Lessons learned from the local calibration of a debris flow model and importance to a geohazard assessment

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ABSTRACT

Post-wildfire debris flows are a common hazard in many locales throughout the world. There is a demand for predicting the runout, inundation, and probability of occurrence to educate property owners, inform mitigation, and local planning in the wildland urban interface. Here, we calibrate our model to debris flow that occurred outside of a recent project area. The model can accurately predict the runout, including an avulsion that took place on the alluvial fan and the spatial extent of other surges that extended across much of the alluvial fan. The model was also able to predict the flow depths that could be used to account for the loss of homes at the debris flow site. Not only is modeling and our approach a critical tool in geohazard assessments after a wildfire, but it could also be used as a more proactive tool for planning and mitigation for debris flows in current and future development that would make our communities more resilient.

RÉSUMÉ

Les coulées de débris post-incendie sont un danger commun omniprésent dans de nombreux endroits du monde. Il existe une demande pour prédire le ruissellement, l'inondation et la probabilité d'occurrence afin d'éduquer les propriétaires fonciers, d'éclairer l'atténuation et la planification locale dans l'interface urbaine des terres sauvages. Ici, nous calibrons notre modèle sur la coulée de débris qui s'est produite en dehors d'une zone de projet récente. Le modèle peut prédire avec précision le ruissellement, y compris une avulsion qui a eu lieu sur le cône alluvial et l'étendue spatiale d'autres surtensions qui se sont étendues sur une grande partie du cône alluvial. Le modèle a également été en mesure de prédire les profondeurs d'écoulement qui pourraient être utilisées pour tenir compte de la perte de maisons sur le site de la coulée de débris. Non seulement la modélisation et notre approche sont un outil essentiel dans les évaluations des géorisques après un incendie de forêt, mais elles pourraient également être utilisées comme un outil plus proactif pour la planification et l'atténuation des coulées de débris dans le développement actuel et futur qui rendraient nos communautés plus résilientes.

1 INTRODUCTION

Models remain an essential tool in a geohazard specialists' toolbox. They provide a means to approximate spatial patterns and processes associated with geohazards that often cannot be experienced or measured from a field observation (sensed or recorded) or multiple observations (Barnhart, et al. 2021). However, uncertainties exist in the model inputs that impact overall model performance and the ability to predict potential outcomes. Therefore, model calibration is performed to help assure the model is fit to the purpose for which it is being employed.

Calibration involves several steps consisting of, but not limited to, confirming input data accuracy, developing a base model with appropriate elements, and where possible considering the model in relation to multiple historic events. Debris flow modeling is often limited by the lack of site-specific debris flow data. A central clearinghouse for debris flow data does not exist in meaningful way, such as data from weather stations, stream gages, or satellites. There is also inherent variability in initial conditions, topography, geology, and weather conditions that often produce site-specific characteristics that must be measured in the field or adopted from existing scientific or engineering research (McDougall 2017). However, opportunities exist whereby a recent or well-documented historical debris flow can be observed to provide supporting information to inform inputs for calibrating the model to the local conditions.

Here, we evaluate the performance of an agent-based probabilistic model by calibrating the results to the Black Hollow debris flow (BHdf) that occurred in Larimer County, Colorado, USA. The BHdf occurred outside of a then active project area in which we were conducting a post-wildfire debris flow hazard assessment. The BHdf provided an opportunity to evaluate the performance of our regional modeling efforts and inform hazard assessment and mitigation approaches moving forward.

2 METHODS

2.1 Study Site

The Black Hollow drainage basin contains a perennial tributary stream to the Cache La Poudre River. The site is located west of Rustic, Colorado, USA (Figure 1). The drainage area is 17.28 km^2. The maximum basin elevation of 3,475 m and minimum basin elevation of 2954 m with a mean slope of 32%. The basin receives mean annual precipitation of 51.18 cm. Stored colluvium and alluvium are consistently one meter or more deep throughout much of the drainage basin.

The drainage basin was burned in the 2020 Cameron Peak Fire. The fire reduced or eliminated canopy and ground cover and altered the soil structure (BAER 2020). Hydrophobicity was highly inconsistent across the Cameron Peak Fire and was estimated to be 55% across half the burned area (BAER 2020).

The Black Hollow debris flow occurred on 20 July 2021, taking four lives, and destroying five homes, after an intense rainstorm within the burned watershed (Figure 1). The peak 15 min rainfall intensity was 37 mm/hr as recorded from the nearby Washout Gulch rain gage (Kean 2021). The rainfall intensity equates to an approximate 1-year recurrence interval rainstorm according to NOAA Atlas 14. Staley et al. (2020) show the return interval (RI) for rainfall intensities sufficient to produce debris flows is less than 2 years for much of the southwestern United States including Colorado. The geometric means from all Colorado debris flow data highlighted RIs of 0.7, 0.6, and 0.4 for 15-, 30-, and 60-minute rainfall durations, respectively (Staley et al., 2020). The occurrence of a storm with sufficient intensity to produce a debris flow using 15-minute storm-duration is plotted for this area for 1-, 2-, and 3-years following a fire (Figure 2).

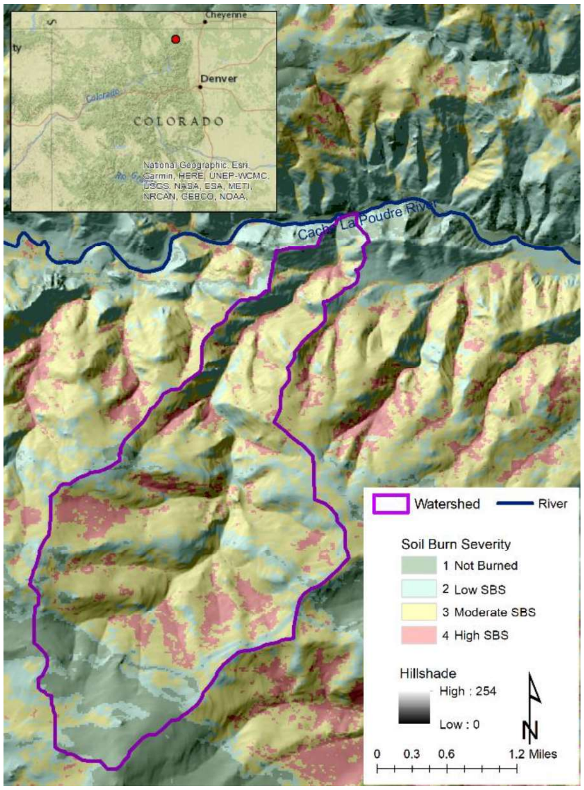


Figure 1. Map of Black Hollow drainage basin and soil burn severity. Black Hollow Rd is located at the outlet of the drainage basin.

2.2 Debris Flow Modeling

The landslide runout modeling software DebrisFlow Predictor was used to determine depth, volume, and the likelihood of a debris flow occupying portions of the landscape downslope of the initiation points. Originally conceived to answer questions about the magnitude-frequency characteristics of open slope debris flows and debris avalanches, DebrisFlow Predictor predicts landslide travel paths, and erosion and deposition along those paths (Guthrie and Befus 2021; Guthrie et al. 2021; Crescenzo et al. 2021). The software is predicated on the idea that shallow landslides of the flow-type (debris flows and debris avalanches) exhibit similar aggregate behavior, based largely on topography, independent of geology, triggering event, rheology, or other secondary and tertiary order effects.

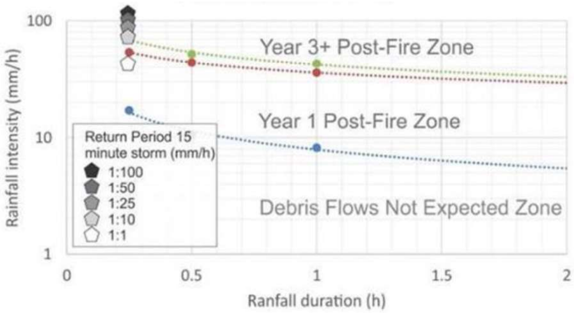


Figure 2. Rainfall intensity duration thresholds for the area after a wildfire.

2.2.1 Model Initialization

An estimated sediment volume (erosion and deposition) along a landslide path is derived by deploying ‘agents’, or autonomous sub-routines over a 5 m spatial resolution DEM (Rustic DEM is 10m resolution because of data availability). The DEM surface provides basic information to each agent, in each time-step, that triggers the rule set that comprises the subroutine. In this manner, agents interact with the surface and with other agents. Each agent occupies a single pixel in each time-step.

The user defines a starting location by injecting a single agent at the resolution of a DEM raster cell. By default, the software is optimized for 5 m DEM to provide computational efficiency and sufficient resolution to map debris flow runout (Guthrie and Befus 2021). A group of nine agents are commonly used to initiate a debris flow in small drainages and frequently multiple small sub-drainages are used to trigger debris flows in larger watersheds. In the case of a 5 m DEM, this would equate to a 15 m x 15 m initiation zone. Alternatively, there is also the option to paint a user-defined zone (unlimited size) as indicated by field morphology. Multiple agents may be generated at the same time using any of these methods, or any combination of these methods. The software can also automatically create nine agents for a series of points imported from a point shapefile.

The starting location of a single agent, or a group of connected agents, is the initiation of a landslide. Agents follow probabilistic rules for scour (erosion) and deposition at each time-step based on the underlying slope. Rules for scour and deposition are independent probability distributions for 12 slope classes (bins), modified from Guthrie et al. (2008) to account for a wider range of slopes than those used in the original study. The slope classes are based on data gathered for coastal British Columbia (Wise 1997; Guthrie et al. 2010), but the model has been applied to several locations internationally (Guthrie and Befus 2021; Guthrie et al. 2021; Crescenzo et al. 2021). The software has functions that control the spreading behavior of landslides. Spreading behavior causes landslides to redistribute mass by generating new agents described by a probability density function where the mean is centered around the facing direction of an individual agent (accounting for the local slope by including the eight surrounding cells or Moore neighbors) and the standard deviation, σ, is defined by:

$$\sigma = \left(\left(\frac{m_{MAX} - m}{m_{MAX}}\right)^n * \left((\sigma_L - \sigma_S) + \sigma_S\right)\right)$$

Where: m_{MAX} = Fan Maximum Slope, m = DEM slope, n =Skew coefficient, σ_L= Low Slope coefficient, σ_S = Steep Slope coefficient. Spread is calibrated experimentally based on empirical or observed behaviors of actual landslides.

Slider-type controls within the program allow the landslide professional to calibrate results for local second-order effects by controlling the spread, the maximum number of agents that can be triggered, minimum initiation depth, sediment loss in corners, and finally, by increasing or decreasing the erosion and deposition lookup tables. Calibration is typically done visually by comparing the results to mapped or visible (e.g., on air photographs) debris flows, and analytically by comparing the results to magnitude-frequency curves or area-volume relationships for a region. Once calibrated, the model is relatively easy to deploy over a large area.

2.2.2 Running the Model and Calibration

A publicly available 10m x 10m DEM was imported and used as the underlying surface for the model. A user-defined initiation zone (nine agents comprising a 30 m x 30 m footprint) was established for the current project based on Burned Area Emergency Response (BAER) SBS map (Figure 1). This was consistent with the USGS Landslide Hazards Program's post-fire debris flow predictive model that uses the proportion of the watershed area containing high to moderate soil burn severity as a key driver in their modeling system (Staley et al. 2013; Staley et al. 2016; Staley et al. 2017). Points were established in steep, first-order channels where high to moderate SBS were dominant.

2.3 Calibration Process

Calibration of the model is based on field observations and mapping of the BHdf. Observations included gathering pictures, confirming extents of the runout, and estimating deposition at the site. The mapping was performed from a combination of aerial and ground-based photos as well as from notes taken in the field. The extents and depths were used to rectify the model results.

3 RESULTS

Debris flow runout from the modeled debris flows (500 simulated debris flows) was coincident with what was evidenced in the field. Deposits extended across the channel to the north bank of the La Cache Poudre River and the debris flow avulsed to the west portion of the alluvial fan at Black Hollow Road (Figure 3). Runout to the northeast was consistent with what was mapped below the bridge (Figure 3). The model did underestimate the extent of runout to the eastern portion of the fan and did not run out to this portion of the fan (Figure 3). The mapped fan area was 13,844 m^2 and the modeled fan area was 14,348 m^2.

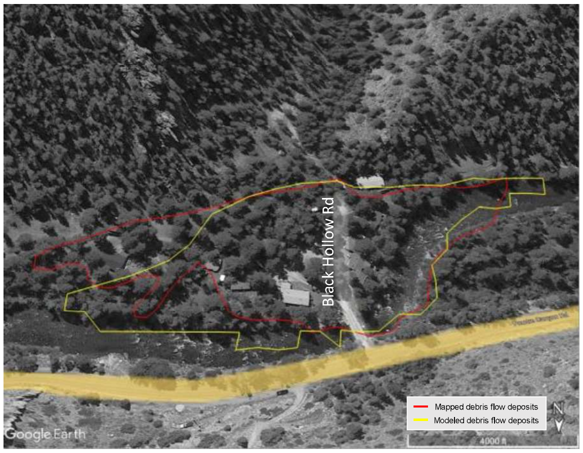
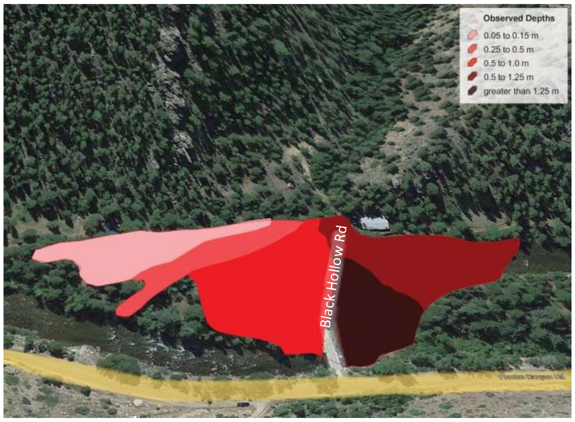


Figure 3. Deposit boundaries for the mapped debris flow (red) and the modeled debris flow (yellow).

A comparison of the observed (field and qualitative mapping) depths with the modeled depths reveals the magnitude of the mean of the depths (all points in the mapped area of each depositional class, which were derived from an average of 500 debris flows) are consistent, but lower for modeled depths (Figure 4). Maximum modeled debris flow depths (means) similarly match the magnitude of the observed classes, but the values are reasonably representing the observed classes (Figure 4). While we did not estimate volumes in the field, the model predicted debris flow volumes in the range of 24,515.6 m^3 to 44,083.8 m^3.

The probability of debris flow occurrence within alluvial fan surface where homes occurred ranged between 56% and 94% (Figure 5). Maximum flow depths at the home locations indicated that a >80% expected loss to a single-story timber frame home would have been anticipated at all homes given the modeled scenario and based on the widely used damage curves for wood structures (Ciurean, et al. 2017). A 50% to 100% expected loss would be projected if all homes were two-story timber frame structures.

The model calibration process required an increase in the erosion multiplier from our regional model performed prior to the calibration to accommodate for the perennial stream flowing at Black Hollow Rd. Bed material in the stream were saturated and therefore, pore water pressure was higher. Increased pore water pressures in the stream bed produces a scenario where materials are more mobile during a debris flow, which would increase the potential for erosion.



depth	>1.25m	0.5-1.25m	0.5-1.0m	0.25-0.5m
mean	0.64	0.53	0.44	0.35
low	0.34	0.14	0.16	0.00
max	0.81	1.06	0.81	0.67
variance	0.02	0.02	0.02	0.03

max_depth	>1.25m	0.5-1.25m	0.5-1.0m	0.25-0.5m
mean	1.85	1.29	1.10	0.79
low	0.37	0.41	0.62	0.00
max	2.59	1.85	2.47	2.02
variance	0.29	0.13	0.23	0.23

Figure 4. Map observed debris flow depths compared with modeled depths in the tables.

4 DISCUSSION

The BHdf represents a tragic episode for the residents at the site and in the local community. It and recent debris flows where loss of life and destruction of property continue to highlight the need for better educating residents about these hazards, developing more comprehensive early warning systems, and mitigating these types of hazards. Models represent one approach to advancing our understanding debris flows by assessing the potential hazard, providing evidence-based information for educating individuals, and by providing information to take proactive measures in designing mitigation solutions.

Our model calibration exercise verifies the importance models can play in examining runout, inundation, depth, probability of occurrence, and in identifying the expected loss that occurred at Black Hollow Rd. An avulsion similar in extent and direction to the actual alluvial fan avulsion was captured in our modeling scenario. This complex response is a common occurrence in alluvial fans (de Haas, et al. 2018) and occurred in the exact same location where the post-wildfire debris flow dammed the La Cache Poudre River and caused a change in the channel direction.

The flow depths were comparable with what we saw in the field although slightly underpredicting if we just consider the averaged results from the 500 debris flow and very good approximations when the mean of the cells within the mapped areas are considered in relation to our field estimates. Five homes were destroyed in the BHdf and the modeled mean maximum depths accurately measured the expected loss of these homes.

The model did underpredict the flows to the eastern portion and no flow information was recorded in the lowest depth class we mapped. Two points should be made here: (1) the amount of flow to this area was relatively low and (2) a drainage channel had been dug after the capture of the DEM data. The BHdf did follow the drainage channel that had been put in place to divert water to the river away from the road until the debris dammed the drainage channel (Figure 6). The topography of the channel not being incorporated into the DEM likely led to the underrepresentation of deposition in this area.

Another item to note is the debris flow modeling does not have the ability to capture the large amount of large woody debris that was transported in the BHdf (Figure 6). Transport of large woody debris is an underrepresented flux of material in post-wildfire modeling and further advances are needed to integrate this into models as this represents a significant load and likely played a role in the loss of homes and lives at Black Hollow.

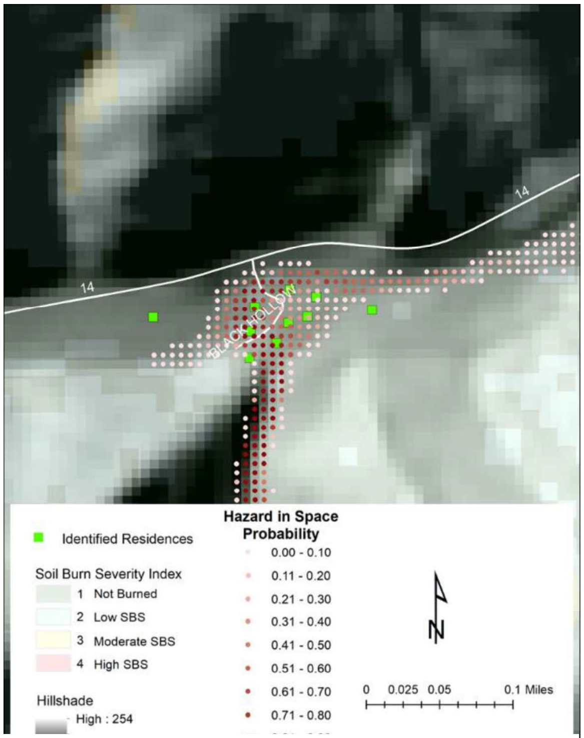


Figure 5. Probability of debris flow occurrence at Black Hollow Rd.


Figure 6. Debris dam of the drainage channel at the site.

5 CONCLUSIONS

Clear evidence is supplied from the calibration of larger regional debris flow hazard assessment model to local a local debris flow that occurred outside our project area that modeling represent one key aspect to reducing the risks associated with post-wildfire debris flows. Our modeled results morphometrically represent debris flow inundation and accurately predict the loss of homes. While our efforts here are post-casting the debris flow, there is no reason why the model could not be used in a more proactive manner to supply evidenced-based knowledge of the potential risks to people, critical infrastructure, and property, which can be used to inform decision-making and engineering mitigation solutions.

6 REFERENCES

BAER. 2020. Cameron Peak Fire Forest Service Burned Area Emergency Response Executive Summary Arapaho Roosevelt National Forest December 15, 2020. US Forest Service.

Barnhart, K.R., Jones, R.P., George, D.L., McArdell, B.W., Rengers, F.K. Staley, D.M., and Kean, J.W. 2021. Model Comparison of Computed Debris Flow Runout for the 9 January 2018 Montecito, California Post-Wildfire Event. Journal of Geophysical Research: Earth Surface, 126: e2021JF006245.

Ciurean, R.L., Hussin, H.Y., van Westen, H.Y., Jaboyedoff, M., Nicolet, P., Chen, L., Frigerio, S., and Glade, T. 2017. Multi-scale debris flow vulnerability assessment and direct loss estimation of buildings in the Eastern Italian Alps. Natural Hazards, 85: 929-957.

Crescenzo, L, Pecoraro, G., Calvello, M., and Guthrie, R.H. 2021. A probabilistic model for assessing debris flow propagation at regional scale: a case study in Campania region, Italy. EGU General Assembly 2021: NH3.2 – Debris flows: advances on mechanics, controlling factors, monitoring, modelling and risk management. Online Conference: European Geophysical Union.

de Haas, T., Densmore, A.L., Stoffel, M., Suwa, H., Imaizumi, F., Ballesteros-Canovas, J.A., and Wasklewicz, T.A. 2018. Avulsions and the spatio-temporal evolution of debris-flow fans. Earth-Science Reviews, 177: 53-75.

Guthrie, R.H., Hockin, A., Colquhoun, L., Nagy, T., Evans, S.G., and Ayles, C. 2010. An examination of controls on debris flow mobility: Evidence from coastal British Columbia. Geomorphology, 114: 601-613.

Guthrie, R H, and Befus, A. 2021. DebrisFlow Predictor: an agent-based run-out program for shallow landslides. Natural Hazards and Earth System Science, 21: 1029-1049.

Guthrie, R.H., Grasso, K., and Befus, A. 2021. A new landsldie runout model and implications for understanding post wildfire and earthquake threats to communities in California. ASCE Lifelines Conference 2022. Los Angeles: American Society of Civil Engineers.

Guthrie, R.H., Deadman, P.J., Cabrera, A.R., and Evans, S.G. 2008. Exploring the magnitude-frequency distribution: a cellular automata model for landslides. Landslides, 5: 151-159.

Kean, J.W. 2021. Initial spot check of USGS debris flow likelihood and volume models for the Cameron Peak burn area and the 20 July 2021 flow event. Golden, CO, USA: USGS.

McDougall, S. 2017. 2014 Canadian Geotechnical Colloquium: Landslide runout analysis—current practice and challenges. Canadian Geotechnical Journal, 54: 605-620.

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

Staley, D M, Negri J.A., Kean, J.W., Laber, J.L., Tillery, A.C., and Youberg, A.M. 2016. Updated Logistic Regression Equations for the Calculation of Post-Fire Debris-Flow Likelihood in the Western United States. U. S. Geological Survey Open-File Report.

Staley, D.M., Smoczyk, G.M., and Reeves, R.R. 2013. Emergency Assessment of Post-fire Debris-flow Hazards for the 2013 Powerhouse Fire, Southern California. U.S. Geological Survey Open-File Report 2013–1248.

Staley, D. M., Kean, J.W., and Rengers, F.K. 2020. The recurrence interval of post-fire debris-flow generating rainfall in the southwestern United States. Geomorphology 370: 1-10.

Wise, M.P. 1997. Probabilistic Modelling of Debris Flow Travel Distance Using Empirical Volumetric Relationships. MSc Thesis, Vancouver: University of British Columbia.