Advancing debris flow hazard and risk assessments using debris flow modeling and radar derived rainfall intensity data

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Abstract. Debris flow hazard and risk assessments are critical tools in mitigating and planning forthese events. Existing debris flow hazard assessments can provide a rapid view of the likelihood of debris flows in recently burned watersheds and along stream segments within the watershed. Furthermore, debris flow volumes can be predicted for these watersheds and along the stream segments. Advances in modeling and remote-sensing data can add further value to the rapid assessments. Here, modeled debris flow volumes and a more detailed understanding of rainfall conditions highlight a need to reconcile debris flow probabilities and volumes using local conditions. Modeled debris flow volumes are consistently lower than even the lowest predicted volumes from empirical models used in the debris flow hazard assessments. Watershed probability and volume relations also over predict based on our probabilities derived from rainfall intensity from Multi-Radar/Multi-Sensor System 1-hr data. Probability and volume measures needto be further considered as the conservative measures of the rapid assessments have implicationfor risk analyses required for planning and management decisions, and ultimately for design and cost of mitigation to manage risk.

1 Introduction

Prediction of post-wildfire debris flows has been a constant theme of geomorphology and geohazard research. Climate change has been linked to increased magnitude and frequency of wildfires in many parts of the world [1] and an expected increase of extreme rainfall following wildfires [2], which have further complicated this understanding as well as heightened the need for scientists and engineers to rapidly advance our understanding of post-wildfire debris flow initiation, runout, and inundation.

Knowledge of debris flow initiation has grown incrementally through investigations of rainfall intensity-duration thresholds [3, 4], landslide-generated debris flows [5, 6], progressive sediment-bulking [7], and sediment availability [8] among others. While significant advances have been brought about by these, and other studies, there is a need for further developments that inform models and allow us to predict the likelihood of debris flow occurrence, runout, and volumes to better assess the potential for debris flow hazards and risks.

Here, a combination of rainfall intensity thresholds and debris flow modeling provide new insights into the likelihood of debris flows, as well as begin to advance our understanding of debris flow volume estimates. These findings help advance analyses beyond the watershed approaches commonly used for debris flow hazard assessment and volume measurement tools used in the United States. The findings provide further information to inform debris flow hazard and risk analyses and aid communities, government agencies, and industry recognize and mitigate these hazards.

1.1 Current US debris flow hazard assessment

The most utilized emergency (rapid) assessment of post-fire debris flow hazards in the United States of Americacontinues to be the model (referred to USGS Model) developed by the United States Geological Survey Landslide Hazards program [4, 9]. The likelihood modelproduces probability and volume of debris flow data forrecently burned areas using inputs from basin shape and size, topography, soil burn severity, soil properties, and 15-minute rainfall intensity. The debris flow likelihood model is based on a logistic regression approach to predict the probability of debris flows at the watershed and stream segment level as a percentage of the likelihood [4]. Volume calculations are derived from multiple linear regression models that estimate the volume of material at point within the watershed, as wellas at the outlet of the watershed [10]. The approach has been used broadly across Western United States but haslargely been based on research and findings developed from Southern California.

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1.2 Current knowledge on debris flows

There have been strong links made to rainfall thresholds and shallow landslide and debris flow formation in a variety of locations [11]. This work was grounded in landslide triggering thresholds from Caine 1980 [12]. Initial empirically derived post-wildfire rainfall ID thresholds were developed for Southern California by Cannon et al. [13] and expanded upon by Staley et al. [3]. The <60-minute rainfall intensities were identified as important from this initial work. The 15-min duration thresholds were later found to lead to the most accurate predictions of the post-wildfire debris flow initiation in the USGS logistic regression equations and field measurements [14], which are well identified for Southern California and other locations in the Western US. Recent research has identified the potential for variability in the rainfall ID thresholds based on climate, geology, and hydraulic properties of burned soils [15], which has implications for refining this type of modeling approach.

Predictive models of post-wildfire debris flow occurrence, magnitude, and volumes have been used frequently. The model used in the USGS debris flow hazard assessment is an empirical model developedfrom data in Southern California [10]. This model relieson sediment volumes from debris flows and debris floods derived from debris-retention basins at watershedoutlets. New models have extended analyses to estimate the amount of post-wildfire debris flow sediment transported throughout watershed [16] and to alluvial fans [17]. Other recent modeling experiments have identified topography, burn severity, and the percent soil organic matter following wildfire to be more important than rainfall when predicting debris flow volumes [18]. Sediment sources are being more widely recognized as key contributors to debris flow development and propagation [8].

2 Study areas

The focus is on three wildfires, Cameron Peak, East Troublesome, and the Grizzly Creek Fires, occurring in 2020 - an active wildfire season in Colorado (Fig.1). The Cameron Peak Fire was reported on August 13, 2020, and burned an area of 84,544 ha over 112 days. The East Troublesome Fire was reported on October 14, 2020, and consumed 78,437 ha over 47 days. The Grizzly Peak Fire started on August 10, 2020, and consumed 13,205 ha over 130 days.

3 Methods

We mapped the post-wildfire landslides from several storms of varying intensity the year after the Grizzly Creek Fire. One-hour rainfall intensity data from the Multi-Radar/Multi-Sensor System (MRMS) were collected to aid in the development of a rainfall intensity and probability/ha/duration relationship for the Grizzly Peak Fire. MRMS data were clipped to the Grizzly Creek Fire perimeter and interpolated to hectare-sized grids. Known debris flow locations from outlets along Interstate-70 were linked to watersheds.

Fig. 1. Subject wildfire locations in Colorado, USA.

A total of 329 initiation points identified from Goggle Earth Imagery were linked to the nearest watershed that experienced adebris flow. A landslide mask that aligned to the griddedprecipitation data was developed and used to estimate the time of landslide occurrence at a maximum 1-hr rainfall intensity based on the nearest known debris flowat the outlet of a watershed. Rainfall was grouped into 1mm/hr intensity bins and the number of landslides perbin were used to estimate a probability (Fig. 2).

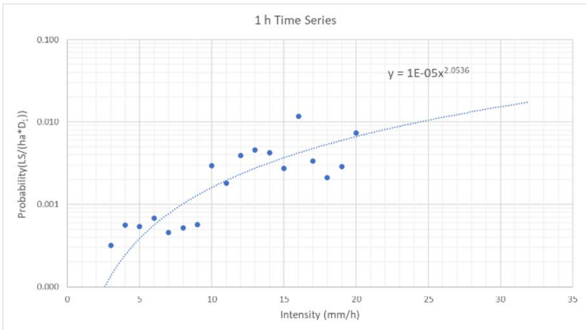

Fig. 2. Probability of landslides per hectare from GrizzlyCreek Fire.

The 15-min rainfall intensity was extracted near thehead of multiple watersheds in each of the wildfires to develop an understanding of the return interval for the peak 15-minute intensity of 24 mm/h used in the USGS debris flow assessment.

Debris flow modeling was performed using DebrisFlow Predictor [19], which is a probabilistic cellular automata model. Models were locally calibrated using a variety of parameters at each of the fires.

Debris flow volumes generated from the USGS Debris Flow Hazard Assessment, and from our model were compared for the Cameron Peak, Grizzly Creek, and East Troublesome study areas across USGS definedwatersheds.

Modeled debris flow outputs were compared to the corresponding minimum USGS debris flow volumes across all drainage sizes and to typical USGS debris flow volumes at four subbasins. For each USGS basin throughout the study areas, the total modeled volume was calculated as the sum of all debris flow volumes along the runout paths that initiated from the corresponding USGS basin.

4 Results

Across all drainage basin sizes, the modeled debris flowvolume is like, but less than, the minimum volume calculated by the USGS (***Fig.3***). The contrast between the modeled volumes versus USGS minimum debris flow volume is consistent regardless of drainage basin size or differences between wildfires.

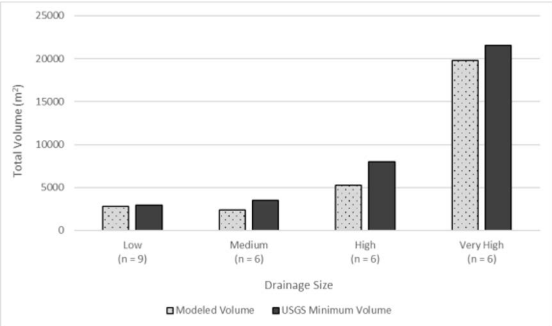

Fig. 3. Comparison of USGS volumes and modeled debris flow volumes across drainage basin size at Cameron Peak study area.

To better understand the difference between our model and the USGS model, and perhaps refine the post-wildfire hazard assessment, results from four typical sub-basins with high burn severity were examined (Table 1). Probability is largely driven by burn severity irrespective of basin size. Further, the volumes estimated would require an unusually large percentage of the basins to be subject to landslides.

Table 1. USGS debris flow probability and volume at watershed-scale.

Fire	**Basin Name**	**USGS Basin Landslide Probability**	**Basin Area (km^2)**	**Volume (m^3)**
Grizzly Ck	Blue Gulch	0.684	4.6	32206
Grizzly Ck	Unnamed	0.6	1.8	16510
Cameron Pk	Unnamed	0.677	0.1	16269
Cameron Pk	Sheep Gulch	0.623	7.5	32206

To refine the estimates of debris flow activity, we use the relation from Figure 2 to adjust for the area-based probability of severely burned watersheds (Table 2). The likelihood of at least one landslide is higher for larger watersheds and probabilities for more than one landslide decline rapidly for smaller basins (Table 2). Typical modeled volumes for an individual landslide within the study areas is small, while interactions between landslides leads to larger expected debris flow volumes. However, these volumes do not reach the magnitude of the medium volume calculations from USGS assessments (Table 1). It is the authors' belief that this latter approach provides better approximation of hazards by accounting for burned ground exposed to high intensity rainfall.

Table 2. Probabilities for the number of potential debris flows from recently burned watershed.

Fire	**Basin Name**	**USGS Basin Landslide Probability**	**Basin Area (km^2)**	**Probability of at least n landslides**						
				1	**2**	**3**	**4**	**5**	**6**	**7**
Grizzly Ck	Blue Gulch	0.684	4.6	0.953	0.804	0.574	0.342	0.171	0.073	0.027
Grizzly Ck	Unnamed	0.6	1.8	0.697	0.323	0.105	0.025	0.004	0	-0.0006
Cameron Pk	Unnamed	0.677	0.1	0.066	0.002	0	-4E-05	-4E-05	-4E-05	-4E-05
Cameron Pk	Sheep Gulch	0.623	7.5	0.993	0.958	0.868	0.718	0.532	0.351	0.206
Typical modeled landslide size in m^3				**1837**	**3674**	**5511**	**7348**	**9185**	**11022**	**12859**

5 Conclusions

Our initial findings show a disparity in the debris flow volumes developed by the different approaches. These differences have direct implications for designing mitigation prior to and after wildfires. The larger volumes derived from the USGS empirical equations would provide a more conservative measure requiring more substantial structures to address the loads, impacts, runups and volumes of material released in the event of debris flow. Building this structure(s) would also potentially reduce the risk to communities and infrastructure. However, the cost-benefit ratio of designing to this level might be cost prohibitive. We acknowledge further modeling and research is required to understand why these volumes differ and what are best design criteria would be once these volumes are more thoroughly reconciled. Our experience indicates that the approaches presented here permit us to model debris flows using a more nuanced view of debris flow initiation likelihoods in the watersheds which improves our capabilities to assess risk to infrastructure and properties. Further refinement and validation of these approaches will enhance our ability to identify the potential for debris flow initiation, assess runout and inundation before and after wildfires, and provide a more detailed understanding of the risk to property and lives.

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