PROJECTED CLIMATE CHANGES IN POST-WILDFIRE DEBRIS-FLOW LIKELIHOOD, VOLUME, AND RUNOUT APPLIED TO THE 2017 CALIFORNIA THOMAS FIRE

by

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ABSTRACT

Using current post-fire debris-flow models of the 2017 California Thomas Fire, created by the United States Geological Survey (USGS), this research intends to show the effects of climate change on fire size, fire severity, and rain intensities as well as post-fire debris-flow likelihood, volume, hazard, and runouts. This research aims to provide answers to the following research questions:

1. How would projected future climate conditions affect post-fire debris-flow likelihood, volume, runout, and combined hazard were the California 2017 Thomas Fire to occur in the years 2050 and 2075?
2. How can these results be projected to the (south)western United States in terms of post-fire debris flows?
3. How will this research aid in debris-flow prediction and management under climate change conditions?

Using available data and technical literature values, fire size, fire severity, and design storm rain intensities were projected to the years 2050 and 2075. Three sets of models were created to show the changes in the Thomas Fire under climate change. The first set of models kept the fire conditions of the Thomas Fire the same but included scaled rainfall intensities. These models accounting for rainfall intensity changes show an increase in high-hazard basins of approximately 12% by 2050 and 14% to 18% by 2075 when compared to 2017. The second set of models use the estimated volumes of debris flows to generate 36 runout inundation models. The runout models show an increase in debris-flow inundation with increasing rainfall intensity in the future, mostly in the form of longer runout paths. The last set of models incorporates increases in fire size, fire severity, and rain intensity. The 2050 model predicts 6% more high-hazard basins, and the 2075 models predict 10% to 13% more high-hazard basins when compared to 2017.

Implementing climate change projections into the post-fire debris-flow likelihood and volume calculations resulted in increased hazard and runout for all models. The results of this project, in combination with the background information, show that climate change will increase post-fire debris-flow hazards and inundation in the western United States.
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CHAPTER 1 INTRODUCTION

In recent history, the size, amount, and severity of wildfires are increasing, and climate change is the main driving component of these changes. Climate scientists use climate change models to model atmospheric conditions and predict future changes in climate regimes. These models predict dryer conditions, an increase in temperatures, and changes in precipitation patterns. Dryer conditions fuel fires to burn larger areas with more severity. In addition to increased variability in precipitation return periods, rainfall intensities are expected to increase with changes in the climate. These changes are expected to increase the likelihood, volume, runout, and overall hazard of post-fire debris flows. One of the challenges for debris-flow hazard management is estimating how future climate conditions would modify the impacts of post-fire debris flows.

After a wildfire is extinguished or even possibly still burning, post-fire debris flows are an immediate significant geohazard that needs to be studied and mitigated. A wildfire removes vegetation and alters the soil surface, which allows for higher surface erosion during a precipitation event creating unstable ground conditions that lead to higher debris-flow probabilities. For example, in December of 2017, the Thomas Fire in Southern California burned 114,078 hectares in 38 days. Before the fire was 100% contained, heavy precipitation hit the area causing several debris flows that killed 23 people and caused extreme damage to infrastructure. The Thomas Fire burn area covered a wide range of drainage basin sizes, burn severities, and created debris flows with varying characteristics. This event is, therefore, an ideal study area to demonstrate how the Thomas Fire would change in size and severity under predicted future climate conditions. Additionally, the study area is also suited for demonstrating how post-fire debris-flows volume, likelihood, hazard, and runout would change under predicted future climate conditions.

For each significant wildfire, the United States Geological Survey (USGS) uses burn severity, terrain changes, soil information, precipitation data, and historical debris-flow data in conjunction with geographic information systems (GIS) to create models of debris-flow likelihood, volume, and hazard. The models use a 15-minute rainfall intensity design storm in millimeters per hour (mm/hr) to estimate debris-flow activation probabilities. Using ArcGIS, the USGS creates user-friendly maps that the public can use to understand the anticipated debris-
flow size and overall hazard in their area. Each fire has a set of 6 models, which are broken down into either segment or basin models. Both types of models have probability, volume, and hazard maps so that the user can view the basin as a whole or view a specific section of the basin. This research will be focused on changes to the basin prediction models from future climate conditions.

It should be noted that the USGS models do not predict downstream impacts, potential debris-flow runout paths, and the areal extent of debris-flow or flood inundation. However, because debris-flow runout is such a key component of the overall hazard, and because it could change significantly as a result of climate change, we include an evaluation of debris-flow runout in this study, using Laharz_py.

Laharz_py is a Python-based ArcMap GIS toolbox model created by the USGS that can be used to map lahar, debris flow, and rock avalanche inundation hazard zones. The program can model post-fire debris-flow inundation zones using the estimated volumes calculated by USGS equations with modification to the Python code. This modification will be applied to this study, along with the predicted changes due to climate variability so that the hazards can be projected for future conditions.

Using the USGS post-fire debris-flow models, this research intends to show the effects of climate change on fire size, fire severity, and rain intensities as well as post-fire debris-flow likelihood, volume, hazard, and runouts. This research aims to provide answers to the following research questions:

1. How would projected future climate conditions affect post-fire debris-flow likelihood, volume, runout, and combined hazard were the California 2017 Thomas Fire to occur in the years 2050 and 2075?

2. How can these results be projected to the (south)western United States in terms of post-fire debris flows?

3. How will this research aid in debris-flow prediction and management under climate change conditions?
The Thomas Fire burn area provides a variety of basin sizes and conditions that will dramatically show how climate change affects the post-fire debris-flow hazard. The models will evaluate the predicted changes in design storm rain intensities, fire sizes, and fire severities for the years 2050 and 2075. The importance of this project is that it will show how the debris-flows hazards will change beyond the immediate future so that scientists can look at the long-term safety of people and infrastructure. The results of these models will serve as an important reference for community planning, hazard management, and future scientific direction.
CHAPTER 2 BACKGROUND

2.1 Post-fire Debris-flow Components

A debris flow is a rapid moving slurry of water, sediment, and debris, such as trees and boulders, that follows a channel and spreads out after unconfinement. They can cause fatalities as well as damage or destroy homes, bridges, and other critical infrastructure. Debris flows are typically initiated by intense rainfall, long-duration rainfall, or rapid snowmelt and pose significant geohazards globally. Burned landscapes create surface conditions that allow debris flows to be larger and more frequent, making post-fire debris-flow mitigation a priority following wildfire (Riley et al., 2013). USGS models show that debris-flow likelihood increases with moderate to high burn severity on slopes greater than 23 degrees (Staley et al., 2017). Field observations show that storms similar in size to a 2-year return interval can initiate debris flows in burned basins that otherwise would not have initiated (Riley et al., 2013). Empirical methods show that the peak 15-minute average rainfall intensity (I15) is a useful metric for predicting the likelihood and magnitude of post-fire debris flows (Mcguire et al., 2021). As the basins recover from the burn, the likelihood of debris flows decrease, and the rain intensity initiation thresholds increase (Riley et al., 2013, Mcguire et al., 2021). As the climate changes with increasing temperatures, the size, severity, and frequency of wildfires are also expected to increase (Langridge, 2018, Wehner et al., 2017), which in turn will increase debris-flow hazards.

2.2 Study Area

This research will focus on the burn area of the December 2017 Thomas Fire. Located near the city of Montecito, in Ventura County, California, the Thomas Fire burned 114,078 hectares and was fueled by record hot temperatures, high winds, and low fuel moisture (Langridge, 2018). Using satellite data, a burn severity analysis showed the Thomas Fire burn area was 11% unburned, 31% low burn severity, 56% moderate burn severity, and 1% high burn severity (Addison & Oommen, 2020). The Montecito area is bounded to the east by sloping alluvial fans and outlets of steep canyons in the Santa Ynez Mountains, many of which are surrounded by residential housing and other developments. The burn area contains alluvial and surficial sediments underlain by interbedded sandstone and shale rock formations (Schwartz 2017). The newly burned soil on the slopes of the Santa Ynez Mountains had low permeability, and hydrophobic properties that were major factors in the formation of the devastating debris
flows that impacted Montecito (Langridge, 2018). The rainfall that activated the debris flows had an average rainfall intensity of 87 mm/hr, which represented a 200-year storm event (Langridge, 2018). Many debris flows were initiated, including San Ysidro Creek Canyon that produced a deadly 297,000 m$^3$ debris flow consisting of large boulders (up to 4.3 meters in diameter) and a silty sand matrix (Bessette-Kirton et al., 2019). The debris flows inundated the town of Montecito, damaged at least 163 structures, and destroyed 92 structures (Bessette-Kirton et al., 2019). Figure 2.1 shows the location of the Thomas Fire Burn Area in the western United States.

![2017 Thomas Fire Burn Area](image)

Figure 2.1 The Thomas Fire, circled in blue, location relative to the western United States. The burn area is highlighted in orange.

### 2.3 Climate Models and Predicted Changes

#### 2.3.1 Global Climate Models

Global climate models (GCM) are mathematical environments that simulate different aspects of the Earth's climate. These models can simulate temperature, precipitation, characteristics of storm tracks and cyclones, and changes in ocean temperatures (Hayhoe et al., 2017). The GCMs simulate future climate conditions using different carbon emissions scenarios,
referred to as Representative Concentration Pathways (RCPs). The four standard scenarios, RCP2.6, RCP4.5, RCP6.0, and RCP8.5, are labeled based on the measure of radiative forcing in the year 2100 in watts per square meter (W/m²) (Wuebbles et al., 2017, Hayhoe et al., 2017). Radiative forcing measures the influence of different factors, such as emissions, on atmospheric energy exchanges. Factors such as amounts of greenhouse gases, air pollutants, carbon dioxide, and aerosols are changed based on the RCP scenario (Wuebbles et al., 2017). The RCP8.5 scenario represents a ‘business as usual’ model with little to no emissions mitigation (worst case scenario), and the RCP4.5 scenario represents moderate emissions mitigation with emissions plateauing around 2050 and then declining. The RCP2.6 and RCP6.0 scenarios represent additional, but less commonly modeled, degrees of emissions management. Each decrease in the RCP value represents the increase in emissions mitigation and a decrease in the expected change in global temperature.

2.3.2 Projected Changes in Temperature

Each RCP projects different ranges of increases in global average temperature. Relative to 1976-2005, the projected average temperature increase is approximately 1.4°C for all RCP scenarios for the period 2021-2050 (Wuebbles et al., 2017, Vose et al., 2017). After 2050, each scenario increases the projected average global temperature with each subsequent increase in the radiative forcing. However, relative to 1976-2005 in late century 2071-2100, the projected average global temperature increase is 1.6° to 4.1°C for RCP4.5 and 3.2° to 6.6°C for RCP8.5 (Wuebbles et al., 2017, Vose et al., 2017). The temperature ranges are bounded by the difference between the average increase of the three coolest models and the average increase in the three warmest models (Vose et al., 2017). In Figure 2.3, Wuebbles et al. (2017) showed RCP annual carbon emissions plotted against the year and the corresponding projected change in global temperatures.
2.3.3 Projected Change in Rain Events

Global climate models show an increase in both the intensity and frequency of heavy rainstorm events with high confidence (Wuebbles et al., 2017). Smaller rain events are expected to occur less often, and heavy rain events are expected to occur more often, but the average annual precipitation is expected to remain relatively the same, meaning fewer days with rain events (Langridge, 2018). The increase in dry days and little change in annual average precipitation may lead to increased drought (Langridge, 2018). The GCMs show a drying of soil moisture across the United States in all seasons, which is attributed to increased evapotranspiration because of the increased surface temperatures (Wehner et al., 2017). Areas of high population density could see 20% more intense extreme precipitation events and may become twice as frequent despite an unchanged annual mean precipitation (Ragno et al., 2018).

The RCP4.5 scenario for 20-year storms projects a 10% increase and a 14% increase in daily precipitations for the middle- and late-century, respectively (Easterling et al., 2017). For the mid- and late-century, the RCP8.5 scenario projects a 20% increase in 20-year storm daily precipitation and approximately a 30% increase for a 100-year storm daily precipitation (Easterling et al., 2017). The Clausius-Clapeyron relation estimates the intensity of heavy rainstorm events to increase by 6% to 7% for every degree Celsius increase in global average temperature (Westra et al., 2014, Easterling et al., 2017, Kean & Staley, 2021)
2.3.4 Projected Changes in Wildfires

Since the 1980s, large forest fire occurrence has increased and is expected to continue to increase under projected future climate conditions (Wuebbles et al., 2017). Using statistics from the Fire Program Analysis Fire Occurrence Database (FPA-FOD), the mean fire size, fire frequency, and fire season length have increased by 78%, 12%, and 17%, respectively, between 1992 and 2015 (Cattau et al., 2020). Fire is affected by increased fuel flammability created by a dryer, warmer conditions, and increased fuel loads driven by decreased moisture. Global climate models indicate that Santa Ana winds in Southern California will likely become hotter with climate change and will continue to maintain their usual pattern of increased frequency in December and January (Langridge, 2018). Fire risk increases under drought conditions, and droughts are expected to continue to be a problem in California. Cloud to ground lightning strikes is projected to increase by 12 ± 5% per degree Celsius temperature increase in global warming, showing an approximate 50% increase in lightning strikes by mid to late century (Romps et al., 2014). Fires greater than 20,234 hectares (50,000 acres) in size in the western United States are projected to increase by midcentury for both the RCP 4.5 and RCP8.5 scenarios (Wehner et al., 2017).

Burn intensity is a measure of the rate at which the fire produces heat and is measured in temperature or heat yield. Burn severity, which is more commonly reported, is a measure of the heat produced from the burn (intensity) and the duration of the burn. Burn severity is ranked from low to high based on how damaging the burn was to the soil, vegetation, and other factors. Burn severity depends on fuel availability, weather, long-term climate, topography, and fire frequency. The area of high burn severity from wildfires has increased in large parts of the western United States, but Southern California does not appear to have clear data trends for soil burn severities (Kean & Staley, 2021). The unclear trends in fire severity are thought to be attributed to the burning of chaparral and replacing it with grass which burns at lower severities (Kean & Staley, 2021). Fire severity is expected to increase, but the projected changes in fire burn severity are currently unknown in the western United States (Spracklen et al., 2009). In one of the few studies evaluating changes in burn severity, Parks et al. (2016) reviewed previous soil burn severity data for the fires greater than 400 hectares in the years 1984-2012 and evaluated the potential response of burn severity to climate change in the western United States (under the
RCP 8.5 scenario). The produced models show that fire burn severity in mid-century (2040-2069) for the Montecito area will likely be low to moderate burn severities (Parks et al., 2016).

Other studies estimated the expected increase in areas burned under future climate change scenarios. The total area burned in the western United States is projected to increase by 47% to 86% relative to 2001-2010 for a typical fire year and 48% to 61% for extreme fire years in 2041 to 2050 for the Mediterranean California ecoregion (Zhu & Reed, 2012). The extreme fire years have a lower increase in total area burned since they have a larger total area burned and are less likely to have the same increase in total area burned than that of a normal fire year. Spracklen et al. (2009) projected that the total burned area across the western U.S. to increase by 54% for 2046-2055 relative to 1996-2005.

2.4 Modeling Equations and Software

This research will expand on the models produced by USGS for the emergency assessment of post-fire debris flows. USGS uses burn severity, terrain changes, soil information, precipitation data, and historical debris-flow data in conjunction with geographic information systems (GIS) to model the likelihood, volume, and hazard of the post-fire debris flows. The models use a 15-minute rainfall intensity design storm in millimeters per hour (mm/hr) and soil burn severity data to estimate debris-flow activation probabilities and volumes. The likelihood equation comes from a regression approach proposed by Staley et al. (2017), and the volume equation comes from a regression approach proposed by Gartner et al. (2014).

2.4.1 Likelihood Model

The likelihood model uses two logistic regression equations that incorporate the peak 15-minute rainfall intensity to estimate the probability of a debris flow. Equation 2.1 gives the probability of the debris flow, and Equation 2.2 gives the variable x as an input into equation 2.1 (Staley et al., 2017). The likelihood values range from 0 to 1 and are separated into five bins to separate the likelihoods into classes. The bins are separated into 20% ranges over the span from 0% to 100%.

\[ P = \frac{e^x}{1 + e^x} \]  

- \( P \) is the probability of debris-flow.
- \( e^x \) is the exponential function (\( e = 2.718 \))
\[ x = -3.63 + (0.41 \times X1R) + (0.67 \times X2R) + (0.7 \times X3R) \]  

- **X1R** is the proportion of upslope area classified as high or moderate soil burn severity and with gradients ≥ 23°, multiplied by the peak 15-minute rainfall accumulation of the design storm (in millimeters [mm])

- **X2R** is the average differenced normalized burn ratio (dNBR) of the upslope area, multiplied by the peak 15-minute rainfall accumulation of the design storm (in millimeters [mm])

- **X3R** is the soil KF-Factor of the upslope area, multiplied by the peak 15-minute rainfall accumulation of the design storm (in millimeters [mm])

### 2.4.2 Volume Model

Post-fire debris-flow volumes are predicted for the area of a given basin at the basin outlet (pour point) using Equation 2.3 (Gartner et al., 2014). Volume estimates are classified by magnitude ranges of 0–1,000 m³; 1,000–10,000 m³; 10,000–100,000 m³; and greater than 100,000 m³.

\[ \ln(V) = 4.22 + (0.13 \times \sqrt{\text{ElevRange}}) + (0.36 \times \ln(HM_{km})) + (0.39 \times \sqrt{i15}) \]  

- **ElevRange** is the range (maximum elevation–minimum elevation) of elevation values within the upstream watershed (in meters)

- **HM_{km}** is the area upstream of the calculation point that was burned at high or moderate severity (in km²)

- **i15** is the spatially averaged peak 15-min rainfall intensity for the design storm in the upstream watershed (in mm/h)

### 2.4.3 Combined Hazard

The combined hazard model is a combination of probability and volume. The probability estimates are divided into bins of 1-5 with 1 representing low probability and 5 representing high probability (1 = 0-20%, 5 = 80-100%). The volume estimates are divided into bins of 1-4 with 1 representing small volumes and 4 representing very large volumes (1 = 0–1,000 m³, 4 = >100,000 m³). The ranks are added together, with 9 representing the highest hazard. The hazard
is then classified as low (1 = sum of ranks is 2-3), moderate (2 = sum of ranks is 4-6), and high (3 = sum of ranks is 7-9).

2.4.4 Laharz Runout Modeling

The runout model will be created using Laharz_py, which is a Python-based ArcMap GIS toolbox model created by USGS. Laharz_py is a tool that can be used to map lahar, debris flow, and rock avalanche inundation hazard zones. Laharz_py uses different equations to estimate planimetric and cross-sectional area depending on the type of geohazard inundation. For each entered volume, Laharz will estimate the cross-sectional area A (the area of the channel at any given point) and planimetric area B (the total surface area covered by the flow). Laharz then simulates debris-flow inundation by using a cell-by-cell approach and filling the channel identified in the DEM to cross-sectional area A until the planimetric area B is reached, which results in the delineation of the inundation zone. Currently, the Laharz program is coded with equations for lahars, debris flows, and rock avalanches, summarized in Table 2.1.

Table 2.1 Equations in The Laharz Program (Bernard et al., 2021, Schilling, 2014). V is debris-flow volume in cubic meters.

<table>
<thead>
<tr>
<th>Type of Event</th>
<th>Cross-sectional Area (A)</th>
<th>Planimetric Area (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock Avalanche</td>
<td>( A = 0.2V^{2/3} )</td>
<td>( B = 20V^{2/3} )</td>
</tr>
<tr>
<td>Debris Flow</td>
<td>( A = 0.1V^{2/3} )</td>
<td>( B = 20V^{2/3} )</td>
</tr>
<tr>
<td>Lahar</td>
<td>( A = 0.05V^{2/3} )</td>
<td>( B = 200V^{2/3} )</td>
</tr>
</tbody>
</table>

Laharz_py is not coded with equations specifically used for post-fire debris-flow inundation estimation. However, Bernard et al. (2021) used regression analysis to calculate equation coefficients that will best model the cross-sectional area (A) and planimetric areas (B) of the post-fire debris flows based on the estimated volume. Equations 2.4 (\( R^2 = 0.69 \)) and 2.5 (\( R^2 = 0.70 \)), from Bernard et al. (2021), are considered to be the best estimates for post-fire debris-flows inundation in Laharz. The volume (V) of a debris flow is measured in cubic meters.

\[
A = 0.26V^{0.40} \tag{2.4}
\]

\[
B = 7.4V^{0.81} \tag{2.5}
\]
CHAPTER 3 SCOPE OF WORK

3.1 Available Data

3.1.1 Digital Elevation Models (DEMs)

To create an elevation profile, two 10-meter 1/3 arc-second digital elevation model (DEM) .tif files were downloaded from the USGS National Map Data Download and Visualization Services website. The two .tif files, titled “USGS_13_n35w119.tif” and “USGS_13_n35w120.tif” respectively, were imported into ArcMap.

3.1.2 Thomas Fire GIS Data and Shapefiles

The folder “Shapefile” was downloaded from the Thomas Fire section of the Emergency Assessment of Post-Fire Debris-flow Hazard’s website. This folder contains all the shapefiles used to create the likelihood, volume, and hazard models by USGS. From this file, the analysis extent for the area of interest and the debris-flow volume predictions, named “thm2017_analysis_perim_feat” and “thm2017_Basin_DFPredictions _15min_40mmh” respectively, were imported into ArcMap. These two shapefiles were used to estimate debris-flow volumes within each delineated watershed basin and the extents of the Thomas Fire area of interest within the imported DEMs.

3.1.3 Laharz_py

The Laharz_py toolbox and associated folders were downloaded from the USGS Volcano Hazards Program website. The toolbox, named “Laharz_py,” was imported into the ArcToolbox within ArcMap.

3.1.4 San Ysidro Inundation Shapefile

To compare the actual inundation of the San Ysidro Creek basin to a modeled Laharz runout, a shapefile of the measured inundation in the field was downloaded from the USGS ScienceBase-Catalog website.
3.1.5 Thomas Fire Soil Burn Data

Soil burn severity and differenced Normalized Burn Ratio (dNBR) raster data for the Thomas Fire was downloaded from the BAER Imagery Support Data Download website and was imported into ArcGIS.

3.1.6 California Soils Data

A shapefile of California containing soils data was downloaded from the USGS Water Mission Area NSDI Node website. The data was used to determine the soil KF-Factor.

3.2 Workflow Diagram

The workflow for this research is summarized in Figure 3.1, a project methodology flow diagram. The gray box (box 1) represents the input data needed to modify and produce likelihood, volume, hazard, and runout models. In this step, the data is prepared for use and set up in ArcGIS. The yellow box (box 2) is the step in which the 15min-40mm/hr intensity USGS likelihood, volume, and hazard models are reproduced. The orange box (box 3) is the step in which the Python code for the Laharz program is adapted to use the post-fire equations. The light green box (box 4) represents a comparative runout model of the San Ysidro Creek basin. This model showed a comparison between the field measured inundation and the lahaz modeled inundation. The purple box (box 5) is the step during which the fire size, fire severity, and rain intensities are scaled according to RCP4.5 and RCP8.5 scenarios. Since both RCP scenarios project a 46mm/hr intensity in 2050, only one set of likelihood, volume, and hazard models will be created for that year. The year 2075 will have two different models, one representing the RCP4.5 scenario with a 47mm/hr intensity and the other representing the RCP8.5 scenario with a 50mm/hr intensity. The light blue boxes (boxes 6-9) are the set of likelihood, volume, and hazard models that will include the changes in rain intensity only for the years 2050 and 2075 under the RCP scenarios. The dark green box (box 10) is the Laharz runouts that will model inundation of the four volumes that are estimated according to the four modeled rain intensities (40mm/hr, 46mm/hr, 47mm/hr, 50mm/hr) for each selected debris-flow basin. The red boxes (boxes 11-14) represent the set of likelihood, volume, and hazard models that will combine the projected fire size, fire severity, and rain intensities. The fire burn area will be scaled to %154 in the year 2050
and %181 in the year 2075. Fire severity will be kept at similar proportions as the original fire burn severity.

Figure 3.1 Project flow diagram of models.
CHAPTER 4 MODELING ASSUMPTIONS AND METHODOLOGY

4.1 Reproduced USGS Models

The likelihood, volume, and combined hazard maps were reproduced from the USGS Thomas Fire data and are shown in Figures 4.1, 4.2, and 4.3. The reproduced USGS models are the calculated response to a 15-minute-40mm/hr rainfall intensity, which is the highest rainfall intensity modeled by the USGS for a debris-flow response. Therefore, the 40mm/hr rainfall intensity is considered the worst-case scenario and will be used as the baseline for estimating future rainfall intensities. A 15min-40mm/hr intensity has a return period of approximately 1-2 years in the Montecito area (NOAA, 2021). The fire area, burn severities, and other estimated parameters set forth by USGS are assumed to be reasonable and well informed. Additionally, estimated likelihoods, volumes, and combined hazard models created by USGS are assumed to be reasonable and will serve as the baseline against which the projected 2050 and 2075 models are compared.

![Reproduced USGS model](image)

Figure 4.1 Reproduced USGS model, showing the calculated likelihood of a debris flow following a 15min-40mm/hr design rainstorm event.
Figure 4.2 Reproduced USGS model, showing the calculated volume of a debris flow if generated by a 15min-40mm/hr design rainstorm event.

Figure 4.3 Reproduced USGS model, showing the combined likelihood and volume hazard from a 15min-40mm/hr design rainstorm event.
4.2 Laharz_py Runout Modeling

Before starting the runout analysis, the Laharz distal inundation Python file was modified to accommodate the cross-sectional area (A) and planimetric area (B) post-fire debris-flow equations (Equations 2.4 and 2.5). However, only the code affecting the “Laharz distal zones” tool within the Laharz_py toolbox was modified. The “Laharz distal zones with Conf Levels” tool uses the portion of the code related to confidence levels and will not produce confidence levels for the post-fire debris flows. This is because the 2/3 exponent for the lahar, debris flow, and rock avalanches (Table 2.1) has been hardcoded into the confidence levels. Changing the confidence-levels code to adopt two different exponents requires advanced Python programming and is outside the scope of the project.

Laharz uses the estimated volumes from USGS and projected volumes from this research to model the post-fire debris-flow inundation zones. The Laharz program needs defined coordinates for the initiation of deposition for the debris-flow runout path. These points were selected as the x, y coordinates of the basin pour points since the volumes of the debris flows are estimated to that point. These points are similar to locations of deposition initiation assumed by the USGS.

Each Laharz model requires an input volume (up to 7 different volumes can be run in each batch) and at least one point (pour point) representing the start of deposition (any number of points in each batch). For each point entered (xy-coordinates), Laharz will automatically generate a debris-flow inundation for each of the volumes entered. This means specific volumes cannot be used for specific points and each basin will need to be modeled individually. This severely limits the program’s ability to be used to assess runouts for large fires with hundreds or thousands of delineated debris-flow basins. Because there are 1736 delineated basins in the Thomas Fire burn area, calculating runout for every basin is unrealistic; therefore, a subset of basins (21 basins) from one contiguous area was selected as representative of the runout analysis. In addition, the 14 basins with the highest combined hazard rating of 9 were also analyzed to represent the responses of the most dangerous areas. Finally, because of its severe impacts on the community, the San Ysidro Creek basin was also modeled as a comparative model against field measured inundation of the 2017 Thomas Fire debris flows. Therefore, a total of 36 basins were used for the runout analysis, shown in Figure 4.4. For each of the 36 basins, a runout analysis of
the debris-flow volumes estimated from the scaled rain intensities was modeled. Each post-fire debris-flow runout model will show four runouts stacked on each other from smallest volume to largest volume for each of the predicted design rainfall intensities (40mm/hr, 46mm/hr, 47mm/hr, 50mm/hr).

Figure 4.4 Selected basins on which to perform Laharz runout analysis. The representative group of basins (21 basins) are shown in blue. The 14 high-hazard basins (combined hazard = 9) are shown in red, and the San Ysidro Creek basin is shown in dark green.

4.3 Projecting Rain Intensities

The projected rainfall intensities were estimated under two representative concentration pathways (RCPs) to represent a range of predicted values. Projected intensities were calculated as a function of projected temperature changes. Average temperature changes can be estimated based on the RCP8.5 scenario, which represents a business as usual with no emissions mitigation (worst case scenario), and the RCP4.5 scenario, which shows a smaller increase in temperatures because of emissions mitigation. The projected rainfall intensities are scaled by 7% under the
RCP4.5 and RCP8.5 scenarios to the years 2050 and 2075 using estimated changes in average global temperature (Celsius) for those scenarios.

The projected average global temperature change expected in Ventura County was estimated using the website Cal-adapt (2021). The site uses the average of 4 climate models to project and estimate average annual maximum temperature and average annual minimum temperatures according to RCP4.5 and RCP8.5 scenarios. The average high and low temperature estimates for both RCP scenarios for the years 2050 and 2075 were averaged to find an average annual temperature. The difference between the average annual temperature for 1976-2005 and the calculated annual averages gives the estimated change in global temperature felt by Ventura County. Table 4.1 shows the temperatures measured for each year the associated change in global temperature.

Table 4.1 Temperatures measured from Cal-adapt (2021) and the associated change in global temperature.

<p>| Projected Temperature Change in Ventura County (°C) |</p>
<table>
<thead>
<tr>
<th>Model</th>
<th>Obs. Hist.</th>
<th>RCP 4.5</th>
<th>RCP 8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>1976-2005</td>
<td>2050</td>
<td>2075</td>
</tr>
<tr>
<td>Max</td>
<td>20.3</td>
<td>22.6</td>
<td>23.1</td>
</tr>
<tr>
<td>Min</td>
<td>6.1</td>
<td>7.9</td>
<td>8.3</td>
</tr>
<tr>
<td>Average</td>
<td>13.2</td>
<td>15.3</td>
<td>15.7</td>
</tr>
<tr>
<td>Temp. Increase</td>
<td>0.0</td>
<td>2.0</td>
<td>2.4</td>
</tr>
</tbody>
</table>

The USGS 15min-40mm/hr design storm intensity was increased by 7% for every degree Celsius increase in global average temperature (Westra et al., 2014, Easterling et al., 2017, Kean & Staley, 2021). Table 4.2 shows the resulting new projected rainfall intensities under the RCP4.5 and RCP8.5 scenarios for the years 2050 and 2075.
Table 4.2 Projected rain intensities for the years 2050 and 2075 under RCP4.5 and RCP8.5 scenarios.

<table>
<thead>
<tr>
<th>Projection Scenario</th>
<th>RCP 4.5</th>
<th>RCP 8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>2050</td>
<td>2075</td>
</tr>
<tr>
<td>Temperature Increase (°C)</td>
<td>2.0</td>
<td>2.4</td>
</tr>
<tr>
<td>Current 15 min-Intensity (mm/hr)</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>7% Rainfall Intensity Scaling (mm/hr)</td>
<td>46</td>
<td>47</td>
</tr>
</tbody>
</table>

Since both RCP scenarios estimate a 46mm/hr intensity for the year 2050, only one set of models was created for that year. The year 2075 was modeled for both the 47mm/hr intensity and the 50mm/hr intensity.

4.4 Projecting Fire Size

Using the estimates by Spracklen et al. (2009) and Zhu & Reed (2012), described above for the rate of an annual increase in fire size, the total area burned was projected to the years 2050 and 2075, shown in Figure 4.5. When plotted, the Spracklen et al. (2009) projection of 54% increase of total area burned lies between the two projections by Zhu & Reed (2012). The 54% projection relative to 1996-2005 shows an approximate increase of total area burned to 81% by 2075. Figure 4.5 shows the projection of the fire size from 2050 to 2075 and shows the Spracklen et al. (2009) projection as the median value. The Spracklen et al. (2009) values were chosen since they represent the median projections of the total area burned of 154% in 2050 and 181% in 2075.
Figure 4.5 Projection’s percent increase in total area burned for 2050 and 2075. Note that the 54% projection lies between the two upper bounds and the two lower bounds.

Next, the 2017 burn perimeter of the Thomas fire was scaled to 154% for the 2050 models and 181% for the 2075 models. These projections were scaled by expanding the surface area homogeneously and do not necessarily represent how a fire might burn and spread naturally. The boundaries were edited so that the burn boundary does not enter the ocean. Additionally, the “donut” hole in the middle was an area not burned during the original fire and contained a lake and, therefore, will remain as an unburned area during the 2050 and 2075 analyses. Figure 4.6 shows the original fire boundary overlain on top of the new projected fire boundaries.
Figure 4.6 The 2017 fire boundary is shown in blue, the 154% fire boundary is shown in yellow, and the 181% fire boundary is shown in red.

4.5 Generating Debris Flow Basins

USGS uses an algorithm in conjunction with the program “LANDFIRE” to produce basins for their debris-flow models. Since the use of LANDFIRE requires advanced knowledge of fire processes and access to USGS’s algorithm is not readily available, the basins in the fire models were created using the hydrology toolset within ArcGIS.

The hydrology toolset contains the “Watershed” tool, which uses defined points and a flow direction raster to generate basins. A filled DEM was clipped to each of the projected fire boundaries. For each of the clipped filled DEMs (154% and 181%), the “Flow Direction”, “Flow Accumulation”, “Con”, “Stream Link”, and “Stream Order” ArcGIS tools were performed in succession. These tools delineated a stream network showing where water would collect and flow. The “Stream Order” output raster defines tributaries by the rank of intersections. The intersections were ranked using the Strahler method in which the stream order increases when two streams of the same order intersect. In order to generate basins using the “Watershed” tool,
an input feature class containing pour points for each of the basins was created. For each of the fire projections, pour points were placed by hand inside each of the fire boundaries. A point was placed where the stream network intersects the fire boundary and is flowing out of the fire boundary. Additionally, points were placed at intersections of 1st, 2nd, and 3rd order streams with 4th order streams and larger. These guidelines were used to maintain consistent placement of points. For the 154% fire size projection 3,247 points were placed and for the 181% fire size projection, 3,673 points were placed. These points were entered into the “Watershed” tool, which delineated the basins. Any basins less than two hectares in size were removed from the analysis to match the minimum basin size modeled by the USGS for the 40 mm/hr design storm. This process delineated 3,115 basins within the 154% fire boundary and 3,559 basins within the 181% fire boundary.

4.6 Projecting Fire Severity and dNBR

Fire severity was assumed to maintain the same proportions in future burn scenarios that account for climate change. Projections and models of fire severity for pre-burn analysis have not been quantified in the technical literature. However, Parks et al. (2016) showed that the area around Montecito may burn with low to moderate severity in mid-century conditions. Therefore, the fire burn severity data will be scaled to the 154% and 181% projected fire boundaries and kept at similar proportions of burn severity as 2017 (11% unburned, 31% low burn severity, 56% moderate burn severity, and a 1% high burn severity (Addison & Oommen, 2020)). Figures 4.7 and 4.8 show the projected 154% fire burn severity and the 181% burn severity, respectively.
Figure 4.7 Projected 154% fire burn severity.

Figure 4.8 Projected 181% fire burn severity.
The original concept was to scale the dNBR data to each of the fire boundaries. However, the large amount of data in a dNBR raster made scaling the raster impractical. Due to the large amount of data in the dNBR raster, ArcGIS would crash when the entire raster was selected before any attempts were made to scale the raster. However, since fire burn severity is a function of dNBR, fire severity could be used to estimate dNBR values for each basin. Using defined technical ranges (Lutes et al., 2006) for burn severity classification, each burn severity classification was given an average dNBR value. Table 4.3 shows the dNBR ranges for each burn severity classification and the average of those ranges. The upper limit of the high severity dNBR range was defined by the highest dNBR value in the original dNBR data (1235.36). The input value column is the value given to each burn severity classification. The dNBR value of each basin was calculated using a weighted average of the area covered by each type of burn severity using the averaged input dNBR values.

Table 4.3 dNBR values given to each burn severity classification based on given technical ranges.

<table>
<thead>
<tr>
<th>Burn Severity Class</th>
<th>Low</th>
<th>High</th>
<th>Average</th>
<th>Input Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unburned</td>
<td>-100</td>
<td>99</td>
<td>-0.5</td>
<td>0</td>
</tr>
<tr>
<td>Low Severity</td>
<td>0</td>
<td>269</td>
<td>134.5</td>
<td>135</td>
</tr>
<tr>
<td>Moderate Severity</td>
<td>270</td>
<td>659</td>
<td>464.5</td>
<td>465</td>
</tr>
<tr>
<td>High Severity</td>
<td>660</td>
<td>1235</td>
<td>947.5</td>
<td>948</td>
</tr>
</tbody>
</table>

4.7 Determining KF-Factor

The KF-Factor is a soil erodibility index of the fines within the soil; a higher value represents a higher potential for erosion. The California soils data contains KF-Factors for the entire state of California. In order to determine the KF-Factor, the “Identity” and “Dissolve” ArcGIS tools were used to determine the KF-Factor in each basin. In the case of several KF-Factors intersecting a basin, the maximum KF-Factor was used since the likelihood equation (Equation 2.2) is sensitive to the KF-Factor (Staley et al., 2017).
CHAPTER 5 MODELING RESULTS

This section will present the results of the models. First, the projected rain intensity models’ results are presented and discussed. These models include the scaled rain intensities only. Next, the Laharz runout models are presented and discussed. These models use the volumes calculated in the rain intensity models. This section includes the San Ysidro Creek basin comparative model. Lastly, the projected fire models are presented and discussed. These models use a combination of scaled rain intensities, fire size, and fire severity. All the generated models that are not present in this chapter are shown in the appendices.

5.1 Projected Rain Intensity Models

Three likelihood, volume, and combined hazard post-fire debris-flow models were created using the projected rain intensities. These models represent a scenario in which the Thomas fire burned under the same fire conditions in 2050 and 2075, but the rain intensity is scaled for climate change. These models show how post-fire debris-flow likelihood, volume, and combined hazard will increase under the climate scaled rain intensity for a 15min-40mm/hr design storm. The year 2050 only has one set of models since the rain intensities under the RCP4.5 and RCP8.5 both scaled to 46 mm/hr. The year 2075 has two sets of models; the RCP4.5 scenario uses a 47mm/hr intensity and the RCP8.5 scenario uses a 50mm/hr intensity. Figures 5.1, 5.2, and 5.3 show the RCP8.5 likelihood, volume, and combined hazard of 1,736 basins. These can be compared to Figures 4.1, 4.2, and 4.3 to show the change in response accounting for future climate change. Noted differences between the modern day and the 2075 RCP8.5 models are the increase in the likelihood, volume, and hazard. These differences can be seen visually when the models are compared. Furthermore, the likelihood, volume, and hazard increased from the modern day to 2050 and increased further from 2050 to the 2075 models. The RCP4.5 2050 and 2075 models can be seen in Appendix A.
Figure 5.1 2075 RCP8.5 model showing the calculated likelihood of a debris flow following a 15min-50mm/hr design rainstorm event.

Figure 5.2 2075 RCP8.5 model showing the calculated volume of a debris flow if generated by a 15min-50mm/hr design rainstorm event.
5.2 Laharz Runout Models

The field measured estimated volume of the San Ysidro debris flow that inundated the Montecito area is 297,000 m$^3$. The modeled Laharz runout of the 297,000 m$^3$ debris flow follows the flow path taken by the original debris flow, although with less spreading. This runout represents an 87mm/hr rain intensity and a 200-year storm event. This model was generated to assess the reasonableness of the Laharz modeling software. Figure 5.4 shows the Laharz runout compared to the actual inundation of the debris flow. The Laharz runout path (dark blue) shows a reasonable length of runout when compared to the actually mapped inundation (light blue). However, the Laharz runout does not show much lateral spreading. This is because Laharz does not simulate avulsion or lateral spreading very well.
Laharz was used to generate runout maps for the calculated volumes for the four different rain intensities of 40mm/hr, 46mm/hr, 47mm/hr, and 50mm/hr. When multiple volumes are entered into the Laharz program, Laharz stacks the runouts from smallest volume to largest volume. Figures 5.5 and 5.6 show the modeled Laharz runout on a single basin from the group basins (group of 21 basins) and a single basin from the high-hazard basins (group of 14 highest hazard basins), respectively. Figure 5.7 shows the runout for the calculated volumes of the San Ysidro Basin. The remainder of the modeled runouts is included in Appendix B. A few of the modeled basins show only 2 or 3 modeled runouts; this is because the changes in volumes between the different rain intensities were not significant enough to change the inundation modeled by Laharz. Therefore, Laharz only produced modeled inundation of the four volumes that had a large enough difference between each other to inundate more cells. Surprisingly, the runout and inundation zone are expected to change only a small amount based on expected changes in design rainstorm intensity. In general, smaller basins were not as sensitive to the

Figure 5.4 San Ysidro Basin with the Lahars runout (dark blue) overlaid on the mapped inundation zone (light blue).
increase in rain intensities and the larger basins were more sensitive to the increase in rain intensities. The high-hazard basins had the largest increases in the inundated area, while the smaller group basins have the smallest increases in the inundated area. These trends are to be expected since as a basin increases in size, the amount of material that can be activated for a debris flow increases.

Figure 5.5 Laharz runout model of the four calculated volumes for this group basin.
Figure 5.6 Laharz runout model of the four calculated volumes for this high-hazard basin.

Figure 5.7 Laharz runout model of the four calculated volumes for the San Ysidro basin.
5.3 Projected Fire Size, Severity, and Rain Intensity Models

Three likelihood, volume, and combined hazard post-fire debris-flow models were created using the projected fire size, fire severity, and rain intensities. The 2050 model represents a projected RCP4.5 and 8.5 scenarios in which the Thomas fire burned 154% of its size with the same proportions of burn severity as 2017 with a 15min-46mm/hr rain intensity design storm. The 2075 RCP4.5 model represents a scenario in which the Thomas fire burned 181% of its size with the same proportions of burn severity as 2017, with a 15min-47mm/hr rain intensity design storm. The 2075 RCP8.5 model represents a scenario in which the Thomas fire burned 181% of its size with the same proportions of burn severity as 2017 with a 15min-50mm/hr rain intensity design storm. Figures 5.8, 5.9, and 5.10 show the 2050 and 2075 hazard models. These can be compared to Figure 4.1 to see the change in hazard in the future. In general, with the increase in fire size, the hazard does not only increase in size, but the basins also increase in hazard when compared to current conditions. The basins in the south-east have a lower hazard due to lower fire severity and less terrain with slopes greater than 23 degrees. The individual likelihood and volume models are shown in Appendix C.

Figure 5.8 2050 post-fire debris-flow hazard model of the 154% fire size and 46mm/hr rainfall intensity design storm.
Figure 5.9 2075 RCP4.5 post-fire debris-flow hazard model of the 181% fire size and 47mm/hr rainfall intensity design storm.

Figure 5.10 2075 RCP4.5 post-fire debris-flow hazard model of the 181% fire size and 47mm/hr rainfall intensity design storm.
CHAPTER 6 STATISTICAL ANALYSIS

6.1 Analysis of Projected Rain Intensity Models (Rain Intensity Models)

6.1.1 Summary and Visual Statistics

The calculated post-fire debris-flow likelihood and volume for each modeled rain intensity for each drainage basin were exported from ArcGIS and imported into MATLAB for statistical analysis. Tables 6.1 and 6.2 show the summary statistics of the likelihood and volume, respectively. Summary statistics consist of mean, 25th percentile (Q1), median, 75th percentile (Q3), and the interquartile range (IQR). The mean, Q1, median, and Q3 all increase with a larger projected rain intensity for both the calculated likelihood and volume values. The IQR of the calculated volumes increases with the projected rain intensities. Conversely, the IQR of the calculated likelihoods decreases with each increase in the projected rain intensity.

Table 6.1 Summary statistics of the calculated likelihood of post-fire debris-flow occurrence for all drainage basins in the rain intensity models.

<table>
<thead>
<tr>
<th>Year</th>
<th>Rain Intensity (mm/hr)</th>
<th>RCP Scenario</th>
<th>Mean</th>
<th>Q1</th>
<th>Median</th>
<th>Q3</th>
<th>IQR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>40</td>
<td>-</td>
<td>80.8%</td>
<td>68.6%</td>
<td>88.8%</td>
<td>98.3%</td>
<td>29.7%</td>
</tr>
<tr>
<td>2050</td>
<td>46</td>
<td>4.5 &amp; 8.5</td>
<td>87.2%</td>
<td>80.9%</td>
<td>94.9%</td>
<td>99.4%</td>
<td>18.6%</td>
</tr>
<tr>
<td>2075</td>
<td>47</td>
<td>4.5</td>
<td>88.0%</td>
<td>82.5%</td>
<td>95.5%</td>
<td>99.5%</td>
<td>17.0%</td>
</tr>
<tr>
<td>2075</td>
<td>50</td>
<td>8.5</td>
<td>90.3%</td>
<td>86.8%</td>
<td>97.0%</td>
<td>99.7%</td>
<td>13.0%</td>
</tr>
</tbody>
</table>

Table 6.2 Summary statistics of the calculated volume of each post-fire debris flow for all drainage basins in the rain intensity models.

<table>
<thead>
<tr>
<th>Year</th>
<th>Rain Intensity (mm/hr)</th>
<th>RCP Scenario</th>
<th>Mean (m³)</th>
<th>Q1 (m³)</th>
<th>Median (m³)</th>
<th>Q3 (m³)</th>
<th>IQR (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>40</td>
<td>-</td>
<td>6541</td>
<td>849</td>
<td>1645</td>
<td>3900</td>
<td>3051</td>
</tr>
<tr>
<td>2050</td>
<td>46</td>
<td>4.5 &amp; 8.5</td>
<td>7819</td>
<td>1015</td>
<td>1966</td>
<td>4662</td>
<td>3647</td>
</tr>
<tr>
<td>2075</td>
<td>47</td>
<td>4.5</td>
<td>8046</td>
<td>1045</td>
<td>2023</td>
<td>4797</td>
<td>3753</td>
</tr>
<tr>
<td>2075</td>
<td>50</td>
<td>8.5</td>
<td>8751</td>
<td>1136</td>
<td>2201</td>
<td>5218</td>
<td>4082</td>
</tr>
</tbody>
</table>
Figure 6.1 depicts sixteen histograms consisting of likelihood classifications (Like-Class), volume classifications (Vol-Class), combined hazards (Comb-Haz), and the combined hazard classifications (Haz-Class), using the category definitions given earlier. The combined hazard is the sum of the volume and likelihood classifications, while the combined hazard classification is the classification of the combined hazard values into the Low, Moderate, and High-hazard categories. The first row of histograms (Like-Class) shows the distribution of the basins according to their likelihood classifications for each of the four rain intensities. The likelihood classification histograms show higher proportions of basins with likelihoods between 80% and 100% (class 5) with each increase in rain intensity, with a corresponding decrease in all other classes. The second row of histograms (Vol-Class) shows the distribution of the basins according to their volume classifications for each of the four rain intensities. The volume classification histograms show the increase in volumes associated with larger rain intensities. The greatest increase is seen in basins with volumes between 1,000 m$^3$ and 10,000 m$^3$ (class 2), with a corresponding decrease in basins with volumes between 0 m$^3$ and 1,000 m$^3$ (class 1), which is consistent with the calculated means seen in Table 6.2. The third row of histograms (Comb-Haz) shows the distribution of the basins according to their combined hazard for each of the four rain intensities. The combined hazard is the sum of the likelihood classification value (1-5) plus the volume classification value (1-4) and has a range from 2-9. The combined hazard histograms show the increase in combined hazard associated with larger rain intensities. The greatest increase is seen in basins with combined hazards of 7 (class 7), with small corresponding decreases in lower categories. The fourth and final row of histograms (Haz-Class) shows the distribution of the basins according to their combined hazard classifications for each of the four rain intensities. The combined hazard classification histograms show the increase in hazard associated with larger rain intensities, especially those in class 3 “High” hazard classification.
Figure 6.1 Histogram distributions of the likelihood classifications, volume classifications, combined hazard, and combined hazard classifications for the rain intensity models.

6.1.2 Comparative Classification Statistics

The likelihood, volume, and combined hazard classifications, in addition to combined hazard, were broken down by each classification to look at the number of basins and compare the models to each other. The comparison of these classifications is expected to show an increase in post-fire debris-flow hazards. Table 6.3 shows the number of basins in each of the five likelihood classifications under each of the four rain intensities (40mm/hr, 46mm/hr, 47mm/hr, and 50mm/hr). When compared to the 40mm/hr intensity, all three projected rain intensities show a decrease in the number of basins in the 0%-80% range (class 1 to class 4). However, all three projected rain intensities show an increase in basins with a likelihood between 80% and 100% (class 5). The 2050 projected RCP4.5 and RCP8.5 46mm/hr rain intensity model shows a 14.4%
increase in basins with a likelihood between 80% and 100%. The 2075 projected RCP4.5 47mm/hr rain intensity and the RCP8.5 50mm/hr rain intensity shows a 16.2% and 21.7% increase in basins with a likelihood between 80% and 100%, respectively.

Table 6.3 Post-fire debris-flow likelihood classifications for all four rain intensities. The red means a decrease in the number of basins in that classification. The blue means an increase in the number of basins in that classification.

| Post-fire Debris-flow Likelihood Classification Statistics |
|---------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Rain Intensity (mm/hr)          | 40     | 46     | 47     | 50     | 40     | 46     | 47     | 50     | 40     | 46     | 47     | 50     |
| Class 1 (0%-20%)                |        |        |        |        |        |        |        |        |        |        |        |        |
| Number of Basins (out of 1736)  | 6      | 2      | 2      | 1      | 366    | 255    | 242    | 178    | 108    | 39     | 28     | 18     |
| % of Basins                     | 0.3%   | 0.1%   | 0.1%   | 0.1%   | 21.1%  | 14.7%  | 13.9%  | 10.3%  | 6.2%   | 2.2%   | 1.6%   | 1.0%   |
| % Change From Previous          | -      | -0.2%  | 0.0%   | -0.1%  | -6.4%  | -0.7%  | -3.7%  |        | -4.0%  | -0.6%  | -0.6%  | -5.2%  |
| % Change From 40mm/hr           | -      | -0.2%  | -0.2%  | -0.3%  | -6.4%  | -7.1%  | -10.8% |        | -4.0%  | -0.6%  | -0.6%  | -5.2%  |
| Class 2 (20% -40%)              |        |        |        |        |        |        |        |        |        |        |        |        |
| Number of Basins (out of 1736)  | 108    | 39     | 28     | 18     | 1067   | 1317   | 1349   | 1444   | 189    | 123    | 115    | 95     |
| % of Basins                     | 6.2%   | 2.2%   | 1.6%   | 1.0%   | 61.5%  | 75.9%  | 77.7%  | 83.2%  | 10.9%  | 7.1%   | 6.6%   | 5.5%   |
| % Change From Previous          | -      | -4.0%  | -0.6%  | -0.6%  | 14.4%  | 1.8%   | 5.5%   |        | -3.8%  | -0.5%  | -1.2%  |        |
| % Change From 40mm/hr           | -      | -4.0%  | -4.6%  | -5.2%  |        | 14.4%  | 16.2%  | 21.7%  |        |        |        |        |
| Class 3 (40% -60%)              |        |        |        |        |        |        |        |        |        |        |        |        |
| Number of Basins (out of 1736)  | 189    | 123    | 115    | 95     |        |        |        |        |        |        |        |        |
| % of Basins                     | 10.9%  | 7.1%   | 6.6%   | 5.5%   |        |        |        |        |        |        |        |        |
| % Change From Previous          | -      | -3.8%  | -0.5%  | -1.2%  |        |        |        |        |        |        |        |        |
| % Change From 40mm/hr           | -      | -3.8%  | -4.3%  | -3.4%  |        |        |        |        |        |        |        |        |

Table 6.4 shows the number of basins in each of the four volume classifications under each of the four rain intensities. When compared to the 40mm/hr intensity, all three projected rain intensities show a decrease in the number of basins in the 0m³ – 1,000m³ range (class 1). However, all three projected rain intensities show an increase in basins with a volume between 1,000m³ and greater than 100,000m³ (classes 2, 3, and 4). The 2050 projected RCP4.5 and RCP8.5 46mm/hr rain intensity model shows a 4.3% increase in class 2, a 1.7% increase in class 3, and a 0.4% increase in class 4. The 2075 projected RCP4.5 47mm/hr rain intensity shows a 5.6% increase in class 2, a 1.7% increase in class 3, and a 0.5% increase in class 4. The 2075 projected RCP8.5 50mm/hr rain intensity shows a 7.0% increase in class 2, a 2.1% increase in class 3, and a 0.7% increase in class 4.
Table 6.4 Post-fire debris-flow volume classifications for all four rain intensities. The red means a decrease in the number of basins in that classification. The blue means an increase in the number of basins in that classification.

### Post-fire Debris-flow Volume Classification Statistics

<table>
<thead>
<tr>
<th>Rain Intensity (mm/hr)</th>
<th>40</th>
<th>46</th>
<th>47</th>
<th>50</th>
<th>Rain Intensity (mm/hr)</th>
<th>40</th>
<th>46</th>
<th>47</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1 (0m$^3$ - 1,000m$^3$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Class 3 (10,000m$^3$ - 100,000m$^3$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Basins (out of 1736)</td>
<td>533</td>
<td>422</td>
<td>398</td>
<td>363</td>
<td>Number of Basins (out of 1736)</td>
<td>220</td>
<td>250</td>
<td>249</td>
<td>257</td>
</tr>
<tr>
<td>% of Basins</td>
<td>30.7%</td>
<td>24.3%</td>
<td>22.9%</td>
<td>20.9%</td>
<td>% of Basins</td>
<td>12.7%</td>
<td>14.4%</td>
<td>14.3%</td>
<td>14.8%</td>
</tr>
<tr>
<td>% Change From Previous</td>
<td>-</td>
<td>-6.4%</td>
<td>-1.4%</td>
<td>-2.0%</td>
<td>% Change From Previous</td>
<td>-</td>
<td>1.7%</td>
<td>-0.1%</td>
<td>0.5%</td>
</tr>
<tr>
<td>% Change From 40mm/hr</td>
<td>-</td>
<td>-6.4%</td>
<td>-1.4%</td>
<td>-2.0%</td>
<td>% Change From Previous</td>
<td>-</td>
<td>1.7%</td>
<td>-0.1%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Class 2 (1,000m$^3$ - 10,000m$^3$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Class 4 (&gt;100,000m$^3$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Basins (out of 1736)</td>
<td>969</td>
<td>1043</td>
<td>1066</td>
<td>1090</td>
<td>Number of Basins (out of 1736)</td>
<td>14</td>
<td>21</td>
<td>23</td>
<td>26</td>
</tr>
<tr>
<td>% of Basins</td>
<td>55.8%</td>
<td>60.1%</td>
<td>61.4%</td>
<td>62.8%</td>
<td>% of Basins</td>
<td>0.8%</td>
<td>1.2%</td>
<td>1.3%</td>
<td>1.5%</td>
</tr>
<tr>
<td>% Change From Previous</td>
<td>-</td>
<td>4.3%</td>
<td>1.3%</td>
<td>1.4%</td>
<td>% Change From Previous</td>
<td>-</td>
<td>0.4%</td>
<td>0.1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>% Change From 40mm/hr</td>
<td>-</td>
<td>4.3%</td>
<td>5.6%</td>
<td>7.0%</td>
<td>% Change From Previous</td>
<td>-</td>
<td>0.4%</td>
<td>0.5%</td>
<td>0.7%</td>
</tr>
</tbody>
</table>

Table 6.5 shows the number of basins with the same combined hazard under each of the four rain intensities. When compared to the 40mm/hr intensity, all three projected rain intensities show a decrease in the number of basins with a combined hazard between 2 and 6. However, all three projected rain intensities show an increase in basins with a combined hazard between 7 and 9. The 2050 projected RCP4.5 and RCP8.5 46mm/hr rain intensity model shows a 8.5% increase in basins with a combined hazard of 7, a 2.9% increase in basins with a combined hazard of 8, and a 0.4% increase in basins with a combined hazard of 9. The 2075 projected RCP4.5 47mm/hr rain intensity shows a 10.5% increase in basins with a combined hazard of 7, a 3.0% increase in basins with a combined hazard of 8, and a 0.46% increase in basins with a combined hazard of 9. The 2075 projected RCP8.5 50mm/hr rain intensity shows a 14.1% increase in basins with a combined hazard of 7, a 3.7% increase in basins with a combined hazard of 8, and a 0.63% increase in basins with a combined hazard of 9.
Table 6.5 Post-fire debris-flow combined hazards for all four rain intensities. The red means a decrease in the number of basins in that classification. The blue means an increase in the number of basins in that classification.

<table>
<thead>
<tr>
<th>Combined Hazard 2</th>
<th>Combined Hazard 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Basins (out of 1736)</td>
<td>Number of Basins (out of 1736)</td>
</tr>
<tr>
<td>% of Basins</td>
<td>% of Basins</td>
</tr>
<tr>
<td>% Change From Previous</td>
<td>% Change From Previous</td>
</tr>
<tr>
<td>% Change From 40mm/hr</td>
<td>% Change From 40mm/hr</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Combined Hazard 3</th>
<th>Combined Hazard 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Basins (out of 1736)</td>
<td>Number of Basins (out of 1736)</td>
</tr>
<tr>
<td>% of Basins</td>
<td>% of Basins</td>
</tr>
<tr>
<td>% Change From Previous</td>
<td>% Change From Previous</td>
</tr>
<tr>
<td>% Change From 40mm/hr</td>
<td>% Change From 40mm/hr</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Combined Hazard 4</th>
<th>Combined Hazard 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Basins (out of 1736)</td>
<td>Number of Basins (out of 1736)</td>
</tr>
<tr>
<td>% of Basins</td>
<td>% of Basins</td>
</tr>
<tr>
<td>% Change From Previous</td>
<td>% Change From Previous</td>
</tr>
<tr>
<td>% Change From 40mm/hr</td>
<td>% Change From 40mm/hr</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Combined Hazard 5</th>
<th>Combined Hazard 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Basins (out of 1736)</td>
<td>Number of Basins (out of 1736)</td>
</tr>
<tr>
<td>% of Basins</td>
<td>% of Basins</td>
</tr>
<tr>
<td>% Change From Previous</td>
<td>% Change From Previous</td>
</tr>
<tr>
<td>% Change From 40mm/hr</td>
<td>% Change From 40mm/hr</td>
</tr>
</tbody>
</table>

Table 6.6 shows the number of basins in each combined hazard classification under each of the four rain intensities. When compared to the 40mm/hr intensity, all three projected rain intensities show a decrease in the number of basins with a combined hazard classification of 1 (low hazard) and 2 (moderate hazard). However, all three projected rain intensities show an increase in basins with a combined hazard classification of 3 (high hazard). The 2050 projected RCP4.5 and RCP8.5 46mm/hr rain intensity model shows a 11.9% increase in basins with a high-hazard classification. The 2075 projected RCP4.5 47mm/hr rain intensity shows a 14% increase in basins with a high-hazard classification. The 2075 projected RCP8.5 50mm/hr rain intensity shows an 18.4% increase in basins with a high-hazard classification.
Table 6.6 Post-fire debris-flow combined hazard classification for all four rain intensities. The red means a decrease in the number of basins in that classification. The blue means an increase in the number of basins in that classification.

<table>
<thead>
<tr>
<th>Post-fire Debris-flow Combined Hazard Classification Statistics</th>
<th>Rain Intensity (mm/hr)</th>
<th>40</th>
<th>46</th>
<th>47</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazard Classification 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Basins (out of 1736)</td>
<td></td>
<td>77</td>
<td>25</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>% of Basins</td>
<td></td>
<td>4.4%</td>
<td>1.4%</td>
<td>1.0%</td>
<td>0.7%</td>
</tr>
<tr>
<td>% Change From Previous</td>
<td></td>
<td>-</td>
<td>-3.0%</td>
<td>-0.4%</td>
<td>-0.3%</td>
</tr>
<tr>
<td>% Change From 40mm/hr</td>
<td></td>
<td>-</td>
<td>-3.0%</td>
<td>-3.4%</td>
<td>-3.7%</td>
</tr>
<tr>
<td>Hazard Classification 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Basins (out of 1736)</td>
<td></td>
<td>730</td>
<td>576</td>
<td>546</td>
<td>475</td>
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<tr>
<td>% of Basins</td>
<td></td>
<td>42.1%</td>
<td>33.2%</td>
<td>31.5%</td>
<td>27.4%</td>
</tr>
<tr>
<td>% Change From Previous</td>
<td></td>
<td>-</td>
<td>-8.9%</td>
<td>-1.7%</td>
<td>-4.1%</td>
</tr>
<tr>
<td>% Change From 40mm/hr</td>
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<td>-</td>
<td>-8.9%</td>
<td>-10.6%</td>
<td>-14.7%</td>
</tr>
<tr>
<td>Hazard Classification 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Basins (out of 1736)</td>
<td></td>
<td>929</td>
<td>1135</td>
<td>1172</td>
<td>1249</td>
</tr>
<tr>
<td>% of Basins</td>
<td></td>
<td>53.5%</td>
<td>65.4%</td>
<td>67.5%</td>
<td>71.9%</td>
</tr>
<tr>
<td>% Change From Previous</td>
<td></td>
<td>-</td>
<td>11.9%</td>
<td>2.1%</td>
<td>4.4%</td>
</tr>
<tr>
<td>% Change From 40mm/hr</td>
<td></td>
<td>-</td>
<td>11.9%</td>
<td>14.0%</td>
<td>18.4%</td>
</tr>
</tbody>
</table>

6.1.3 Rank Sum Test

A ranksum analysis was used on the combined hazard (Table 6.5) to test if the 2050 and 2075 models are statistically different from each other and from the 2017 model. The Mann-Whitney U Test was used to analyze the difference between ranksums of two independent groups. The null hypothesis (H = 0) tests that the data in X and Y are from continuous distributions with the same medians. The alternate hypothesis (H = 1) tests that the data in X and Y are not from continuous distributions with the same medians. The ranksum analysis was used on the combined hazard to test to see if the 2050 and 2075 models are statistically different from the 2017 model. The ranksum analysis was also used to check that the 2050 and 2075 models were statistically different from each other. The results of the analysis show that all the models are statistically different from each other except the 46mm/hr and 47mm/hr models. The models were tested with a 5% (α = 0.05) significance level and a flag of H=0 represents a failure to reject the null hypothesis at that level. Table 6.7 shows the model comparisons, the resulting p-value, and the flag result.
Table 6.7 Ranksum analysis results showing all models were statistically different from each other except for the 46mm/hr and 47mm/hr models (blue row).

<table>
<thead>
<tr>
<th>RankSum Analysis</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Input (X,Y)</td>
<td>P - Value</td>
<td>H (Flag)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 46</td>
<td>3.76E-14</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 47</td>
<td>0.0</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 50</td>
<td>0.0</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>46 47</td>
<td>0.1635</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>46 50</td>
<td>2.00E-05</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>47 50</td>
<td>0.003962</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.2 Analysis of Projected Fire Size, Fire Severity, and Rain Intensity Models

6.2.1 Summary Statistics

The calculated post-fire debris-flow likelihood and volume for each basin were exported from ArcGIS and imported into MATLAB. Tables 6.8 and 6.9 show the summary statistics of the likelihood and volume for all three fire models and the 2017 Thomas Fire. Summary statistics consist of mean, 25th percentile (Q1), median, 75th percentile (Q3), and the interquartile range (IQR). The mean, Q1, median, and Q3 all increase with a larger projected rain intensity for both the calculated likelihood and volume values. The IQR of the calculated volumes increases with the projected rain intensities. Conversely, the IQR of the calculated likelihoods decreases with each increase in the projected rain intensity. These trends are consistent with the rain intensity model summary statistics despite the difference in the number of basins.

Table 6.8 Summary statistics of the calculated likelihood of post-fire debris-flow occurrence in the fire models for projected increases in fire size.

<table>
<thead>
<tr>
<th>Post-fire Debris-flow Likelihood Summary Statistics</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>Fire Size (%)</td>
<td># of Basins</td>
<td>Rain Intensity (mm/hr)</td>
<td>RCP Scenario</td>
<td>Mean</td>
<td>Q1</td>
<td>Median</td>
<td>Q3</td>
</tr>
<tr>
<td>2017</td>
<td>100</td>
<td>1736</td>
<td>40</td>
<td>-</td>
<td>80.8%</td>
<td>68.6%</td>
<td>88.8%</td>
<td>98.3%</td>
</tr>
<tr>
<td>2050</td>
<td>154</td>
<td>3115</td>
<td>46</td>
<td>4.5 &amp; 8.5</td>
<td>79.0%</td>
<td>63.3%</td>
<td>89.4%</td>
<td>98.5%</td>
</tr>
<tr>
<td>2075</td>
<td>181</td>
<td>3559</td>
<td>47</td>
<td>4.5</td>
<td>80.8%</td>
<td>67.4%</td>
<td>91.4%</td>
<td>99.9%</td>
</tr>
<tr>
<td>2075</td>
<td>181</td>
<td>3559</td>
<td>50</td>
<td>8.5</td>
<td>83.5%</td>
<td>73.2%</td>
<td>94.0%</td>
<td>99.3%</td>
</tr>
</tbody>
</table>
Table 6.9 Summary statistics of the calculated post-fire debris-flow volume of each basin in the fire models for projected increases in fire size.

<table>
<thead>
<tr>
<th>Year</th>
<th>Fire Size (%)</th>
<th># of Basins</th>
<th>Rain Intensity (mm/hr)</th>
<th>RCP Scenario</th>
<th>Mean (m$^3$)</th>
<th>Q1 (m$^3$)</th>
<th>Median (m$^3$)</th>
<th>Q3 (m$^3$)</th>
<th>IQR (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>100</td>
<td>1736</td>
<td>40</td>
<td>-</td>
<td>6541</td>
<td>849</td>
<td>1645</td>
<td>3900</td>
<td>3051</td>
</tr>
<tr>
<td>2050</td>
<td>154</td>
<td>3115</td>
<td>46</td>
<td>4.5 &amp; 8.5</td>
<td>7157</td>
<td>1214</td>
<td>2659</td>
<td>6440</td>
<td>5225</td>
</tr>
<tr>
<td>2075</td>
<td>181</td>
<td>3559</td>
<td>47</td>
<td>4.5</td>
<td>7234</td>
<td>1256</td>
<td>2842</td>
<td>6614</td>
<td>5358</td>
</tr>
<tr>
<td>2075</td>
<td>181</td>
<td>3559</td>
<td>50</td>
<td>8.5</td>
<td>7868</td>
<td>1366</td>
<td>3091</td>
<td>7193</td>
<td>5827</td>
</tr>
</tbody>
</table>

Figure 6.2 depicts sixteen histograms consisting of likelihood classifications (Like-Class), volume classifications (Vol-Class), combined hazards (Comb-Haz), and the combined hazard classifications (Haz-Class) using the category definitions given earlier. The first row of histograms (Like-Class) shows the distribution of the basins according to their likelihood classifications for each of the four models. The likelihood classification histograms show higher proportions of basins with likelihoods between 80% and 100% (class 5) with each increase in rain intensity, with corresponding decreases in all other classes. The second row of histograms (Vol-Class) shows the distribution of the basins according to their volume classifications for each of the four models. The volume classification histograms show the increase in volumes associated with larger rain intensities. The fourth and final row of histograms (Haz-Class) shows the distribution of the basins according to their combined hazard classifications for each of the four models. The combined hazard classification histograms show the increase in hazard associated with larger rain intensities, especially those in class 3 “High” hazard classification. These trends are consistent with the rain intensity models despite the changes in the number of modeled basins.
6.2.2 Comparative Statistics

The likelihood, volume, and combined hazard classifications, in addition to combined hazard, were broken down by each classification to look at the number of basins and compare the models to each other. Table 6.10 shows the number of basins in each of the five likelihood classifications for each of the four models (40mm/hr, 46mm/hr, 47mm/hr, and 50mm/hr). All four models have a majority of basins with a post-fire debris-flow likelihood between 80% and 100% (Class 5), which is consistent with the rain intensity models.
Table 6.10 Post-fire debris-flow likelihood classifications for the fire models for the projected increase in fire size.

<table>
<thead>
<tr>
<th>Year</th>
<th>2017</th>
<th>2050</th>
<th>2075</th>
<th>Year</th>
<th>2017</th>
<th>2050</th>
<th>2075</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Size %</td>
<td>100</td>
<td>154</td>
<td>181</td>
<td>181</td>
<td>100</td>
<td>151</td>
<td>181</td>
</tr>
<tr>
<td>Number of Debris-flow Basins</td>
<td>1736</td>
<td>3115</td>
<td>3559</td>
<td>3559</td>
<td>Number of Debris-flow Basins</td>
<td>1736</td>
<td>3115</td>
</tr>
<tr>
<td>Rain Intensity (mm/hr)</td>
<td>40</td>
<td>46</td>
<td>47</td>
<td>50</td>
<td>Rain Intensity (mm/hr)</td>
<td>40</td>
<td>46</td>
</tr>
</tbody>
</table>

Class 1 (0%-20%)

| Number of Basins in Class | 6 | 3 | 10 | 9 | Number of Basins in Class | 366 | 513 | 514 | 515 |
| % of Total Basins | 0.3% | 0.1% | 0.3% | 0.3% | % of Total Basins | 21.1% | 16.5% | 14.4% | 14.5% |

Class 2 (20%-40%)

| Number of Basins in Class | 108 | 301 | 287 | 218 | Number of Basins in Class | 1067 | 1900 | 2316 | 2461 |
| % of Total Basins | 6.2% | 9.7% | 8.1% | 6.1% | % of Total Basins | 61.5% | 61.0% | 65.1% | 69.1% |

Class 3 (40%-60%)

| Number of Basins in Class | 189 | 398 | 432 | 356 |
| % of Total Basins | 10.9% | 12.8% | 12.1% | 10.0% |

Table 6.11 shows the number of basins in each of the four volume classifications under each of the four models. All four models have the majority of basins with a volume between 1,000 and 10,000 cubic meters (Class 2), which is consistent with the rain intensity models.

Table 6.11 Post-fire debris-flow volume classifications for the fire models for projected increase in fire size.

<table>
<thead>
<tr>
<th>Year</th>
<th>2017</th>
<th>2050</th>
<th>2075</th>
<th>Year</th>
<th>2017</th>
<th>2050</th>
<th>2075</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Size %</td>
<td>100</td>
<td>154</td>
<td>181</td>
<td>181</td>
<td>100</td>
<td>151</td>
<td>181</td>
</tr>
<tr>
<td>Number of Debris-flow Basins</td>
<td>1736</td>
<td>3115</td>
<td>3559</td>
<td>3559</td>
<td>Number of Debris-flow Basins</td>
<td>1736</td>
<td>3115</td>
</tr>
<tr>
<td>Rain Intensity (mm/hr)</td>
<td>40</td>
<td>46</td>
<td>47</td>
<td>50</td>
<td>Rain Intensity (mm/hr)</td>
<td>40</td>
<td>46</td>
</tr>
</tbody>
</table>

Class 1 (0m³ - 1,000m³)

| Number of Basins in Class | 533 | 643 | 732 | 670 | Number of Basins in Class | 220 | 506 | 609 | 662 |
| % of Total Basins | 30.7% | 20.6% | 20.6% | 18.8% | % of Total Basins | 12.7% | 16.2% | 17.1% | 18.6% |

Class 2 (1,000m³ - 10,000m³)

| Number of Basins in Class | 969 | 1952 | 2204 | 2209 | Number of Basins in Class | 14  | 14  | 14  | 18  |
| % of Total Basins | 55.8% | 62.7% | 61.9% | 62.1% | % of Total Basins | 0.8% | 0.4% | 0.4% | 0.5% |

Table 6.12 shows the number of basins with the same combined hazard for each of the four models. The three projected fire models show a majority of basins with a combined hazard of 7 and a combined hazard of 8. These results vary from the rain intensity models in that the majority of the basins had a combined hazard of 7 and 6.
Table 6.12 Post-fire debris-flow combined hazards for the fire models for the projected increase in fire size.

<table>
<thead>
<tr>
<th>Year</th>
<th>Fire Size %</th>
<th>Fire Size %</th>
<th>Number of Debris-flow Basins</th>
<th>Number of Debris-flow Basins</th>
<th>Rain Intensity (mm/hr)</th>
<th>Rain Intensity (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2017 2050 2075</td>
<td>2017 2050 2075</td>
<td>1736 3115 3559 3559</td>
<td>1736 3115 3559 3559</td>
<td>40 46 47 50</td>
<td>40 46 47 50</td>
</tr>
</tbody>
</table>

Table 6.13 Post-fire debris-flow combined hazard classification for the fire models for the projected increase in fire size.

<table>
<thead>
<tr>
<th>Year</th>
<th>Fire Size %</th>
<th>Fire Size %</th>
<th>Number of Debris-flow Basins</th>
<th>Number of Debris-flow Basins</th>
<th>Rain Intensity (mm/hr)</th>
<th>Rain Intensity (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2017 2050 2075</td>
<td>2017 2050 2075</td>
<td>1736 3115 3559 3559</td>
<td>1736 3115 3559 3559</td>
<td>40 46 47 50</td>
<td>40 46 47 50</td>
</tr>
</tbody>
</table>

Table 6.13 shows the number of basins in each combined hazard classification for each of the four models. All four models show a majority of their basins have a high-hazard classification which is consistent with the rain intensity models.
6.2.3 Rank Sum Test

The Mann-Whitney U Test (Ranksum test) analysis was used on the combined hazard classification (Table 6.12) to test whether the 2075 RCP4.5 and RCP8.5 models are statistically different from each other. The other models were not compared to each other since the difference in the number of basins will result in a statistical difference when using a ranksum analysis. The models were tested with a 5% ($\alpha = 0.05$) significance level and a flag of H=0 represents a failure to reject the null hypothesis at that level. Table 6.14 shows the model comparison, the resulting p-value, and the flag result. The two 2075 models are statistically different from each other.

Table 6.14 Ranksum analysis results showing the 2075 models were statistically different from each other.

<table>
<thead>
<tr>
<th>RankSum Analysis</th>
<th>Input (X,Y)</th>
<th>P - Value</th>
<th>H (Flag)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>47</td>
<td>50</td>
<td>4.80E-04</td>
</tr>
</tbody>
</table>

6.3 Comparison of Rain Intensity and Fire Models

When simultaneously comparing all the rain and fire models, all the models (Table 6.15), show a larger total volume of debris flows and a higher percentage of high-hazard basins. This is expected: higher rainfall intensity in the future and larger wildfires both result in increased debris-flow volume and likelihood, which results in an increased number of high-hazard basins.

Table 6.15 A comparison of all models.

<table>
<thead>
<tr>
<th>Comparison of Rain Intensity and Fire Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>2017</td>
</tr>
<tr>
<td>2050</td>
</tr>
<tr>
<td>2080</td>
</tr>
<tr>
<td>2075</td>
</tr>
<tr>
<td>2075</td>
</tr>
<tr>
<td>2075</td>
</tr>
<tr>
<td>2075</td>
</tr>
</tbody>
</table>
6.4 Uncertainty, Error, and Reasonableness of Models and Analysis

6.4.1 Uncertainty in USGS Likelihood and Volume Equations

The likelihood equation was developed using regression analysis. Each variable in the logistic model equation has a 90% significance and the equation is best used in the western United States (Staley et al., 2017). The volume equation was also developed using regression analysis and had an $R^2$ of 67.0%. During their analysis, the Gartner et al. (2014) model predicted 100% of their volumes with a 95% prediction interval. The $R^2$ values and the significance levels provide room for uncertainty in these models. The volumes and likelihoods calculated in this research are not 100% accurate however they provide values reasonable enough to quantify the hazard. These equations produce reasonable estimates of post-fire debris-flow likelihood and volume for the western United States and are assumed to be reasonable in this analysis.

6.4.2 Uncertainty in Temperature and Rain Intensity Scaling

The estimates of change in temperature are an average of 4 climate models. The change in average temperature may vary depending on different emissions scenarios and other influences. The range of the Representative Concentration Pathways is expected to capture a reasonable range of future average temperature increases. The estimated temperature increases using Cal-Adapt (2021) fall within the projected temperature ranges described in technical literature and are therefore assumed to be reasonable. The rain intensities were scaled by 7% using the Clausius-Clapeyron relation. The rainfall intensity is likely to increase concurrently with the atmospheric moisture capacity, which is at about 7%, with some small range of variability in this assumption (Westra et al., 2014). There is uncertainty in the modeling capabilities of Global Climate Models. These uncertainties propagate from the accuracy of GCMs and the resulting use of the GCMs to estimate different changes in weather patterns and fire regimes. However, these models are the most accurate and most current method used to estimate changes in climate.

6.4.3 Uncertainty in Laharz Equations and Models

The Laharz equations represent a 50th percentile distribution for both the A and B equations with an $R^2$ of 69% and 70%, respectively (Bernard et al., 2021). The $R^2$ values and the distribution in the Laharz equations means the modeled runout can be larger or smaller than what
was produced. However, these equations will produce reasonable estimates of post-fire debris-flow inundation with the Laharz program at least in terms of runout length, as seen in the San Ysidro comparison model.

6.4.4 Uncertainty in Fire Size, dNBR, and Fire Severity

Fire size change by the year 2050 was projected to increase by 54% with an error of +10% to -25% depending on the ecoregion and was significant using a student’s t-test (p = 0.03) (Spracklen et al., 2009). The projected fire size burn area does not represent how the fire would naturally spread and burn in the area of interest. Since fire size varies depending on field conditions, the fire size has uncertainty. However, the fire size projections used are found within the ranges seen in technical literature and, therefore, can be assumed to be reasonable.

The use of dBNR has been shown to have a high correlation to soil burn data (Lutes et al., 2006). Soil burn severity is a classification of dNBR data; in this analysis, the burn severity was scaled to each of the fire boundaries. The scaling of this data does not represent how the burn severity would be naturally distributed within the modeled areas. Additionally, the dNBR values were calculated using averages of the ranges of the dNBR value classifications for burn severity. This inherently will give uncertainty to the models; however, these models are meant to be representative of how climate change will expand and change hazards and give a reasonable estimate of dNBR and soil burn severity.

6.4.5 Uncertainty in Basin Size and Point Placement.

The basins generated for the fire models were created using different methods than those produced by USGS. The difference in the methods to place pour points and generate basins may show a slight difference in basin shape and size. However, these basins were created using a reasonable approach and will give results similar to those basins produced using LANDFIRE.

6.4.6 Sources of Error and Reasonableness of Models

Inherently there may be human error in the models generated in this research. Human error could have also occurred in the data that was imported into and used in this research. The data imported and used in this research also has tolerances for accuracy in the collection methods. Another source of error is the range of error within the global climate model estimations of temperature and other data that is projected using RCP scenarios. Defining a
range of error for these models is exceptionally difficult when working with a large amount of data from many different sources. These errors will propagate through the models and affect the results. However, the methods and values used for the models fell within ranges defined by technical literature or provide a reasonable result for the purpose of the models. These models were created to show how climate change will affect post-fire debris-flow likelihood, volume, hazard, and runout using reasonable means. These models should be viewed as a reasonable representation of the increase in post-fire debris-flow hazards under climate change.
CHAPTER 7 DISCUSSION

The models created in this research show the expansion of hazards under climate change on the Thomas Fire. While many of the variables used to generate these models have uncertainties, these values are intended to represent a realistic response to climate change of a future fire in the Thomas Fire area. This is supported by the consistent trends in the statistics in both the rain and fire models.

7.1 Rain Intensity Models

The rain intensity models predict an increase in debris-flow hazards. The likelihoods and volumes of the debris flows increased under the changes in rain intensities, which resulted in more high-hazard basins. The models accounting for rainfall intensity changes show an increase in high-hazard basins of approximately 12% by 2050 and 14% to 18% by 2075 when compared to 2017. This is an unsurprising result since the volume and likelihood of post-fire debris flows are directly influenced by the increase in rainfall intensity. However, it quantifies how much the hazard is predicted to increase.

7.2 Laharz Runout Models

The Laharz runout models show an increase in debris-flow inundation with increasing rainfall intensity in the future, mostly in the form of longer runout paths. For example, the San Ysidro Laharz runout followed the path of the original debris flow, although it did not cover the entire original mapped inundation area. Furthermore, Laharz does not readily simulate avulsion or lateral spread very well. Using San Ysidro as a template, then, the Laharz modeling of other drainage basins, included in Appendix B, are expected to provide reasonable estimates of changing runout length, indicating the increasing impacts of debris flows under a changing climate, but do not provide an indication of the change in the spreading or avulsing nature of the debris-flow deposit. In general, the larger the basin, the larger the increase in inundation with each increase in rain intensity under climate change.

7.3 Fire Models

When looking at expected increases in fire size, the models show an increase not only in the area impacted, but also in the hazard level of drainage basins. The 2050 model predicts 6% more high-hazard basins, and the 2075 models predict 10% to 13% more high-hazard basins
when compared to 2017. The results of the models also show that increasing the fire size also increases the likelihood and volume of post-fire debris flows.
CHAPTER 8 CONCLUSIONS

Climate change will have an influence on the factors that increase the likelihood for fires to occur, which in turn will lead to more post-fire debris flows. With increased fire season length, increased drought conditions, increased lightning strikes, and hotter surface temperatures, the size, frequency and possibly severity of fires in the western United States will likely increase. A burned landscape decreases the rain intensity initiation thresholds for debris flows, while climate change will increase the frequency and intensity of rainstorms. Rainfall intensities may increase by 7% for every increase in global average temperature Celsius and larger storms may become more frequent. These climate conditions, when combined, increase the hazard posed by post-fire debris flows. These increases may also cause more interactions between post-fire debris flows and wildland urban interfaces (WUI).

Using available data and technical literature values, fire size, fire severity, and design storm rain intensities were projected to the years 2050 and 2075. Three sets of models were created to show the changes in the Thomas Fire under climate change. The first set of models kept the fire conditions of the Thomas Fire the same but included scaled rainfall intensities. These models accounting for rainfall intensity changes show an increase in high-hazard basins of approximately 12% by 2050 and 14% to 18% by 2075 when compared to 2017. The second set of models use the estimated volumes of debris flows to generate 36 runout inundation models. The runout models show an increase in debris-flow inundation with increasing rainfall intensity in the future, mostly in the form of longer runout paths. The last set of models incorporates increases in fire size, fire severity, and rain intensity. The 2050 model predicts 6% more high-hazard basins, and the 2075 models predict 10% to 13% more high-hazard basins when compared to 2017. Implementing climate change projections into post-fire debris-flow likelihood and volume calculations resulted in increased hazard and runout for all models. Implementing climate changes onto the Thomas Fire showed larger burned areas and a higher percentage of high-hazard basins. The results of this project in combination with the background information show that climate change will increase post-fire debris-flow hazard and inundation in the western United States.

To protect communities from the increase in these hazards, geo-engineers will need to inform themselves about climate change and incorporate those changes into their post-fire debris-flow engineering and community hazard management plans. Additionally, geohazard engineers
should consider the fire-burn potential during site investigation and the possible post-fire debris flows associated with the burn. Lastly, geo-engineers should consider informing communities in fire-prone areas about post-fire debris-flow hazards before the fire occurs. Further study could include standardized methods for geohazard engineers to assess the potential for post-fire debris flows during a standard site investigation in a wildland urban environment.
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averages/

started fires are becoming larger and more frequent over a longer season length in the

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APPENDIX A RAIN MODELS

Figure A.1 2050 RCP4.5&8.5 model showing the calculated likelihood of a debris flow following a 15min-46mm/hr design rainstorm event.

Figure A.2 2075 RCP4.5 model showing the calculated likelihood of a debris flow following a 15min-47mm/hr design rainstorm event.
Figure A.3 2050 RCP4.5&8.5 model showing the calculated volume of a debris flow if generated by a 15min-46mm/hr design rainstorm event.

Figure A.4 2075 RCP4.5 model showing the calculated volume of a debris flow if generated by a 15min-47mm/hr design rainstorm event.
Figure A.5 2050 RCP4.5 & 8.5 model showing the combined likelihood and volume hazard of a debris flow from a 15min-46mm/hr design rainstorm event.

Figure A.6 2075 RCP4.5 model showing the combined likelihood and volume hazard of a debris flow from a 15min-47mm/hr design rainstorm event.
APPENDIX B LAHARZ RUNOUT MODELS

Group Basin Runouts

Figure B.1 Laharz runout model of the four calculated volumes for group basin ID 23645. Note only three inundations were produced because the difference in volume between the 46mm/hr and the 47mm/hr was not significant enough to inundate another cell.

Figure B.2 Laharz runout model of the four calculated volumes for group basin ID 24680.
Figure B.3 Laharz runout model of the four calculated volumes for group basin ID 23227.

Figure B.4 Laharz runout model of the four calculated volumes for group basin ID 23139.
Figure B.5 Laharz runout model of the four calculated volumes for group basin ID 22668. Note only two inundations were produced because the difference in volume between the 40mm/hr and both the 46mm/hr and the 47mm/hr was not significant enough to inundate another cell.

Figure B.6 Laharz runout model of the four calculated volumes for group basin ID 22629.
Figure B.7 Laharz runout model of the four calculated volumes for group basin ID 22621.

Figure B.8 Laharz runout model of the four calculated volumes for group basin ID 22075.
Figure B.9 Laharz runout model of the four calculated volumes for group basin ID 21224.

Figure B.10 Laharz runout model of the four calculated volumes for group basin ID 21009.
Figure B.11 Laharz runout model of the four calculated volumes for group basin ID 20504.

Figure B.12 Laharz runout model of the four calculated volumes for group basin ID 20499.
Figure B.13 Laharz runout model of the four calculated volumes for group basin ID 20386. Note only three inundations were produced because the difference in volume between the 46mm/hr and the 47mm/hr was not significant enough to inundate another cell.

Figure B.14 Laharz runout model of the four calculated volumes for group basin ID 20384.
Figure B.15 Laharz runout model of the four calculated volumes for group basin ID 20308.

Figure B.16 Laharz runout model of the four calculated volumes for group basin ID 19777.
Figure B.17 Laharz runout model of the four calculated volumes for group basin ID 19167. Note only three inundations were produced because the difference in volume between the 46mm/hr and the 47mm/hr was not significant enough to inundate another cell.

Figure B.18 Laharz runout model of the four calculated volumes for group basin ID 19165.
Figure B.19 Laharz runout model of the four calculated volumes for group basin ID 13002.

Figure B.20 Laharz runout model of the four calculated volumes for group basin ID 12341.
Figure B.21 Laharz runout model of the four calculated volumes for the high-hazard basin ID 12919.

Figure B.22 Laharz runout model of the four calculated volumes for the high-hazard basin ID 7215.
Figure B.23 Laharz runout model of the four calculated volumes for the high-hazard basin ID 16984.

Figure B.24 Laharz runout model of the four calculated volumes for the high-hazard basin ID 18447.
Figure B.25 Laharz runout model of the four calculated volumes for the high-hazard basin ID 18640.

Figure B.26 Laharz runout model of the four calculated volumes for the high-hazard basin ID 19763.
Figure B.27 Laharz runout model of the four calculated volumes for the high-hazard basin ID 21157.

Figure B.28 Laharz runout model of the four calculated volumes for the high-hazard basin ID 22516.
Figure B.29 Laharz runout model of the four calculated volumes for the high-hazard basin ID 23860.

Figure B.30 Laharz runout model of the four calculated volumes for the high-hazard basin ID 24989.
Figure B.31 Laharz runout model of the four calculated volumes for the high-hazard basin ID 31999.

Figure B.32 Laharz runout model of the four calculated volumes for the high-hazard basin ID 33905.
Figure B.33 Laharz runout model of the four calculated volumes for the high-hazard basin ID 34360.
APPENDIX C FIRE MODELS

Figure C.1 2050 RCP4.5&8.5 model showing the calculated likelihood of a debris flow following a 15min-46mm/hr design rainstorm event for 154% fire size.

Figure C.2 2075 RCP4.5 model showing the calculated likelihood of a debris flow following a 15min-47mm/hr design rainstorm event for 181% fire size.
Figure C.3 2075 RCP8.5 model showing the calculated likelihood of a debris flow following a 15min-50mm/hr design rainstorm event for 181% fire size.

Figure C.4 2050 RCP4.5&8.5 model showing the calculated volume of a debris flow if generated by a 15min-46mm/hr design rainstorm event for 154% fire size.
Figure C.5 2075 RCP4.5 model showing the calculated volume of a debris flow if generated by a 15min-47mm/hr design rainstorm event for 181% fire size.

Figure C.6 2075 RCP8.5 model showing the calculated volume of a debris flow if generated by a 15min-50mm/hr design rainstorm event for 181% fire size.