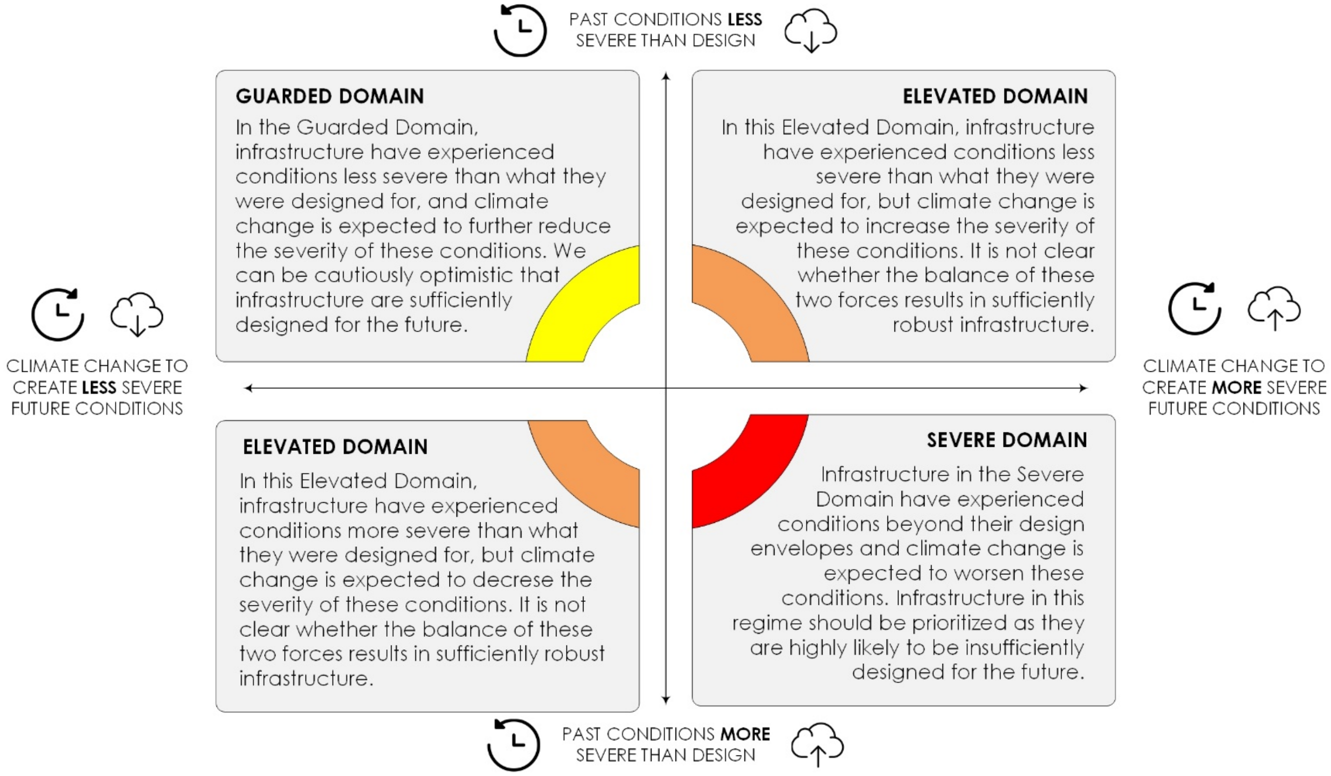
The data limitations include the simplification of infrastructure datasets, and the lack of climate change projects for other parameters. Only divided highways, arterials, and parts of non-major routes are considered in this study. For the future climate scenarios, only fire burned area and precipitations are expected to be affected by climate change, while vegetation type, and roadway networks, are assumed to remain the same.

Resilience Strategies

The findings have broad implications for how California approaches resilience of roadways to post-wildfire debris flows. As California and other communities develop strategies for preparing infrastructure for climate change, they must confront a concurrent set of challenges that affect their ability to deploy solutions (Chester et al., 2019a). This includes limited (and possibly insufficient) funding, large uncertainty about where and how climate impacts will manifest, and limited insights into the radically changing landscape for how we demand transportation services. These forces are emerging and appear to contradict state-of-the-art design and operation principles of infrastructure which remain rooted in certainty and intentionally long design lifetimes. In an uncertain future, rigidity of systems and an emphasis on predictability, are potentially problematic (Chester et al., 2019b) .Reconciling future conditions with current with an emphasis on how infrastructure is designed and operated is paramount to resilience for adaptation (Chester et al., 2020).

Resilience in transportation has often emphasized approaches rooted in armoring, strengthening, and armoring, and these may be sufficient at some scale but likely fall short as systemic solutions (Markolf et al., 2018). Traditional approaches for protecting infrastructure from hazards focus on controlling or holding back the hazard. Stormwater systems channelize or pipe away intruding flows up to a particular intensity, and retaining walls push back intruding land. Much of our engineered infrastructure is designed to control or push back the environment (Chester et al., 2019c), and the uncertainty inherent in climate change raises serious questions about the efficacy of this approach into the future. To what future intensity event should roadways be able to withstand given the uncertainty in climate futures? Can California afford to upgrade roadway assets to be able to withstand a chosen intensity? Would upgrading assets result in infrastructure that is unacceptably intrusive to communities (e.g., a massive open culvert that bisects a neighborhood)? Given that infrastructure design may scale non-linearly with changes in the hazard, these questions raise serious barriers to the implementation of present day state-of-the-art thinking. As such, California should deploy a multi-tiered strategy to addressing post-fire debris flow roadway adaptation. Hardening assets (through armoring or strengthening) has its place, most likely at the asset level, but systemic strategies are also needed that consider failure as inevitable and alternative means for satisfying function (Markolf et al., 2018) . First, California should consider how mobility and accessibility can be extended in the face of surprise. Instead of simply focusing on hardening the roadway system in anticipation of a particular intensity event, California should also create conditions for mobility and accessibility needs to be met when the system is overwhelmed. Put simply, California should view the transportation network through a lens of it being capable to adapt to handle surprise. This might include shifting from physical to virtual connectivity through investments in high bandwidth cybertechnologies, or rapid and large-scale mode shifting as particular assets go offline. Given the long lifetimes of the infrastructure and organizations that manage them, California should also begin to consider the conditions necessary for sustained adaptation, i.e., the expected rapid change in how we demand and supply services, into the future (Chester et al., 2019b). The coming century is expected to be characterized by change at rates and scales that California, or anywhere else, has never experienced (Steffen et al., 2015). To assume that the technologies and processes that supply transportation services, and the ways in which we demand transportation services will remain similar to today, or even predictable, is problematic. Instead, California must recognize that the transportation system, the technologies that define it, and what we ask of it, is going to change more and more rapidly into the future, and combined with the uncertainty of climate hazards, warrants approaches committed to sustained adaptability. Sustained adaptability is the commitment to perpetual change, the perpetual reassessment of the conditions, hazards, needs, and technologies that form the foundation for how we design our systems (Woods, 2015). California should recognize that the changing conditions in environment (climate and otherwise) represent a fundamental challenge to rigid design approaches. Instead, they should embrace agility and flexibility in how they design, operate, and govern their transportation systems (Chester et al., 2019b) . They should establish processes and governance models that commit to reassessment of the conditions and needs that surround infrastructure, and a willingness to change systems rapidly as the environment changes. This is many ways is counter to the models of infrastructure design today (Chester et al., 2019a).

Focusing back on climate change, its critical to recognize that that there is inherent complexity in the confluence of several uncertainties in infrastructure design. Upgrading roadway infrastructure writ-large across California to be able to better manage future post-fire debris flows is a very long undertaking and a massive financial commitment. Any strategy that can prioritize limited resource investments will be critical. Infrastructure exist at the confluence of past and future uncertainty (Chester et al., 2020) The majority of California's infrastructure was built in the past century. Environmental sensor networks that detect, e.g., precipitation events, were deployed beginning in middle of the twentieth century. When infrastructures were built in the middle of the twentieth century their designs were informed by relatively limited data streams as sensor networks were in their infancy. As such there may have been significant uncertainty around the frequency and intensity of local events. Guidelines that specified return periods by which to design infrastructure assets (e.g., a 50-year event) may have over- or under-estimated these critical events, leading to assets that were over- and under-designed. While under-designed assets likely experienced problems that were corrected over the past decades, this may not have been universally true, and over-designed assets also exist. Today, climate change represents an additional layer of uncertainty, where conditions in some regions worsen and other regions get better. The confluence of these uncertainties can be characterized by four domains that can aid decisionmakers to surgically invest limited resources (Figure 12) (Chester et al., 2020). In the Severe Domain, infrastructure have experienced conditions that surpass their design, and climate change is expected to worsen the severity. Here, a roadway was designed to withstand a low intensity post-fire flow, flows turned out to be more intense, and climate change is expected to make those flows worse. Roadways in the Severe Domain should be the top priority. At the other end of the spectrum is the Guarded Domain where roadways were overdesigned for what they were actually experience and climate change is expected to lessen the hazard. These are the lowest priority assets. The most difficult, and troubling assets are found in the Elevated Domains, where either the asset is experiencing conditions i) *less severe* than what they were designed for and climate change is *worsening* the hazard, or ii) *more severe* than what they were designed for and climate change is *weakening* the hazard. These domains are problematic because they do not provide a clear picture of robustness of the asset to future climate. Assets in these domains require new knowledge and insights to be able to make decisions for their future. As California looks to prepare their roadways against post-fire debris flows, taking stock of past design conditions relative to future climate becomes critically important for how to prioritize investments.



GUARDED DOMAIN

In the Guarded Domain, infrastructure have experienced conditions less severe than what they were designed for, and climate change is expected to further reduce the severity of these conditions. We can be cautiously optimistic that infrastructure are sufficiently designed for the future.

ELEVATED DOMAIN

In this Elevated Domain, infrastructure have experienced conditions less severe than what they were designed for, but climate change is expected to increase the severity of these conditions. It is not clear whether the balance of these two forces results in sufficiently robust infrastructure.

ELEVATED DOMAIN

In this Elevated Domain, infrastructure have experienced conditions more severe than what they were designed for, but climate change is expected to decrease the severity of these conditions. It is not clear whether the balance of these two forces results in sufficiently robust infrastructure.

SEVERE DOMAIN

Infrastructure in the Severe Domain have experienced conditions beyond their design envelopes and climate change is expected to worsen these conditions. Infrastructure in this regime should be prioritized as they are highly likely to be insufficiently designed for the future.

Figure 12: Domains of Past and Future Climate Uncertainty in Infrastructure Design. *[Reprinted from Chester et al. 2020]*

Given the uncertainties with future climate, the massive investments required to adapt infrastructure, and the long lifetimes of assets, California should consider safe-to-fail strategies. Infrastructure have and continue to be designed as fail-safe, i.e, they are designed to withstand a particular intensity shock, and when failure happens generally the impacts are externalized. Safe-to-fail is a resilience framework that calls for the internalizing of the impacts of failure into the design process, towards minimizing and better managing failure consequences (Kim et al., 2017). Infrastructure failure under climate change may be inevitable, and as such planning for its eventuality is prudent. In planning for failure California will rethink how failures occur and will likely identify novel ways of avoiding or compensating for that failure. For example, given the remoteness and low use of some post-fire flow vulnerable roads, the state may choose to allow for those roads to fail instead of investing in keeping them functional when impacted. However, when examining what it means for those roads to fail – certain services being inaccessible – California may identify alternatives to those services (i.e., graceful extensibility) that may be cheaper than traditional robustness-centric approaches (Kim et al., 2017; Woods, 2015). Safe-to-fail is not about uncontrolled failure, but more so the acceptance that failure is inevitable and should always be planned for in design.

Adapting California roadways to future post-fire debris flows will likely requiring extensive planning and novel investment strategies for the diverse conditions and needs of the state. A one size fits all approach may not be prudent; what works in the Mojave desert may be fundamentally different than the forested High Sierra. Adaptation strategies should embrace agility and flexibility, that diverse and rapidly changing conditions are not conducive to rigid and single vision strategies (Chester et al., 2019b). Preparing roadways for future post-fire debris flows will require new outlooks, financing, and possibly governance models that embrace agility and flexibility.

References

Cal-Adapt, 2017. About Cal-Adapt — Cal-Adapt API Docs 1.0 documentation [WWW Document]. Cal-Adapt API Docs. URL https://berkeley-gif.github.io/caladapt-docs/index.html (accessed 3.23.20).

Camp, J., Abkowitz, M., Hornberger, G., Benneyworth, L., Banks, J.C., 2013. Climate Change and Freight-Transportation Infrastructure: Current Challenges for Adaptation. J. Infrastruct. Syst. 19, 363–370. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000151

Cannon, S.H., Gartner, J.E., Rupert, M.G., Michael, J.A., Rea, A.H., Parrett, C., 2010. Predicting the probability and volume of postwildfire debris flows in the intermountain western United States. Bull. Geol. Soc. Am. 122, 127–144. https://doi.org/10.1130/B26459.1

Cannon, S.H., Gartner, J.E., Wilson, R.C., Bowers, J.C., Laber, J.L., 2008. Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern Colorado and southern California. Geomorphology 96, 250–269. https://doi.org/10.1016/j.geomorph.2007.03.019

Cannon, S.H., Gartner, J.E., Wilson, R.C., Bowers, J.C., Laber, J.L., Kean, J.W., Staley, D.M., Cannon, S.H., Gartner, J.E., Holland-sears, A., Thurston, B.M., Survey, U.S.G., Drive, S., Gleason, J.A., Moody, J.A., Shakesby, R.A., Robichaud, P.R., Cannon, S.H., Martin, D.A., 2011. Current research issues related to post-wildfire runoff and erosion processes. J. Geophys. Res. Earth Surf. 122, 250–269. https://doi.org/10.1016/j.earscirev.2013.03.004

Chester, M. V., Allenby, B., 2019a. Infrastructure as a wicked complex process. Elem Sci Anth 7, 21. https://doi.org/10.1525/elementa.360

Chester, M. V., Allenby, B., 2019b. Toward adaptive infrastructure: flexibility and agility in a non-stationarity age. Sustain. Resilient Infrastruct. 4, 173–191. https://doi.org/10.1080/23789689.2017.1416846

Chester, M. V., Markolf, S., Allenby, B., 2019c. Infrastructure and the environment in the Anthropocene. J. Ind. Ecol. 23, 1006–1015. https://doi.org/10.1111/jiec.12848

Chester, M. V., Underwood, B.S., Samaras, C., 2020. Keeping infrastructure reliable under climate uncertainty. Nat. Clim. Chang. 10, 488–490. https://doi.org/10.1038/s41558-020-0741-0

Cohn, P.J., Carroll, M.S., Kumagai, Y., 2006. Evacuation behavior during wildfires: Results of three case studies. West. J. Appl. For. 21, 39–48. https://doi.org/10.1093/wjaf/21.1.39

Cova, T.J., Theobald, D.M., Norman, J.B., Siebeneck, L.K., 2013. Mapping wildfire evacuation vulnerability in the western US: The limits of infrastructure. GeoJournal 78, 273–285. https://doi.org/10.1007/s10708-011-9419-5

De Graff, J. V., Shelmerdine, B., Gallegos, A., Annis, D., 2015. Uncertainty associated with evaluating rockfall hazard to roads in burned areas. Environ. Eng. Geosci. 21, 21–33. https://doi.org/10.2113/gseegeosci.21.1.21

Dijst, M., Böcker, L., Kwan, M.P., 2013. Exposure to weather and implications for travel behaviour: introducing empirical evidence from Europe and Canada. J. Transp. Geogr. 28, 164–166. https://doi.org/10.1016/j.jtrangeo.2013.01.004

Dowds, J., Sentoff, K., Sullivan, J.L., Aultman-Hall, L., 2017. Impacts of Model Resolution on Transportation Network Criticality Rankings. Transp. Res. Rec. J. Transp. Res. Board 2653, 93–100.

https://doi.org/10.3141/2653-11

Elliott, J.G., Smith, M.E., Friedel, M.J., Stevens, M.R., Bossong, C.R., Litke, D.W., Parker, R.S., Costello, C., Wagner, J., Char, S.J., Bauer, M.A., Wilds, S.R., 2004. Analysis and mapping of post-fire hydrologic hazards for the 2002 Hayman, Coal Seam, and Missionary Ridge Wildfires, Colorado. US Geol. Sci. Investig. Rep. 5300, 1–109.

Evans, C., Tsolakis, D., Naudé, C., 2009. Framework to Address the Climate Change Impacts on Road Infrastructure Assets and Operations. Paper submitted for presentation at 13th REAAA Conference, 2009.

FRAP, 2017. Statewide map of wildland Fire Threat data developed by FRAP with the assistance of several cooperators [WWW Document]. URL https://frap.fire.ca.gov/mapping/gis-data/ (accessed 1.13.20).

Fraser, A.M., Chester, M. V, Underwood, B.S., 2020. Wildfire risk , post-fire debris flows , and transportation infrastructure vulnerability vulnerability. Sustain. Resilient Infrastruct. 00, 1–13. https://doi.org/10.1080/23789689.2020.1737785

Gartner, J.E., Cannon, S.H., Santi, P.M., 2014. Empirical models for predicting volumes of sediment deposited by debris flows and sediment-laden floods in the transverse ranges of southern California. Eng. Geol. 176, 45–56. https://doi.org/10.1016/j.enggeo.2014.04.008

Gartner, J.E., Cannon, S.H., Santi, P.M., Dewolfe, V.G., 2008. Empirical models to predict the volumes of debris flows generated by recently burned basins in the western U . S . 96, 339–354. https://doi.org/10.1016/j.geomorph.2007.02.033

Hagberg, A., Schult, D., Swart, P., 2020. NetworkX Reference [WWW Document]. URL https://networkx.github.io/documentation/latest/_downloads/networkx_reference.pdf (accessed 3.23.20).

Ice, G.G., Neary, D.G., Adams, P.W., 2004. Effects of Wildfire on Soils and Watershed Processes. J. For. 102, 16–20. https://doi.org/10.1093/JOF/102.6.16

Kean, J.W., Staley, D.M., Cannon, S.H., 2011. In situ measurements of post-fire debris flows in southern California: Comparisons of the timing and magnitude of 24 debris-flow events with rainfall and soil moisture conditions. J. Geophys. Res. 116, F04019. https://doi.org/10.1029/2011JF002005

Kean, J.W., Staley, D.M., Lancaster, J.T., Rengers, F.K., Swanson, B.J., Coe, J.A., Hernandez, J.L., Sigman, A.J., Allstadt, K.E., Lindsay, D.N., 2019. Inundation, flow dynamics, and damage in the 9 January 2018 Montecito debris-flow event, California, USA: Opportunities and challenges for post-wildfire risk assessment. Geosphere 15, 1140–1163. https://doi.org/10.1130/GES02048.1

Kermanshah, A., Derrible, S., 2016. A geographical and multi-criteria vulnerability assessment of transportation networks against extreme earthquakes. Reliab. Eng. Syst. Saf. 153, 39–49. https://doi.org/10.1016/j.ress.2016.04.007

Kim, Y., Eisenberg, D.A., Bondank, E.N., Chester, M. V., Mascaro, G., Underwood, B.S., 2017. Fail-safe and safe-to-fail adaptation: decision-making for urban flooding under climate change. Clim. Change 145, 397–412. https://doi.org/10.1007/s10584-017-2090-1

LANDFIRE, 2016. LANDFIRE Program: Data Products - Vegetation [WWW Document]. URL https://www.landfire.gov/vegetation.php (accessed 6.29.20).

Li, J., Ozbay, K., 2012. Evaluation of Link Criticality for Day-to-Day Degradable Transportation Networks. Transp. Res. Rec. J. Transp. Res. Board 2284, 117–124. https://doi.org/10.3141/2284-14

MacArthur, Mote, P., Ideker, J., Figliozzi, M., Ming Lee WA-RD, J., 2012. Climate Change Impact Assessment for

Surface Transportation in the Pacific Northwest and Alaska.

Macdonald, L.H., Larsen, I.J., 2008. Runoff and Erosion from Wildfires and Roads: Effects and Mitigation.

Markolf, A.S., Hoehne, C., Fraser, A., Chester, V.M., Underwood, B.S., 2018. Transportation resilience to climate change and extreme weather events – Beyond risk and robustness. Transp. Policy 74, 174–186. https://doi.org/10.1016/j.tranpol.2018.11.003

Moody, J.A., Shakesby, R.A., Robichaud, P.R., Cannon, S.H., Martin, D.A., 2013. Current research issues related to post-wildfire runoff and erosion processes. Earth-Science Rev. 122, 10–37. https://doi.org/10.1016/j.earscirev.2013.03.004

Morton, D.C., Roessing, M.E., Camp, A.E., Tyrrell, M.L., 2003. Assessing the Environmental, Social, and Economic Impacts of Wildfire.

OSM, 2019. Planet dump [WWW Document]. OpenStreetMap Contrib. URL https://planet.openstreetmap.org/ (accessed 3.23.20).

Peterson, T.C., Mcguirk, M., Houston, T.G., Horvitz, A.H., Wehner, M.F., 2010. Climate Variability and Change with Implications for Transportation.

Pierce, D.W., Kalansky, J.F., Cayan, D.R., 2018a. Climate, Drought, and Sea Level Rise Scenarios for California's Fourth Climate Change Assessment. https://doi.org/CNRA-CEC-2018-006

Pierce, D.W., Kalansky, J.F., Cayan, D.R., 2018b. Extreme Precipitation [WWW Document]. Cal-adapt. URL https://cal-adapt.org/tools/extreme-precipitation/ (accessed 1.16.20).

Researcher Information - OpenStreetMap Wiki [WWW Document], 2017. URL https://wiki.openstreetmap.org/wiki/Researcher_Information (accessed 6.23.20).

Schwartz, G.E., Alexander, R.B., 1995. Soils data for the conterminous United States derived from the NRCS State Soil Geographic (STATSGO) data base, US Geological Survey Open-File Report. https://doi.org/1.1

Staley, D.M., Negri, J.A., Kean, J.W., Laber, J.L., Tillery, A.C., Youberg, A.M., 2017. Prediction of spatially explicit rainfall intensity–duration thresholds for post-fire debris-flow generation in the western United States. Geomorphology 278, 149–162. https://doi.org/10.1016/j.geomorph.2016.10.019

Staley, D.M., Tillery, A.C., Kean, J.W., Mcguire, L.A., 2018. Estimating post-fire debris-flow hazards prior to wildfire using a statistical analysis of historical distributions of fire severity from remote sensing data 595–608.

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., Ludwig, C., 2015. The trajectory of the Anthropocene: The Great Acceleration. Anthr. Rev. 2, 81–98. https://doi.org/10.1177/2053019614564785

USGS, 2017. Unites States geological Survey, The National Map, 3D Elevation Program [WWW Document]. URL https://www.usgs.gov/core-science-systems/national-geospatial-program/national-map (accessed 9.13.19).

Viger, R.J., Rea, A., Simley, J.D., Hanson, K.M., 2016. NHDPlusHR: A National Geospatial Framework for Surface-Water Information. JAWRA J. Am. Water Resour. Assoc. 52, 901–905. https://doi.org/10.1111/1752-1688.12429

Walker, L., Figliozzi, M.A., Haire, A.R., MacArthur, J., 2011. Climate Action Plans and Long-Range Transportation Plans in the Pacific Northwest and Alaska. Transp. Res. Rec. J. Transp. Res. Board 2252, 118–126. https://doi.org/10.3141/2252-15

Westerling, A.L., 2018a. Wildfire simulations for California’s fourth climate change assessment: Projecting changes in extreme wildfire events with a warming climate, California’s Fourth Climate Change Assessment, California Energy Comission. https://doi.org/CCCA4-CEC-2018-014

Westerling, A.L., 2018b. Wildfire simulations for California’s fourth climate change assessment: Projecting changes in extreme wildfire events with a warming climate [WWW Document]. Cal-adapt. URL https://cal-adapt.org/tools/wildfire/ (accessed 1.13.20).

Wilks, D.S., 2011. Statistical Methods in the Atmospheric Sciences, Volume 100 - 3rd Edition, 3rd Editio. ed. Academic Press Oxford.

Wolshon, B., Marchive, E., 2007. Emergency Planning in the Urban-Wildland Interface: Subdivision-Level Analysis of Wildfire Evacuations. J. Urban Plan. Dev. 133, 73–81. https://doi.org/10.1061/(ASCE)0733-9488(2007)133:1(73)

Woods, D.D., 2015. Four concepts for resilience and the implications for the future of resilience engineering. Reliab. Eng. Syst. Saf. 141, 5–9. https://doi.org/10.1016/j.ress.2015.03.018

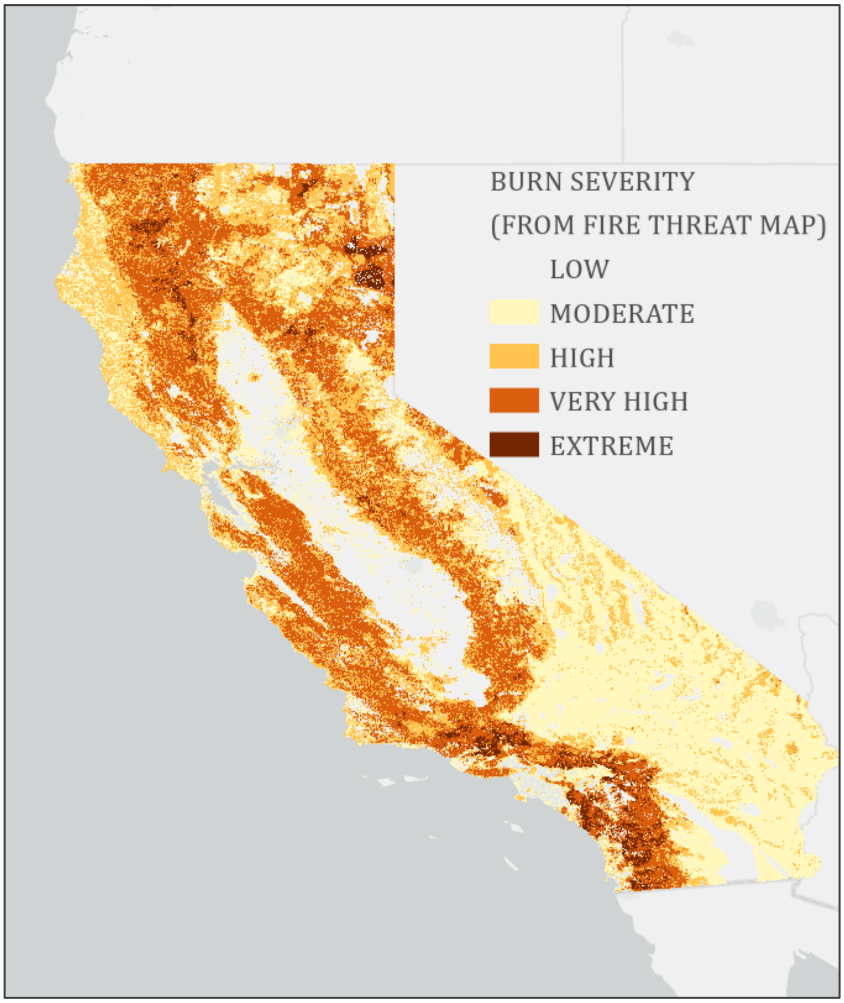
Wu, T.-C., 2001. Application of Remote Sensing for the Prediction, Monitoring, and Assessment of Hazard and Disasters that Impact Transportation. Mississippi State University.

Yang, S., Hu, F., Thompson, R.G., Wang, W., Li, Y., Li, S., Ni, W., 2018. Criticality ranking for components of a transportation network at risk from tropical cyclones. Int. J. Disaster Risk Reduct. 28, 43–55. https://doi.org/10.1016/j.ijdrr.2018.02.017

Zhang, X., Miller-Hooks, E., Denny, K., 2015. Assessing the role of network topology in transportation network resilience. J. Transp. Geogr. 46, 35–45. https://doi.org/10.1016/j.jtrangeo.2015.05.006

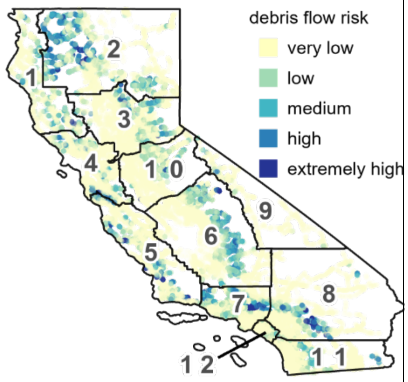
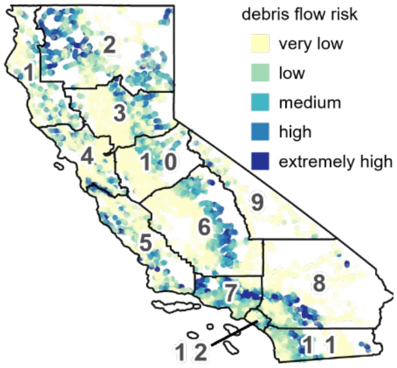
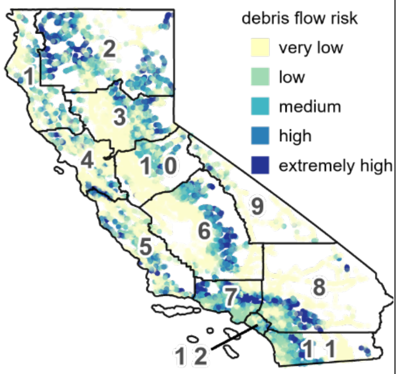
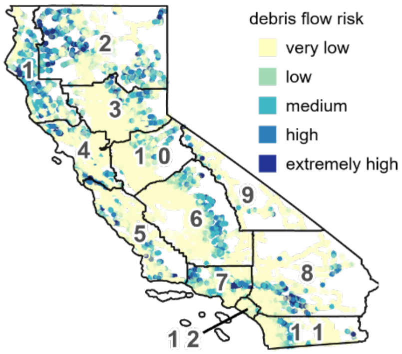
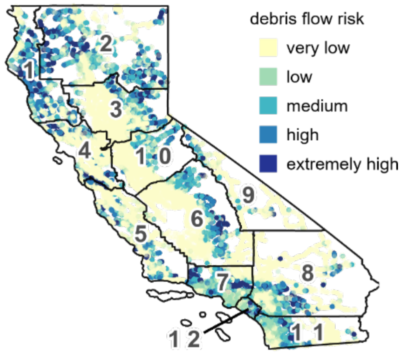
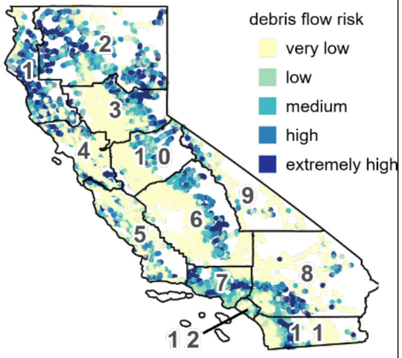
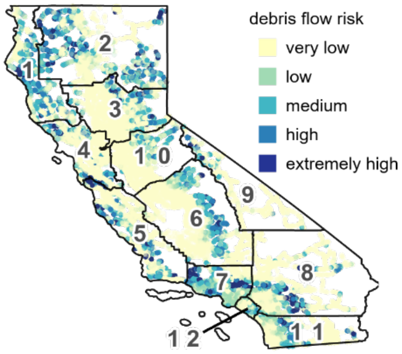
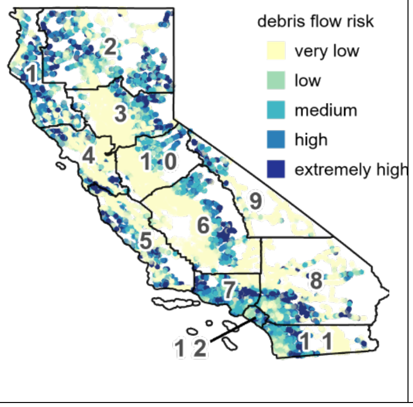
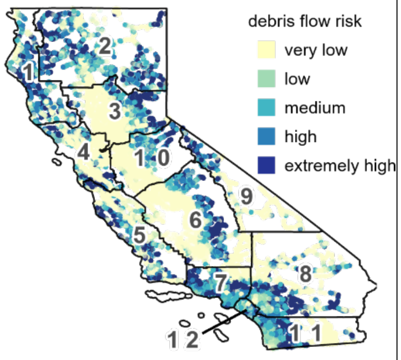
Appendix A

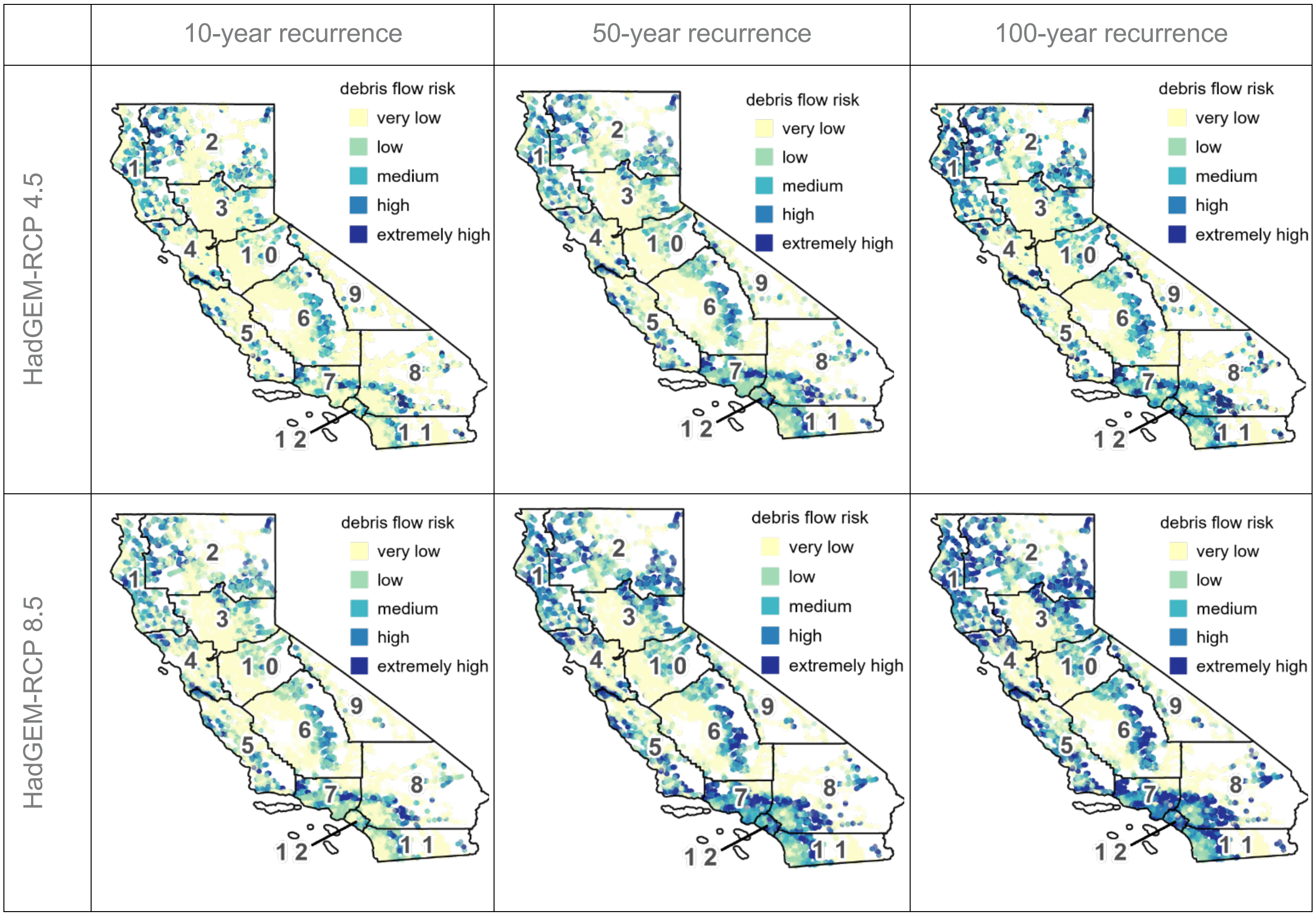
Burn severity map derived from the fire threat map.



Appendix B

Watershed post-fire debris flow risk.

	10-year recurrence	50-year recurrence	100-year recurrence
Current			
CanESM-RCP 4.5			
CanESM-RCP 8.5			


10-year recurrence
50-year recurrence
100-year recurrence
HadGEM-RCP 4.5
HadGEM-RCP 8.5
debris flow risk
very low
low
medium
high
extremely high
1
2
3
4
5
6
7
8
9
10
11
12