February 23, 2017

Lucinda Andreani, Deputy Public Works Director
Coconino County Public Works
5600 E. Commerce Avenue
Flagstaff, AZ 86004

RE: Coconino County Post-Wildfire Flood and Debris Flow Risk Assessment, Post-Wildfire Debris Flow Risk Assessment Summary

Lucinda Andreani:

Enclosed is a letter report that describes Tasks 7, Post-Wildfire Debris-Flow Risk Assessment, of the ongoing Coconino County Post-Wildfire Flood and Debris Flow Risk Assessment Pilot Project. This task follows Task 4 in which we conducted an assessment of the two selected pilot study areas, Fort Valley and Williams, to identify tributaries with evidence of past debris flows. Evidence of past debris-flow activity indicates that there is a potential for future debris-flow activity. Basins that have had debris flows in the past are more likely to have debris flows in the future, given the right hydroclimatic and/or disturbance scenarios such as extensive, moderate to high severity burns. Results from Task 4 informed the modeling conducted in Task 7.

Task 7 was conducted in several steps. First, geomorphic data collected after the Schultz Fire was used to evaluate the current U.S. Geological Survey (USGS) post-fire debris-flow volume model (Gartner *et al.*, 2014; Staley *et al.*, 2017) with mapped post-Schultz Fire deposits (Youberg, 2015). The purpose of this step was to assess how well modeled volumes compare to estimated volumes from field mapping. These data were then used to select volumes for modeling potential inundation zones with Laharz (Schilling, 1998; Schilling, 2014). Modeled Laharz inundation zones were compared with mapped post-Schultz Fire deposits to inform the interpretation of model results in the study areas. Finally, the pilot study areas were assessed using the current USGS post-fire debris-flow probability and volume models (Gartner *et al.*, 2014; Staley *et al.*, 2017), and potential inundation zones were identified using Laharz (Schilling, 1998; Schilling, 2014).

Sincerely,

Ann M. Youberg, Ph.D.

Senior Research Scientist

Arizona Geological Survey

CC: Joe Loverich, PE, CFM; JE Fuller/Hydrology and Geomorphology, Inc.

Mike Kellogg, PG, CFM, GISP; JE Fuller/Hydrology and Geomorphology, Inc.

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BACKGROUND

Wildfires dramatically alter watershed hydrologic conditions by reducing infiltration and increasing runoff, significantly increasing the probability and frequency of post-wildfire sediment-laden floods and debris flows (Wells, 1987; Meyer and Wells, 1997; Cannon, 2001; Neary *et al.*, 2005; Ebel *et al.*, 2012; Moody *et al.*, 2013; Moody *et al.*, 2016). While post-fire sediment-laden flood flows occur more frequently, impacting larger areas, debris-flows are significantly more destructive than floods (Cannon *et al.*, 2005) and are often followed by sediment-laden floods or hyperconcentrated flows that continue to move sediment downstream (Costa, 1988). Post-wildfire debris-flows can be generated by relatively common, low-magnitude storms (Cannon *et al.*, 2008); the timing and the magnitude of these debris flows are most strongly controlled by short-duration (< 30 min), high-intensity rainfall and are best correlated with the 15-minute (I_{15}) rainfall intensity (Kean *et al.*, 2011; Kean *et al.*, 2012; Staley *et al.*, 2013; Staley *et al.*, 2015). These hydrologic conditions and watershed responses are important factors to consider during post-wildfire assessments.

Following a wildfire on federally owned lands, it is common practice to conduct a Burned Area Emergency Response (BAER) assessment to evaluate post-fire damages and potential hazards. As part of the BAER assessment, the probabilities and potential magnitudes of post-fire debris flows are often evaluated, typically by the USGS, which has developed a methodology for conducting rapid emergency post-wildfire debris-flow hazard assessments (http://landslides.usgs.gov/hazards/postfire_debrisflow/index.php). Although BAER teams provide rapid assessments of potential post-fire hazards so that mitigation measures can be implemented to reduce the risks, typically in the Southwestern U.S. there is not enough time between the end of the wildfire and the first rainfall to fully implement the mitigation measures.

The purpose of this pilot project is to assess potential post-fire flooding and debris-flow hazards, similar to a BAER assessment, prior to the occurrence of a wildfire. The goal of the pilot project is to identify at-risk areas and potential mitigation measures that could significantly reduce those risks. Conducting this assessment prior to a wildfire allows time to find funding and to implement mitigation measures in a more measured and cost-effective manner. For this Post-Wildfire Debris-Flow Risk Assessment, Task 7, three USGS models are employed to assess 1) the probability for debris flows, 2) the potential debris-flow volumes, and 3) the possible extents of debris-flow hazard zones. The results from these models will be used to predict post-fire debris-flow hazards within the pilot study areas.

METHODS

The primary focus of this task was to assess the probability of post-wildfire debris flows in the study watersheds and potential runout zones. Three models were used to accomplish this. First, the 2016 USGS post-fire debris-flow logistic regression probability model, M1, is used to assess debris-flow occurrence probabilities (Staley *et al.*, 2016; Staley *et al.*, 2017). Then the 2014 post-fire debris-flow volume model is used to provide potential magnitudes of the debris flows (Gartner *et al.*, 2014). Finally, Laharz, an empirical model used to identify hazard zones (Schilling, 1998; Schilling, 2014), is used with a modified equation for Arizona (Magirl *et al.*, 2010) to estimate potential debris-flow hazard zones in the two study areas. Data to run the models were extracted from the provided 1-m resolution Light Detection and Ranging (lidar) topographic data and the modeled burn severity maps (Task 5) using Esri ArcMap 10.4 and the TauDEM toolbox, version 5.3.7 (Tarboton, 2005). Model calculations were made in ArcMap 10.4 and in Excel.

The models were first run on the 2010 Schultz Fire burned area on the east side of the San Francisco Peaks. These results were compared with existing post-fire geomorphic deposits mapped during the first summer after the fire (A. Youberg, unpublished data) to inform modeling procedures and evaluations in the study areas. These results provide a means to determine appropriate volume estimates for Laharz modeling and to assess model results with ground conditions to understand how well the models represent processes in the study areas. In addition, these steps provided an opportunity to assess channel slopes and deposit locations to evaluate channel conditions where debris-flow deposits are most likely to occur, and to use burn severity data from the Schultz Fire to obtain reasonable burn severity model parameters for the study areas (discussed below).

USGS Logistic Regression Models for Debris-Flow Probabilities and Volumes

Empirical models developed by the USGS provide information on the likelihood of post-fire debris-flow occurrence and possible volumes given site and burn severity conditions. Results from these models can be combined to assess relative risks between basins. The first probability and volume models (Cannon *et al.*, 2010), used prior to 2016, were developed with data from burned areas in the Intermountain West but did not include any data from Arizona. The current probability model, released in 2016, was developed with a larger dataset including data from Arizona (Staley *et al.*, 2016; Staley *et al.*, 2017). The probability of debris-flow occurrence is determined by:

$$P = \frac{e^{X}}{1+e^{X}} \qquad (1)$$

where P is the probability and X is calculated using one of four logistic regression models, M1-M4, developed during the model update. Staley et al. (2017) recommends model M1 using a 15-minute rainfall intensity. M1 is calculated by:

$$X = -3.63 + (0.41 \cdot X1 \cdot R) + (0.67 \cdot X2 \cdot R) + (0.70 \cdot X3 \cdot R) \qquad (2)$$

Where:

X1 = the proportion of upslope pixels burned at high or moderate severity on slopes ≥ 23°,

X2 = the average differenced normalized burn ratio (dNBR) of the upslope pixels divided by 1000,

X3 = the average soil KF Factor, a soil erosion value from the STATSGO database, and

R = the 15-minute (I_{15}) rainfall intensity (mm h^{-1}) of the design storm.

Probabilities can be calculated for each burned basin for several design storms (e.g. 2-year, 10-year, etc.) and then ranked based on probability classes.

There are two advantages to using this new model. First, the new model was developed with a larger, and presumably more robust, dataset including data from this region. Second, the model can be re-arranged to calculate a probable rainfall accumulation (R_p) necessary for a given specific debris-flow occurrence probability, here using the M1 model:

$$R_p = \frac{ln\left(\frac{p}{1-p}\right)-(-3.63)}{0.41X1+0.67X2+0.70X3} \quad (3)$$

The R_p accumulation value is converted into rainfall intensity by:

$$I_p = \frac{R_p}{D} \quad (4)$$

where I_p is rainfall intensity (mm h^{-1}) and D is the duration (h), in this case 0.25 h. This provides a means to select a risk level and find an associated rainfall intensity that would likely trigger a post-fire debris flow.

The current post-fire debris-flow volume model has also been updated (Gartner *et al.*, 2014) to reflect the newer research showing short-duration rainfall correlates better with post-fire debris flows than total storm rainfall, the parameter used in the previous model (Cannon *et al.*, 2010; Kean and Staley, 2011; Staley *et al.*, 2013). Although this model was updated with data only from California burn sites, it is currently used for assessments in all burned areas (D. Staley, USGS, personal communication). Potential debris-flow volume for each basin is calculated by:

$$\ln V = 4.22 + \left(0.31 \times \sqrt{V1}\right) + (0.36 \times \ln V2) + \left(0.39 \times \sqrt{V3}\right) \quad (5)$$

Where:

V1 = elevation range within the watershed (m),

V2 = upslope area burned at moderate and high severity (km^2),

V3 = I_{15} (mm h^{-1}).

For each basin, based on model predictions, both the occurrence probability and volume estimate are classified and then combined into a single hazard class and rank (low, moderate, high) (Table 1) following the methodology of the USGS (http://landslides.usgs.gov/hazards/postfire_debrisflow/index.php).

Table 1 Hazard Classification and Ranking Scheme Based on Occurrence Probability and Estimated Volume. From http://landslides.usgs.gov/hazards/postfire_debrisflow/index.php

Classified Occurrence Probability Predictions		Classified Volume Predictions		Combined Hazard Classes and Rankings	
Probability Range	Hazard Class	Volume Range	Hazard Class	Combined Class	Rank
0 – 20%	1	< 1,000 m^3	1	2 – 3 = 1	Low
20 – 40%	2	1,000-10,000 m^3	2	4 – 6 = 2	Moderate
40 – 60%	3	10,000-100,000 m^3	3	7 – 9 = 3	High
60 – 80%	4	> 100,000 m^3	4		
80 – 100%	5				

LAHARZ Modeling for Predicting Debris-Flow Inundation Limits

Laharz is an empirical model first developed to identify potential hazard zones from lahars, a type of volcanic flow (Iverson *et al.*, 1998). Laharz was later modified to include rock avalanches and worldwide debris flows (Griswold and Iverson, 2008), and subsequently Arizona debris flows (Magirl *et al.*, 2010). Laharz is a toolbox addin for ArcMap. It provides a first-order approximation of the area that could be inundated by a debris flow for a given volume (m^3). The user selects either where flows will initiate or deposition begins, then Laharz uses the digital topography and two equations representing flow mobility (described by the coefficients) to define cross-sectional and planimetric areas occupied by the flow as it moves down the channel (Schilling, 2014). The equations, modified for Arizona debris flows (Magirl *et al.*, 2010), are:

Cross-sectional area: $$A = 0.1V^{2/3} \tag{6}$$

Planimetric area: $$B = 40V^{2/3} \tag{7}$$

where A is cross-sectional area, B is planimetric area, and V is volume (m^3). Because this model provides only an approximation, volumes are considered using an order, or a half-order, of magnitude.

Debris-flow deposition zones have generally been considered to begin where channel slopes decrease to 10° or less (Rickenmann, 2005). Reid et al. (2016) assessed debris flows in Oregon and found erosion and entrainment of materials occurred in channels with slopes >10°, while in channels with slopes < 5° erosion generally ceased and materials had about an equal chance of depositing. Channel confinement influences debris-flow behavior, as does water and clay content and channel roughness (Iverson *et al.*, 2010; Hürlimann *et al.*, 2015), thus transportation and deposition can continue in confined channels with slopes <5°. In fact, a wide range of slopes where deposition begins has been reported in the literature, ranging from low single-digit values (~1° for lahars) up to 35° (e.g. Benda and Cundy, 1990; Fannin and Wise, 2001; Rickenmann, 2005). For this study, post-Schultz Fire geomorphic and topographic data, mapped post-Schultz Fire debris-flow deposits, and other deposits observed along study basin channels during Task 4, were used to evaluate dominant erosion or deposition zones within channel slope categories of ≥10°, <10° - ≥5°, <5° - ≥2.5°, and <2.5°. These data were then compared with scoured channel segments and mapped debris-flow deposits in the Schultz burn area, along with channel slope, confinement, and other topographic features such as fan morphology, to guide selection of deposition points for Laharz modeling in the study areas.

GIS Procedures for Extracting Model Parameters

High-resolution (1 m) lidar topographic data representing the bare earth (no vegetation) were used to conduct the GIS analyses. The lidar data for the Schultz Fire burned area were collected in 2012, two years after the fire. The lidar data for the pilot study areas were collected in the fall of 2016. The lidar point bare-earth data, in LAS files, were converted to 1-m resolution digital elevation models (DEMs). TauDEM toolbox, version 5.3.7 (Tarboton, 2005), was used to condition the DEMs and extract basin morphometric data for running the models. The soils KF factor, describing erosion, were extracted from STATSGO data (https://gdg.sc.egov.usda.gov/). Burn severity data were extracted using the modeled scenarios from Task 5. ArcMap-extracted model parameters were exported to Excel where calculations were performed.

Schultz Fire Data Assessment

The Schultz Fire burned just over 15,000 acres in June of 2010. This hot, fast-moving fire burned much of the area at moderate to high severity, especially on the steeper slopes (USDA Forest Service, 2010). During the remainder of the summer, the area experienced a wet monsoon, the 4th wettest at the time, which caused repeated flooding and numerous debris flows (Youberg *et al.*, 2010). Conditions in the burned basins were documented, with the main purposed to identify flood and debris flows and to map the locations and extent of debris-flow deposits (A. Youberg, unpublished data). These data are used here to evaluate where erosion and deposition occurred in relation to channel slopes, confinement and surface morphology to inform selecting Laharz deposition points, to compare with modeled volumes to inform the selection of Laharz volumes, and to compare the extent of mapped deposits with Laharz results to evaluate the efficacy of the Laharz modeling.

Twenty-five basins were assessed in this study (Table 2 , Figure 1). Some of these basins (2001, 2002, 4-9) are equivalent to the BAER assessment basins. The smaller, higher basins were derived based on where debris-flow deposits were mapped. Morphometric data that describe the basins includes basin size, relief (range of basin elevation), ruggedness, and channel slopes. Ruggedness, also called the Melton Ratio, is basin relief ÷ square root of the basin area which gives a non-dimensional number that allows comparisons between basins of different sizes; higher numbers indicate greater relief or ruggedness (Melton, 1965). Basin sizes range from 0.1-4.7 km^2 (average = 1.7 km^2), relief ranges from 324—1,264 m (average = 691 m), and ruggedness values range from 0.4-0.9 (average = 0.7) (Table 2). Upper channel slopes are ≥ 10°, decreasing to ≥5° – 10° below the steep upper slopes of the San Francisco Peaks, and ≥2.5° - 5° above the Schultz Pass Road (Figure 2).

Most debris-flow deposits were documented in areas where channel slopes are generally between 5° - 10° (Figure 2). Some debris-flow deposits, however, did occur on channels with slopes ≥10° in locations where the Waterline Road crossed the drainage creating a significant decrease in channel slope and confinement. One debris-flow deposit, and several mixed debris flow/flood deposits were located on channel sections between ≥2.5°-5° where channel confinement decreased (Figure 2). Below the Schultz Pass Road channels were somewhat re-confined and additional significant channel transport occurred (Carroll, 2011). In the Basin 5 channel between Schultz Pass Road and the forest boundary (Figure 2), several small debris-flow deposits were noted. These were likely due to “breach hydrology”, locations where log jams occur in confined channel sections, causing temporary dams that subsequently break resulting in small debris flows. Where the lower channels debouched onto unconfined Holocene alluvial surfaces, near the forest boundary, coarse fans were deposited; these were mapped as hyperconcentrated or flood-flow deposits (Youberg, unpublished data).

During Task 4, large-caliber levee deposits were observed along both sides of Cataract Creek above City Dam in the Williams study area. The channel in this area of the mountain has slope of 2.5°-5°. Debris-flow deposits in the Fort Valley study area were found on channel sections with slopes as low as 2.5° but slopes with debris-flow deposits were generally > 5°. Based on these observations, for this study, debris-flow deposition points will generally be located on slopes ≥5° but may be located on slopes as low as 2.5° depending on channel confinement.

Table 2. Basin morphometric and model parameter data of the Schultz Fire basins.

Basin_ID	Area (km^2)	Area (mi^2)	Basin Relief (m)	Ruggedness	M1_X1	M1_X2	M1_X3	V_X1	V_X2
2001	3.54	1.37	1160	0.62	0.13	0.30	0.19	34.05	0.50
2002	3.29	1.27	766	0.42	0.01	0.39	0.14	27.67	0.89
4	4.59	1.77	1081	0.50	0.16	0.46	0.23	32.88	1.46
5	3.83	1.48	1104	0.56	0.35	0.54	0.18	33.23	1.34
6	4.70	1.81	1264	0.58	0.44	0.47	0.17	35.55	1.37
7	3.81	1.47	910	0.47	0.22	0.51	0.24	30.17	1.28
8	2.86	1.10	899	0.53	0.28	0.41	0.27	29.98	0.80
9	4.63	1.79	846	0.39	0.22	0.40	0.29	29.09	1.35
5111	0.37	0.14	406	0.66	0.36	0.56	0.13	20.15	-0.99
5210	1.12	0.43	837	0.79	0.71	0.54	0.13	28.92	0.09
5310	0.38	0.15	529	0.86	0.64	0.56	0.13	23.00	-0.97
6310	1.24	0.48	884	0.79	0.56	0.38	0.13	29.74	-0.27
6320	1.81	0.70	735	0.55	0.71	0.52	0.13	27.12	0.49
7110	0.65	0.25	604	0.75	0.67	0.58	0.13	24.57	-0.44
7120	0.22	0.08	391	0.83	0.54	0.57	0.13	19.78	-1.51
7130	0.16	0.06	338	0.85	0.53	0.55	0.13	18.38	-1.85
7140	0.17	0.07	374	0.90	0.62	0.52	0.13	19.35	-1.78
7160	0.30	0.12	324	0.59	0.30	0.57	0.25	18.01	-1.19
8110	1.01	0.39	681	0.68	0.72	0.56	0.18	26.11	0.01
9110	0.58	0.22	675	0.89	0.58	0.55	0.23	25.98	-0.55
9120	0.56	0.22	547	0.73	0.62	0.51	0.23	23.39	-0.59
9130	0.14	0.05	347	0.92	0.54	0.53	0.19	18.63	-1.95
9140	0.51	0.20	415	0.58	0.33	0.43	0.20	20.37	-0.76
10	0.77	0.30	553	0.63	0.22	0.30	0.22	23.51	-0.60
11	1.48	0.57	600	0.49	0.45	0.38	0.13	24.50	0.11

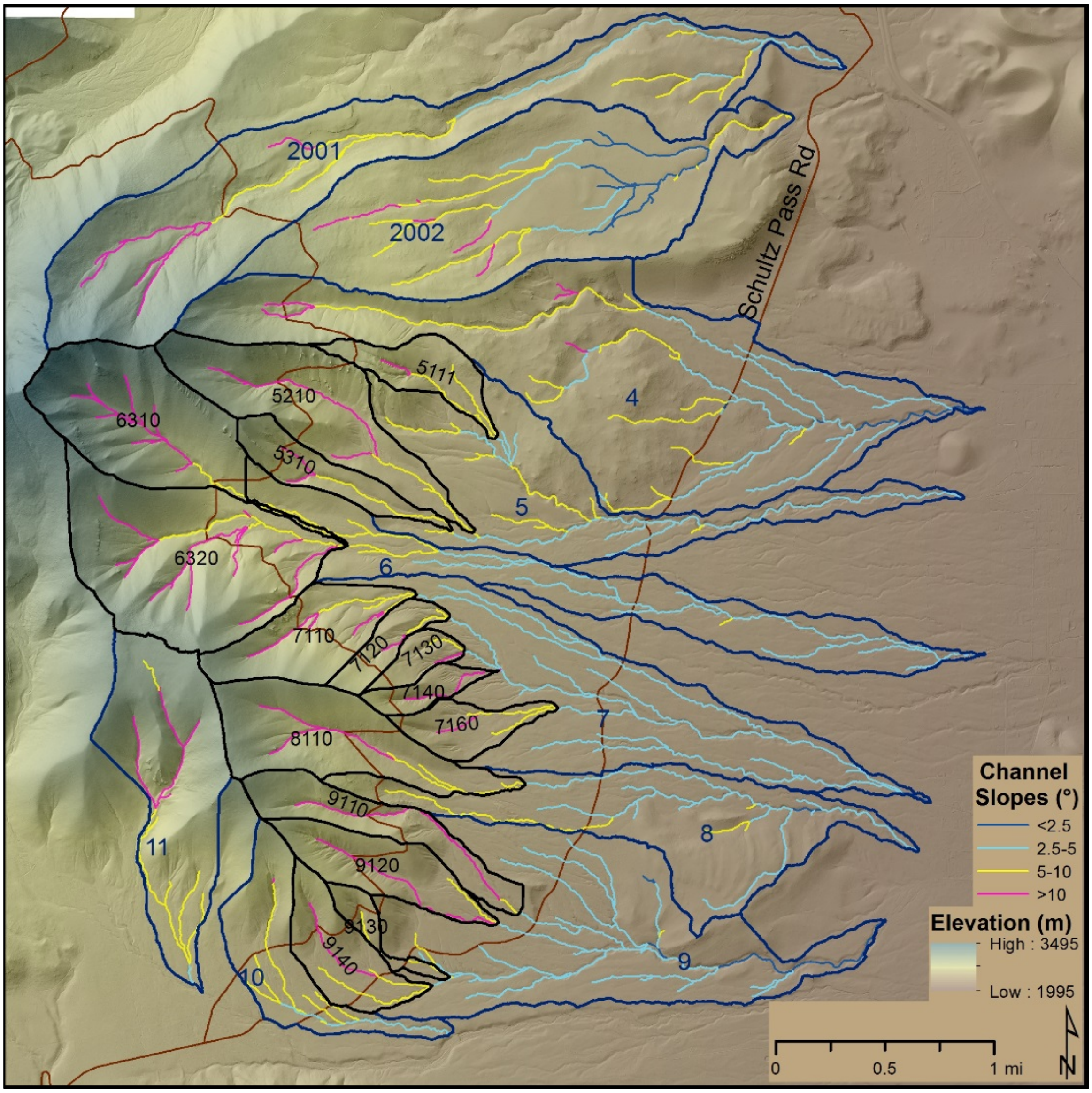

Figure 1 Basins within the Schultz Fire burn perimeter (red) used in this study. The larger blue basins were derived during the BAER assessment. The smaller black basins were derived basin on field mapping of debris-flow deposits (Youberg, unpublished data).

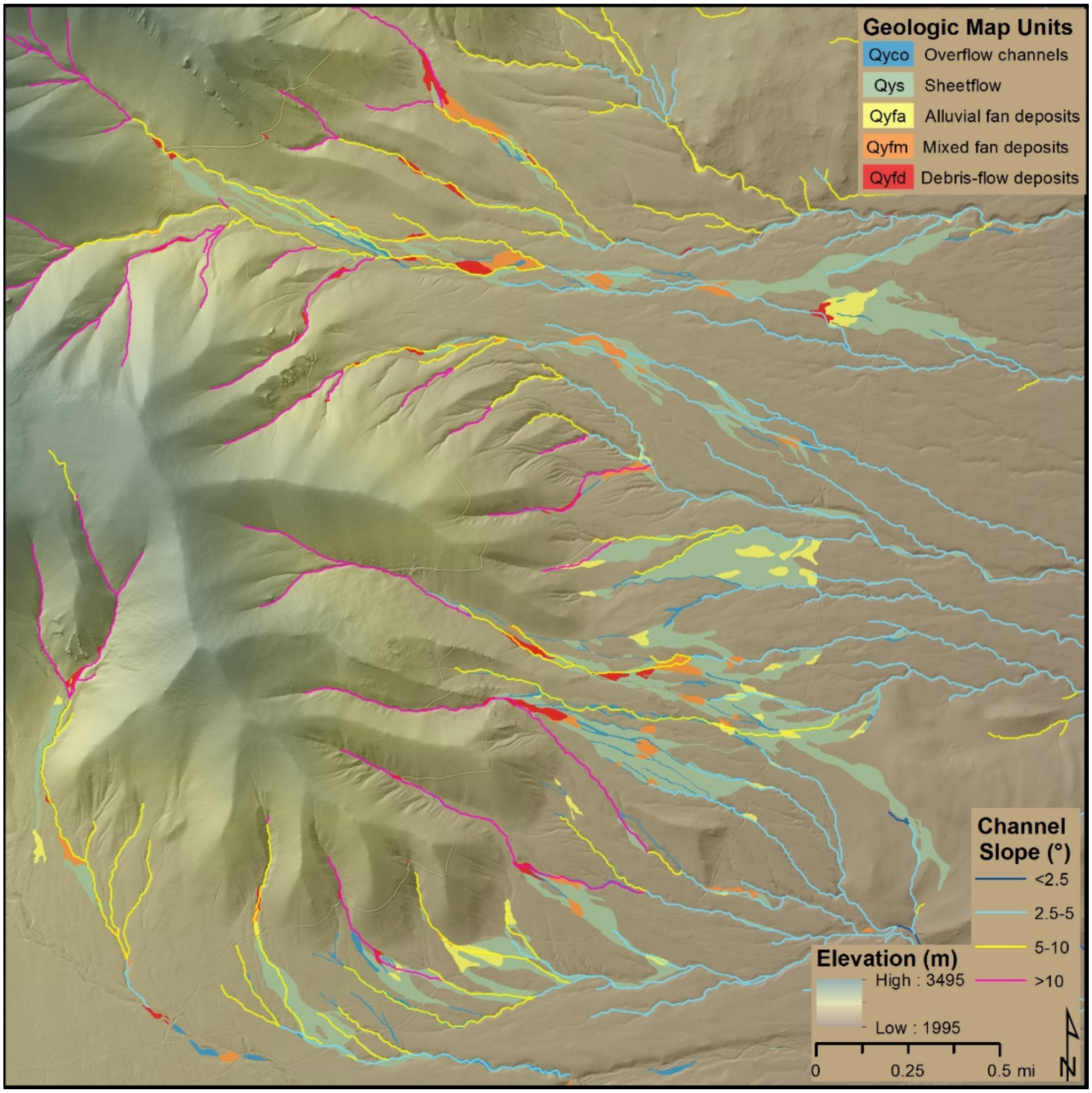

Figure 2 Mapped geologic deposits during the months after the 2010 Schultz Fire.

Proxy dNBR data from Burn Severity Modeling for Model Parameters

The 2016 USGS post-fire debris-flow probability model, M1, (Staley *et al.*, 2017) and associated 2014 debris-flow volume model (Gartner *et al.*, 2014) use measurements of burn severity to define a model parameter (Eq. 2, Table 2). Burn severity scenario modeling, Task 5 (Loverich, 2016), was used to create proxy classified burn severity maps (unburned, low, moderate, high). The volume model parameter describes the amount of basin area burned at moderate and high severity (Gartner *et al.*, 2014), which can be calculated directly from the proxy burn severity maps. The probability model, however, requires a parameter based on the differenced normalized burn ratios (dNBR) (Staley *et al.*, 2017) which are derived by comparing pre- and post-wildfire remotely sensed imagery (Brewer *et al.*, 2005). Burned area reflectance classification (BARC) maps are created by categorizing the continuous dNBR ratios into unburned, low, moderate and high burn severity classes (Figure 3, https://www.fs.fed.us/eng/rsac/baer/).

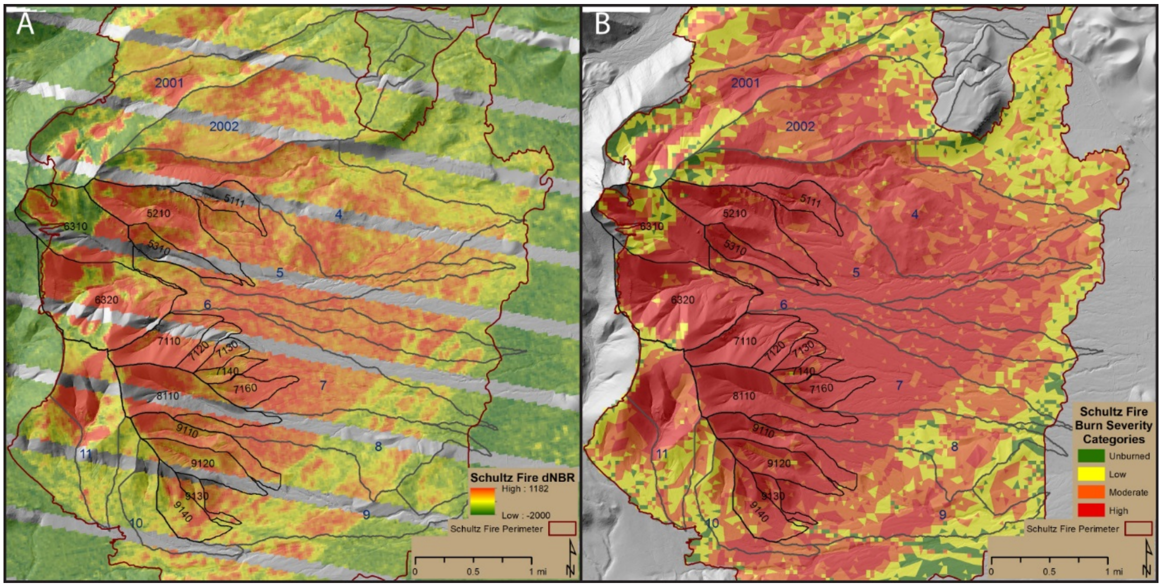

Figure 3. Schultz Fire burn severity maps showing continuous dNBR values (A) and classified burn severity (B). Gray stripes in panel A are areas of No Data due to a satellite malfunction. No Data area were interpreted to create the image in panel B.

The probability model, M1, has a burn severity parameter, X2, that is the normalized average dNBR value of upslope (basin) area. While the dNBR data from the Schultz Fire is problematic, due to a satellite malfunction that resulted in bars of No Data (gray stripes, Figure 3A), it is the best-available and most appropriate data to create proxy dNBR values. To create the proxy values, the Schultz continuous dNBR data (Figure 3A) were statistically analyzed in ArcMap using zonal statistics and the classified burn severity map (Figure 3B). The minimum, maximum, median and mean dNBR values were extracted for each classification and tested to assess the best value to use in the model. The median dNBR value, applied to each classification (Table 3) provided model results that reasonably reflected on-the-ground conditions. To create proxy dNBR burn severity maps for modeling in the study areas, the median dNBR value for each category was calculated to the correlated pixels in the various burn severity scenario maps from Task 5 (Loverich, 2016). These proxy dNBR rasters were then used to extract X2 model parameter for each burn condition in the both pilot study areas.

Table 3. Schultz Fire median dNBR values for each burn severity classification.

Category	Median dNBR Value
Unburned	57
Low	129
Moderate	287
High	582

Comparison of Mapped and Modeled Volume Estimates

Mapped debris-flow deposits from the Schultz Fire (Figure 2) also provides a means to assess how well the past (Cannon *et al.*, 2010) and current (Gartner *et al.*, 2014) debris-flow volume models correlate to documented deposits. Mapped deposits provide a snapshot volume, however, due to possible re-working, erosion, burial, or additional deposits from subsequent flows that may have occurred between initial deposition and mapping. The largest measured debris-flow volumes in Schultz Fire burned area were 12,000 and 14,000 m^3 (10^4 m^3); the smallest were <1000 m^3 (<10^3 m^3) (Youberg, 2014). The magnitude of these debris flows (<10^3 -~10^4) show similar trends to debris-flow volumes documented on several other fires in Arizona (Youberg, 2015).

A comparison of mapped Schultz Fire debris-flow volumes with both predicted volumes from the 2010 and 2014 models show that for smaller volumes (<$10^{3.5}$) both models over estimate mapped volumes (Figure 4); the 2014 model appears slightly better than the 2010 model. For larger volumes (≥10^4), however, the models tend to reflect mapped volumes more closely. There are several possible explanations for why these models over-estimate smaller volumes. The smallest volumes from the Schultz Fire were found in deposits along the Waterline Road (Youberg, 2014). These deposits occurred because of the break in channel slope due to the road and thus did not reflect the conditions at the basin outlets. Deposits mapped below the mouth of the steep upper basins, those found below the Waterline Road but above the Schultz Pass Road, were larger. Conditions at these deposits may more accurately reflect those data that were used to develop the empirical volume models. Another possibility is that the smaller deposits could be more easily removed or buried and therefore underestimated in the field. Overall, estimated volumes from the current 2014 model provide conservative estimates for smaller volumes and reasonable estimates for larger volumes. Based on this comparison, five volumes were selected for the Laharz modeling. Because Laharz provides a first-order assessment of inundation, volumes are based on half-order of magnitudes (Table 4).

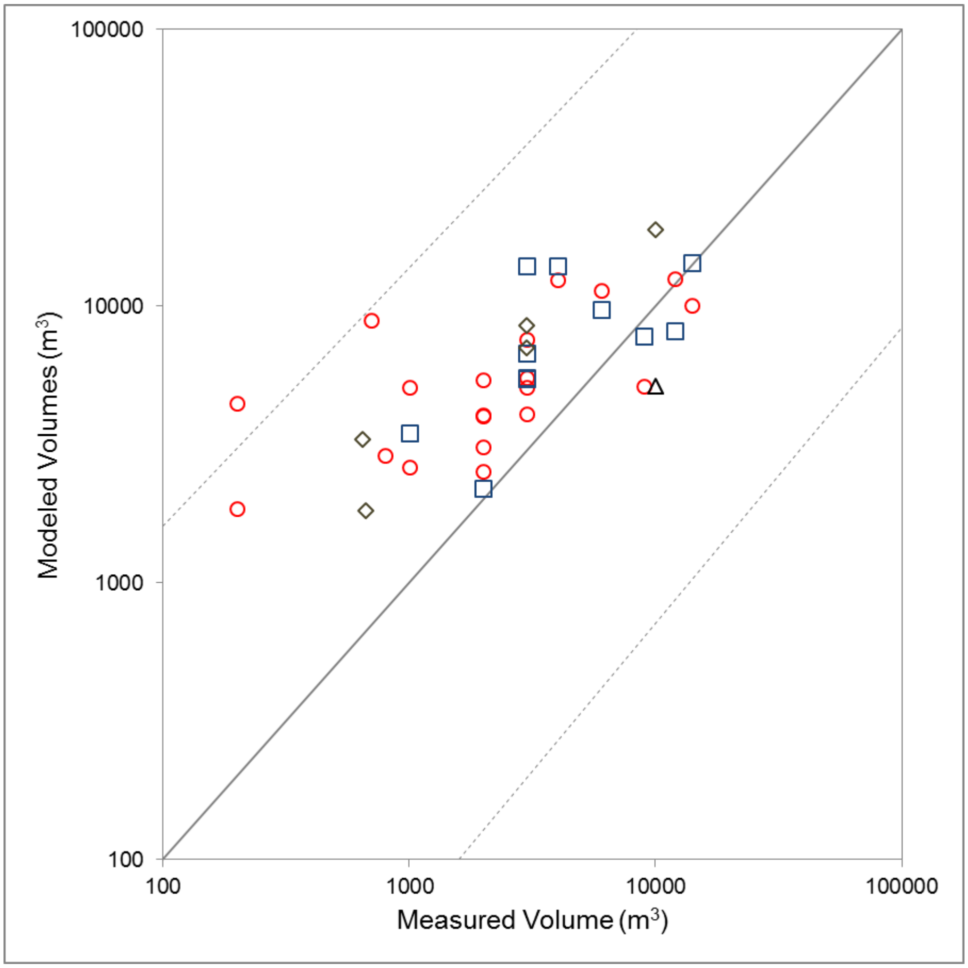

Figure 4. Comparison of post-fire debris-flow volumes estimated from field-mapped deposits and models. Data from the 2010 Schultz Fire modeled with the 2010 model (red circles) and the 2014 model (blue boxes). The 201 model was also used to compare with field mapped deposits from the 2011 Horseshoe 2 and Monument Fires in southeastern Arizona (gray diamonds) and the 2011 Wallow Fire in east central Arizona (black triangle). (Modified from Youberg, 2014).

Table 4. Volumes used for Laharz modeling in this project.

Volumes		
Half-Order Magnitude	~Half-Order Magnitude (m^3)	~Half-Order Magnitude (yds^3)
10^3	1,000	1,300
$10^{3.5}$	3,200	4,100
10^4	10,000	13,100
$10^{4.5}$	31,600	41,300
10^5	100,000	130,800

Comparison of Laharz Inundation Zones with Mapped Deposits

Laharz results for the 25 Schultz Fire basins are shown on Figure 5 and Figure 6. Laharz deposition points were selected based on topography, channel slope and channel confinement. The USGS probability and volume models were calculated and assessed for 1) the I_{15} rainfall needed to provide a 50% probability that the basin would have a debris flow, and 2) to find the probability and estimated volume of flows for a given design storm of 1-, 2- and 5-year return intervals (Table 5). The combine hazard class, ranked low, medium or high (Table 5), is based on both the probability that a basin will produce a debris flow and the estimated volume of the debris flow (Table 1) (http://landslides.usgs.gov/hazards/postfire_debrisflow/background2016.php).

Laharz was used to model potential inundation zones for the selected volumes (Table 4). These results were compared with mapped deposits (Figure 6), although the mapped deposits in some cases are likely fragmented remnants of what were probably larger flow deposits immediately after deposition. Nevertheless, comparing Laharz modeled inundation with mapped deposits indicates that reasonable Laharz volumes for the smaller upper basins are 10^3 -10^4, and up to $10^{4.5}$ for the larger of these basins or in areas where several channels coalesced. The modeled inundation limits extend laterally farther than the mapped debris-flow and mixed debris/flood deposits suggest which may indicate a problem with the mobility coefficients. This modeling, however, reasonably represents the mapped deposits, especially for the smaller volumes (10^3 -$10^{3.5}$). For basins 4-9, debris-flow deposits were not observed at the basin outlets but sediment rich fans were. These fans are located where channel confinement ceases. Based on the coarseness of these fans, the flows that deposited them probably had some hyperconcentrated-flow phases. While these modeled Laharz inundation zones correlate somewhat with the extent of these coarse fans, the actual flows were not debris flows.

Table 5. Schultz Fire Basins. "Strm2" refers to the second debris-flow producing storm during the first summer after the fire, on 16 Aug 2010.

Basin _ID	I15_P50% (mm/h)	I15_P50 % (in/h)	P_1yr_I15 _45mm/h	EstVol_1yr_ I15_45mm/ h (m3)	Combined Hazard Class	P_2yr_I15 _59mm/h	EstVol_2yr_ I15_59mm/ h (m3)	Combined Hazard Class	P_5yr_I15_7 9mm/h	EstVol_5yr_I15 _79mm/h (m3)	Combined Hazard Class	P_Strm2_I15 _64mm/h	EstVol_Strm2_I15 _64mm/h (m3)	Combined Hazard Class
2001	38	1.5	72%	25,171	High	91%	30,430	High	98%	38,506	High	94%	32,382	High
2002	40	1.6	68%	12,666	High	88%	15,312	High	98%	19,376	High	92%	16,294	High
4	27	1.1	93%	30,588	High	99%	36,978	High	100%	46,791	High	99%	39,350	High
5	23	0.9	98%	30,601	High	100%	36,994	High	100%	46,812	High	100%	39,367	High
6	24	0.9	97%	41,836	High	100%	50,576	High	100%	63,998	High	100%	53,820	High
7	24	0.9	97%	20,147	High	100%	24,356	High	100%	30,819	High	100%	25,918	High
8	25	1.0	96%	16,517	High	99%	19,968	High	100%	25,267	High	100%	21,249	High
9	26	1.0	95%	17,934	High	99%	21,681	High	100%	27,435	High	100%	23,072	High
5111	24	0.9	97%	2,422	High	100%	2,928	High	100%	3,705	High	100%	3,116	High
5210	20	0.8	99%	11,173	High	100%	13,165	High	100%	17,091	High	100%	14,373	High
5310	20	0.8	99%	3,529	High	100%	4,158	High	100%	5,398	High	100%	4,540	High
6310	25	1.0	96%	10,911	High	99%	12,858	High	100%	16,692	High	100%	14,037	High
6320	20	0.8	99%	10,189	High	100%	12,006	High	100%	15,586	High	100%	13,107	High
7110	19	0.8	99%	5,243	High	100%	6,178	High	100%	8,020	High	100%	6,745	High
7120	21	0.8	99%	1,908	High	100%	2,248	High	100%	2,918	High	100%	2,454	High
7130	21	0.8	99%	1,411	High	100%	1,663	High	100%	2,159	High	100%	1,815	High
7140	21	0.8	99%	1,640	High	100%	1,932	High	100%	2,508	High	100%	2,109	High
7160	21	0.8	99%	1,703	High	100%	2,006	High	100%	2,605	High	100%	2,191	High
8110	18	0.7	100%	7,526	High	100%	8,868	High	100%	11,512	High	100%	9,682	High
9110	19	0.7	99%	6,051	High	100%	7,130	High	100%	9,256	High	100%	7,784	High
9120	19	0.8	99%	4,264	High	100%	5,024	High	100%	6,523	High	100%	5,485	High
9130	20	0.8	99%	1,405	High	100%	1,655	High	100%	2,149	High	100%	1,807	High
9140	26	1.0	95%	2,707	High	99%	3,190	High	100%	4,141	High	100%	3,483	High
10	33	1.3	84%	4,306	High	96%	5,205	High	100%	6,587	High	98%	5,539	High
11	27	1.1	93%	6,316	High	99%	7,635	High	100%	9,662	High	99%	8,125	High

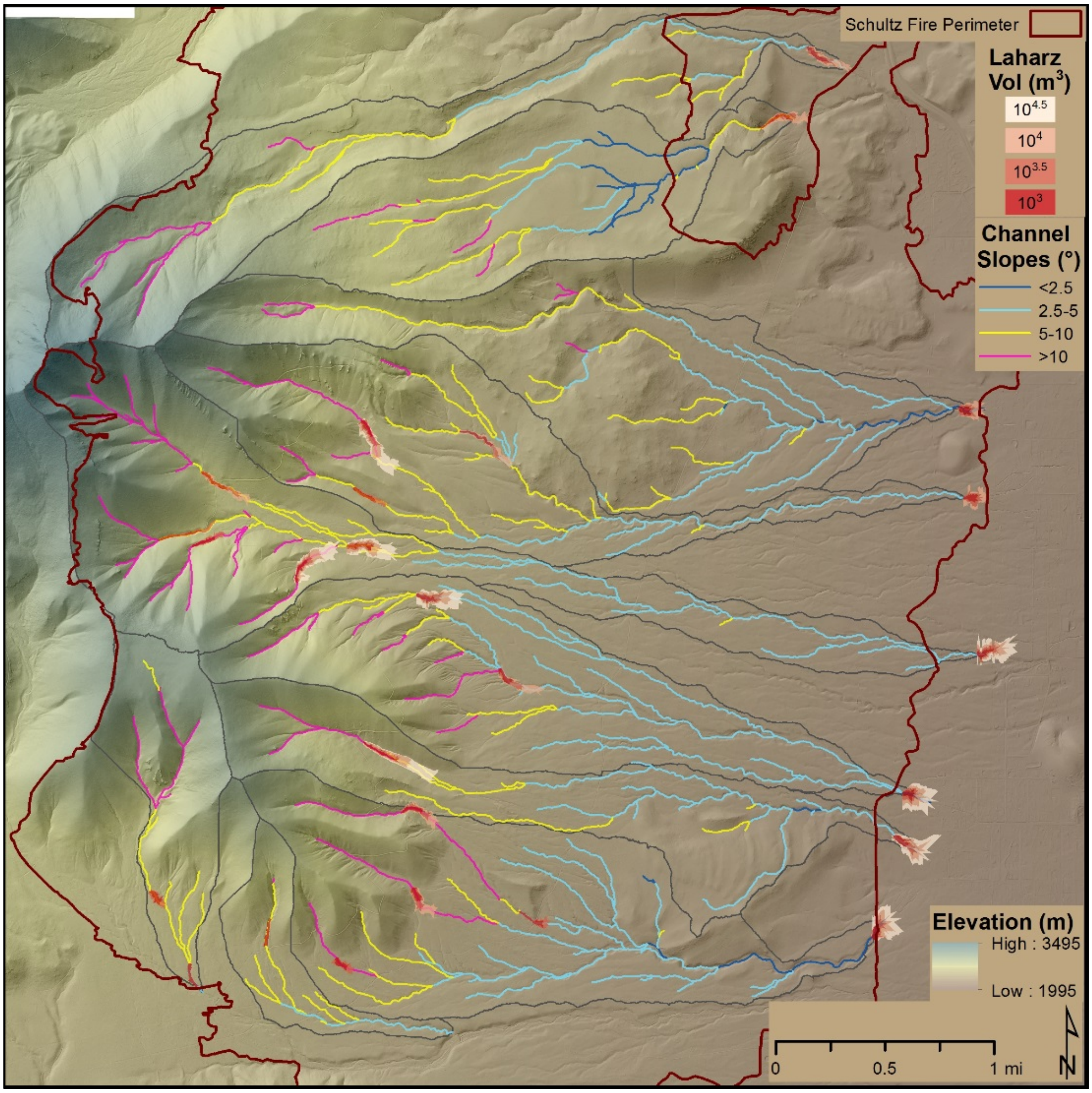

Figure 5. Results from Laharz modeling (volumes in shades of red) with channel slopes.

Modeling Considerations and Limitations

While modeling provides a means to assess or predict possible outcomes, it is important to keep in mind the limitations inherent with modeling. Some important considerations include the resolution of digital data (topography), the integrity of field data (mapped and observed deposits), and the ability of models to accurately reflect on-the-ground conditions and predict behavior. Topography is this study is well represented. High-resolution (1 m) LiDAR data was collected in 2016 for the Williams and Fort Valley study areas, and in 2012 for the Schultz Fire burned area. It is important to remember that the Schultz Fire data were collected two years after the fire at which point the channels and deposits were significantly altered. Similarly, mapped deposits were based on intermittent field visits; channels and deposits were being re-worked with each storm event so the location and extent of some deposits are likely not captured accurately. Additionally, it is sometimes difficult to identify debris-flow from flood or hyperconcentrated deposits. Subsequent flows can re-work, remove or bury previous deposits. Field maps, therefore, are a depiction of the best available data but may contain errors. Finally, empirical models are based on previous events and can help predict likely future events but cannot account for all variables. Deposition zones, for example, can vary between each storm as channels erode and material is moved around. In a similar vein, the burn severity modeling presents reasonable scenarios but will not accurately reflect an actual burn. Therefore, the results from this modeling effort will help provide context for future events and identify areas for mitigation efforts but will likely not reflect an actual burn should one happen.

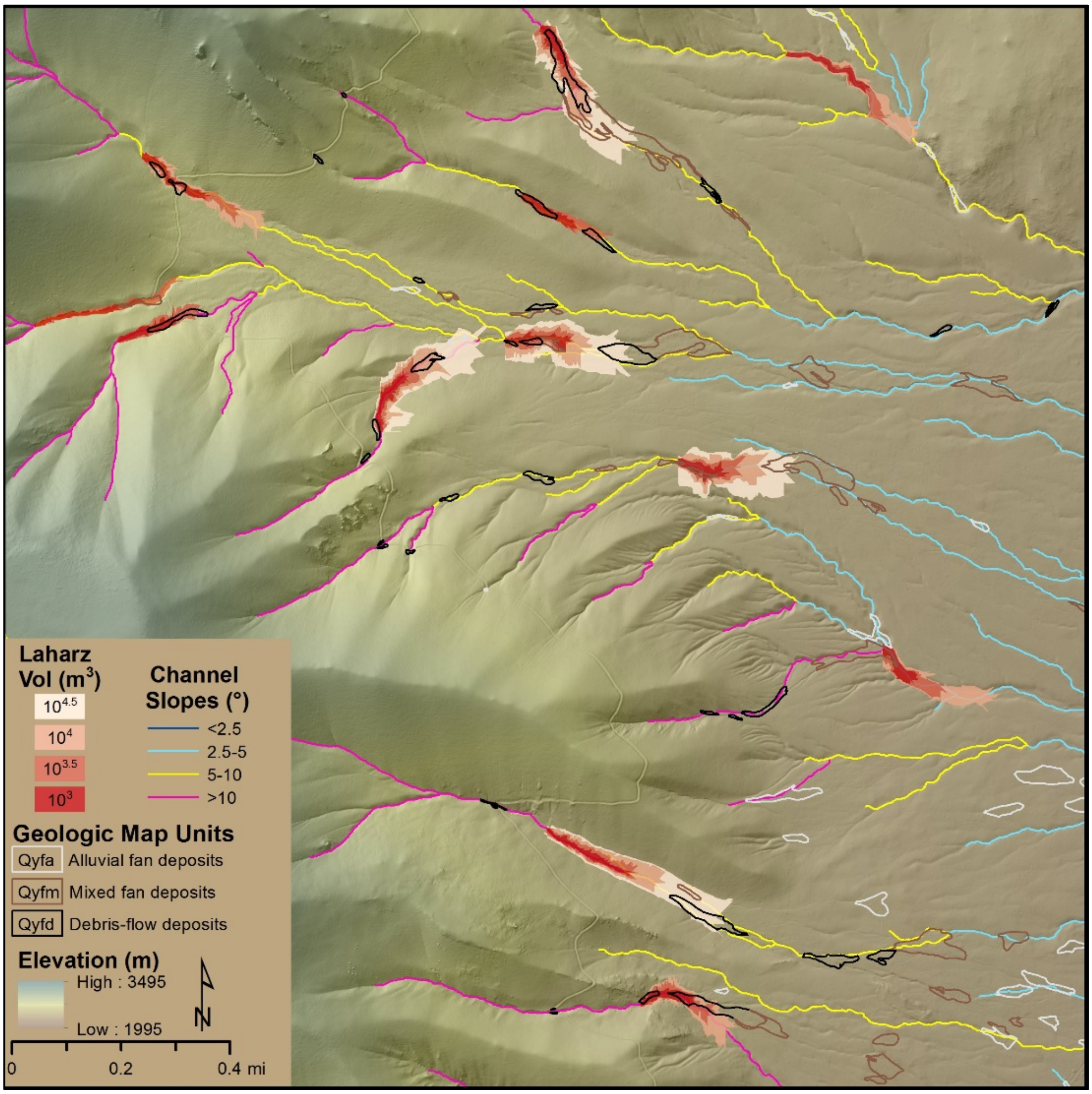

Figure 6. A comparison of Laharz modeled inundation (red shades) with mapped debris-flow deposits (black outlines), mixed debris and flood deposits (brown), and flood deposits (white).

RESULTS FROM TASK 7

Fort Valley Debris-Flow Assessment

Fort Valley Basins

Ten basins on the southwest side of the San Francisco Peaks (Table 6, Figure 7) were modeled using the USGS probability and volume models (Table 7). Basin sizes range from 0.3-4.1 km^2 (average = 1.6), basin relief varies from 206 - 1,214 m (average = 819), and ruggedness values range from 0.3 – 1.1 (average = 0.7) (Table 6). Overall these basins are similar to the Schultz Fire basins on the east side of the peaks (Table 2), however a notable difference is that there are few channel segments with channel slopes ≥10° in the Fort Valley basins (Figure 7). In the Schultz basins, all of the stream channels in the upper elevations have slopes ≥10° while only two basins in the Fort Valley study area show this relationship.

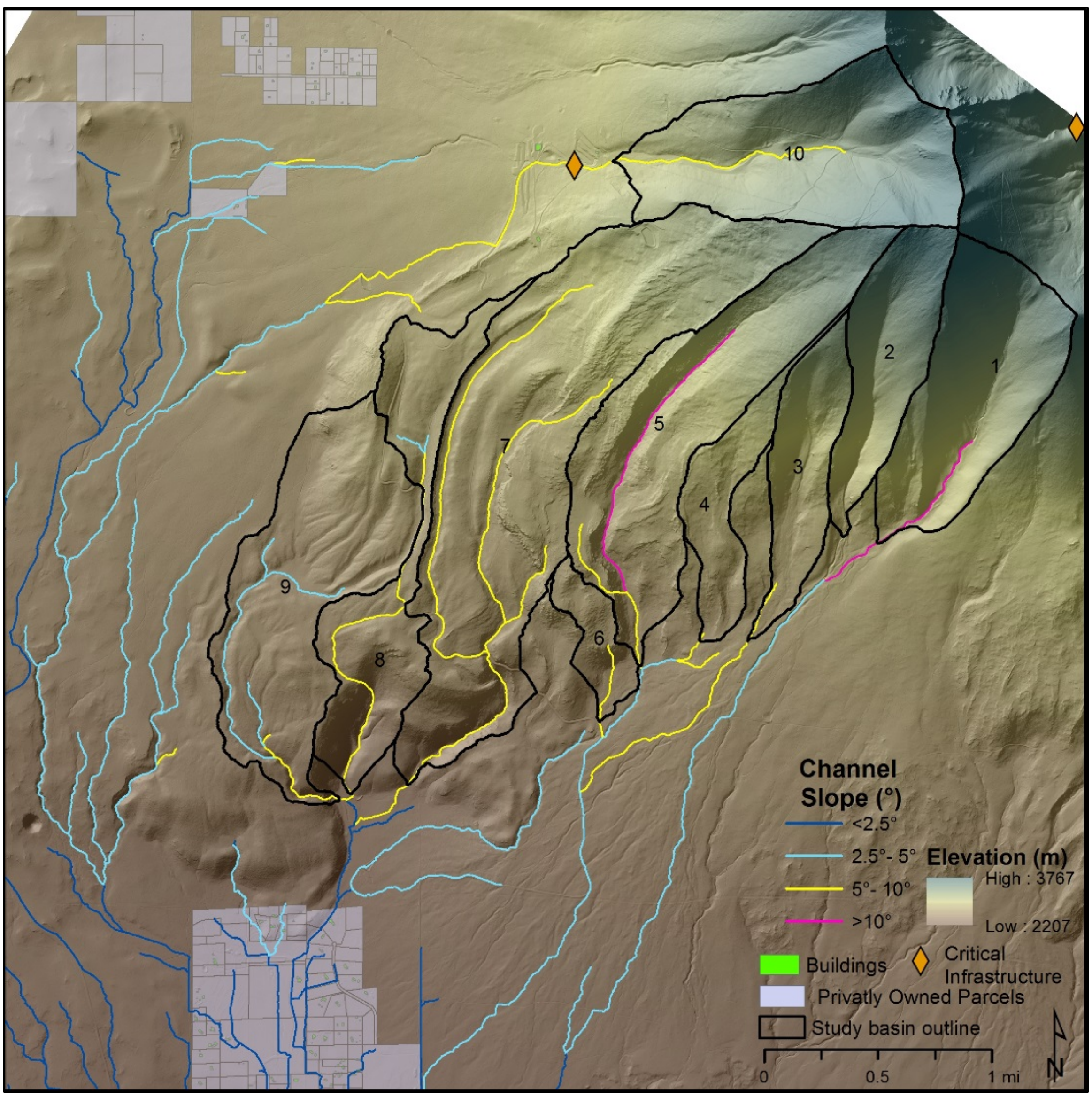

Figure 7. Fort Valley modeled basins with channel slopes.

Table 6. Basin morphometric and model parameter data of the Fort Valley study basins.

Ft Valley - Treated All									
Basin_ID	Area (km^2)	Area (mi^2)	Relief (m)	Ruggedness	M1_X1	M1_X2	M1_X3	V_X1	V_X2
1	1.6	0.6	1037	0.82	0.30	0.26	0.13	32.21	-0.68
2	1.0	0.4	1058	1.07	0.27	0.25	0.13	32.53	-1.30
3	0.8	0.3	805	0.91	0.02	0.14	0.13	28.37	-3.67
4	0.6	0.2	858	1.09	0.00	0.13	0.13	29.28	-6.11
5	2.3	0.9	1182	0.78	0.05	0.16	0.13	34.38	-1.88
6	0.3	0.1	206	0.36	0.00	0.13	0.23	14.35	0.00
7	4.1	1.6	1214	0.60	0.01	0.14	0.16	34.85	-2.12
8	1.4	0.6	572	0.48	0.00	0.13	0.21	23.92	-6.23
9	2.2	0.9	440	0.30	0.00	0.13	0.27	20.98	-5.91
10	2.1	0.8	849	0.59	0.16	0.20	0.13	29.14	-0.88
Ft Valley - Treated 8200									
Basin_ID	Area (km^2)	Area (mi^2)	Relief (m)	Ruggedness	M1_X1	M1_X2	M1_X3	V_X1	V_X2
1	1.6	0.6	1037	0.82	0.77	0.46	0.13	32.21	0.37
2	1.0	0.4	1058	1.07	0.81	0.45	0.13	32.53	-0.16
3	0.8	0.3	805	0.91	0.52	0.36	0.13	28.37	-0.38
4	0.6	0.2	858	1.09	0.14	0.37	0.13	29.28	-0.61
5	2.3	0.9	1182	0.78	0.35	0.43	0.13	34.38	0.73
6	0.3	0.1	206	0.36	0.09	0.35	0.23	14.35	-1.78
7	4.1	1.6	1214	0.60	0.10	0.37	0.16	34.85	1.16
8	1.4	0.6	572	0.48	0.03	0.27	0.21	23.92	-0.28
9	2.2	0.9	440	0.30	0.02	0.23	0.27	20.98	-0.33
10	2.1	0.8	849	0.59	0.39	0.34	0.13	29.14	0.23
Ft Valley - Untreated									
Basin_ID	Area (km^2)	Area (mi^2)	Relief (m)	Ruggedness	M1_X1	M1_X2	M1_X3	V_X1	V_X2
1	1.6	0.6	1037	0.82	0.77	0.46	0.13	32.21	0.37
2	1.0	0.4	1058	1.07	0.81	0.45	0.13	32.53	-0.16
3	0.8	0.3	805	0.91	0.52	0.36	0.13	28.37	-0.38
4	0.6	0.2	858	1.09	0.14	0.37	0.13	29.28	-0.61
5	2.3	0.9	1182	0.78	0.35	0.43	0.13	34.38	0.73
6	0.3	0.1	206	0.36	0.10	0.43	0.23	14.35	-1.46
7	4.1	1.6	1214	0.60	0.13	0.40	0.16	34.85	1.25
8	1.4	0.6	572	0.48	0.13	0.34	0.21	23.92	0.00
9	2.2	0.9	440	0.30	0.03	0.28	0.27	20.98	-0.02
10	2.1	0.8	849	0.59	0.39	0.34	0.13	29.14	0.23

Probability and Volume Modeling

The Fort Valley basins were modeled for debris-flow probability and volumes based on three burn scenarios from Task 5 (Loverich, 2016): 1) Treated All - the entire mountain, including the wilderness area that encompasses the upper peaks, is treated (thinned) prior to a fire; 2) Treated 8200- only the forest below the wilderness boundary is thinned prior to a fire, 8200 represents the approximate contour interval at the base of the wilderness; and 3) Untreated – no treatment occurs prior to a fire. Because debris flows typically initiate in the steep headwaters of basins, the area encompassed by the wilderness, the Treated All scenario was included to assess if different responses could be seen between the three forest conditions.

Model parameters for each burn scenario are shown in Table 6. The I_{15} rainfall intensities (Table 7, columns 2 and 3) needed for a 50% probability that a debris flow would occur in that basin ranges from 37-81 mm h^{-1} (<1-yr to 5-yr recurrence interval (RI); http://hdsc.nws.noaa.gov/hdsc/pfds/) under the Treated All scenario (Figure 8A), but drop to 20-46 mm h^{-1} for the Treated 8200 scenario (Figure 8B)and 20-37 mm h^{-1} for the Untreated scenario (Figure 8C). Rainfall thresholds for basins 8 and 9 in the Treated 8200 scenario are within the range of 1-year RIs but the other values are <1-yr, as are all of the values in the untreated scenario.

Other columns in Table 7show debris-flow probabilities and estimated volumes for the 1-, 2-, and 5-year design storms. Results from the 1-year storm show a response difference between the three scenarios. The Treated All basins have probabilities ranging from 45%-77% and volumes from <10^3-10^4. The combine hazard class ranking in all basins is moderate (Figure 9A). The Treated 8200 basins have probabilities ranging from 66%-99% and volumes from 10^3-$10^{4.5}$, with combine hazard rankings varying from moderate to high (Figure 9B). The Untreated basins have probabilities ranging from 77%-99% and volumes from 10^3-$10^{4.5}$, with combine hazard rankings of moderate in one basin and high in the others (Figure 9C). This same pattern continues in the 2- and 5-year design storms, with the Treated All basins having slightly lower probabilities and volumes than the Treated 8200 or Untreated basins, which are similar. Beyond the 5-year storm, all basins in all scenarios, have high probabilities and combined hazard rankings of high except for basins 4 and 9 in Treated All scenario which reach high probabilities and high combined hazard rankings in the 25-year storm (not shown).

Table 7. Probability and volume model results of the Fort Valley study basins based on three forest treatment scenarios.

Ft Valley - Treated All											
Basin _ID	I15_P50% (mm/h)	I15_P50% (in/h)	P_1yr_I15 _47mm/h	EstVol_1yr_I15 _47mm/h (m3)	Combined Hazard Class	P_2yr_I15 _60mm/h	EstVol_2yr_I15 _60mm/h (m3)	Combined Hazard Class	P_5yr_I15 _81mm/h	EstVol_5yr_I15 _81mm/h (m3)	Combined Hazard Class
1	37	1.5	77%	2,680	Moderate	92%	20,284	High	99%	20,243	High
2	39	1.5	75%	1,765	Moderate	90%	21,140	High	98%	16,925	High
3	74	2.9	47%	173	Moderate	39%	12,318	Moderate	64%	4,192	Moderate
4	81	3.2	45%	31	Moderate	34%	13,870	Moderate	57%	1,962	Moderate
5	67	2.6	50%	1,454	Moderate	47%	26,886	Moderate	74%	17,478	High
6	59	2.3	45%	439	Moderate	58%	1,990	Moderate	84%	2,542	High
7	69	2.7	46%	1,288	Moderate	45%	28,584	Moderate	71%	17,020	High
8	62	2.4	45%	14	Moderate	54%	6,908	Moderate	80%	938	Moderate
9	52	2.0	45%	12	Moderate	69%	4,710	Moderate	91%	715	Moderate
10	50	2.0	63%	612	Moderate	73%	13,604	High	93%	12,657	High
Ft Valley - Treated 8200											
Basin _ID	I15_P50% (mm/h)	I15_P50% (in/h)	P_1yr_I15 _47mm/h	EstVol_1yr_I15 _47mm/h (m3)	Combined Hazard Class	P_2yr_I15 _60mm/h	EstVol_2yr_I15 _60mm/h (m3)	Combined Hazard Class	P_5yr_I15 _81mm/h	EstVol_5yr_I15 _81mm/h (m3)	Combined Hazard Class
1	20	0.8	99%	19,500	High	100%	23,198	High	100%	29,624	High
2	20	0.8	99%	16,749	High	100%	19,925	High	100%	25,445	High
3	27	1.1	95%	9,033	High	99%	10,746	High	100%	13,723	High
4	36	1.4	79%	9,370	Moderate	93%	11,147	High	99%	14,235	High
5	28	1.1	94%	29,372	High	99%	34,941	High	100%	44,620	High
6	33	1.3	85%	881	Moderate	96%	1,048	High	100%	1,338	High
7	36	1.4	80%	36,477	High	93%	43,392	High	99%	55,413	High
8	43	1.7	66%	5,254	Moderate	85%	6,250	High	97%	7,981	High
9	41	1.6	69%	3,515	Moderate	88%	4,182	High	98%	5,341	High
10	30	1.2	91%	12,436	High	98%	14,794	High	100%	18,893	High

Table 7 Continued.

Ft Valley - Untreated											
Basin _ID	I15_P50% (mm/h)	I15_P50% (in/h)	P_1yr_I15 _47mm/h	EstVol_1yr_I15 _47mm/h (m3)	Combined Hazard Class	P_2yr_I15 _60mm/h	EstVol_2yr_I15 _60mm/h (m3)	Combined Hazard Class	P_5yr_I15 _81mm/h	EstVol_5yr_I15 _81mm/h (m3)	Combined Hazard Class
1	20	0.8	99%	19,500	High	100%	23,198	High	100%	29,624	High
2	20	0.8	99%	16,749	High	100%	19,925	High	100%	25,445	High
3	27	1.1	95%	9,033	High	99%	10,746	High	100%	13,723	High
4	36	1.4	79%	9,370	High	93%	11,147	High	99%	14,235	High
5	28	1.1	94%	29,395	High	99%	34,968	High	100%	44,655	High
6	29	1.2	92%	990	Moderate	98%	1,178	High	100%	1,504	High
7	33	1.3	85%	37,677	High	96%	44,820	High	100%	57,236	High
8	34	1.3	84%	5,814	High	95%	6,916	High	99%	8,832	High
9	37	1.5	77%	3,931	High	92%	4,676	High	99%	5,972	High
10	30	1.2	91%	12,436	High	98%	13,135	High	100%	16,774	High

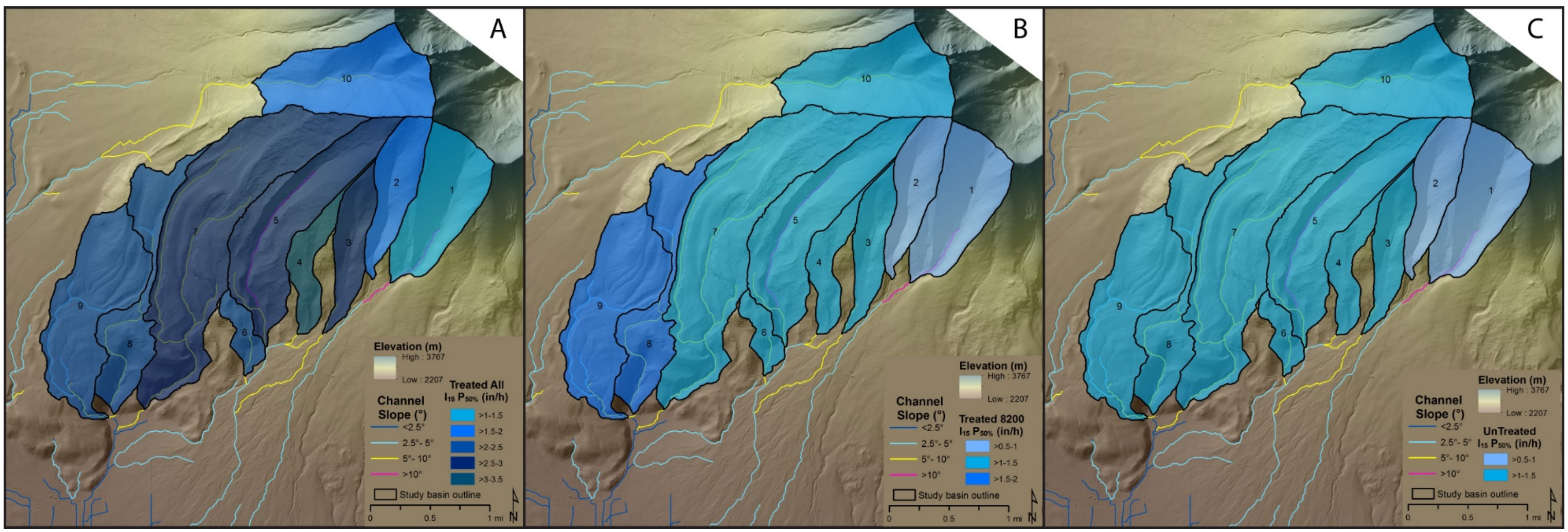

Figure 8. Model results showing the I_{15} rainfall intensity required for a 50% probability of a debris flow for the TreatedAll (A), Treated8200 (B), and Untreated (c) scenarios.

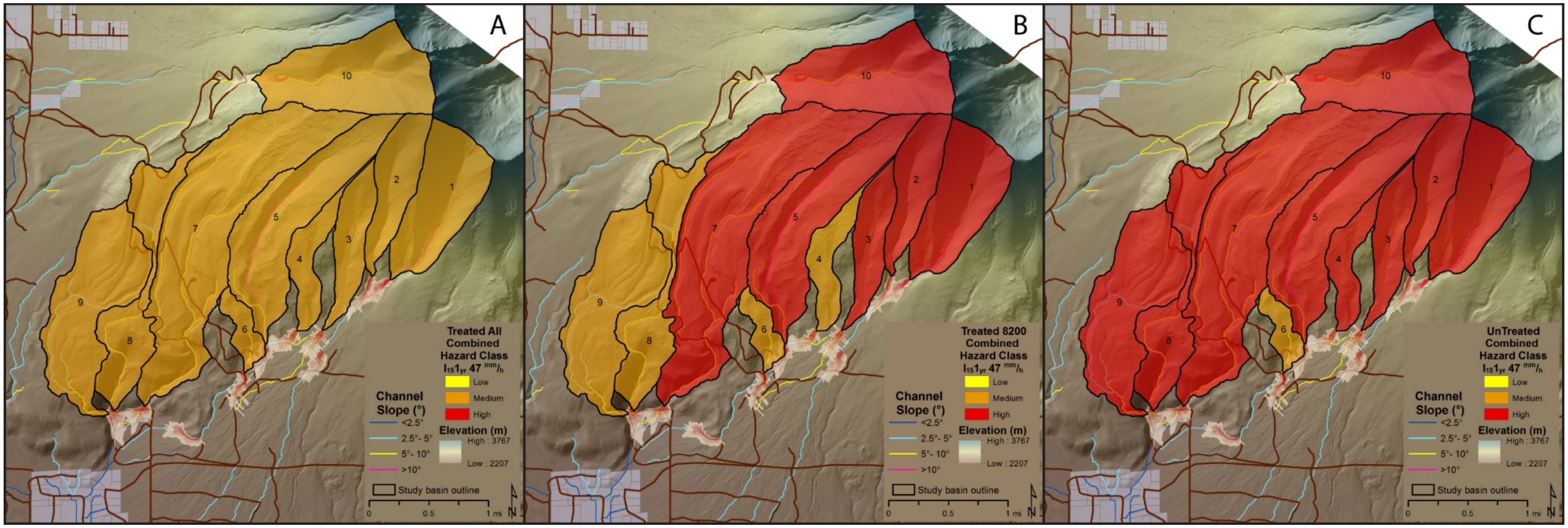

Figure 9. Model results show the combined hazard ranking of the TreatedAll (A), Treated8200 (B), and Untreated (c) scenarios for the I_{15} 1-year storm.

Laharz Modeling

Potential debris-flow inundation zones were assessed in the Fort Valley basins using Laharz (Figure 10, volumes 10^3-10^5 m^3 shown). Laharz deposition points were selected for basins 1-9 based on the channel gradient change at or near the basin mouth, and on loss of channel confinement. Additional deposition points were selected downfan where channels, confined above, lost confinement, and also at the end of debris-flow corridors developed during Task 1. The deposition point for basin 10 was selected above the Snowbowl Ski Area where the channel sharply turns across the terrace. All volume runs are shown although the larger volumes ($10^{4.5}$-10^5) exhibit spatial patterns that appear unlikely (e.g. perpendicular flow from channels across fan surfaces). In general, the patterns of volumes 10^3-10^4 show better correlation with the topography and are probably more reasonable representations of hazard zones from possible flows.

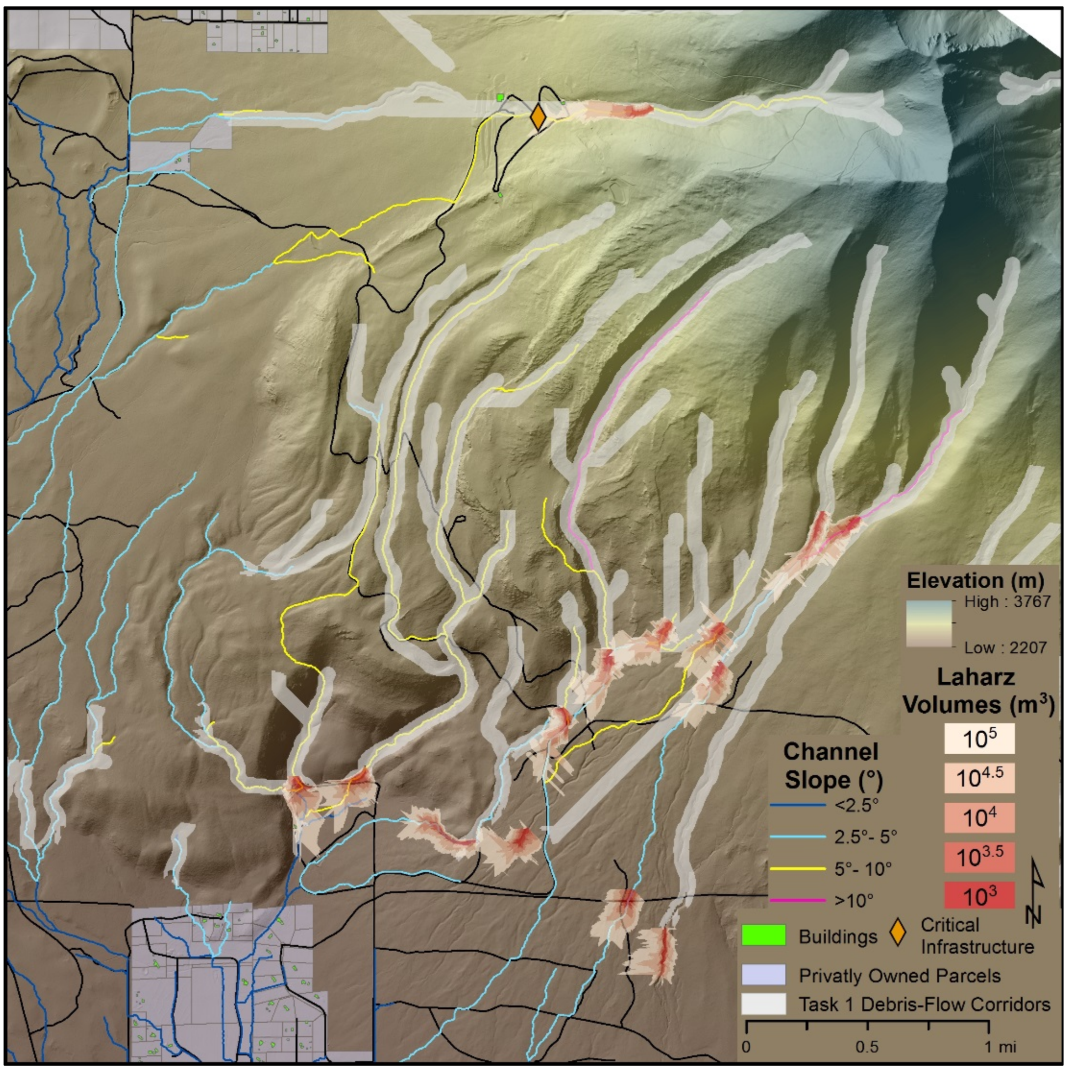

Figure 10. Fort Valley study area with Laharz model results with privately owned parcels (light blue polygons), county-identified buildings (bright green polygons), county-identified critical infrastructure (orange diamonds), and debris-flow corridors identified in Task 1.

Assessments of Potential Hazard Zones to Critical Infrastructure and Developed Areas

Snowbowl Ski Area is located below a bowl on the west side of the San Francisco Peaks and does not flow directly into Fort Valley (Basin 10, Figure 7). While hillslopes in the bowl are steep, channel slopes are 5-10°. LiDAR topography shows terraces along the channel above the ski area. If a post-fire debris flow initiated on the steep hillslopes, there appears to be a good source of transportable material in the terraces that could be eroded and entrained in a flow. Based on observations in the Schultz Fire burned area, debris flows could travel down channels with these slopes. The Laharz hazard zones shows confined and consistent runout patterns for all volumes modeled (Figure 11). If a wildfire burned the slopes above the ski area at high and moderate severity, and a debris flow was initiated during a storm, it is likely that the ski area would be impacted, if not directly by a debris flow, then by flood or hyperconcentrated flows. Depending on where debris-flow deposition begins and the runout distance, various facilities at the Snowbowl Ski Area could be impacted including buildings (Figure 11, bright green polygons) and a cell tower (Figure 11, orange diamond).

Figure 11. Laharz model results at Snowbowl Ski Area with buildings (green polygons) and critical infrastructure identified in the multi-jurisdictional hazard mitigation plan (orange diamond). No private parcels are in this area.

Laharz model results from the 9 basins that flow directly into the meadows of Fort Valley indicate that debris flows are unlikely to directly impact private property or county-identified buildings or critical infrastructure, if deposition begins near points selected in this modeling (Figure 12). Generally the inundation patterns seem reasonable for volumes 10^3 --10^4 but show unlikely lateral spreading patterns (perpendicular to flow) for volumes $10^{4.5}$ -10^5 (Figure 12). While none of the modeled inundation zones approach the developed meadows below, impacts will depend on where deposition actually begins and the characteristics of the flows. High flows across fan surfaces could erode existing channels, or cut new channels, providing additional sediment for delivery into the developed areas. In newly incised and confined channels, breach hydrology (debris jams) could occur resulting in temporary dams, dam breaks, and debris-flows redeveloping and traveling farther downstream. The developed areas will certainly be impacted from sediment-laden flood flows and hyperconcentrated flows that will carry sediment, some of which may be large caliber (large cobbles to small boulders), into the developed areas below. The developed meadows will probably be impacted similarly to those developed areas below the Schultz Fire.

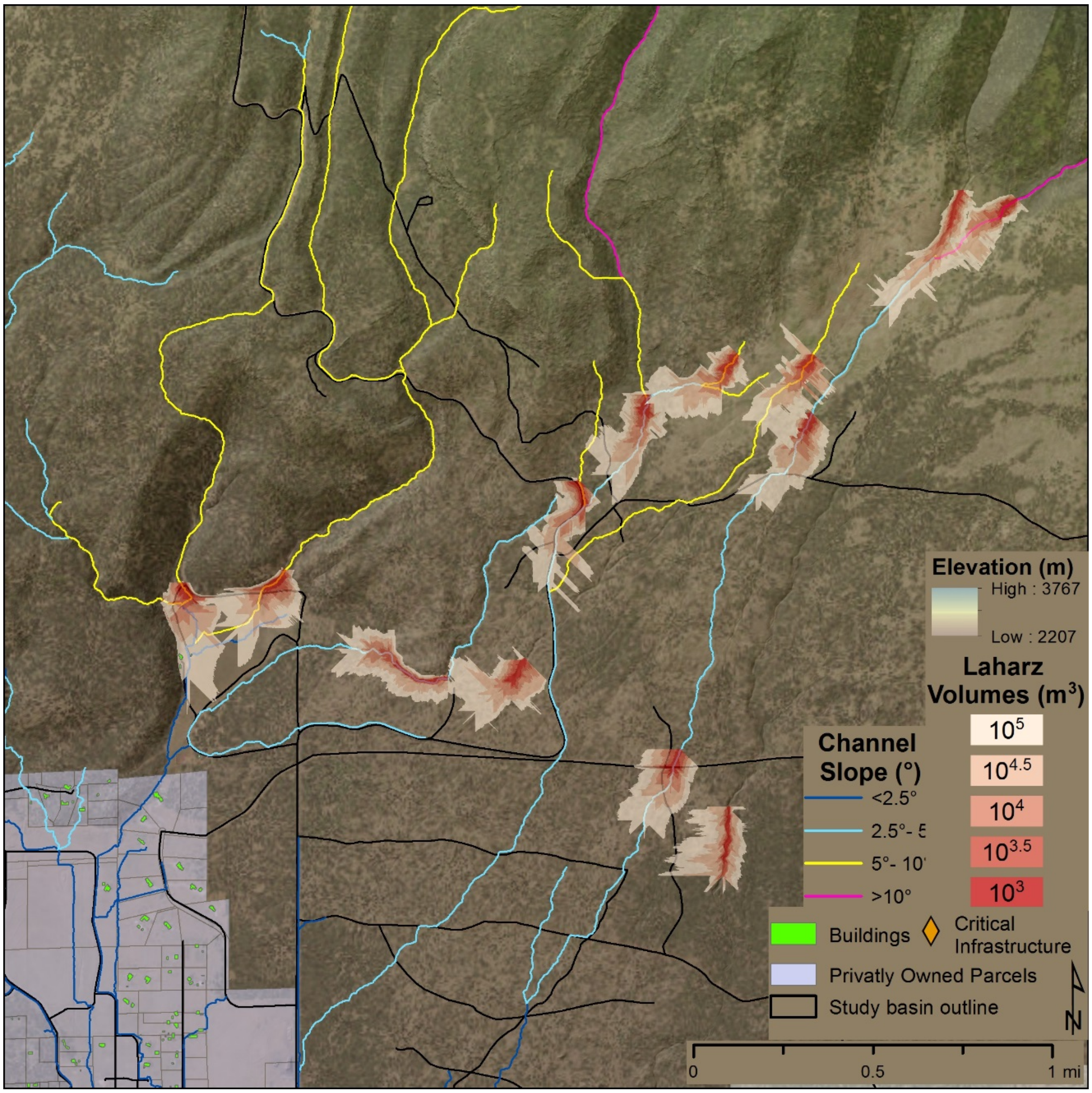

Figure 12. Laharz modeled inundation zones in the Fort Valley study area.

Williams Debris-Flow Assessment

Bill Williams Basins

Twenty-two basins, numbered 1-16 (central and eastern basins) and 21-26 (western basins), were included in the Williams study area (Figure 13, Table 8, Table 9). Selected study basins were based on the modeled burn severity maps of Task 5; therefore not all debris-flow corridors identified in Task 1 are included in this assessment. All basins are located on the north side of Bill Williams Mountain and flow toward the City of Williams. Basin sizes range from 0.1-3.3 km^2 (average = 0.8 km^2), relief ranges from 88-699 m (average = 290 m), and ruggedness ranges from 0.2-0.7 (average = 0.4). The relief and ruggedness numbers indicate that these basins are not as steep as the study basins at Fort Valley and in the Schultz burned area.

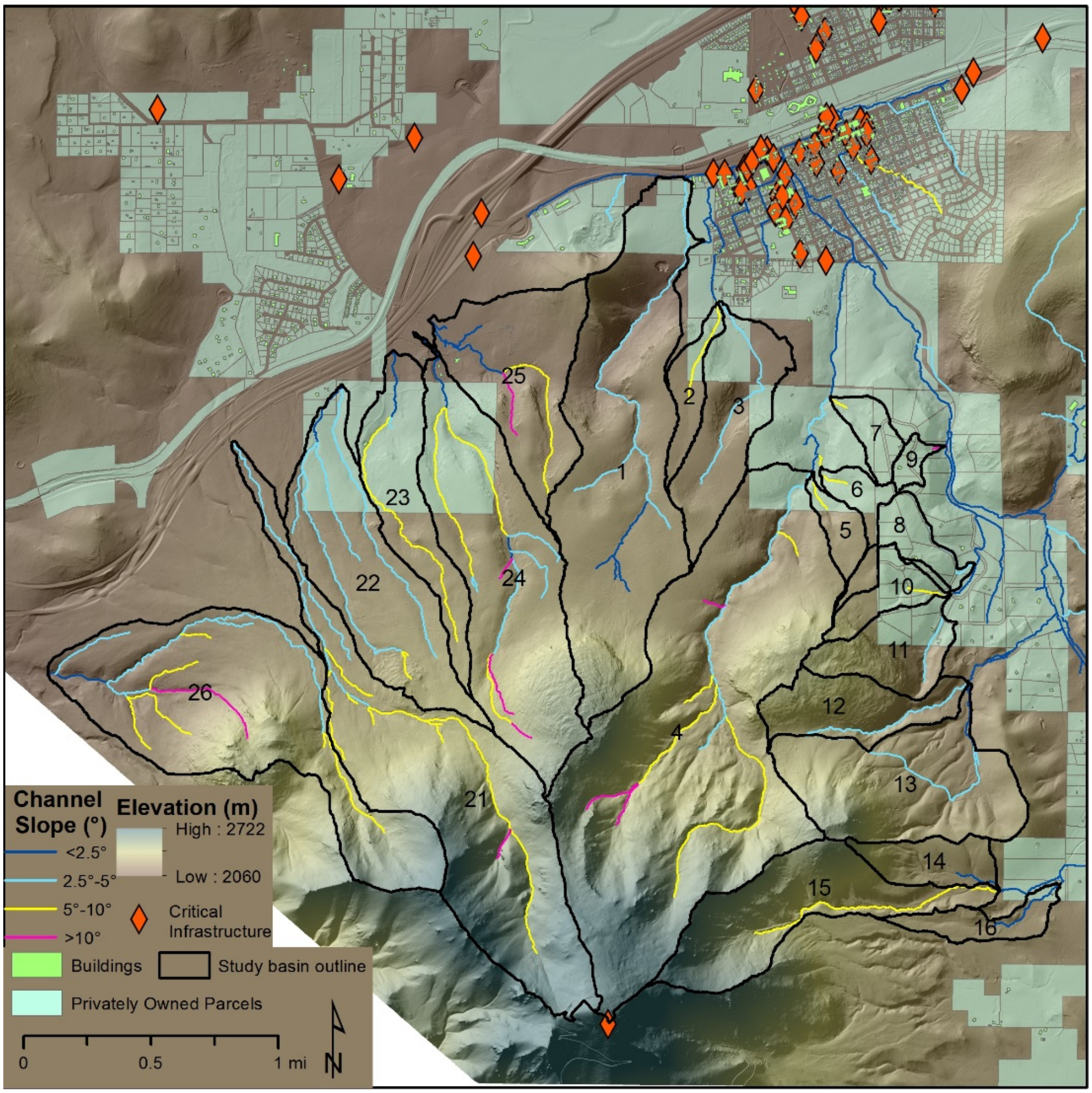

Figure 13. Williams study basins. Basins are numbered 1-16 (central and eastern basins) and 21-26 (western basins). Also shown are privately owned parcels (light blue polygons), county-identified buildings (bright green polygons) and county-identified critical infrastructure (orange diamonds).

Channel slopes are not as steep in the Williams study area as those in the Schultz basins, appearing more similar to the Fort Valley study basins with fewer segments at slopes ≥10° (Figure 13). Some of the steeper segments, however, are located in smaller drainages near the developed areas. The channel of Cataract Creek above City Dam has a channel slope between 2.5°-5°. These gradients are typically considered low enough to result in deposition, and debris-flow deposits were observed along the channel just upstream of City Dam reservoir (Youberg, 2016). Debris-flow deposits were also mapped on channels within this gradient class in the Schultz Fire burn area (Figure 2).

Table 8. Basin morphometric and model parameter data of the Williams study basins Treated burn scenario.

Basin_ID	Area (km2)	Area (mi2)	Basin Relief (m)	Ruggedness	M1_X1	M1_X2	M1_X3	V_X1	V_X2
1	1.95	0.75	439	0.31	0.05	0.22	0.29	20.94	0.12
2	0.16	0.06	132	0.33	0.03	0.17	0.33	11.49	0.52
3	0.57	0.22	159	0.21	0.04	0.26	0.33	12.59	2.76
4	3.31	1.28	694	0.38	0.18	0.27	0.16	26.35	0.07
5	0.12	0.05	227	0.65	0.01	0.18	0.33	15.08	0.09
6	0.11	0.04	113	0.35	0.06	0.24	0.33	10.61	0.12
7	0.13	0.05	106	0.30	0.07	0.25	0.33	10.28	0.17
8	0.20	0.08	204	0.46	0.04	0.27	0.31	14.29	0.05
9	0.06	0.02	94	0.40	0.05	0.27	0.33	9.69	0.15
10	0.18	0.07	218	0.52	0.16	0.30	0.19	14.75	0.32
11	0.35	0.13	232	0.39	0.13	0.28	0.13	15.24	0.37
12	0.40	0.15	211	0.33	0.10	0.27	0.13	14.52	0.89
13	0.96	0.37	309	0.32	0.17	0.22	0.13	17.57	0.19
14	0.23	0.09	255	0.53	0.12	0.19	0.15	15.97	0.68
15	0.79	0.31	480	0.54	0.46	0.37	0.14	21.92	0.16
16	0.18	0.07	88	0.21	0.00	0.15	0.26	9.40	1.56
21	1.87	0.72	699	0.51	0.43	0.41	0.17	26.45	0.54
22	1.00	0.39	261	0.26	0.00	0.15	0.32	16.15	0.43
23	0.57	0.22	234	0.31	0.02	0.19	0.33	15.30	1.23
24	1.45	0.56	469	0.39	0.09	0.28	0.28	21.65	0.73
25	0.81	0.31	149	0.17	0.03	0.20	0.33	12.19	1.57
26	1.77	0.68	609	0.46	0.21	0.22	0.27	24.68	0.00

Probability and Volume Modeling

The Williams study area basins were modeled for debris-flow probability and volumes based on two burn scenarios of Treated and Untreated. The burn severity modeling had previously been conducted by the U.S. Forest Service (Loverich, 2016). Model parameters for each burn scenario are shown in Table 8 (Treated) and Table 9 (Untreated). The I_{15} rainfall intensities (Table 8 and Table 9, columns 2 and 3) needed for a 50% probability that a debris flow would occur in a basin ranges from 27-47 mm h^{-1} (≤1-yr RIs; http://hdsc.nws.noaa.gov/hdsc/pfds/) under the treated scenario (Figure 14A), and 11-44 mm h^{-1} for the untreated scenario (Figure 14Figure 8B, <1-yr RIs).

Table 9. Basin morphometric and model parameter data of the Williams study basins Untreated burn scenario.

Basin_ID	Area (km2)	Area (mi2)	Basin Relief (m)	Ruggedness	M1_X1	M1_X2	M1_X3	V_X1	V_X2
1	1.95	0.75	439	0.31	0.08	0.48	0.29	20.94	0.49
2	0.16	0.06	132	0.33	0.03	0.44	0.33	11.49	-2.12
3	0.57	0.22	159	0.21	0.04	0.48	0.33	12.59	-0.65
4	3.31	1.28	694	0.38	0.27	0.49	0.16	26.35	1.01
5	0.12	0.05	227	0.65	0.06	0.34	0.33	15.08	-2.71
6	0.11	0.04	113	0.35	0.10	0.44	0.33	10.61	-2.40
7	0.13	0.05	106	0.30	0.08	0.48	0.33	10.28	-2.09
8	0.20	0.08	204	0.46	0.05	0.45	0.31	14.29	-1.80
9	0.06	0.02	94	0.40	0.05	0.50	0.33	9.69	-2.93
10	0.18	0.07	218	0.52	0.19	0.46	0.19	14.75	-1.88
11	0.35	0.13	232	0.39	0.20	0.48	0.13	15.24	-1.14
12	0.40	0.15	211	0.33	0.16	0.47	0.13	14.52	-1.00
13	0.96	0.37	309	0.32	0.19	0.51	0.13	17.57	-0.12
14	0.23	0.09	255	0.53	0.14	0.49	0.15	15.97	-1.64
15	0.79	0.31	480	0.54	0.49	0.48	0.14	21.92	-0.39
16	0.18	0.07	88	0.21	0.00	0.52	0.26	9.40	-1.84
21	1.87	0.72	699	0.51	0.43	0.50	0.17	26.45	0.45
22	1.00	0.39	261	0.26	0.00	0.35	0.32	16.15	-0.62
23	0.57	0.22	234	0.31	0.02	0.44	0.33	15.30	-0.84
24	1.45	0.56	469	0.39	0.10	0.50	0.28	21.65	0.21
25	0.81	0.31	149	0.17	0.04	0.48	0.33	12.19	-0.32
26	1.77	0.68	609	0.46	0.26	0.51	0.27	24.68	0.45

Probabilities and estimated volume assessments for the 1-, 2-, and 5-year design storms are shown in Table 10 andTable 11. Results from the 1-year storm show a response difference between the two scenarios. The Treated basins have probabilities ranging from 38%-94% and volumes from <10^3-10^4. The combine hazard class rankings varies from low to high (Figure 15A). The Untreated basins have probabilities ranging from 66%-99% and volumes from 10^3-$10^{4.5}$, with combine hazard rankings varying from moderate to high (Figure 9B). With larger design storms (2- and 5-year shown on Table 10 and Table 11, 10- and 25-year not shown), more basins rank high in the hazard class due to increasing probabilities, but some smaller basins remain moderate because of limited potential debris-flow volumes.

Table 10. Probability and volume model results of the Williams study basins, treated burn scenarios.

Basin_ID	I15_P50% (mm/h)	I15_P50% (in/h)	P_1yr_I15 _45mm/h	EstVol_1yr_I15 _45mm/h (m3)	Combined Hazard Class	P_2yr_I15 _58mm/h	EstVol_2yr_I15 _58mm/h (m3)	Combined Hazard Class	P_5yr_I15 _78mm/h	EstVol_5yr _I15_78m m/h (m3)	Combined Hazard Class	P_10yr_I15 _95mm/h	EstVol_10yr _I15_95mm /h (m3)	Combined Hazard Class
1	39	1.5	63%	3,101	Moderate	85%	3,701	High	97%	4,692	High	99%	5,608	High
2	41	1.6	58%	277	Moderate	82%	331	Moderate	96%	419	Moderate	99%	501	Moderate
3	35	1.4	75%	778	Moderate	92%	929	Moderate	99%	1,177	High	100%	1,407	High
4	39	1.5	63%	8,667	Moderate	85%	10,345	High	97%	13,113	High	99%	15,674	High
5	41	1.6	58%	465	Moderate	81%	555	Moderate	96%	703	Moderate	99%	841	Moderate
6	35	1.4	74%	324	Moderate	92%	387	Moderate	99%	491	Moderate	100%	587	Moderate
7	34	1.3	77%	350	Moderate	93%	418	Moderate	99%	530	Moderate	100%	633	Moderate
8	35	1.4	74%	672	Moderate	92%	802	Moderate	99%	1,017	High	100%	1,215	High
9	34	1.3	77%	237	Moderate	93%	283	Moderate	99%	359	Moderate	100%	429	Moderate
10	36	1.4	70%	710	Moderate	89%	848	Moderate	98%	1,075	High	100%	1,285	High
11	44	1.7	53%	996	Moderate	77%	1,189	Moderate	95%	1,508	High	99%	1,802	High
12	46	1.8	47%	946	Moderate	71%	1,129	Moderate	92%	1,431	High	98%	1,710	High
13	47	1.9	46%	1,722	Moderate	69%	2,055	Moderate	91%	2,605	High	97%	3,114	High
14	52	2.0	38%	749	low	60%	894	Moderate	86%	1,133	High	95%	1,354	High
15	27	1.1	91%	3,566	High	98%	4,256	High	100%	5,395	High	100%	6,449	High
16	51	2.0	39%	223	low	62%	266	Moderate	87%	337	Moderate	96%	403	Moderate
21	25	1.0	94%	8,359	High	99%	9,977	High	100%	12,646	High	100%	15,117	High
22	45	1.8	50%	872	Moderate	74%	1,041	Moderate	94%	1,320	High	98%	1,578	High
23	40	1.6	62%	830	Moderate	84%	991	Moderate	97%	1,256	High	99%	1,502	High
24	35	1.4	75%	3,408	Moderate	92%	4,068	High	99%	5,156	High	100%	6,163	High
25	39	1.5	64%	751	Moderate	85%	897	Moderate	97%	1,137	High	99%	1,359	High
26	34	1.3	76%	5,090	Moderate	93%	6,076	High	99%	7,702	High	100%	9,206	High

Table 11. Probability and volume model results of the Williams study basins, untreated burn scenarios.

Basin_ID	I15_P50% (mm/h)	I15_P50% (in/h)	P_1yr_I15 _45mm/h	EstVol_1yr_I15 _45mm/h (m3)	Combined Hazard Class	P_2yr_I15 _58mm/h	EstVol_2yr_I15 _58mm/h (m3)	Combined Hazard Class	P_5yr_I15 _78mm/h	EstVol_5yr _I15_78m m/h (m3)	Combined Hazard Class	P_10yr_I15 _95mm/h	EstVol_10yr _I15_995m m/h (m3)	Combined Hazard Class
1	19	0.7	93%	4,564	High	99%	5,448	High	100%	6,905	High	100%	8,254	High
2	33	1.3	92%	522	Moderate	98%	623	Moderate	100%	790	Moderate	100%	944	Moderate
3	24	0.9	94%	1,024	High	99%	1,222	High	100%	1,550	High	100%	1,852	High
4	11	0.4	93%	11,146	High	99%	13,304	High	100%	16,864	High	100%	20,159	High
5	32	1.3	85%	674	Moderate	96%	805	Moderate	100%	1,020	High	100%	1,220	High
6	30	1.2	94%	421	Moderate	99%	502	Moderate	100%	637	Moderate	100%	761	Moderate
7	29	1.2	95%	452	Moderate	99%	539	Moderate	100%	684	Moderate	100%	817	Moderate
8	30	1.2	92%	845	Moderate	98%	1,009	High	100%	1,279	High	100%	1,529	High
9	32	1.2	95%	310	Moderate	99%	369	Moderate	100%	468	Moderate	100%	560	Moderate
10	36	1.4	90%	870	Moderate	98%	1,038	High	100%	1,316	High	100%	1,573	High
11	35	1.4	88%	1,212	High	97%	1,447	High	100%	1,834	High	100%	2,192	High
12	35	1.4	85%	1,158	High	96%	1,382	High	100%	1,752	High	100%	2,095	High
13	27	1.1	90%	2,363	High	98%	2,820	High	100%	3,575	High	100%	4,273	High
14	44	1.7	87%	1,113	High	97%	1,328	High	100%	1,683	High	100%	2,012	High
15	18	0.7	96%	3,774	High	100%	4,504	High	100%	5,709	High	100%	6,825	High
16	40	1.6	91%	441	Moderate	98%	526	Moderate	100%	667	Moderate	100%	797	Moderate
21	12	0.5	97%	9,198	High	100%	10,979	High	100%	13,916	High	100%	16,635	High
22	30	1.2	83%	1,645	High	96%	1,964	High	100%	2,490	High	100%	2,976	High
23	29	1.1	92%	1,359	High	98%	1,623	High	100%	2,057	High	100%	2,459	High
24	19	0.7	94%	4,529	High	99%	5,406	High	100%	6,853	High	100%	8,191	High
25	24	0.9	94%	1,096	High	99%	1,308	High	100%	1,658	High	100%	1,981	High
26	17	0.7	97%	7,333	High	100%	8,753	High	100%	11,095	High	100%	13,262	High

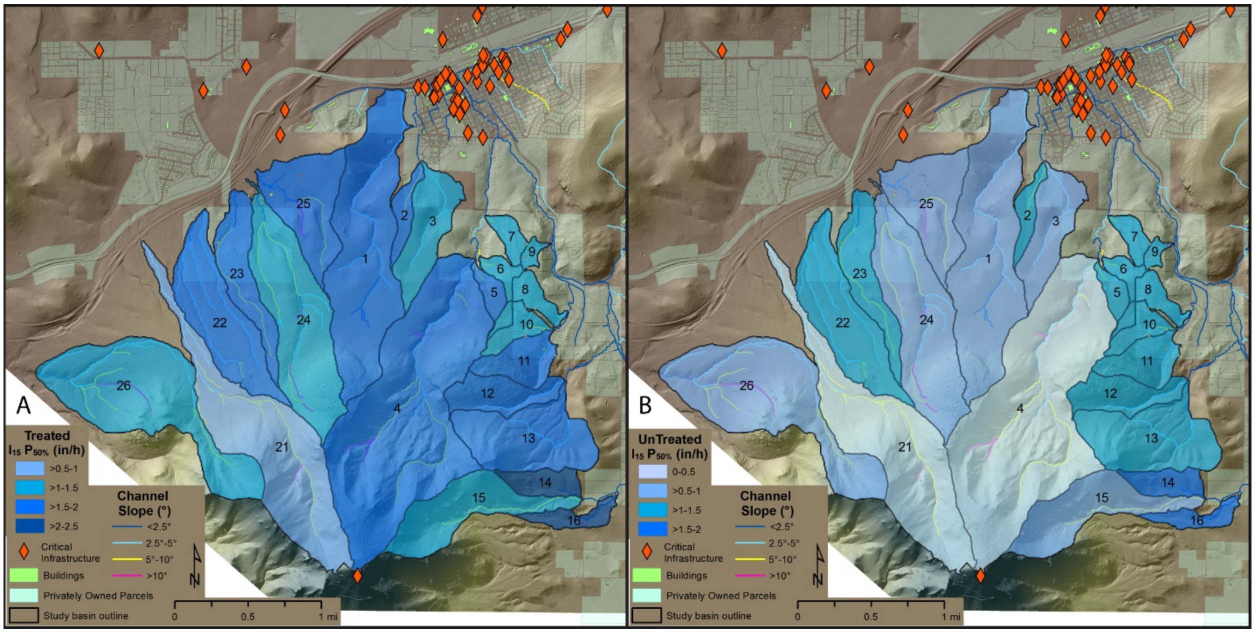

Figure 14. Model results showing the I_{15} rainfall intensity required for a 50% probability of a debris flow for the Treated (A) and Untreated (B) scenarios.

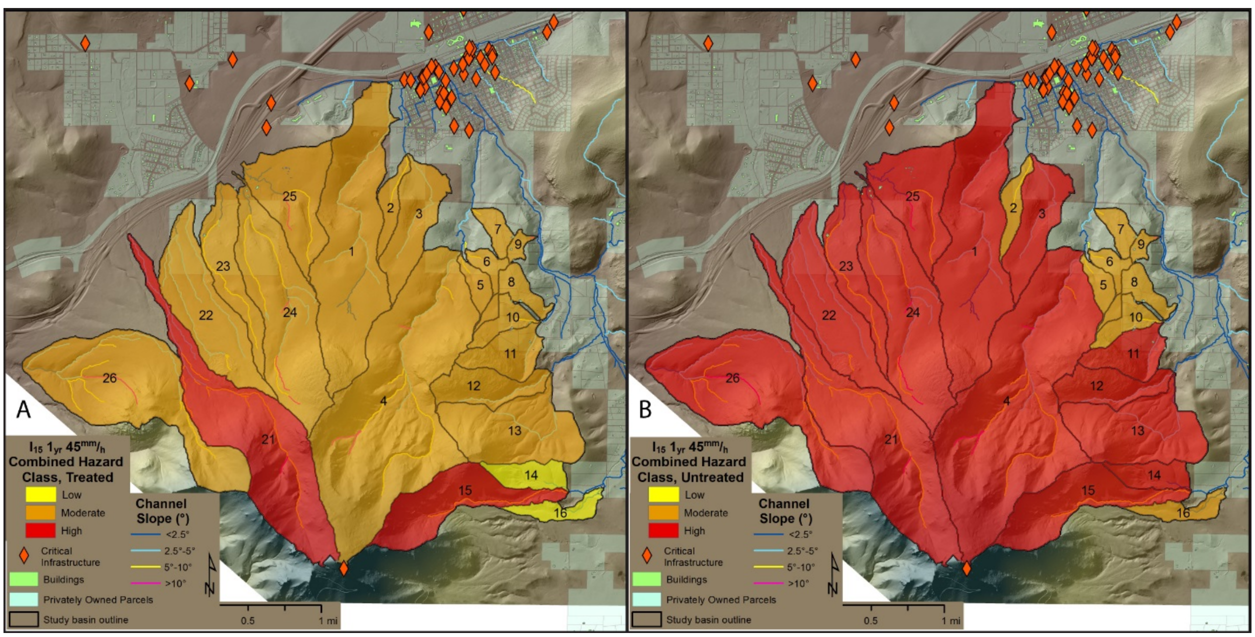

Figure 15. Model results show the combined hazard ranking of the treated (A) and untreated (B) scenarios for the I_{15} 1-year storm.

Laharz Modeling

Potential debris-flow Hazard zones were assessed in the Williams study area using Laharz (Figure 16, volumes 10^3 -$10^{4.5}$ m^3 shown). Laharz deposition points were selected based on channel gradient changes at or near the basin mouth, and on loss of channel confinement. In general, the patterns of modeled inundation correlates with topography, however, smaller volumes of 10^3 -10^4 m^3 are probably more reasonable representations of possible flows.

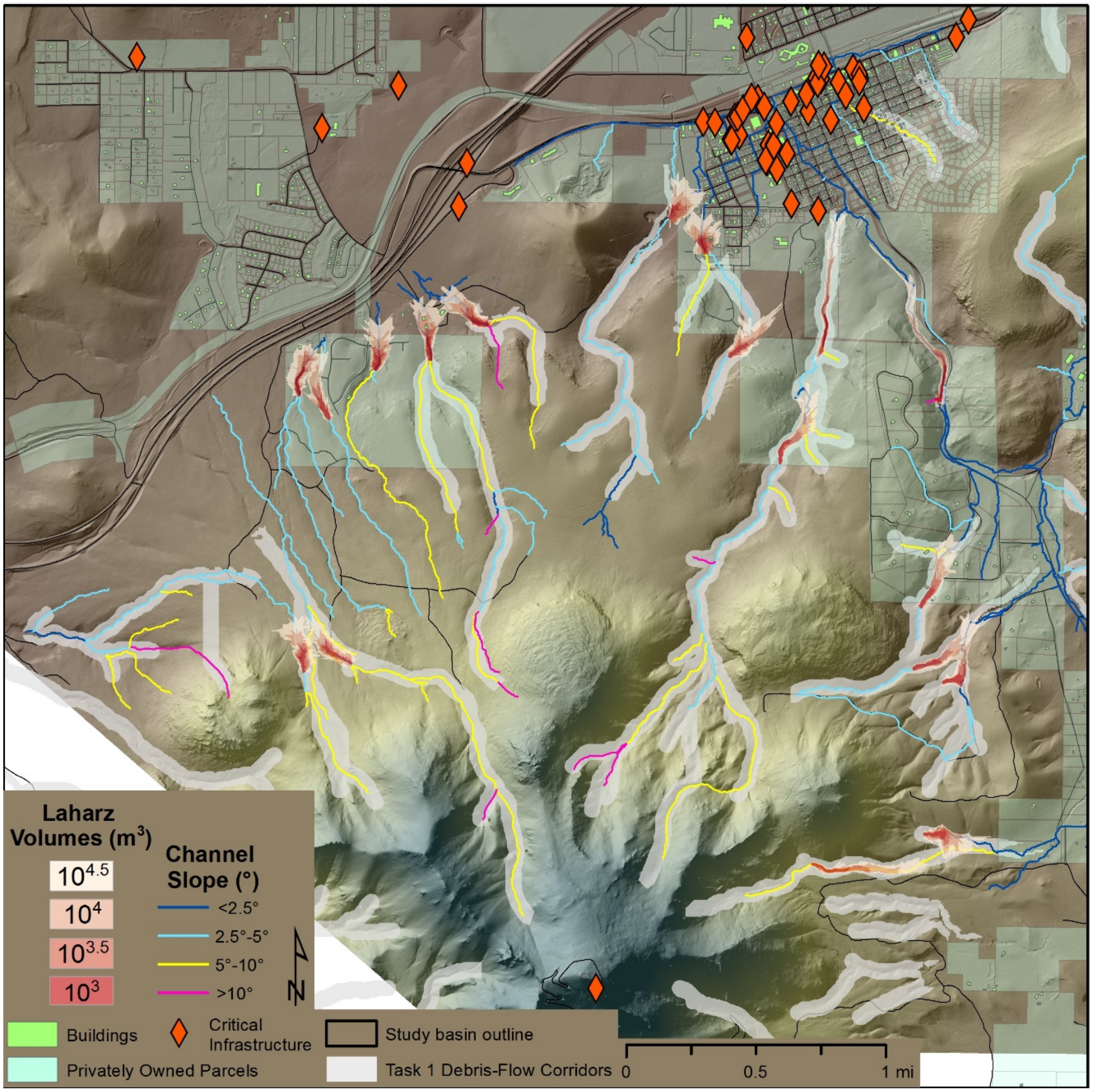

Figure 16. Overview of Laharz model results for the Williams study area with privately owned parcels (light blue polygons), county-identified buildings (bright green polygons), county-identified critical infrastructure (orange diamonds), and debris-flow corridors identified in Task 1.

Assessments of Potential Hazard Zones to Critical Infrastructure and Developed Areas

Laharz model results from the Williams study area indicate that debris flows could directly or indirectly impact developed areas (Figure 17, Figure 18 and Figure 19). Generally, modeled hazard zones seem reasonable for volumes 10^3 --10^4 but show unlikely lateral spreading patterns (perpendicular to flow) in a few basins for volumes $10^{4.5}$. Inundation limits in several basins indicate that debris flows, even those with smaller volumes could impact privately owned property and some county-identified buildings (Figure 17, Figure 18 and Figure 19). Several basins are generally small with lower gradient channels so debris-flow volumes and runout distances are likely to be smaller, however they debouche directly into developed areas. Many of these basins have a combined hazard rand of medium, even for larger storms, due to the limited potential volumes. They pose a larger risk, however, simply because of their proximity to developed areas. Adjacent and downstream areas will also be impacted by subsequent sediment-laden floods and hyperconcentrated flows that could carry large-caliber clasts (large cobbles to small boulders). Downstream developed areas will probably be impacted similarly to those developed areas below the Schultz Fire.

There is a strong likelihood that post-wildfire debris flows could impact City Dam reservoir. In addition to the main tributary of Cataract Creek that flows into City Dam reservoir, there are several small side tributaries at the mouth of the reservoir that could contribute sediment from post-fire sediment-laden floods or debris flows into the reservoir. While it is unlikely there will be sufficient debris-flow volume to overfill City Dam reservoir (capacity ~$10^{5.5}$ m^3), the drinking water will be compromised and extremely expensive to mitigate.

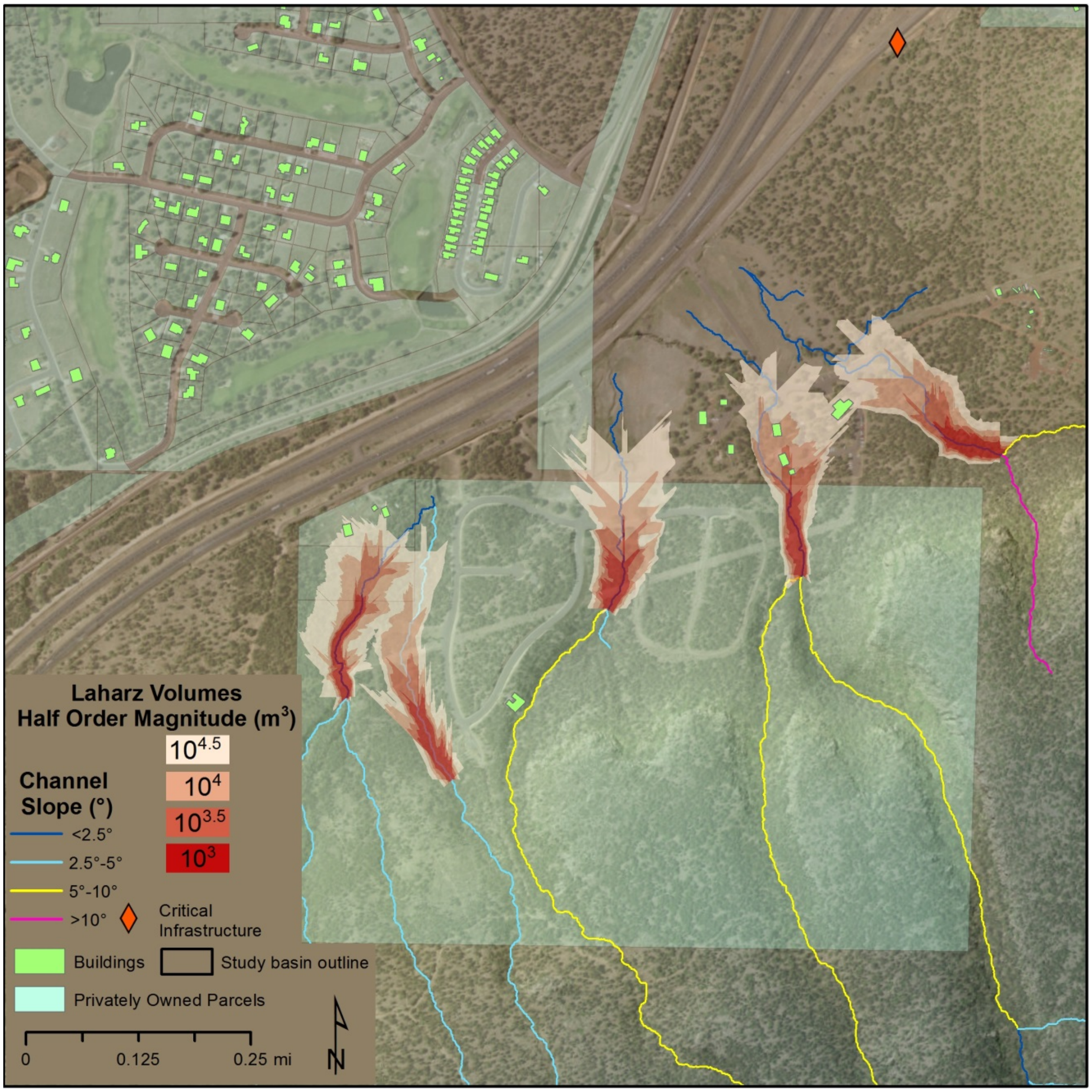

Figure 17. Laharz model results of four western basins in the Williams study area with privately owned parcels (light blue polygons), buildings (bright green polygons) and critical infrastructure identified in the multi-jurisdictional hazard mitigation plan (orange diamond).

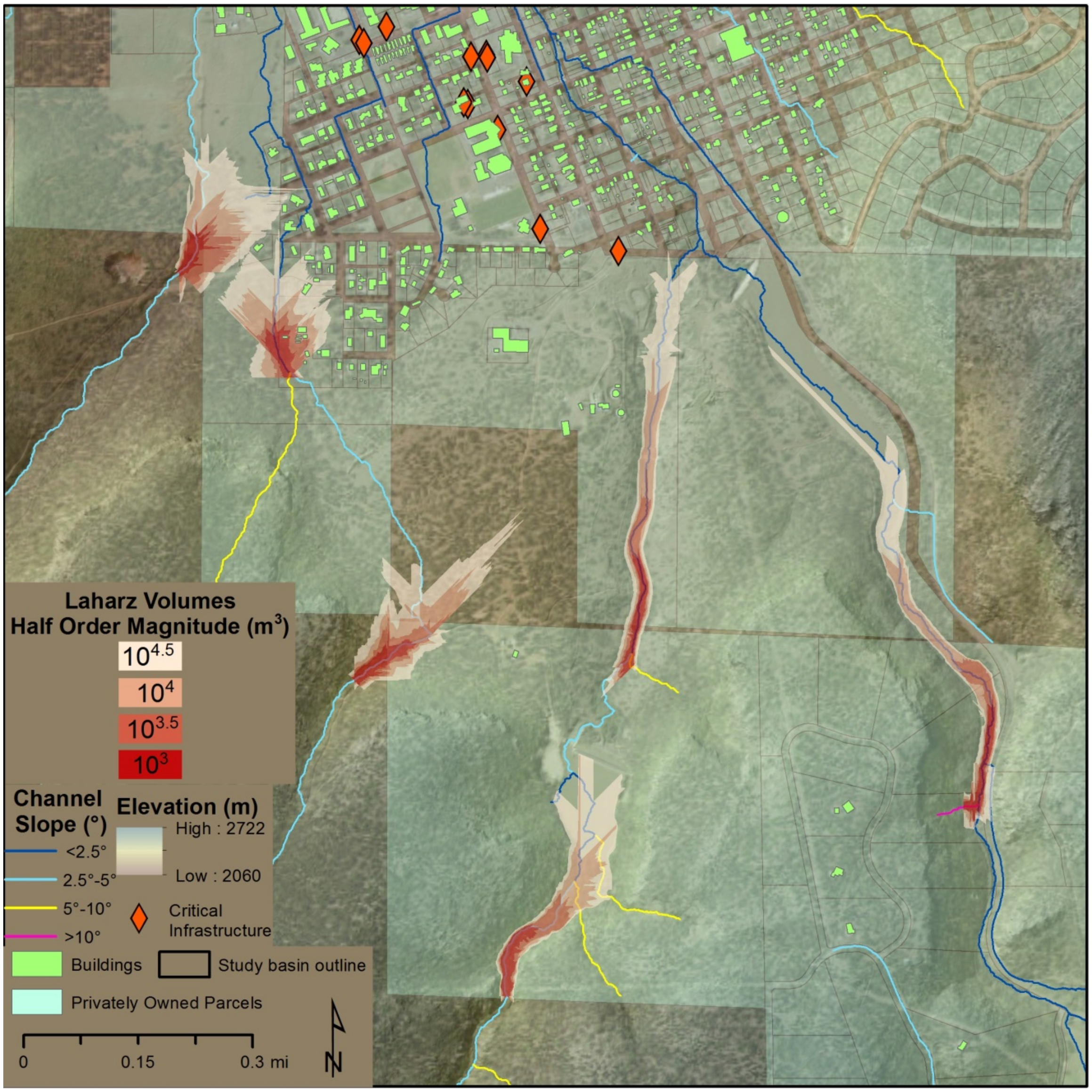

Figure 18. Laharz model results of the central basins in the Williams study area with privately owned parcels (light blue polygons), buildings (bright green polygons) and critical infrastructure identified in the multi-jurisdictional hazard mitigation plan (orange diamond).

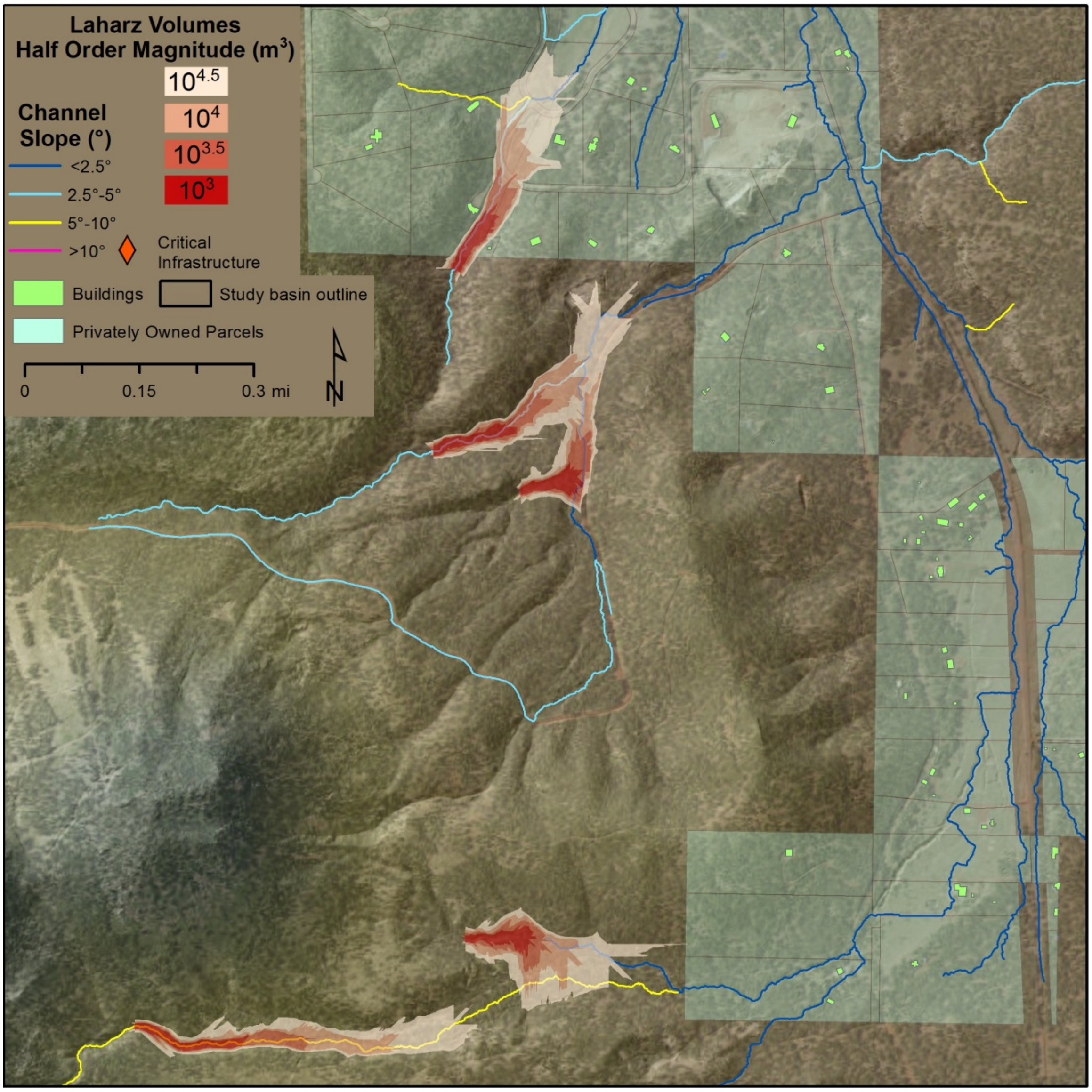

Figure 19. Laharz model results of the southeastern basins in the Williams study area with privately owned parcels (light blue polygons), buildings (bright green polygons) and critical infrastructure identified in the multi-jurisdictional hazard mitigation plan (orange diamond).

DISCUSSION

Data from the Schultz Fire burned area showed that the 2014 USGS debris-flow volume model is reasonable for modeling post-fire debris flows in this area. The 2016 USGS probability model was not tested as it was derived with a large, robust dataset including data from the Schultz Fire. The Schultz Fire data also showed that Laharz sufficiently models hazard zones for debris-flow volumes on the order of $<10^3$ m^3 to about 10^4 m^3. Mapped deposits, and basin and channel morphology was used to compare with modeled results and to inform the modeling in the study areas in terms of debris-flow deposition zones. Schultz Fire burn severity data was also used to develop proxy dNBR burn severity values for use in the pilot study areas.

Not surprisingly, basin sizes, relief and ruggedness values were similar between the Schultz and Fort Valley basins. The Williams basins were slightly smaller with much lower relief and somewhat lower ruggedness values. The ruggedness number has been used elsewhere to help identify potential debris-flow basins (Bovis and Jakob, 1999; Wilford *et al.*, 2004; Kovanen and Slaymaker, 2008). A comparison of slopes and relief in burned basins of Arizona indicated that non-debris-flow basins are not as steep or rugged as debris-flow basins but the relationship is not statistically significant (Youberg, 2014). Within these study areas, the Williams basins are not as steep as the Fort Valley or Schultz basins. Debris-flow deposits were identified in the Williams study area (Cataract Creek), however, showing that debris flows have occurred in the past.

Channel slopes are generally steeper in the Schultz basins than either the Fort Valley or the Williams basins. These data may reflect channel differences between disturbed and undisturbed conditions. Channels in the Schultz basin have been heavily scoured and eroded since the Schultz Fire. In many cases, incision immediately after the fire was 2-4 m (~6-15 ft) deep and channels were scoured to bedrock. In the Fort Valley and Williams basins, channel slopes are generally not as steep and have wide, broad swales that reflect undisturbed conditions with long-term deposition.

Based on mapped data in the Schultz Fire area and the modeling here, it is reasonable to expect that the mostly likely debris-flow volumes would be on the order of 10^3 - $10^{3.5}$ m^3 in both the Fort Valley and Williams basins. There is the potential for larger debris-flow volumes in the larger basins of Fort Valley and Williams, perhaps on the order of 10^4 - $10^{4.5}$ m^3. Basins in the Williams study area are generally smaller than and not as steep as either the Schultz or Fort Valley basins, thus the upper range of likely debris-flow volumes are on the order of 10^3 - 10^4 m^3. Basins in the Fort Valley area may have debris flows with volumes on the order of 10^3 - $10^{4.5}$ m^3. Based on responses within the Schultz Fire burn area, however, volumes on the order of $\leq 10^3$ m^3 are most likely.

CONCLUSION

Post-fire debris flows are very likely in either study area if a wildfire with enough high to moderate burn severity on upper slopes of watersheds should occur. Debris flows are more likely to directly impact Williams and the Snowbowl Ski area, and indirectly impact Fort Valley. Debris flows erode and scour channels as they travel downslope, releasing sediment for additional transport by hyperconcentrated flows and sediment-laden flood flows. While debris flows may not travel far enough to directly impact houses, infrastructure or other critical facilities, they will indirectly impact these areas of concern by eroding and transporting released sediments via hyperconcentrated and flood flows. Downstream areas will see a significant increase in flooding and sedimentation.

There are two significant concerns in the Williams study area: 1) debris flows directly impacting developed areas, and 2) debris flows entering and impacting City Dam reservoir. While the drainages near developed areas are generally small and maybe not quite so steep, they debouche into developed areas and could therefore impact homes or other infrastructure. Based on model results and data from the Schultz Fire basins, it is unlikely that debris flows would have enough volume to fill the reservoir and exit City Dam, but post-fire sediments could significantly decrease the capacity of the reservoir and will certainly compromise water quality (Hohner et al., 2016).

Within the Fort Valley study area, the major concern is hyperconcentrated and flood flows entering developed areas, similar to the post-Schultz-Fire flooding (Figure 20). Channels on the fans at the base of the San Francisco Peaks could erode and evolve with each storm, resulting in unexpected flood pathways and newly eroded channels. Sediment from newly eroded channels could impact developed areas via hyperconcentrated and flood flows, or perhaps by minor debris flows if temporary debris dams form and break in the channels on the fan.

Figure 20. Large amounts, and larger caliber, sediment transported by post-Schultz Fire hyperconcentrated flows.

Another important result from this modeling is that forest treatments can help reduce risks from post-fire debris flows in certain cases. In the Williams study area, forest treatments do reduce risks of post-fire debris flows, at least for the more common storms (≤ 1-yr RIs). In the Fort Valley area, however, modeling suggests that treatment efforts will reduce risks only if treatments can occur on the whole mountain, including within the wilderness area. Debris flows are generated on the steep upper slopes of burned basins which, in this study area is occupied by the Wilderness. Finally, it is important to remember that it is not possible to know through modeling how events will unfold under actual circumstances. Modeling represents what might happen to provide information for planning purposes.

REFERENCES

Benda, L.E., and Cundy, T.W., 1990, Predicting deposition of debris flows in mountain channels: Canadian Geotechnical Journal, v. 27, no. 4, p. 409-417.

Bovis, M.J., and Jakob, M., 1999, The role of debris supply conditions in predicting debris flow activity: Earth Surface Processes and Landforms, v. 24, no. 11, p. 1039-1054.

Brewer, C.K., Winne, J.C., Redmond, R.L., Opitz, D.W., and Mangrich, M.V., 2005, Classifying and Mapping Wildfire Severity: Photogrammetric Engineering & Remote Sensing, v. 71, no. 11, p. 1311-1320.

Cannon, S.H., 2001, Debris-flow generation from recently burned watersheds: Environmental and Engineering Geoscience, v. 7, no. 4, p. 321-341.

Cannon, S.H., Gartner, J.E., Rupert, M.G., and Michael, J.A., 2005, The wildfire; debris flow connection in the U.S. Intermountain West, *in* Geological Society of America, Rocky Mountain Section, 57th annual meeting., Abstracts with Programs - Geological Society of America

Geological Society of America, p. 33-34.

Cannon, S.H., Gartner, J.E., Rupert, M.G., Michael, J.A., Rea, A.H., and Parrett, C., 2010, Predicting the probability and volume of postwildfire debris flows in the intermountain western United States: Geological Society of America Bulletin, v. 122, no. 1-2, p. 127-144.

Cannon, S.H., Gartner, J.E., Wilson, R.C., Bowers, J.C., and Laber, J.L., 2008, Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern Colorado and southern California: Geomorphology, v. 96, no. 3-4, p. 250-269.

Carroll, M.D., 2011, MOvement of channel-borne sediments in teh 2010 Schultz Fire burn area: Flagstaff, Arizona, Univeristy of Northern Arizona, 62 p.

Costa, J.E., 1988, Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows, *in* Baker Victor, R., Kochel, R.C., and Patton Peter, C., eds., Flood geomorphology.: New York, NY, United States, John Wiley & Sons, 113-122 p.

Ebel, B.A., Moody, J.A., and Martin, D.A., 2012, Hydrologic conditions controlling runoff generation immediately after wildfire: Water Resources Research, v. 48, no. 3, p. W03529.

Fannin, R.J., and Wise, M.P., 2001, An empirical-statistical model for debris flow travel distance: Canadian Geotechnical Journal, v. 38, no. 5, p. 982-994.

Gartner, J.E., Cannon, S.H., and Santi, P.M., 2014, Empirical models for predicting volumes of sediment deposited by debris flows and sediment-laden floods in the transverse ranges of southern California: Engineering Geology, v. 176, no. 0, p. 45-56.

Griswold, J.P., and Iverson, R.M., 2008, Mobility Statistics and Automated Hazard Mapping for Debris Flows and Rock Avalanches [electronic resource]. U.S. Geological Survey U.S Geological Survey Scientific Investigations Report 2007-5276, 59 p. http://pubs.usgs.gov/sir/2007/5276/sir2007-5276.pdf

Hohner, A.K., Cawley, K., Oropeza, J., Summers, R.S., and Rosario-Ortiz, F.L., 2016, Drinking water treatment response following a Colorado wildfire: Water Research, v. 105, p. 187-198.

Hürlimann, M., McArdell, B.W., and Rickli, C., 2015, Field and laboratory analysis of the runout characteristics of hillslope debris flows in Switzerland: Geomorphology, v. 232, p. 20-32.

Iverson, R.M., Logan, M., LaHusen, R.G., and Berti, M., 2010, The perfect debris flow? Aggregated results from 28 large-scale experiments: J. Geophys. Res., v. 115, no. F3, p. F03005.

Iverson, R.M., Schilling, S.P., and Vallance, J.W., 1998, Objective delineation of lahar-inundation hazard zones: Geological Society of America Bulletin, v. 110, no. 8, p. 972-984.

Kean, J.W., and Staley, D.M., 2011, Direct measurement of the hydrologic conditions leading up to and during post-fire debris flow in southern California, USA, *in* Genevois, R., Hamilton, D.L., and Prestininzi, A., Debris-Flow Hazards Mitigation, Mechanics, Prediction, and Assessment: Casa Editrice Univ. La Sapienza, Rome, 685-694 p.

Kean, J.W., Staley, D.M., and Cannon, S.H., 2011, In situ measurements of post-fire debris flows in southern California: comparisons of the timing and magnitude of 24 debris-flow events with rainfall and soil moisture conditions: J. Geophys. Res., v. 116, no. F4, p. F04019.

Kean, J.W., Staley, D.M., Leeper, R.J., Schmidt Kevin, M., and Gartner, J.E., 2012, A low-cost method to measure the timing of postfire flash floods and debris flows relative to rainfall: Water Resour. Res., v. 48, no. W05516.

Kovanen, D.J., and Slaymaker, O., 2008, The morphometric and stratigraphic framework for estimates of debris flow incidence in the North Cascades foothills, Washington State, USA: Geomorphology, v. 99, no. 1-4, p. 224-245.

Loverich, J., 2016, Coconino County Post-Wildfire Flood and Debris-Flow Risk Assessment: Fort Valley Fire Modeling and Assignment of Post-Wildfire Curve Numbers: JE Fuller, Inc., Flagstaff, Arizona, 20 p.

Magirl, C.S., Griffiths, P.G., and Webb, R.H., 2010, Analyzing debris flows with the statistically calibrated empirical model LAHARZ in southeastern Arizona, USA: Geomorphology, v. 119, no. 1-2, p. 111-124.

Melton, M.A., 1965, The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona: The Journal of Geology, v. 73, no. 1, p. 1-38.

Meyer, G.A., and Wells, S.G., 1997, Fire-related sedimentation events on alluvial fans, Yellowstone National Park, U.S.A: Journal of Sedimentary Research, v. 67, no. 5, p. 776-791.

Moody, J.A., Ebel, B.A., Nyman, P., Martin, D.A., Stoof, C., and McKinley, R., 2016, Relations between soil hydraulic properties and burn severity: International Journal of Wildland Fire, v. 25, no. 3, p. 279-293.

Moody, J.A., Shakesby, R.A., Robichaud, P.R., Cannon, S.H., and Martin, D.A., 2013, Current Research Issues Related to Post-wildfire Runoff and Erosion Processes: Earth-Science Reviews, v. 122, p. 10-37.

Neary, D.G., Ryan, K.C., and DeBano, L.F., 2005, Wildland Fire in Ecosystems: Effects of Fire on Soil and Water. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-42 General Technical Report RMRS ; GTR-42, 250 p.

Reid, M.E., Coe, J.A., and Brien, D.L., 2016, Forecasting inundation from debris flows that grow volumetrically during travel, with application to the Oregon Coast Range, USA: Geomorphology, v. 273, p. 396-411.

Rickenmann, D., 2005, Runout prediction methods, *in* Jakob, M., and Hungr, O., eds., Debris-flow Hazards and Related Phenomena: Chichester, UK Praxisp.

Schilling, S.P., 1998, LAHARZ: GIS Programs for Automated Mapping of Lahar-Inundation Hazard Zones: U.S. Geological Survey Open-File Report 98-638, Reston, VA, 80 p.

Schilling, S.P., 2014, Laharz_py—GIS tools for automated mapping of lahar inundation hazard zones. U.S. Geological Survey Open-File Report 2014-1073, 78 p. http://dx.doi.org/10.3133/ofr20141073

Staley, D., Kean, J., Cannon, S., Schmidt, K., and Laber, J., 2013, Objective definition of rainfall intensity–duration thresholds for the initiation of post-fire debris flows in southern California: Landslides, v. 10, p. 547-652.

Staley, D.M., Gartner, J.E., and Kean, J.W., 2015, Objective Definition of Rainfall Intensity-Duration Thresholds for Post-fire Flash Floods and Debris Flows in the Area Burned by the Waldo Canyon Fire, Colorado, USA, *in* Lollino, G., Giordan, D., Crosta, G.B., Corominas, J., Azzam, R., Wasowski, J., and Sciarra, N., eds., Engineering Geology for Society and Territory - Volume 2: Springer International Publishing, 621-624 p.

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, v. 278, p. 149-162.

Staley, D.M., Negri, J.A., Kean, J.W., Laber, J.M., 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 2016-1106, 13 p. http://dx.doi.org/ofr20161106

Tarboton, D.G., 2005, Terrain Analysis Using Digital Elevation Models (TauDEM): Logan, Utah State Universityp.

USDA Forest Service, 2010, Schultz Fire Burned Area Emergency Response Report. USDA Forest Service, Coconino National Forest, unpublished report, 167 p.

Wells, W.G., 1987, The effects of fire on the generation of debris flows in southern California: Reviews in Engineering Geology, v. 7, p. 105-114.

Wilford, D.J., Sakals, M.E., Innes, J.L., Sidle, R.C., and Bergerud, W.A., 2004, Recognition of debris flow, debris flood and flood hazard through watershed morphometrics: Landslides, v. 1, no. 1, p. 61-66.

Youberg, A., 2015, Geodatabase of Post-Wildfire Study Basins: Assessing the predictive strengths of post-wildfire debris-flow models in Arizona, and defining rainfall intensity-duration thresholds for initiation of post-fire debris flow. Arizona Geological Survey, geodatabase, excel workbook, report 10 p. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1635

Youberg, A., Koestner, K.A., and Neary, D.G., 2010, Wind, rain and floods: a case study of the June 2010 Schultz Wildfire, Flagstaff, Arizona: Arizona Geology, v. 40, no. 3, p. 1-6.

Youberg, A.M., 2014, Prehistoric and modern debris flows in semi-arid watersheds: Implication for hazard assessments in a changing climate: Tucson, University of Arizona, dissertation, 235 p.

Youberg, A.M., 2016, Coconino County Post-Wildfire Flood and Debris Flow Risk Assessment, Pre-Fire Hydrologic Modeling and

Debris Flow Risk Assessment Summary: Arizona Geological Survey, Tucson, Arizona, 9 p.