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Comparison of an empirical and a process-based model for simulating debris-flow inundation following the 2010 Schultz Fire in Coconino County, Arizona, USA.

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Abstract

The importance of understanding the extent of areas threatened by post-wildfire debris flows cannot be overstated, as illustrated by the post-Thomas Fire flows through Montecito, California, in January 2018. Methods and models developed by the U.S. Geological Survey to identify burned basins at risk of producing post-wildfire debris flows are well established, effective and commonly used. In contrast, there is no similarly established methodology for delineating debris-flow hazard zones downstream of basins prone to producing post-fire debris flows. Understanding potential inundation zones is critical for protecting human life, property and infrastructure. Recently, some communities and local government agencies have begun assessing potential risks from post-wildfire hazards before an area burns (pre-fire hazard assessments). These assessments utilize modeled burn severity maps and existing methodologies to identify basins likely to generate post-fire debris flows should the basins burn. In most studies, however, there have been no attempts to delineate hazard zones downstream of the basins that could produce post-fire debris flows. This information is critical for identifying mitigation opportunities and for establishing emergency evacuation routes and procedures. Here, we report on work using a newly developed process-based model and an empirical model, Laharz using two different sets of mobility coefficients, to assess debris-flow runout from a recently burned basin. The actual extent of debris-flow runout is known, which allows us to compare model performance. Laharz is efficient for assessing large areas but requires the user to select the location of deposition *a priori*, and mobility coefficients for post-fire debris flows have not yet been developed. Laharz did not adequately predict the downstream extent of deposition using either set of mobility coefficients. The process-based model using two sets of parameters, friction angle, φ, and ratio of pore fluid pressure to total basal normal stress, λ, provided a range of results. The simulation using parameters $\lambda = 0.8$ and $\varphi = 0.35$ provided the best match between mapped and modeled deposits and provided a better estimate of inundation relative to Laharz. This two-model approach is helpful for assessing the shortcomings and benefits of each model, and for identifying the next steps needed for developing a method to identify post-fire debris-flow hazard zones before a fire begins.

Keywords: Wildfires; debris flows; inundation modeling; Arizona

1. Introduction

Increasing wildfire size and severity across the western U.S. and continued encroachment into the wildland-urban interface place more people, property, and infrastructure at risk from post-wildfire hazards. Extensive research efforts focused on post-wildfire debris flows have led to an improved understanding of initiation mechanisms (e.g. Kean et al., 2013; McGuire et al., 2017), the development of objectively-defined rainfall-intensity duration thresholds (Staley et al., 2013; Staley et al., 2017), and new logistic regression models to predict debris-flow probability and volume (Gartner et al., 2014; Staley et al., 2016). As such, it is possible to identify burned basins at risk of producing post-wildfire debris flows. These methods are now being employed to identify, proactively, basins that are at risk of producing post-fire debris flows should a fire occur (Tillery et al., 2014; Tillery and Haas, 2016; Staley et al., 2018). While these studies provide valuable information, there is also a need for local governments and communities to

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identify post-wildfire hazard zones downstream of burned areas for planning and mitigation purposes. For example, a series of devastating post-fire debris flows and floods from the 2010 Schultz Fire in Coconino County, Arizona (Figure 1; Youberg et al., 2010), caused significant impacts to homes and infrastructure, the loss of one life, and economic impacts to the greater Flagstaff area between $133 and $147 million (Combrink et al., 2013). To help prevent similar situations in other areas of the county, Coconino County Public Works conducted a pre-fire assessment of post-fire hazards in areas not yet burned by wildfires (Loverich et al., 2017).

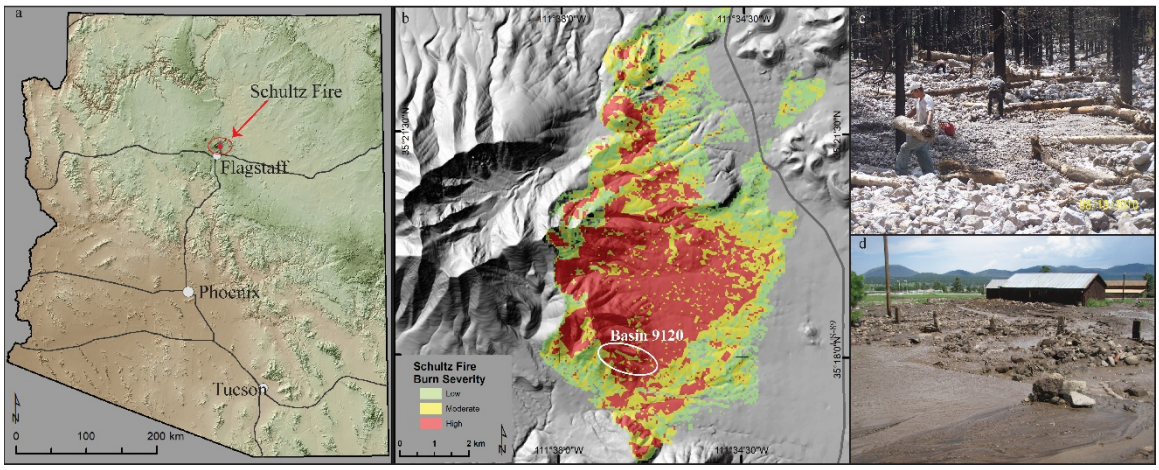

Figure 1. 2010 Schultz Fire location map (a) and burn severity with location of study basin (b). Post-Schultz Fire removal of debris-flow deposits from channels on forest (c; photo: M. Nabel) and debris-laden flows in a subdivision below the burn area (d; photo: A. Youberg).

One of the goals of the Coconino County pre-fire study was to delineate potential debris-flow hazard zones, based on a reasonable wildfire scenario, to identify mitigation opportunities that would reduce impacts from the aftermath of wildfires. A challenge with this study was selecting an appropriate model to assess debris-flow inundation that adequately balanced model complexity with available information. While more detailed, physically based models might have provided better approximations of debris-flow behavior and inundation zones, time and resource constraints, data limitations, and the size of the study areas precluded the use of these models. In addition, few, if any, models have been developed for, calibrated, or tested on post-fire debris flows. Unlike debris flows mobilized from shallow landslides, post-fire debris flows are frequently triggered when runoff concentrates in steep channels (Meyer and Wells, 1997; Kean et al., 2011). As such, post-fire debris-flow surges are often embedded within, and interact with, water-dominated flows. The resulting implications for debris-flow mobility are not clear.

The empirical, volume-driven Laharz model (Iverson et al., 1998; Schilling, 2014) was selected to simulate post-fire debris-flow inundation for the Coconino County study. This model was selected because modified mobility coefficients had been developed for Arizona debris flows (Magirl et al., 2010) and the model could be further tested with data of mapped post-Schultz Fire flow deposits (Youberg, 2017). Laharz, in its current form, requires the user to determine where deposition will begin and, because it simply deposits flow across the topography based on volume and mobility coefficients, it does not accurately reflect flow behavior. Based on Laharz results from the Schultz burn area, this model was deemed acceptable for the Coconino County study. We revisit this issue because better methodologies for assessing and delineating potential inundation zones are needed for upcoming pre-fire hazard assessments. In this study, we use Laharz and a process-based model to assess debris-flow runout from a recently burned basin. The actual extent of debris-flow runout is known, which allows us to compare model performance and assess the utility of the two modelling approaches.

2. Study Area

In June 2010, the small but severe Schultz Fire burned 6100 ha on the eastern slopes of the San Francisco Peaks northeast of Flagstaff, Arizona (Figure 1). This wind-driven fire burned 60% of the area within the first 24 hours with the majority of the fire area burned at moderate (27%) to high (40%) severity on moderate to very steep slopes (Figure 1; USDA Forest Service, 2010). The fire was followed by a wetter than average monsoon which resulted in numerous

debris flows, extensive flooding, the destruction of a city waterline, damage to homes and other infrastructure, and the loss of one life (Youberg et al., 2010). Reconnaissance fieldwork was conducted in August and September 2010 to document which storms and basins produced debris flows (Youberg, 2015) and to map and classify deposits as debris flow, flood, or reworked/mixed (i.e. deposits with debris-flow characteristics - unsorted, snouts, levees - reworked by hyper-concentrated and flood flows) (Youberg, 2017). The modeling efforts in this study focus on basin 9120, which produced debris flows on June 20 and August 16, 2010, and numerous floods throughout the summer (Youberg et al., 2010). The mapped reworked/mixed deposit (Figure 1, orange polygons) may have initially been emplaced during the first debris-flow event, June 20, and subsequently reworked. The mapped debris-flow deposits (Figure 1, dark brown polygons) were likely emplaced during the second debris-flow event, August 16. Debris-flow volume estimates for basins in the Schultz Fire burn area ranged from 1000 m^3 to 14,000 m^3 but were most frequently 3000 m^3 and averaged 5000 m^3 (Youberg, 2015).

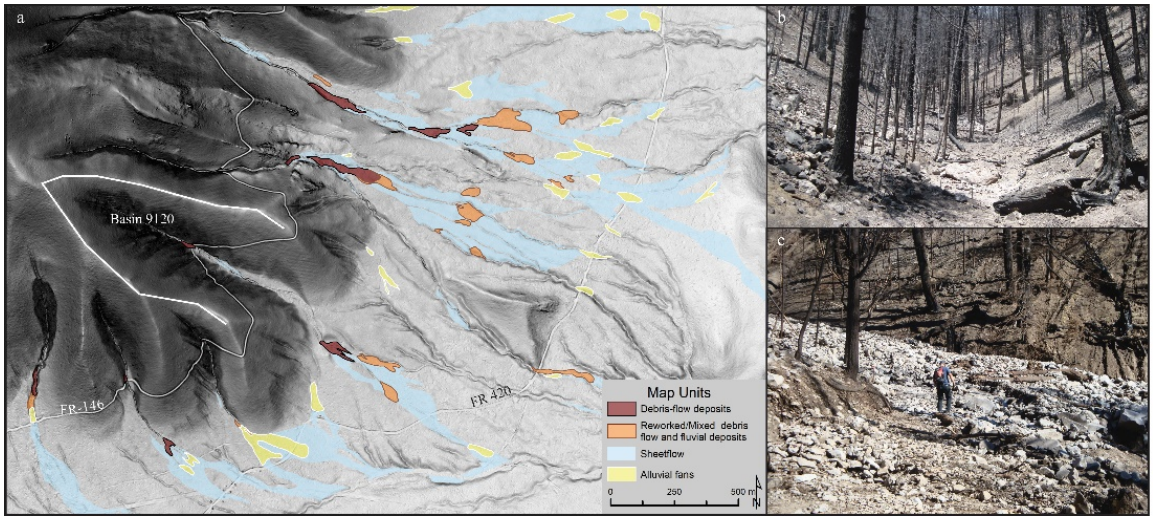

Figure 2. Debris flow (dark brown), reworked/mixed (orange), alluvial (yellow) deposits, and sheetflow areas (light blue) mapped during August and September 2010 (a) (from Youberg, 2017). Basin 9120 on June 29, 2010, looking upstream from FR 146 (b), when it was an unincised swale (Photo: City of Flagstaff), and on August 4, 2010, looking NE from FR 146 (c) with debris-flow deposits on and above the road (Photo: City of Flagstaff). Below the road, the channel is incised 2-3 m.

3. Methods

3.1. Laharz modeling

Laharz is a volume-driven empirical model first developed to identify potential hazard zones from volcanic lahars (Iverson et al., 1998), and later modified to include rock avalanches and worldwide debris flows (Griswold and Iverson, 2008), and saturation-induced debris flows in Arizona (Magirl et al., 2010). Laharz uses digital topography and two volume-based flow equations with mobility coefficients, α_1 and α_2, to define inundation of cross-sectional area, A, and planimetric area, B (Table 1), occupied by the flow as it moves down the channel until the volume is exhausted (Schilling, 2014). The mobility coefficients are statistically derived from past debris-flow inundation data of high-flow marks (e.g. scouring, strandlines, log jams) and runout (e.g. snouts, levees) (Griswold and Iverson, 2008). Here, we calculated and assessed results using both worldwide and modified Arizona mobility coefficients.

Table 1. Laharz coefficients for two different mobility characteristics. Volumes modeled were 1,000, 3,000 and 5,000 m^3.

Mobility coefficients, *x* and *y*	Cross-sectional area, $A = \alpha_1 V^{2/3}$	Planimetric area, $B = \alpha_2 V^{2/3}$
Worldwide (Griswold and Iverson, 2008)	0.1	20
Arizona (Magirl et al., 2010)	0.1	40

Simulations were run to assess inundation downstream of basin 9120 with deposition beginning where the channel debouches onto the piedmont at approximately 444832 m E and 3906084 m N (Figure 3a). Debris-flow volumes of 1000 m3, 3000 m3 and 5000 m3 were chosen based on previous mapping (Youberg, 2015) and expected debris-flow volumes from 1- to 2-year precipitation (Youberg, 2017). The digital topography (1 m) was derived from airborne lidar collected in 2012. We selected this post-event topography as the available pre-event digital topography was of poor quality and hydrologically incorrect (drainages didn't follow actual topography). The extent and locations of modeled deposition and mapped deposits, which reflect geomorphic conditions after the second set of debris-flow-producing storms on August 16, 2010, were assessed using two different metrics. First, we computed the percentage of aerial overlap between modeled and mapped deposits. Second, to assess differences between observed and modeled runout potential, we report the distance between the base of the modeled deposit and the base of the mapped deposits.

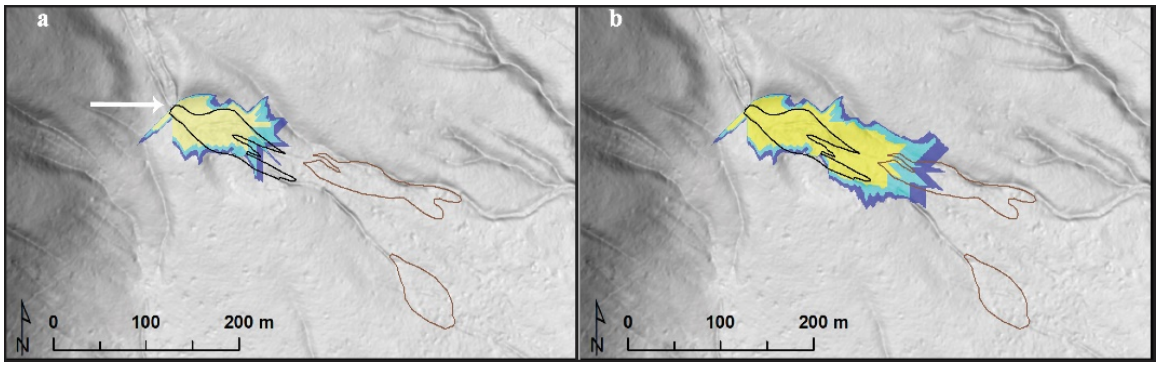

Figure 3. Laharz results for volumes of 1000 m^3 (yellow), 3000 m^3 (light blue), and 5000 m^3 (dark blue) using the equations for worldwide (WW) debris flows (a) and the modified Arizona (AZ) equations (b). Black line is a debris-flow deposit, and brown lines are reworked/mixed debris-flow deposits reworked by hyperconcentrated and flood flows. The white arrow indicates where deposition begins in the model runs.

3.2. Process-based debris flow routing model

The debris flow routing model is based on a set of conservation laws for mass and momentum in a 3D depth-averaged framework, similar to that used by Denlinger and Iverson (2001). The governing equations are given by,

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \qquad (1)$$

$$\frac{\partial (hu)}{\partial t} + \frac{\partial}{\partial x}\left(hu^2 + \frac{1}{2} g_z^2 h\right) + \frac{\partial}{\partial y}(huv) = g_x h - sgn(u)(1-\lambda) g_z h \tan\phi - \frac{2uv_f \mu}{\rho h} \qquad (2)$$

$$\frac{\partial (hv)}{\partial t} + \frac{\partial}{\partial x}(hvu) + \frac{\partial}{\partial y}\left(hv^2 + \frac{1}{2} g_z^2 h\right) = g_y h - sgn(v)(1-\lambda) g_z h \tan\phi - \frac{2vv_f \mu}{\rho h} \qquad (3)$$

where h is flow depth, u and v represent velocity in the x and y directions respectively, g_x, g_y, and g_z are the components of gravitational acceleration in the x, y, and z, directions, $\lambda = p_b/\rho g_z h$ is the ratio of the pore fluid pressure (p_b) to the total basal normal stress, φ is the bed friction angle, and μ is the pore fluid viscosity. The flow resistance is dominated in most cases by the second term on the right-hand side of equations (2) and (3), which represents the effects of friction modified by pore fluid pressure. The viscous resistance, represented by the third term on the right-hand side of equations (2) and (3), is generally small in comparison. Here, we assume a pore fluid viscosity of μ=0.1 Pa s, consistent with muddy water (e.g. Denlinger and Iverson, 2001). The governing equations are solved using a Godunov-type finite volume method, where the numerical fluxes are computed with the Harten-Lax-vanLeer-Contact (HLLC) approximate Riemann solver (e.g. Toro, 2013) and source terms are treated explicitly. Additional details on the numerical solution, including a thorough description of the flux computations, can be found in McGuire et al. (2016).

The ratio of the pore fluid pressure to the total basal normal stress, λ, is held fixed throughout each simulation although its value does vary among simulations. In reality, the pore fluid pressure will change with time throughout the flow event. Here, rather than reconstructing detailed dynamics of a flow event, we instead seek to simulate debris-flow runout following wildfire using a simplified process-based routing model with a minimal number of parameters.

Results from this model can then be used to assess the benefits and weaknesses of employing Laharz and to provide guidance for moving forward with refining the process-based model.

Debris-flow runout simulations were performed using the routing model at basin 9120 (Figure 2). For all simulations, a static volume of debris was initialized in a channel reach defined between points 444539 m E - 30906328 m N and 44698 m E - 3906274 m N (Figure 4a). This particular reach was chosen since it is near the bottom of the study basin, but the banks of the channel are still defined. Thus, it was possible to initialize the debri- flow volume within the channel, where post-fire debris flows typically initiate, in a channel section where we can reasonably assume that the debris flow was no longer entraining a substantial amount of material, and had likely achieved its final volume at that point in the basin. The debris flow moves from its static initial position once the simulation begins and is routed downslope to its final stopping point. Simulations were run with two different volumes, 1000 m^3 and 5000 m^3, as well as for two different values of λ (λ=0.65 and λ=0.8) and two different friction angles (φ=30° and φ=35°) for a total of eight simulations.

4. Results

4.1. Laharz

Laharz runs were conducted using the worldwide debris-flow equations (Griswold and Iverson, 2008) and the modified Arizona equations (Magirl et al., 2010) with volumes of 1000 m^3, 3000 m^3 and 5000 m^3 (Table 1). The Arizona model more reasonably captures the mapped debris-flow deposit and begins to encompass the reworked/mixed deposit, while the worldwide model more dramatically underestimated the runout distance (Table 2, Figure 3).

4.2. Process-based debris flow routing model

Debris-flow runout varies considerably among simulations due to changes in the friction angle, φ, and the ratio of pore fluid pressure to total basal normal stress, λ (Figure 4). In cases were λ=0.65, the debris flow spreads out of the channel and runout is severely underestimated regardless of whether φ=30° or φ=35°. Increasing λ leads to a decrease in the effective normal stress and a corresponding increase in flow mobility, as expected. Varying the friction angle from φ=35° to φ=30° increases the runout distance of the leading edge of the flow by roughly 400 m. Choosing λ=0.8 and φ=35° results in the best match between the modeled and mapped deposits. Although volume clearly affects deposit thickness, it has minimal impacts on flow mobility at our study site.

5. Discussion

Laharz with the Arizona mobility coefficients appears to better capture the extent of the mapped debris-flow deposit (Figure 3, black line) and begins to capture the reworked/mixed deposit (Table 2, Figure 3, brown lines), however neither set of mobility coefficients result in a simulation that fully captures the downstream extent of reworked/mixed deposits. There may be several reasons for this. First, mobility coefficients developed from and for post-fire debris flows may provide better results. Second, mapped debris-flow and reworked/mixed deposits were likely deposited during two different storms and thus may be difficult to reproduce by assuming they were emplaced at the same time. Lastly, we route the debris flows over post-event topography due to the poor quality of pre-event DEMs, which has potential implications for debris-flow spreading and runout. As such, model results reflect those expected under current topographic configurations rather than topography at the time of the flows.

A drawback of using Laharz is that users are required to define where deposition begins, which is difficult to estimate, especially given the dramatic geomorphic changes typical of the disturbed post-fire environment. In the Coconino County study, this problem was addressed by modeling a wide range of volumes (half-order magnitudes from 10^3 to 10^5 m^3), and selecting multiple deposition points using channel gradients and potential fan avulsion areas (Youberg, 2017). Results were then combined and generalized to create debris-flow hazard zones (first-order approximations) in each pilot study area (Loverich et al., 2017).

The benefit of using a process-based routing model is that the deposition location does not need to be defined *a priori*. A debris-flow initiation location is still needed, but it may be possible to estimate initiation locations within a watershed using a hydrologic model and critical discharge thresholds required for bed failure (Gregoretti and Fontana, 2008). The major uncertainties associated with the routing model used here include the friction angle and the ratio of pore fluid pressure to total basal normal stress. Runout extent and deposit shape were quite variable due to changes in

the friction angle, φ, and the ratio of pore fluid pressure to total basal normal stress, λ (Figure 4). Note that post-fire topography was also used with this model which likely influenced lateral spread and runout patterns. In all cases when $\lambda = 0.65$, regardless of friction angle, the model overestimated lateral spread and severely underestimated debris-flow runout (Table 2). The simulations for both volumes using $\lambda = 0.8$ and $\varphi = 0.35$ provided the best match between mapped and modeled deposits and performed better than other model configurations and Laharz (Table 2, Figure 4). A challenge in using a process-based routing model, even one with a minimal number of parameters as presented here, is that the results can be sensitive to small changes of parameters. Both $\lambda = 0.65$ and $\lambda = 0.8$ are reasonable choices, given that pore fluid pressures are likely high initially (i.e. λ=0.9*)* and then decay with time (e.g. Denlinger and Iverson, 2001), yet they result in very different inundation predictions. Using $\lambda = 0.8$ is consistent with a debris flow that maintains high pore fluid pressure throughout the entirety of its runout. The fact that simulations assuming high pore fluid pressures perform the best could be a result of the interaction between the debris flows and the surrounding water-dominated flow. Here, however, we only simulate the debris flow and neglect the water-dominated flow that the debris flow was likely embedded in.

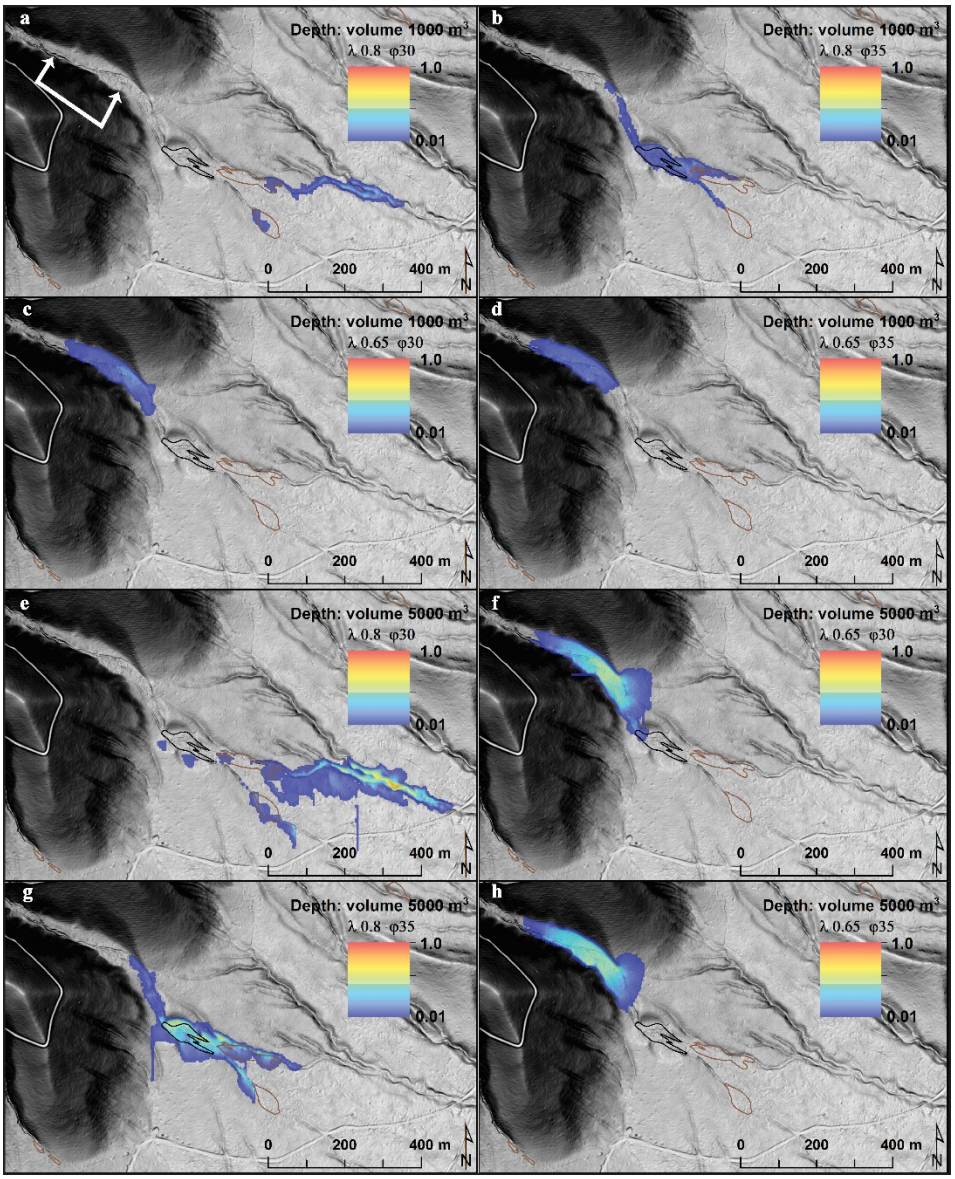

Figure 4. Results from the 8 process-based model runs for various values of λ and φ as well as total flow volumes of 1000 m3 (a, d, b, e) and 5000 m3 (c, f, g, h). White line with arrows in (a) shows the model initiation reach.

While the process-based debris-flow model is generally more complex and time consuming to run compared with Laharz, it may provide results that more accurately reflect debris-flow behavior and it is possible to constrain certain parameters (e.g. friction angle) given knowledge of debris-flow constituents (Table 2). Hence, there is potential for using the process-based routing model described here to develop inundation zones, particularly when there is not an immediate time constraint posed by an impending rainstorm (i.e. pre-fire assessments of post-fire hazards), if λ and φ can be sufficiently constrained. Given the spread in inundation scenarios simulated by the model for relatively narrow parameter ranges ($0.65<\lambda<0.8$, $30°<\varphi<35°$), studies that help to identify typical parameter values for post-fire debris flows would aid in limiting the number of simulations required for sensitivity analyses.

Table 2. Metrics used to compare model results with mapped deposits. The downstream extent of modeled deposits is compared with the downstream extent of mapped debris-flow (column 2) and reworked/mixed flow (column 3) deposits. Negative numbers indicate modeled deposits stop upslope of the downstream extent of the mapped deposits. The percent-area overlap between modeled deposits with mapped debris-flow (column 4) and reworked/mixed (column 5) deposits provides another assessment of each model

	Average distance upstream (-) / downstream (+) from base of modeled deposits to		**Percent area overlap between modeled deposit and mapped deposits**	
Process-Based Model	**Base of mapped debris-flow deposit**	**Base of mapped rework/mixed deposit**	**Mapped debris-flow deposit**	**Mapped reworked/mixed deposits**
depthV1k_λ0.80 φ30	516	320	0%	23%
depthV1k_λ0.80 φ35	137	-77	98%	20%
depthV1k_λ0.65 φ30	-203	-285	0%	0%
depthV1k_λ0.65 φ35	-272	-309	0%	0%
depthV5k_λ0.80 φ30	475	263	0%	42%
depthV5k_λ0.80 φ35	156	-12	100%	57%
depthV5k_λ0.65 φ30	-112	-324	13%	0%
depthV5k_λ0.65 φ35	-179	-353	0%	0%
Laharz Model				
AZ_V1k	28	157	89%	3%
AZ_V3k	99	163	95%	11%
AZ_V5k	68	113	98%	20%
WW_V1k	-56	-254	67%	0%
WW_V3k	-40	-239	82%	0%
WW_V5k	-35	-234	89%	0%

6. Conclusions

The two-model approach presented here is helpful for assessing the shortcomings and benefits of empirical and process-based debris-flow inundation models, and for identifying the next steps needed for developing a method to identify post-fire debris-flow hazard zones before a fire begins. While Laharz is efficient for assessing inundation over large areas, especially under data limitations and constraints of time and resources, it requires the user to reasonably determine the location of deposition *a priori*. Also, mobility coefficients for post-fire debris flows have not yet been developed. A new version of Laharz is under development, and will allow the user to identify initiation areas and channel-slope thresholds below which deposition begins (Reid et al., 2016; D. Brien, personal communication). Once mobility coefficients for post-fire debris flows are developed, Laharz may more adequately represent post-fire debris-flow inundation zones. The process-based routing model, using two sets of parameters, provided quite variable results. Nevertheless, results using $\lambda = 0.8$ and $\varphi = 0.35$ provided a reasonable match between mapped and modeled deposits. Future work with this model could focus on identifying the typical range of key parameters for post-fire debris flows, such as ratio of pore fluid pressure to total basal normal stress (λ), that could be used for developing plausible inundation zones. Mapped deposits from the Schultz Fire and other fires could be used to help develop Laharz mobility coefficients and constrain the range of parameters needed for process-based routing models for post-fire debris flows in Arizona.

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