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# Constraining post-fire debris-flow volumes in the southwestern United States

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**Abstract.** Debris flows pose a serious threat to human life and infrastructure in downstream areas following wildfire. This underscores the necessity for having a hazard assessment framework in place that can be used to estimate the impacts of post-wildfiredebris flows. Current hazard assessments in the western United States (USA) use empirical models to assess the volume of potential post-wildfire debris flows. Volume models provide information regarding the magnitude and potential downstream impacts of debris flows. In this study, we gathered post-wildfire debris-flow volume data from 54 watersheds across the states of Arizona (AZ) and New Mexico (NM), USA, and compared these data to the output of a widely used empirical post-wildfire debris-flow volume model. Results show that the volume model, which was developed using data from the Transverse Ranges of southern California (CA), tends to overestimate observed volumes from AZ and NM, sometimes by several orders of magnitude. This disparity may be explained by regional differences between southern CA and AZ and NM, including differences in sediment supply. However, we found a power- law relationship between debris-flow volume and watershed area that can be used to put first-order constraints on debris-flow volumein AZ and NM.

## 1 Introduction

Debris flows are fast-moving mixtures of sediment and water that occur in mountainous regions across the world. They are especially common, however, on steep slopes recently burned by wildfire. Wildfires reduce vegetation cover [1,2] and alter soil hydraulic properties [3-5], making burned slopes particularly susceptible to runoff generated debris flows [6]. Post-wildfire debris flowspose a significant threat to human life [7,8] and downstream infrastructure, including roads, bridges, and houses [8,9]. These threats have been accentuated in recent years by increases in population along the wildland-urban interface (WUI) [10] and increases inwildfire size, frequency, and severity [11].

The threat posed by post-wildfire debris flows underscores the necessity for having a well-established hazard assessment framework that can be used to estimate the potential impacts of debris flows. Current hazard assessment frameworks in the western United States (USA) often consider post-wildfire debris-flow likelihood [12,13] and volume [14,15]. Likelihood models can help identify which burned watersheds are the most susceptible to debris flows, but they provide little information regarding the downstream impacts of these events. Volume models strengthen hazard assessments by providing an estimate of debris-flow magnitude. They also provide insight into the potential for downstream effects, as debris-flow discharge and runout tend to increase with volume [16,17]. Furthermore, volume is an important input for inundation models that can be used to identify and delineate downstream areas that are most susceptible to debris flow impacts [18,19].

Accurate post-wildfire debris-flow volume models are therefore a critical element of hazard assessments. Currently, the most widely used post-wildfire debris-flow volume model in the western USA is the Emergency Assessment empirical model developed by [15]. The model was developed using data from the Transverse Ranges of southern California (CA). Given the importance of debris-flow volume when assessing downstream impacts, it is critical to collect additional data on post-fire debris-flow volume from a wider range of geologic and climatic settings. It is challenging, in general, to collect data to develop and test post-wildfire debris-flow volume models because debris flows often occur in combination with floods that erode and rework deposits. In this study, we gathered post-wildfire debris-flow volume data from 54 watersheds across the states of Arizona (AZ) and New Mexico (NM), USA. We compare these data with the Emergency Assessment model [15] and provide hypotheses for apparent differences. We also determine a power law relationship between debris-flow volume and watershed area for our study sites in AZ and NM, similar to those calculated for other regions across the world [20].

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## 2 Study Sites

We gathered data for this study from 14 burn scars across the states of AZ and NM in the southwestern USA (Fig. 1). This region is characterized by having a warm year-round climate and low annual precipitation. It is also known for the North American monsoon, a phenomenon that produces nearly 50% of the region's total annual precipitation between the months of July-September. Monsoonal storms are often short in duration but can produce high intensity rainfall [21]. Due to the high interannual and decadal variability in monsoonal rainfall, droughts are not uncommon in this region. Since 2000, the southwestern USA has been mired in its worst megadrought since at least the year 800 CE [22].

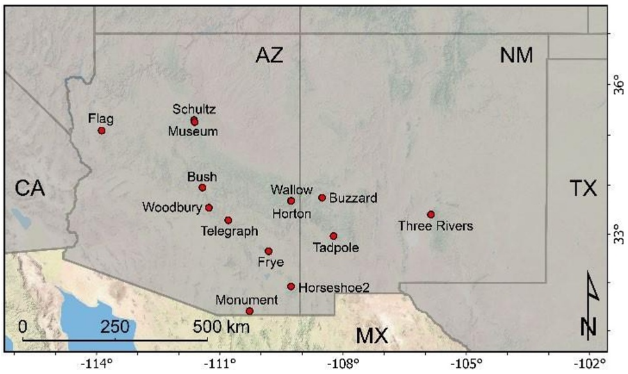


**Fig. 1.** We studied 54 debris flow-producing watersheds across 14 burn scars in Arizona (AZ) and New Mexico (NM), USA.

Over that same time period, the region has seen an increase in large and high severity wildfires [23]. Our study spans the burn scars of 14 wildfires that burned in the southwestern USA between 2010 and 2021. These fires burned through a range of vegetation communities, from the Sonoran Desert at low elevations, to chapparal and scrubland communities at moderate elevations, and ponderosa pine and mixed conifer forests at higher elevations.

For this study, we gathered volume data for 54 debris-flow producing watersheds across the 14 burn scars. These watersheds varied in area from 0.01 $km^2$ to 5.69 $km^2$, and in average slope from 11.9° to 48.4°. They also varied in burn severity as eight watersheds burned at 0% moderate or high severity, while others burned at over 80% moderate or high severity. Most of the watersheds we studied were located entirely on public land and were undeveloped. Subsequently, the debris flows they produced had little/no impact on infrastructure and human life. However, several debris flows, including those at the Woodbury Fire (Fig. 1) severely damaged roads resulting in multi-year closures. One debris flow, which occurred at the Flag Fire (Fig. 1) damaged a private house.

## 3 Methods

### 3.1 Volume Measurements

We measured the volume of sediment deposited by 55 post-wildfire debris-flows from 54 debris flow-producing watersheds. For all of the debris flows that occurred between 2019-2021 (33 of the 55 debris flows), we measured the volume of the deposits in the field. We used either a measuring tape or laser range finder to measure the length of every edge of each deposit. We used these measurements, in conjunction with the azimuth of each measurement, to calculate the area of the deposits. We collected depth measurements at locations where we could easily distinguish the debris-flow deposits from the pre-event surface, such as the edge of the deposit or where subsequent flood flow incised through the debris-flow deposits. We averaged theses values to calculate the depth of the deposit. Then, we multiplied the average depth by the area of the deposit to calculate the debris-flow volume.

For the 22 debris flows that occurred before 2019, we used a variety of methods to calculate the volume of the flow. For 4 of the debris flows, we made pre-event and post-event channel cross-section measurements and calculated the amount of material that was removed from the channel. For the remaining debris flows, we identified deposits on the ground and took GPS points as well as depth estimates. We then used aerial photographs at a scale of 1:12000 to estimate the extent of deposits and to calculate the area. We calculated volumes using the information regarding deposit area and depth [24].

### 3.2 Comparison with Established Methods

After we collected the post-wildfire debris-flow volume data from AZ and NM, we assessed how the Emergency Assessment model [15] performed when compared to the observed volumes. This model predicts the volume of sediment produced by debris flows within two years of a wildfire using the equation:

$$Ln(V) = 4.22 + 0.39\sqrt{ii15} + 0.36\ln Bmh + 0.13\sqrt{R} \quad (1)$$

where $V$ is the volume of sediment ($m^3$), $i15$ is the peak rainfall intensity over a 15-minute period (mm/h), $Bmh$ is the watershed area burned at moderate and high severity ($km^2$), and $R$ is the watershed relief (m) [15].

In order to calculate the predicted volume for each of the 54 watersheds that we studied, we first calculated the values of each of the three input parameters required by the Emergency Assessment model [15]: $i15$, $Bmh$, and $R$. We collected rainfall data using rain gauges that were installed within 3 km of the outlet of each watershed. We used this rainfall data to calculate $i15$. We used soil burn severity data from the Burned Area Emergency Response (BAER) program to calculate the $Bmh$ within each watershed. Finally, we used 10m resolution digital elevation models (DEM) to calculate $R$ for each watershed. We then used the Emergency Assessment model [15] to calculate a debris-flow volume for each of the 54 watersheds for which we had observed volumes.

We also studied the relationship between post-wildfire debris-flow volume and watershed area. Previous studies determined power law relationships for debris-flow volume as a function of watershed area using data from CA and the Intermountain West [20]. We compared the best fit power law for our data to the best fit power for two datasets from [20]: the WUS <1 and WUS 1-3 datasets. The WUS <1 dataset contains debris flows from burned basins in the western USA that occurred within one year following wildfire, and the WUS 1-3 dataset contains debris flows from burned basins in the western USA that occurred between one and three years after wildfire. We compared our data to these two datasets because all of our debris flows occurred within the first three yearsfollowing wildfire.

## 4 Results and Discussion

The debris flows we observed ranged in volume from 25 $m^3$ to 14,000 $m^3$. Most of the debris flows (39 of 55 or 71%) had volumes between 100 $m^3$ and 10,000 $m^3$. Twelve of the debris flows (22%) were less than 100 $m^3$ in volume, while only 4 debris flows (7%) had a volume greater than 10,000 $m^3$. The mean debris-flow volume in our dataset was 2105 $m^3$. The maximum and mean volumes for our AZ and NM dataset are much lower than those of the 92 debris-flow volumes used to develop the Emergency Assessment model [15], which were 864,308 $m^3$ and 46,198 $m^3$, respectively.

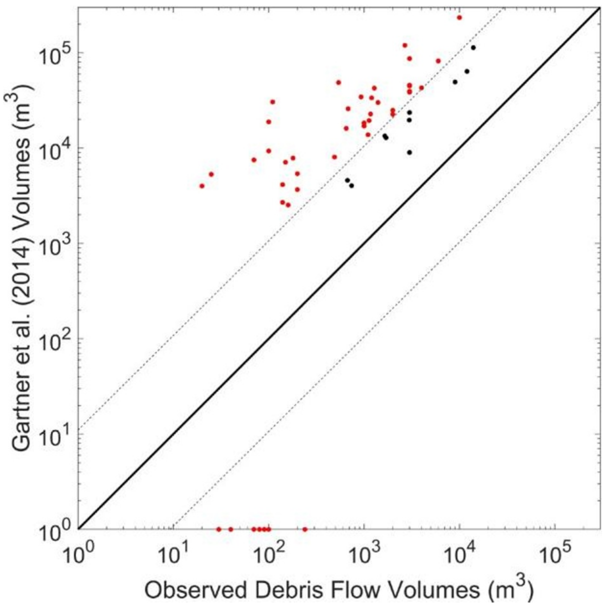


**Fig. 2.** Over 85% of the volumes predicted by the Emergency Assessment Model [15] were overestimated compared to what was observed. Those that were overestimated (or underestimated) by more than an order of magnitude are shown in red. The thing dashed lines indicate an order of magnitude.

The Emergency Assessment model [15] tended to overestimate debris-flow volumes in our AZ and NM dataset. The model overestimated volume for 47 of the 55 (85%) debris flows. Furthermore, only 11 of the 55 (20%) debris-flow volumes were predicted within an order of magnitude (Fig. 2). While the model tended to overestimate debris-flow volumes, there was a pattern between the modeled and observed volume when excluding eight outliers described in more detail below. In other words, the debris flows with smaller observed volumes generally had smaller modeled volumes, while the largest observed debris flows also had the largest modeled volumes (Fig. 2). The correlation coefficient between the observed debris-flow volumes and the modeled volumes was 0.64.

When calculating the correlation coefficient between observed and modeled debris-flow volumes, we excluded the eight watersheds that the Emergency Assessment model underestimated. All eight of those watersheds burned exclusively at low severity. The model requires the natural log of watershed area burned at moderate or high severity (*Bmh*) (Eq 1), so when *Bmh* equals zero, it is undefined and results in a predicted volume of 0 $m^3$. This means that the Emergency Assessment model will always predict a volume of 0 $m^3$ if a watershed is not burned at moderate or high severity, even though watersheds burned at low severity may still be at an elevated risk for post-wildfire debris flows [25].

While the Emergency Assessment volume model [15] generally performs well in the area for which it was developed (the Transverse Ranges of southern CA), regional differences between southern CA and AZ and NM, such as those in vegetation, climatic setting, and rainfall characteristics, may contribute to reduced model accuracy for post-wildfire debris flows in AZ and NM. For example, dry ravel commonly loads channels with relatively fine hillslope sediment immediately following fire in the Transverse Ranges [26,27], providing an abundant source of sediment for debris flows in that region. However, evidence of dry ravel was not observed at our study areas in AZ and NM. These differences resulted in the model overestimating most of the observed volumes by several orders of magnitude (Fig. 2), which could then lead to overestimates of debris-flow runout and inundation extent [18,19].

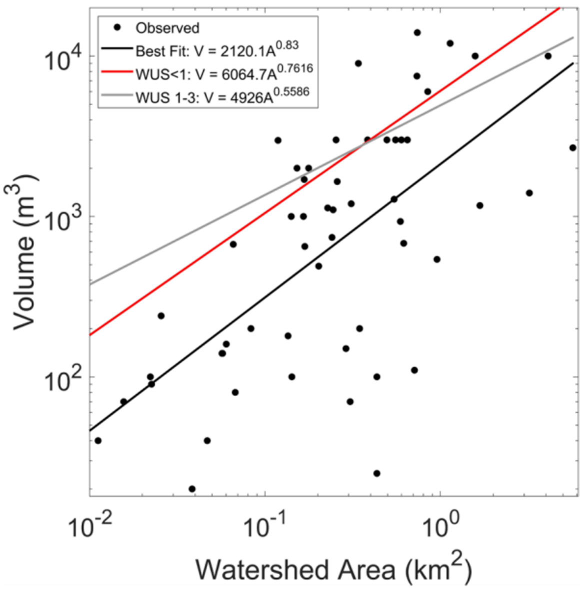


**Fig. 3.** The power law relationship between debris-flow volume and watershed area in AZ and NM indicates that debris flows in this region are smaller in size, but scale in the same way as debris flows in CA and across the Intermountain West [20].

When viewed as a power law function of watershed area, AZ and NM debris-flow volumes followed a relationship similar to that observed elsewhere in the western USA [20] (Fig. 3). The best fit power law equation for our dataset was:

$$V = 2120.1A^{0.83} \quad (2)$$

where $V$ is the debris-flow volume ($m^3$) and $A$ is the watershed area ($km^2$). The coefficient of 2120.1 is lower than those found for the WUS datasets in [20], indicating that the debris flows in our dataset are smaller than those in the WUS datasets (Fig. 3). However, the exponent is similar to that of the WUS <1 dataset, which indicates that volumes scale with watershed area in a similar way in these two datasets (Fig. 3). Results suggest that this relationship can be used to place first-order constraints on post-wildfire debris flows in AZ and NM. However, a volume model specific to AZ and NM could improve debris-flow hazard assessments in this region.

## 5 Conclusions

Post-wildfire debris flows pose a serious threat to human life and infrastructure in many mountainous regions around the world. This threat is exacerbated as wildfire size and severity increase and population continues to grow. Estimates of debris-flow volume are an integral part of many hazard assessments. In this study, we compared the Emergency Assessment model [15], which was developed using data from the Transverse Ranges of southern CA, against 55 observed post-wildfire debris-flow volumes from AZ and NM, USA. Results showed that the Emergency Assessment model [15] overestimated 85% of observed debris-flow volumes, oftentimes bymore than an order of magnitude, and underestimated observed volumes when watersheds burned only at low severity (Fig. 2). We also calculated a power law relationship between volume and watershed area for debris flows in AZ and NM. We found that while post- wildfire debris-flow volumes in AZ and NM are generallysmaller than those in CA and across the Intermountain West, for a given watershed area, they tend to scale with watershed area in a similar way (Fig. 3). Differences in magnitude between the models and observations could bepartially explained by regional differences in sediment supply, among other factors. While the power law relationship can be used to place first-order constraints on debris-flow volume, results suggest that there could be benefits to developing an AZ and NM-specific post- wildfire debris-flow volume model and highlight the need to further examine controls on post-fire debris-flow volume. This effort will be the focus of future studies.

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## References

1. A. Parson, P.R. Robichaud, S.A. Lewis, C. Napper, J.T. Clark, Gen. Tech. Rep. **RMRS-GTR-243** (2010)
2. O.J. Hoch, L.A. McGuire, A.M. Youberg, F.K. Rengers, J. Geophys. Res. **126,** 12 (2021)
3. S.H. Doerr, R. Shakesby, L. MacDonald, *Soil Water Repellency: A Key Factor in Post-fire Erosion,* in Fire Effects on Soils and Restoration Strategies (2009)
4. J.A. Moody, B.A. Ebel, P. Nyman, D.A. Martin, C.R. Stoof, R. McKinley, Int. J. Wildland Fire **25,** 3 (2015)
5. B.A. Ebel, J.A. Moody, Hydrol. Process. **31,** 2 (2017)
6. J.W. Kean, D.M. Staley, S.H. Cannon, J. Geophys. Res. **116** (2011)
7. C.A. Dowling, P.M. Santi, Nat. Hazards **71,** 1 (2014)
8. J.W. Kean, D.M. Staley, J.T. Lancaster, F.K.Rengers, B.J. Swanson, J.A. Coe, J.L. Hernandez, A.J. Sigman, K.E. Allstadt, D.N. Lindsay, Geosphere **15,** 4 (2019)
9. M. Jakob, O. Hungr, *Debris flow hazards and Related Phenomenon* (2005)
10. V.C. Radeloff, D.P. Helmers, H.A. Kramer, M.H. Mockrin, P.M. Alexandre, A. Bar-Massada, V. Butsic, T.J. Hawbaker, S. Martinuzzi, A.D. Syphard, S.I. Stewart, Proc. Natl. Acad. Sci. U.S.A **115,** 13 (2018)
11. A.L. Westerling, H.G. Hidalgo, D.R. Cayan, T.W. Swetnam, Science **313,** 5789 (2006)
12. P. Nyman, G.J. Sheridan, H.G. Smith, P.N.J. Lane, Geomorphology **125,** 3 (2011)
13. D.M. Staley, J.A. Negri, J.W. Kean, J.L. Laber, A.C. Tillery, A.M. Youberg, Geomorphology **278** (2017)
14. J.E. Gartner, S.H. Cannon, P.M. Santi, V.G. Dewolfe, Geomorphology **96,** 3 (2008)
15. J.E. Gartner, S.H. Cannon, P.M. Santi, Eng. Geol. **176** (2014)
16. D. Rickenmann, Nat. Hazards **19,** 1 (1999)
17. T. de Haas, L. Braat, J.R.F.W. Leuven, I.R. Lokhorst, M.G. Kleinhans, J. Geophys. Res. **120,** 9 (2015)
18. K.R. Barnhart, R.P. Jones, D.L. George, B.W. McArdell, F.K. Rengers, D.M. Staley, J.W. Kean, J. Geophys. Res. **126,** 12 (2021)
19. A.N. Gorr, L.A. McGuire, A.M. Youberg, F.K. Rengers, Landslides (2022)
20. P.M. Santi, L. Morandi, Landslides **10** (2013)
21. P. Sheppard, A. Comrie, G. Packin, K. Angersbach, M. Hughes, Clim. Res. **21** (2002)
22. A.P. Williams, B.I. Cook, J.E. Smerdon, Nat. Clim. Chang. **12 (3)**, 232-234 (2022)
23. S.E. Mueller, A.E. Thode, E.Q. Margolis, L.L. Yocom, J.D. Young, J.M. Iniguez, For. Ecol. Manag. **460** (2020)
24. A.M. Youberg, *Prehistoric and modern debris flows in semi-arid watersheds: Implications for hazard assessments in a changing climate* (2013)
25. L.A. McGuire, A.M. Youberg, F.K. Rengers, N.S. Abramson, I. Ganesh, A.N. Gorr, O. Hoch, J.C. Johnson, P. Lamom, A.B. Prescott, J. Zanetell, B. Fenerty, J. Geophys. Res. **126,** 4 (2021)
26. J.L. Florsheim, E.A. Keller, D.W. Best, Geol. Soc. Am. Bull. **103,** 4 (1991)
27. R.A. DiBiase, M.P. Lamb, Geology, **48,** 2 (2019)